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The Use of Multi-Criteria Parameters for Bridge Maintenance Prioritization and Maintenance Categorization Options in Tanzania

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ABSTRACT

A bridge is a structure across physical obstacles like valleys, rivers, seas, oceans, lakes, roads, and railways. Its components get damaged when exposed to harsh conditions resulting from various causes, which reduces its lifetime. Maintenance is necessary to prolong its remaining service life once it gets damaged. Successful maintenance depends on various factors, including the availability of funds, the effectiveness of condition assessment, and other damaging factors. Many developing countries face a scarcity of financial resources to restore the functions of bridges at network levels. In order to have a better plan for financial resources, it is important to devise a methodology for prioritising bridge maintenance at the network level. This research used parameter ratings to determine the Bridge Prioritisation Index (BPI) derived from selected parameters affecting bridge performance. The parameters considered for this study are bridge defects, earthquakes, traffic actions, and scouring potential. The prioritisation indices were determined from four bridges, which are Kikwete, Mvomero, Unkuku, and Nyahua. The bridge ratings from bridge condition indices were determined to be 2 for Unkuku and Mvomero bridges and 1 for Kikwete and Nyahua bridges. Scour ratings from scour indices were determined to be 4 for the Unkuku, Nyahua, and Mvomero bridges and 3 for the Kikwete bridge. Seismic ratings from seismic indices were determined to be 1 for all four bridges, and traffic ratings from traffic indices were determined to be 3 for Unkuku and Nyahua bridges and 2 for Mvomero and Kikwete bridges. Bridge Prioritisation Indices (BPI) determined indicate that Unkuku Bridge has higher priorities in maintenance than other bridges, with a BPI of 2.19, followed by Mvomero Bridge with a BPI of 2.08, Nyahua Bridge with a BPI of 1.67, and lastly, Kikwete Bridge with a BPI of 1.41. Based on the obtained BPI, the maintenance action required was proposed to be preventive maintenance for the Unkuku, Nyahua, and Mvomero bridges and routine maintenance for the Kikwete bridge. Further studies are proposed to include the earthquake amplitude in bridge maintenance prioritisation.

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1.0 Introduction

A bridge is a structure spanning over a physical obstacle such as water bodies, valleys, roads, or railways. It facilitates the movement of people, products, medicines, foods, and the like from one point to another. Thus, the economic development of people and the country as a whole, as well as the social welfare of citizens, are contributed by the availability of bridges (Zhao & Tomm 2018). Bridge failure results in damage to assets, loss of lives, and injuries to people, and it can also lower the economy of a place. A bridge deteriorates due to various factors such as traffic loading and volume, wind pressure, temperature variations, seismic, soil type, hydrologic, and hydraulic actions; hence, a bridge should be designed to endure load-associated distress (Choudhury & Hasnat 2015). These factors are the main causes and acceleration of defects in bridge structures, and therefore, in order to prolong the lifetime of the bridge, maintenance of the damaged bridges should be carried out (Choudhury & Hasnat, 2015; Zhang et al., 2022).

Excess loading causes damage to the bridge structure that reduces the structure's lifetime. The extent of damage depends on the amount of loading and the durability of the structure itself. The damage induced by axle loads may vary from a total bridge collapse to damage that may result in restrictions on bridge use (Deng et al., 2019). Raheel et al. (2018) used Equivalent Standard Axle Load (ESAL) to express the impact of loading on the bridge structure. Traffic volume is the total number of vehicles crossing a point of reference on a road for a specified time. The movement of these vehicles on a structure induces dynamic loads and causes vibration on the bridge. Also, they cause wear and tear on the bridge surface due to load repetition. Traffic volume is used for road capacity analysis and functional classification. Various researchers use the volume of traffic to express the importance of the bridge in a network due to services provided to passengers and goods (Valenzuela et al., 2009; MacDonald & Arjomandi, 2018).

A seismic action is a threat allied with probable earthquakes in a certain area (Valenzuela et al., 2009). These actions may cause significant hazards to structures, including bridges (Tak et al., 2019). The structures behave differently during earthquake occurrences depending on the maximum acceleration, frequency of occurrence, surrounding soil behaviour, distance from the epicentre, and maximum amplitude (Ajom & Bhattacharjee, 2017). Therefore, the inclusion of seismic effects in the decision process for bridge maintenance is fortified (Khan et al., 2022).

