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INVESTIGATION INTO THE POSSIBLE CAUSES OF HYDRAULIC STRUCTURE COLLAPSE ALONG ALKALERI – GOMBE ROAD, BAUCHI.

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ABSTRACT

Hydraulic structures are man-made waterworks that are built across, along, or beside a body of water that interacts with rainfall run-off to store and distribute water (e.g., bridges, roadside channels, and culverts). Among other things, the performance of a hydraulic structure depends on the strength and durability of its components as well as the nature of the soil beneath it. Because hydraulic structures cannot indefinitely withstand all natural forces and hazards, including time-related degradation of materials, they have a limited service life. Failure in hydraulic structures could be a natural or human error that leads to a progressive collapse, causing property damages and loss of lives. With the goal to determine the potential cause or causes of failure of the hydraulic structures along the Alkaleri-Gombe road, this study examined the following aspects: soil characteristics (index and strength properties) using well-known conventional laboratory methods; integrity evaluation of the hydraulic structures and their embankments using the non-destructive rebound hammer method; and hydrologic analysis of the locations. According to the AASHTO classification system, the soil samples range from A2-6 to A5, and according to USCS, they are equally classified as CL, CH, CH, and CH. The structures are strong enough to withstand loading, as demonstrated by the results of the in-situ rebound hammer tests. However, the hydrological analysis indicates that the geometry and the high runoff that was recently recorded between 2021 and 2024 were the main causes of the failure of the hydraulic structures that were installed at these locations. The subsequent reconstruction of these hydraulic structures should therefore take into account an upgrade or adequate geometry, with larger dimensions of the components. Additionally, meteorological stations should be established with proper recording and documentation of both hydrological and meteorological data in order to estimate the accurate design flood in various areas throughout the nation.

KEYWORDS: *Hydraulic Structures, Unconfined Compressive Strength, California Bearing Ratio, Maximum Dry Density, Optimum Moisture Content.*

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1.0 INTRODUCTION

A hydraulic structure is man-made waterworks erected over, along or beside a water body, in fluvial, estuarine and coastal settings; that interacts with the rainfall run-off, to store and transport water. The dangers and occurrence of bridge collapse are connected not only to natural environmental conditions and technical design but also to land-use intensity Rafi *et al.* (2019).

The main purpose of hydraulic constructions like culverts, bridges, and roadside canals is to move water from upstream to downstream (Hubert, 2021). The two main drainage systems that move storm water beneath highways are culverts and bridges. They are designed and installed to keep water from overflowing and crossing the road during more frequent storm occurrences, which makes it unsafe for cars to drive. Facilities for collecting, transporting, and removing water from the highway are part of the drainage design (F.M.W, 2013). The use of hydraulic structures can reduce initial and future maintenance costs by changing the characteristics of the flow to fit the project needs, and by reducing the size and cost of related facilities. It is, however, necessary to adapt the design of the drainage structures in such a way that the water is safely disposed and effectively harvested downstream (Hulya and Alf, 2021). Hydraulic structures have an important role in the past, present and future life, so that the stability of these structures prevents the development or growth of any problem which reflect on the required functionality from these structures (Jibrin *et. al.,* 2018).

Ichiro *et. al.* (2022) revealed that many culverts have deteriorated beyond their useful service life resulting in failures that expose motorists to a variety of safety hazards. Bridge collapse has dramatic consequences in every nation's transportation system. In addition to casualties and loss of lives, the disruption in the service results in tremendous effects on the economic growth especially in developing countries. In countries, where the standard of design is well established and the method of construction follows a rigorous quality control process, bridge collapse is a rare occurrence. However, in many developing countries, bridges are constructed with less quality control procedures and strict adherence to the design code (Gang, 2017).

Analyzing historical failures can be beneficial in reducing the occurrence and likelihood of future failures. The occurrence of bridge failures is a critical issue in the field of infrastructure, which often results in substantial financial damages and human casualties. Adequate drainage is essential in the design of highways since it affects the highways serviceability and usable life (Duy *et al.,* 2018).

Construction deficiency can cause serious damage to hydraulic structure leading to total failure of the structure and embankments. Serious construction deficiencies have been reported for tidal sluices. Inadequate construction supervision is a major bottle necks in the good quality structure. In fact, many hydraulic structures failure due to construction deficiency can be cited.

According to FMW (2013), design of hydraulic structures is guided by manuals and standards and mechanism of operation and maintenance is laid down during the planning phase. However, inadequate field data results in inadequate planning and design of the structures. Construction of hydraulic structures is done under the supervision of concerned professionals.

This research work was carried out to investigate the possible cause(s) of hydraulic structures' failure along Alkaleri – Gombe road. It provides evidence – based possible reasons of the cause(s) of the failures. Findings of this investigation and analyses can be used

to provide a more comprehensive description of the performance of bridges during extreme flood events.

2.0 METHODOLOGY

This research methodology is divided into two phases: field testing (in-situ) and laboratory testing. The field testing includes locating and mapping all the hydraulic structures along Alkaleri – Gombe road (topographical mapping) including their GPS locations, identifying their conditions and then performing a required in-situ integrity assessment test on failed hydraulic structures. Both disturbed and undisturbed samples were collected for laboratory testing. Samples from the foundation of a failed hydraulic structure were taken to the soil laboratory, Abubakar Tafawa Balewa University (ATBU) Bauchi for testing.

Integrity assessment using non–destructive test was performed in–situ on the reinforced concrete elements. Specifically, rebound hammer tests were carried out according to BS 1881–part 202-86 standard method. Soil samples were obtained from the foundation of an existing hydraulic structure at a depth immediately below the foundation level. Three samples were collected from each foundation of an existing hydraulic structure. Tests on the three samples were conducted in accordance with BS 1377 (l990). Laboratory tests for identification, classification, preparation of samples and Atterberg limits were conducted on the natural soil. Other tests conducted includes Compaction test using the West African Standard (WAS), Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests. The tests were carried out on the natural soil to characterize and determine its strength properties.

Catchment area were determined from topographic maps and field surveys to account for major land use changes.Analysis of results at different points within the storm water drainage structures assessed their effects on the flood flows. The principal physical catchment area characteristics affecting the relationship between rainfall and runoff are land use, land cover, soil types, and land slope. The dimensions of the culverts, length, depth and width or breadth of the bed of the channels were measured with the aid of 100-meter tape.

In rational method, runoff estimation or design flow depends on the intensity of rainfall; storm frequency, size, slope, shape and imperviousness of the drainage area and the probable development of the area. Runoff estimates is related to the rainfall intensity by the formula:

$$Q = 0.278CIA \quad \ldots (1)$$

Where;

Q is the quantity of runoff in cubic meters per second (m3/s)

C is the coefficient of runoff expressed as a percentage of imperviousness of the watershed surface

I is the intensity or rate of rainfall expressed in millimeters per hour for a certain time of concentration.

A is the area of the watershed in square kilometers

The runoff coefficient, C, is the most subjective variable of the rational method. The selection of appropriate value of C for a particular catchment requires inspection of the site. The value of C used was established from guidance provided with further guidance on permeability of common materials. For rural areas, C is calculated by aggregating individual values for the catchment surface slope, catchment permeability and vegetation

$$C = Cs + Cp + Cv \quad \ldots (2)$$

The Kerby formula is recommended for the calculation of tc in this case (FMW, 2013). It is only applicable where the slope is fairly even.

$$t_c = \left(\frac{0.87L^2}{1000S_{av}}\right)^{0.385} \quad \ldots (3)$$

Where,

Tc is the time of concentration (hours)

r is the roughness coefficient

L is hydraulic length of catchment measured along the path from the catchment boundary to the point of interest.

3.0 RESULTS AND DISCUSSION

3.1 Location of the Failed Hydraulic Structures

Table1 shows the GPS locations of the failed hydraulic structures while figure 1 shows the geographical map of the locations. It was observed physically that all the failed hydraulic structures are in their total failure modes with little or no unit in its usable capacity. Alternative means to cross the water were developed by road users.

Table 1: GPS locations of Kalajanga, Bara and T/Turmi

Location	Longitude	Latitude
Kalajanga (Locations A, B, C)	10’ 19’’ 35’’’ N	10’ 38’’ 24’’’ E
Bara (Location D, E, F)	10’ 22’’ 35’’’ N	10’ 43’’ 41’’’ E
Tashanturmi (G, H)	10’ 21’’ 46’’’ N	10’ 45’’ 22’’’ E



Figure 1: Topographical Map of Alkaleri – Gombe road.



Figure 2: Kalajanga, Bara and T/Turmi Positions

From Figure 1, all the rivers originated from the Yankari Games reserves around Kolmani area and Figure 2 showed clearly the three locations. The results of geotechnical investigation (laboratory tests) showed that the soil samples all appeared whitish brown in colour.

3.2 Soil Classification and Consistency Result

The index properties of the foundation soil at each location are shown in Table 2.