Hydrological and hydraulic actions are the mechanical processes in which the moving water current flows against the banks and beds of rivers, thereby removing or depositing rock particles. These are the causes of high floods and scour of bridges, which are among the major causes of bridge failures (Abrar & Farooqi, 2021). Floods happen due to heavy rainfall in the area and obstruction of the waterway. These obstructions depend on the geometry of the bridge, the type of structure that obstructs water passage, like piers, and the accumulation of debris, like tree logs.

Scouring is the process resulting in depression or loss of bed materials (erosion) around the bridge piers, abutments, and piles caused by hydrological and hydraulic behaviour (Pasha et al., 2013; Gotvald, 2003). The rate of its occurrence depends on gravity, wind, water, slope, grain size, and soil cohesion. The grain size and soil cohesion are the resisting forces to the occurrence of erosion (Zumrawi & Absim, 2019). The internal attraction forces between the soil molecules that hold the soil particles together are a contributing factor in soil cohesion. The extent of cohesion depends on the looseness and the amount of organic matter in the soil. The weight of the soil grains also produces the resulting forces to resist erosion. This is due to the soil grain's behaviour being heavier as the grains become larger. For both grain size and soil cohesion, water is the disturbing agent that can alter the resulting forces produced by the soil. Water exerts pressure on the soil particles to detach from each other, thus making it easier to erode. Also, water produces an uplift pressure that is directly proportional to the depth and weight per unit volume. For inorganic soil, the fine particles tend to be easily uplifted by flowing water due to their lightweight nature, being transported away, and thus causing erosion. Both water and the fineness of inorganic soil may cause or accelerate bridge damage (Zumrawi & Absim, 2019). Therefore, bridge defects need to be rectified quickly once they have been evidenced. Lack of maintenance will increase bridges' deterioration and badly affect bridge service life (Fitriani et al., 2019).

In developing countries, weak economies are not able to support full maintenance to restore bridges' functions (MacDonald & Arjomandi, 2018). Tanzania, as one of the developing countries, also faces the same financial scarcity. Its current bridge maintenance prioritisation practice considers structural defects only without considering the causes of those defects, and the prioritisation is based on element level without considering the bridge's overall condition. Therefore, it is important to formulate a methodology for prioritising bridge maintenance at the network level that will help in planning the maintenance without biases and that will incorporate factors that damage bridges other than structural defects, which are the result of the causes. Factors that cause or accelerate bridge damage that are considered in this study are traffic and seismic actions and soil characteristics. Other factors include wind loads, floods, and temperature variations. These factors are not considered for this study and can be considered for bridge maintenance prioritisation in areas prone to such factors.

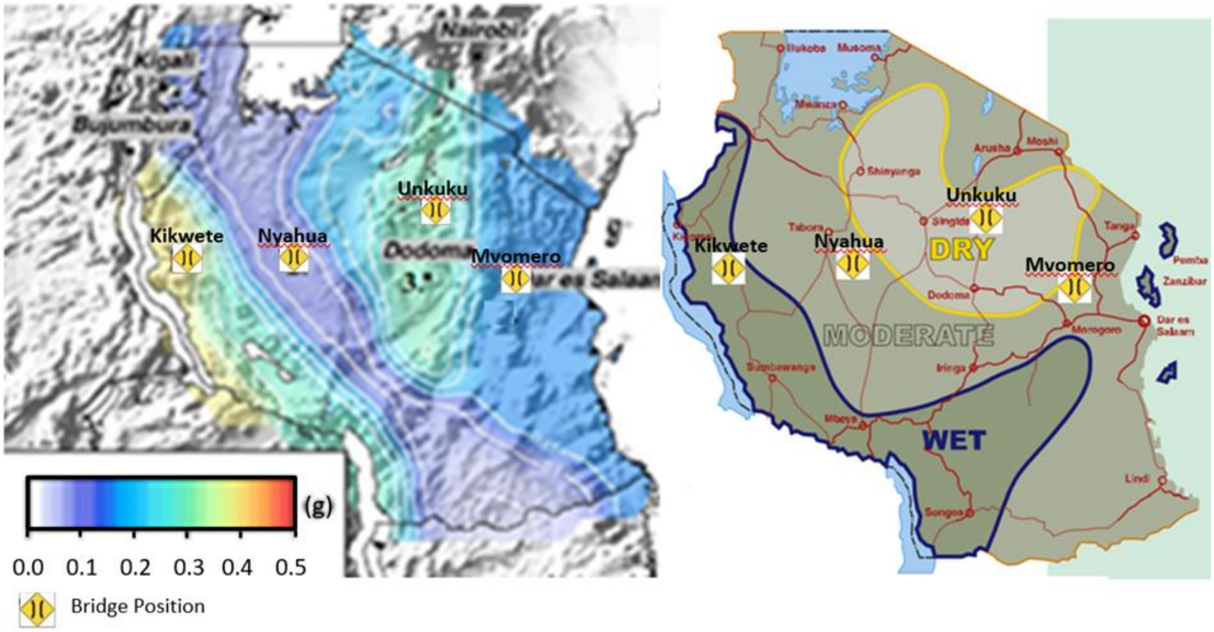
2.0 Prioritisation Approaches and Methods

Bridge maintenance prioritisation options may be based on a single criterion, such as bridge condition indexes. However, several researchers have suggested using multi-criteria parameters to select bridges to be maintained and maintenance options with limited fund resources in a network (Echaveguren & Dechent, 2019; Akhgari, 2017). The study conducted by MacDonald et al. (2018) suggested that bridge prioritisation is commonly done by considering a group of factors, which include traffic volume and axle loads, bridge condition, economics, and natural hazards. They further recommended that considering the multi-hazard assessment approach is vital but that one should only consider those factors sensible for a particular location. Valenzuela et al. (2009) used bridge conditions, seismic risks, availability, and length of detour road, zoning of economic activities, length of the bridge, type of materials used for construction, and hydraulic risks to generate the priority for bridge maintenance. Rashid et al. (2016) developed a bridge prioritisation model using structural efficiency, function efficiency, and the client impact factor. Therefore, consideration of various bridge defects' associated risks can help in prioritising retrofit actions for bridges in a network (Frangopol & Akiyama, 2022). This study introduces the multi-criteria evaluation procedures for bridge maintenance prioritisation in Tanzania, which include bridge condition, vehicle loads and volume, seismic parameters, and soil properties.

Four bridge sites are selected as case study areas, considering seismic zones as described by Poggi et al. (2017) and climatic zones as described by PMDM (1999). These sites are the Kikwete Bridge in Kigoma, the Mvomero Bridge in Morogoro, the

Unkuku Bridge in Dodoma, and the Nyahua Bridge in Tabora, as indicated in Figure 1.

Figure 1
Seismic Hazard Map (left) and Climatic Zones Map (right) in Tanzania (Poggi, et al., 2017; PMDM, 1999)



2.1 Bridge Condition

A bridge condition is the state expressing the damage level of the bridge structure. A study conducted by Bjornsson et al. (2019) highlighted that a vital feature in the preservation of current bridges is the capacity to satisfactorily and precisely assess and appraise the state of the structure. They indicated that the state assessment can be carried out in various ways and provides data on the authentic state of a bridge, including the severity of defects, and these form the base for further maintenance interventions.

To prevent further deterioration of bridge elements, the defects should be quickly rectified. The assessment of these defects is conducted in various ways. Some procedures evaluate a bridge as a single unit, while others split a bridge into a number of units of identical parts to simplify the assessment of each element, especially for large structures (Mombia et al., 2022).

There are many ways of calculating the Bridge Condition Index (BCI). Some researchers use the bridge's physical condition, some use the structural condition, and others use a combination of both the physical state and the structural condition of the bridge elements (Moufti et al., 2014).

The condition assessment for this study follows the procedure stipulated in Mombia et al. (2022), at which each bridge element in a unit is inspected to observe the damages and their corresponding Condition States (CS). Each damage has been given a weight in relation to how the damage affects the bridge's functions. The effects on the bridge functions have been classified into four aspects, namely: carrying capacity (C) of the bridge, traffic passability (T), and maintenance costs (M), and the environment (E), after which the Bridge Element Condition Index (BECI) is calculated based on their damage Condition State (CS) and Damage Weight (DW). Then, the Bridge Element Condition Index is calculated using Equation 1 (Mombia et al, 2022).

$$\mathrm{BECI} = \frac{\sum_{i=1}^{n}(\mathrm{Dw_i} \text{ x } \mathrm{CS_i})}{\sum \mathrm{Dw_i}} \qquad (1)$$

Where: Dwi – is the damage weight corresponding to the damage class.
CSi – is the defect condition score corresponding to defect quantity or coverage.

Mombia et al. (2022) classify the bridge elements in accordance with their significance. Each element is assigned a Significance factor (Sf). Then, all BECI for elements of the same unit is aggregated using Equation 2 to obtain the Bridge Unit Condition Index (BUCI). The critical BUCI is taken to represent the overall Bridge Condition Index (BCI) and is being rated as a Bridge Condition Rating (BCR) as per Table 1.

$$\mathrm{BUCI} = \left(\frac{\sum_{i=1}^{N} \mathrm{Sf_i}.\mathrm{BECI_i}}{\sum \mathrm{Sf_i}}\right) \qquad (2)$$

Where: BUCI – is the bridge unit condition index
N – is the number of elements in a unit,
BECIi – is the Bridge Element Condition Index
Sfi – is the element Significance factor.