Table 2: Index Properties of the Foundation Soil at Each Location

Property	Kalajaga			Bara			T/Turmi	
	A	B	C	D	E	F	G	H
Natural moisture content (%)	13.0	7.9	16.1	6.2	8.7	3.2	8.4	18.2
Liquid limit (%)	27	31	28	23	22	26	26	25
Plastic limit (%)	11	15	10	0	7	7	8	7
Plasticity index (%)	16	16	18	23	15	19	19	18
Specific gravity	2.6	2.55	2.57	2.44	2.62	2.59	2.56	2.67
Percentage passing No. 200 sieve	15.1	15.6	35.9	23.4	24.5	21.5	29.8	22.5
Percentage Sand fraction (0.075 – 4.76mm)	46	43	44	47	45	41	42	44
Percentage silt fraction (<0.075mm)	20	18	21	18	20	19	23	22
Percentage clay fraction (<2µm)	33	38	35	35	35	40	35	34
Maximum dry density WAS (mg/m3)	2.04	2.12	2.08	1.97	1.89	1.90	2.02	1.97
Optimum moisture content WAS (%)	11.8	12.0	10.7	10.2	13.0	12.6	11.0	12.0
AASHTO Classification	A-2–6	A- 2 -6	A – 4	A-2– b	A - 2 –4	A-2-5	A-2 –5	A-2–5
USCS Group Symbol	SC	SC	SC	SM	SMSC	SMSC	SC	SMSC
USCS Group Name	Clayey Sand	Clayey Sand	Clayey Sand	Silty Sand	Clayey Sand	Clayey Sand	Clayey Sand	Clayey Sand

The laboratory tests conducted on the soil showed that natural moisture contents are 13.0, 7.9, 16.1, 6.2, 8.7, 3.2, 18.4 and 18.2 %; with specific gravity values of 2.6, 2.55, 2.57, 2.44, 2.62, 2.59, 2.56 and 2.67 at locations A, B, C (Kalajanga), D, E, F (Bara) and G and H (T/Turmi) respectively. All the soil samples at these locations are classified as A-2-6 to A5, groups according to the American Association of State Highway and Transportation Official, AASHTO classification (AASHTO, 1986) and all belong to CL according to the Unified Soil Classification System (USCS) respectively (ASTM, 2000).

The consistency limit results of the soil samples at various locations are below 35% which clearly indicates a low affinity to water by the soil in these locations. The maximum liquid limit specified by the Federal Ministry of Works and Housing for soil to be used as sub-grade materials is 40%. Thus, all the liquid limit of soil samples are less than 40% and therefore the soils under consideration may be used as road and embankment construction material. The soil samples are well graded with low silt content.

According to Obiefuna and Adamu (2012), the soils from the north-eastern Nigeria indicated moderate to high plasticity, and are easily friable.

3.3 Compaction Result

The result of maximum dry density and Optimum moisture content are presented in Table 3.

Table 3: MDD and OMC Results

Location	A	B	C	D	E	F	G	H
MDD (WAS) (mg/m^3)	2.04	2.12	2.08	1.97	1.89	1.90	2.02	1.97
OMC (WAS) (%)	11.8	12.0	10.7	10.2	13.0	12.6	11.0	12.0

Generally, for all the samples at all locations from A to H, the maximum dry density (MDD) of the samples achieved the minimum value at lower specific gravity of the soil. These results agreed with researchers such as Sadeeq and Salahudeen, (2018) and Akinleye *et al*. (2021). The properties of the subgrade soil obtained showed that the studied soil samples conform to the requirements for subgrade soil as recommended in the FMW, (1997).

3.4 Unconfined Compressive Strength (UCS) Result

The UCS results in all the locations are presented in Table 4.

Table 4: Unconfined Compressive Strength Results

Curing days	UCS (kN/m²)							
	A	B	C	D	E	F	G	H
7	283	276	279	286	288	281	277	288
14	312	301	312	299	315	317	309	303
28	340	341	332	337	329	340	347	338

The UCS test considered the lateral confining pressure to be equal to zero. It is seen that the UCS values of the soil samples at the three locations ranges from 276 to 288; from 301 to 317 and from 329 to 347 having cured for 7, 14 and 28 days respectively. These agree with Salahudeen *et al.* (2019).

3.5 CBR (Soaked and Unsoaked) Result

The CBR result for both soaked and unsoaked are shown in Table 5

Table 5: California Bearing Ratio (CBR Soaked and Un-soaked)

Sample location	California bearing ratio (%) A	B	C	D	E	F	G	H
Soaked (%)	38	39	36	36	41	41	41	43
Unsoaked (%)	85	94	86	82	93	82	89	91

The California Bearing Ratio (CBR) results for un-soaked soil samples presented in Table 5 shows that all the samples meet the requirement of the Nigerian Federal Ministry of Works and Housing (2010) recommended value of 80 % CBR value for the Base-course, it can only serve as an excellent material for sub-grade and sub-base (Vincent *et al*., 2020)

3.6 In – Situ Integrity Assessment of Cell Box Culvert at Kalajanga Village.

In–situ Integrity Assessment (Rebound hammer test) conducted on different elements of the culverts under wet test condition and for both vertical and horizontal orientations, are shown in Tables 6 – 7.