Table 1
Bridge Condition Indexes and State (Mombia et al., 2022)

BCI ranges	**Bridge Condition State**	**BCR**
0.0 – 1.0	Good	1
1.0 – 2.0	Fair	2
2.0 – 3.0	Bad	3
3.0 – 4.0	Very bad	4

2.2 Scouring Potential of River Bed Materials

The movement of the riverbed and bank materials resulting from the erosion of soil due to flowing water is known as scouring (Inamdeen et al., 2021). Scour is one of the major causes of bridge failure (Kazemian et al., 2023; Aly and Dougherty, 2021). Among the factors affecting the bridge scour are bed materials, channel protection measures, and water velocity (Inamdeen et al., 2021). The condition at which the soil is susceptible to erosion is called erodibility. Various studies use the erodibility index to indicate the amount of scouring risks of the soil around the structure (Valenzuela et al., 2009).

The study done by Abidin and Mukri (2002) expanded the erodibility index developed by Bouyoucos (1962) to incorporate the erodibility risks represented in an index obtained using the equation developed by the researchers Roslan and Mazidah, named the ROM scale, as shown in Equation 3. The erodibility index shown in Equation 3 can only be determined if the soil is composed of sand, silt, and clay. In the absence of clay or for pure sand soil and soil with a large amount of gravel and cobbles, the denominator of Equation 3 becomes zero (0), which will result in an undefined integer. Hence, it was not adopted for this study.

$$\mathrm{EI_{ROM}} = \frac{(\%\text{ of sand} + \%\text{ of Silt})}{2(\%\text{ of Clay})} \qquad (3)$$

Where: EI – is the erodibility index.

ROM – is the Roslan and Mazidah.

Based on the cohesion and grain weights of different types of soil, clay contains very fine and light particles with the highest cohesion, which tends to hold particles together and thus be hard to erode (Mirsal 2008). Silt is composed of lightweight particles with little or no cohesion and is thus easy to erode. Sands with medium particles have little or no cohesion, and their erosion resistance is higher compared to silt because their particles are heavier than silt. The nature of gravel materials contains large and heavy particles that tend to resist erosion more than sand. While cobbles are composed of very large and heavy particles that resist erosion by their own weight, they are heavier than gravel (Earle 2019).

Hence, the soil type rating in this study is based on the scouring behaviour of the soil as described above. Table 2 indicates the soil type and the corresponding erosion scores used for this study.

Table 2
Soil Types Erodibility Rating (Mirsal 2008)

Soil type	**Soil erosion score**
Cobbles	1
Gravel	2
Sand and Clay	3
Silt	4

Riverbeds and banks are areas prone to erosion. They are mainly composed of soil with different grain sizes. To incorporate all types of soil, this study used Equation 4 (Rashid & Gibson, 2012) to obtain the Scouring Index (SI) for each soil sample. The amount of each soil type composition is obtained by using particle size distribution. The use of Equation 4 is limited only when the river contains flowing water. For seasonal rivers, water is not flowing during the dry season, so the Scouring index will be zero (0).

$$\mathrm{SI} = \frac{1(\%\ \mathrm{Cobbles}) + 2(\%\ \mathrm{gravel}) + 3(\%\ \mathrm{sand+clay}) + 4(\%\ \mathrm{silt})}{100} \qquad (4)$$

The range of the scouring Index and its corresponding condition ratings are shown in Table 3.

Table 3
Ranges of Scouring Indices and Scouring Ratings of Soil Types

Scouring Index	**Scouring Rating (SR)**
Less than 1	1
1 – 2	2
2 – 3	3
Greater than 3	4

2.3 Seismic Hazard on Bridges

Seismic hazards reflect the consequences of the potential damage to the bridge caused by earthquakes. It is usually accounted for by considering one or more seismic scenarios that correspond to historical earthquakes (Tak et al. 2019) or is established by regional hazard analysis methodology (Kilanitis and Sextos 2018).

Several methods exist to estimate seismic hazards. The study by Valenzuela et al. (2009) estimated the seismic hazard in terms of damage level corresponding to the likelihood of failure by seismic loads and being rated on a scale of 1 to 5.

The study conducted by Fathi and Nikzad (2017) indicated that researchers have different opinions on the distance from the epicentre within which the constructed engineered bridges can be affected and completely destroyed by an earthquake. The study by Naeim (2001) indicated that the distance at which the structure can be affected by an earthquake is 50 km. Davoodi et al. (2012) concluded that there is no specific radius from the epicentre at which the structure can be damaged by an earthquake.

The study conducted by Ghosh et al. (2013) explained that an increase in the number of earthquake pulses on bridge structures also increases the probability of damage due to repeated shocks. They emphasised that multiple earthquake pulses result in the accumulation of damage to the structure when there is no retrofit action taken. Sanchez-Silva et al. (2011) assume that any damage resulting from the earthquake is always fully repaired before the subsequent earthquake. But Ghosh et al. (2013) overruled that not all damages resulting from earthquakes are fully repaired before the subsequent earthquake event happens, and this is due to certain scenarios: when the damage is invisible and does not attract retrofit; when the economy does not support retrofit action after every earthquake; and when the time between the consecutive earthquakes does not support any retrofit action. Also, the historical events of an earthquake have been taken with less concern for the evaluation of existing structural capacity. Therefore, the increase in earthquake pulses can accelerate the defects in the structure. This study used the earthquake's maximum magnitude and the number of occurrences (pulses) of earthquakes covering the period of five years (5) from the year 2017 to the year 2021 because each earthquake event weakens the structure, and the remaining structural capacity may be insufficient to resist future events.

However, it is considered that earthquakes with less than 4 magnitudes have no effect on the structure (USGS 2023). Any value less than 4 is to be taken as zero, which signifies no damage to be caused to the structure by earthquakes. The studies have indicated that the frequency of the occurrence of earthquakes rises by a factor of 10 once the magnitude is reduced by one unit (Rafferty, 2023).

Therefore, the seismic factor of a bridge in the network can be expressed as shown in Equation 5 (Rafferty, 2023).

$$Seismic\ factor\ (SF) = \frac{(X-4)(Log\ P)}{Log\ Y} \quad (5)$$

Where: X–is the maximum earthquake magnitude at a bridge location.

P– is the number of earthquake occurrences at the bridge location

Y–is the total number of earthquake occurrences for the bridge network

The values of SF are rated as per Table 4.

Table 4

Ratings for Seismic Damaging Factors

Seismic Factor (SF) range	**Seismic Damaging Rating (SDR)**
Less than 1.0	1
1.0 - 2.0	2
2.0 - 3.0	3
Greater than 3.0	4

2.4 Traffic Study

In Tanzania, transportation by road takes over 90% of the passengers and 75% of the freight traffic. It also serves as the link between Dar es Salaam Port and the landlocked countries of Malawi, Zambia, the Democratic Republic of the Congo, Rwanda, Burundi, and Uganda. Transportation infrastructure also has an impact on the country's economic growth. The traffic study is composed of two categories, which are traffic volume and axle load studies.

2.4.1 Traffic Volume

Traffic volume is the measure of the number of vehicles flowing at a specified location, usually expressed as average daily traffic (ADT). It is obtained by using classified traffic counts either manually or by the use of counting devices at a specific road point.

2.4.2 Traffic Axle Load

The damaging effects on bridge structures depend on the axle loads and configuration of the vehicles. The daily volume of traffic at a specified location consists of light and heavy vehicles.

The loading effects of light vehicles are lower compared to heavy vehicles. Traffic load is the weight carried by vehicles for the need to be transported from one point to another. It is obtained using a traffic load survey through various weighing devices, i.e., weighbridges. Traffic load data plays a vital role in informing the movement of loads and, hence, infrastructure project cycle implementation. The damaging power of a particular axle load is generally expressed in terms of an equivalent standard axle of 8160 kg, a concept that effectively reduces the varied nature of traffic loadings to a single parameter in terms of structural damage (PMDM 1999). Traffic loading is the major cause of the bending and shearing of bridge components (Sandhyavitri et al., 2019) and has been used in the design of roads and bridges to impart the loading effects for the expected lifetime of the structure. PMDM (1999) uses the equivalent standard axle (E80) of 8160 kg load as indicated in Equation 6 to obtain the Average Equivalency Factor (AEF) for each vehicle category, which is being calculated by the traffic counts to obtain the cumulative E80s traffic loading the road is subjected to over the entire expected lifetime.

$$AEF = \left[\frac{Axle\ Load\ L\ (kg)}{8160}\right]^{4.5} \tag{6}$$

Various studies use traffic volume and loading as factors to obtain the index to be used in the maintenance prioritization model (Shabir et al., 2021; Valenzuela et al., 2009). Valenzuela et al., (2009) used bridge load restriction to rank the roads for maintenance, while PMDM, (1999) uses the traffic loading to classify the road for design as shown in Table 5.