Table 6: Cell Box Culvert Rebound Hammer Reading: Wall

S/N	Rebound Reading	Test Conduction	Test Orientation	Compression Strength (N/mm^2)
1	30	Wet	Horizontal	25
2	40	Wet	Horizontal	42
3	41	Wet	Horizontal	44
4	38	Wet	Horizontal	39
5	37	Wet	Horizontal	37
6	37	Wet	Horizontal	37
7	38	Wet	Horizontal	39
8	40	Wet	Horizontal	42
9	44	Wet	Horizontal	49.5
10	40	Wet	Horizontal	42

Table 7: Cell Box Culvert Rebound Hammer Reading: DECK

S/N	Rebound Reading	Test Conduction	Test Orientation	Compression Strength (N/mm^2)
1	53	Wet	Vertical	67
2	39	Wet	Vertical	40
3	56	Wet	Vertical	70
4	43	Wet	Vertical	48
5	44	Wet	Vertical	49.5
6	40	Wet	Vertical	42
7	44	Wet	Vertical	49.5
8	32	Wet	Vertical	28
9	53	Wet	Vertical	67
10	42	Wet	Vertical	46

The minimum compressive strength value found was $28N/mm^2$ which is above the expected value of $25N/mm^2$. This indicated that deviation has not occurred on the concrete production during the construction of the culverts. There are variations in the estimated compressive strength of the concrete among the different members of the pier wall. Some members exhibited lower estimated compressive strength values ranging from 25 to 37

N/mm², while other members display higher estimated compressive strength values ranging from 38 to 70 N/mm².

3.7 Hydrologic Analysis

The catchment area cover and land use include both agricultural and non-agricultural uses. Items such as type of vegetation, water surfaces, roads, roofs, etc. are all part of the land use.

Table 8 shows the discharge calculated parameters using the rational method as suggested by the FMWHM, (2013).

Table 8: Rational Peak Flood for the Design Flood

Location	Area (km2)	Length (m)	Coefficient of runoff (C)	Time of concentration tc	Peak Discharge (m^3/s)	Quantity of runoff Q (m^3/s)
Kalajanga	3.12	714	0.3	0.74	7.0	26.02
Bara	4.34	625	0.3	0.73	6.9	32.20
T/Turmi	1.25	821	0.3	0.76	7.3	10.25

The times of concentration for the culverts were calculated using equation (3). Times of concentration were found to be 0.73, 0.74 and 0.76 for 50 years flood events at the three locations respectively. Using these values, the peak discharge was determined as 6.9, 7.0 and 7.3m^3/s respectively for the return period. On the basis of these computations, the existing culverts failed due to inadequate dimensions. Collapse in hydraulic structures is frequent all over the world. According to Cristopher and Wesley (2018), out of 428 hydraulic structures that collapsed between 1992 to 2014 in the USA, there are 237 (55.4%) bridges that have collapsed due to a hydraulic-induced failure.

4.0 CONCLUSIONS AND RECOMMENDATION

The following conclusions are drawn based on the investigation carried out,

(i) The physical characteristics of the area compromised of wetlands and swamps, permeable soils and light bush with farmlands having an annual rainfall between 840 – 1085mm.

(ii) The soil samples range from A2-6 to A5 based on AASHTO classification system, and are equally characterized as CL, CH, CH and CH respectively according to USCS. Equally, the structures have adequate strength to resist both the self-weight as well as any imposed loading on the structures. It can thus, be concluded that the geometry as well as the excessive runoff recorded recently were responsible for the failure of the installed hydraulic structures at these locations.

(iii) The soil classification coupled with the low values of MDD, UCS and CBR recorded for the soil samples showed that soil can be used as subgrade material and meet the standard recommendation for most geotechnical construction works especially for sub-base and base courses in highway construction. Thus, the overall strength results of the soil samples at different locations indicate that the soil conditions may be adequate to accommodate the superimposed loads due to vehicles and other materials.

(iv) On the basis of analysis of the time of concentration for the culverts, the existing culvers failed due to inadequate dimensions.

(v) The In-situ rebound hammer test on the installed hydraulic structures showered that the structures have adequate strength to resist both the self-weight as well as any imposed loading on the structures.

(vi) From the hydrological analysis, it can be concluded that the geometry as well as the excessive runoff recorded recently were responsible for the failure of the installed hydraulic structures at these locations.

The following recommendations are drawn based on the investigation carried out,

(i) This study recommends that physical characteristics of soil should be studied for proper design parameters of hydraulic structure at these locations. Thus, detail investigations such as physical assessment, geo-technical investigations as well as hydrological are necessary for any proposed newly hydraulic structure at any location.

(ii) Adequate geometry should be considered in subsequent reconstruction of these hydraulic structures, with larger dimensions of the components. Thus, in order to estimate the accurate design flood in different areas across the country, meteorological stations should be established with proper recording and documentation of both hydrological and meteorological data.

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