Table 5

Equivalent Standard Axle Load (ESAL) per Year and Traffic Load Class (PMDM, 1999)

Traffic Loading [E80 x 10^6]	Traffic Load Class (TLC)
< 0.2	TLC 02
0.2 to 0.5	TLC 05
0.5 to 1	TLC 1
1 to 3	TLC 3
3 to 10	TLC 10
10 to 20	TLC 20
20 to 50	TLC 50

This study adopts the cumulative equivalent factor methodology and the Traffic Loading Class by grouping seven classes in Table 5 (PMDM, 1999) to have four groups for the ESAL per year rating as shown in Table 6 to classify the bridge in terms of traffic.

Table 6

Traffic Index (TI) Rating (PMDM, 1999)

Range of ESAL per Year [E80 x 10^6]	BCR
< 0.5	1
0.5 – 3	2
3 – 20	3
> 20	4

2.5 Maintenance Prioritization Model

Prioritisation is the process used for the selection of options for bridge maintenance based on predetermined criteria. There are many methods used for the prioritisation of bridge maintenance. Darban et al. (2020) used the product of the parameter indexes and their corresponding weights assigned using the expert's views to calculate the maintenance priority index. The weighting factors of the parameters used in the study conducted by Darban et al. (2020) to determine the Bridge Prioritisation Index were adopted and modified to suit this study, as shown in Table 7.

Table 7

Bridge Parameter's Weight

Bridge Parameters	Weight (Darban et al. 2020)	Weight (w) (%)
Bridge Condition	0.331	52
Scour	0.097	15
Seismic	0.143	22
Traffic	0.068	11
Total	**0.639**	**100**

Bridge prioritization indices (BPI) for this study are computed by using Equation 7 (VDOT 2018).

$$\mathrm{BPI} = \sum_{i=1}^{n} PR_i w_i \tag{7}$$

Where:

BPI – is the bridge prioritization index.

PR_i – is the rating of parameter i

wi – is the weight of parameter i.

n – is the number of parameters.

3.0 Classification of Maintenance Level

Bridge maintenance is the process that tends to keep a damaged bridge in an operational condition (TANROADS & NPRA, 2007). It is classified into different levels, which are routine, preventive, repair, and replacement. Routine maintenance involves regular operations to keep the bridge at its full function. These operations involve cleaning the waterway, removing debris, removing soil from bearings, and other elements. In general, it involves all operations that, if not performed for some time, will result in the occurrence of damage to the bridge components. Preventive maintenance is the process of protecting a bridge against the occurrence of damages that are not routine, i.e., painting steel structures to protect against corrosion. Also, it involves the repair or rectification of damaged functional bridge components, including river training, the construction of gabions to protect riverbanks, the replacement and adjustment of bearings, any structural damage, etc. The component replacement is done to the element, which, if not done, will lead to the closure of the bridge. Also, major repair involves the additional bridge function, i.e., increasing the bridge width, deck overlay, and component replacement.

A study conducted by Omar et al. (2017) categorises the required maintenance actions into five categories using the structural condition index ranges. This study adopts the methodology by Omar et al. (2017) by modifying the required maintenance actions to be in three (3) categories, which are shown in Table 8.

Table 8
Categorization of Bridge Maintenance

BPI range	Type of Maintenance
≤ 1.6	Routine
1.6 – 2.5	Preventive
≥ 2.5	Major repair and replacement

Source: Omar et al. (2017)

The indexes to be obtained through equation 7 are ranked as shown in Table 8 to classify the type of maintenance required.

4.0 Data Collection, Analysis and Discussion

Data for this study was obtained from the bridge locations and historical data. The data collected at each bridge are defects in bridge components in order to determine bridge condition indices, soil samples at the river beds for particle size analysis, traffic survey data, i.e., traffic volumes and axle loads, and historically recorded data for earthquakes that occurred around the bridge areas. The bridges involved in the data collection exercise to determine their prioritisation indices were the Kikwete Bridge, Mvomero Bridge, Unkuku Bridge, and Nyahua Bridge.

4.1 Bridge Condition Index (BCI)

The needed information came from inspecting the bridge site. Visual inspection and non-destructive tests on the concrete were used to find defects on the bridge's surface and subsurface. This study adopted the methodology used by Mombia et al. (2022) to determine bridge condition indices. The inspection data obtained are as shown in Tables 9–12 and were used to compute the Bridge Unit Condition Index (BUCI) for each bridge unit, and the value obtained is shown in Table 13

Table 9
Defect Quantification of the Eight-Unit/Grid (Critical Unit) of Kikwete Bridge

Element	**Element Category**	**Total Quantity**	**Units**	**Defect name**	**Defect code**	**Damage class**	**Damage weight (Dw)**	**Defect score (Ds)**
Slab	III	162.5	m^2	Cracks	211	III	1.5	1
Beams	IV	375	m^2	Cracks	0	I	1.5	1
Curbs	I	No curbs	m	No defect	0	0	0	0
Bearings	III	10	No.	No defect	709	0	1.5	1
Abutments	III	148.2	m^2	No defect	0	0	0	0
Pier	IV	-	-	No defect	0	0	1.5	1
Headstock	IV	-	-	No defect	0	0	0	0
Wingwalls	II	51	m^2	No wingwalls	0	0	0	0
Foundation	II	135	m^2	No defect	0	0	0	0
Expansion joints	I	8.9	m	No defect	0	0	0	0
Barriers	I	112.5	m^2	Cracks	211	II	1.5	2
Wearing course	III	162.5	m^2	No defect	0	0	1.5	1
Footway	I	60	m^2	Cracks	211	I	1.5	1

Table 10
Defect Quantification of the First Unit/Grid (Critical Unit) of the Mvomero Bridge

Element	**Element Category**	**Total Quantity**	**Units**	**Defect name**	**Defect code**	**Damage class**	**Damage weight (Dw)**	**Defect score (Cs)**
Slab	III	156	m^2	Cracks	211	C	2.5	2
Beams	IV	360	m^2	Honeycombs	202	M	1.5	2
Curbs	I	-	-	No damage	-	-	0	-
Bearings	III	-	-	No defect	-	-	0	-
Abutments	III	142.5	m^2	Cracks	211	M	1.5	2
Pier	IV	-	-	No damage	-	-	0	-
Headstock	IV	-	-	No damage	-	-	0	-
Wingwalls	II	77	m^2	Cracks	211	C	2.5	2
Foundation	II	-	-	No defect	-	-	0	-
Expansion joints	I	17.8	m	Breaking of sealant	714	M	1.5	2
				The loose part of joint	712	T	2	3
				Blockage of joint	711	M	1.5	3

Barriers	I	108	m^2	Cracks	211	M	1.5	1
Wearing course	III	156	m^2	Cracks	601	M	1.5	3
Footway	I	57.6	m^2	Edge ripping	212	M	1.5	2

Table 11
Defect Quantification of the First Unit/Grid (Critical Unit) of the Unkuku Bridge

Element	Element Category	Total Quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect condition score (Cs)
Slab	III	133.5	m^2	Cracks	211	M	1.5	1
				Leaking	203	C	2.5	4
Beams	IV	195	m^2	Honeycombs	202	M	1.5	1
Curbs	I	No curbs	-	-	-	-	0	0
Bearings	III	5	No.	Blocked	701	M	1.5	3
Abutments	III	22	No.	Defective weep holes	803	M	1.5	3
		79.8	m^2	Honeycombs	202	M	1.5	3
			m^2	Cracks	211	M	1.5	2
Pier	IV	No pier	-	-	-	-	0	0
Headstock	IV	N/A	-	-	-	-	0	0
Wingwalls	II	48	m^2	Honeycombs	202	M	1.5	2
Foundation	II	-	-	No defect	-	-	0	0
Expansion joints	I	8.9	m	Blockage of joint	711	M	1.5	4
Barriers	I	67.5	m^2	Cracks	211	M	1.5	2
Wearing course	III	97.5	m^2	Cracks	601	M	1.5	1
Footway	I	36	m^2	Cracks	211	C	2.5	4

Table 12
Defect Quantification of the First Unit/Grid (Critical Unit) of the Nyahua Bridge

Name of element	Element Category	Total Quantity	Units	Defect name	Defect code	Damage class	Damage weight (Dw)	Defect score (Ds)
Slab	III	104	m^2	Cracks	211	I	2.5	1
Beams	IV	208	m^2	Honeycombs	202	I	2.5	1
Curbs	I	0	0	0	0	0	0	0
Bearings	III	5	No.	No defect	0	0	0	0
Abutments	III	148.2	m^2	Honeycombs	202	II	1.5	2
				Cracks	211	I	1	1
Pier	IV	0	0	No defect	0	0	0	0
Headstock	IV	0	0	No defect	0	0	0	0
Wingwalls	II	102	m^2	Honeycombs	211	III	1.5	1
Foundation	II	160	m^2	No defect	0	0	0	0
Expansion joints	I	8.9	m	Blockage of joint	711	IV	1.5	4

Barriers	I	72	m^2	Ripping on edge	212	I	1.5	1
Wearing course	III	104	m^2	Depression	604	I	1.5	1
Footway	I	38.4	m^2	Cracks	14.4	IV	1.5	4

Table 13

Bridge Unit Condition Index, Total, Average and Critical BUCI

Bridge name	**Bridge Unit/grid**											**Critical BUCI**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	
Kikwete	0.52	0.45	0.55	0.48	0.52	0.03	0.03	0.65	0.26	0.39	0.29	0.65
Mvomero	1.18											1.18
Unkuku	1.42	0.61	0.81									1.42
Nyahua	0.78	0.45	0.52	0.48								0.78

The BUCI with the highest value indicates the critical bridge unit, and its value was taken to represent the overall Bridge Condition Index (BCI), which was used to rate the bridge condition as shown in Table 14.

Table 14

Summary of Bridge Condition Index (BCI) and Bridge Condition Rating (BCR)

Bridge name	**BCI**	**BCR**
Kikwete	0.65	1
Mvomero	1.18	2
Unkuku	1.42	2
Nyahua	0.78	1

Table 14 indicates the BCI for all four bridges, of which the Unkuku Bridge was structurally more affected, having a BCI of 1.42, followed by the Mvomero bridge with a BCI of 1.18, both rated 2, the Nyahua bridge with a BCI of 0.78, and lastly the Kikwete bridge with a BCI of 0.65, both rated 1.

4.2 Scour Index (SI) and Scouring Rating (SR)

The particle size distribution by sieve analysis was carried out to determine the amount of each type of soil in a sample. Figure 2 shows graphs of the particle size distribution of sample soils taken at the river bed of each bridge.

Figure 2

Particle Size Distribution Curves

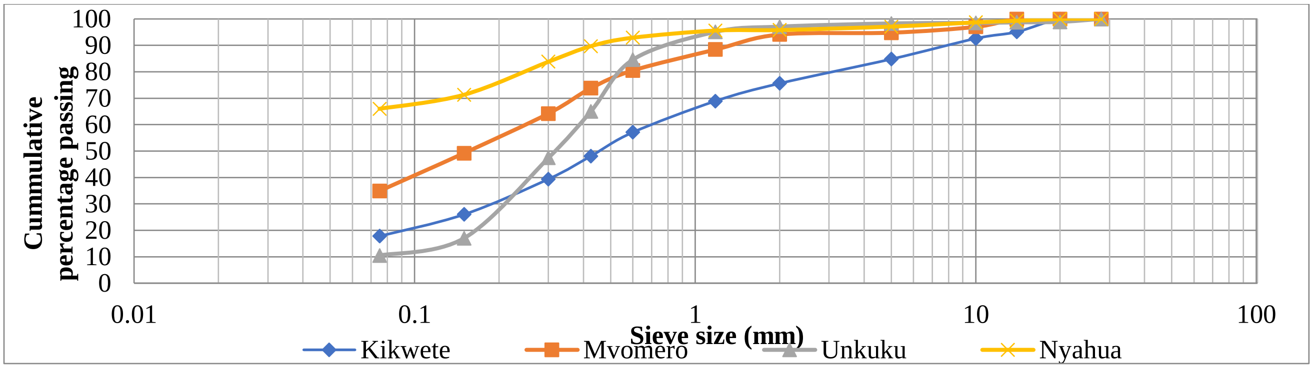


Table 15 shows the proportions of soil mass for all four bridge locations. The soil at Kikwete was characterized by gravel-sand soil dominated by a large amount of sand. Mvomero was characterised by sand-silt soil largely dominated by sand. Unkuku was dominated by sandy soil, and Nyahua was composed of sand-clay soil largely dominated by clay.

Table 15
Particle Size Distribution

Bridge Name	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
Kikwete	17.0	65.2	10.9	6.9
Mvomero	5.5	59.6	32.5	2.4
Unkuku	2.9	86.6	9.7	0.8
Nyahua	3.2	30.8	6.8	59.2

The calculation to obtain the scouring index was carried out using Equation 4 and the value in Table 16 indicates respective bridge's scouring rating obtained using Table 3.

Table 16
Scouring Index and its Corresponding Rating for each Bridge

Bridge name	**Scouring Index (SI)**	**Scouring Rating (SR)**
Kikwete	2.94	3
Mvomero	3.27	4
Unkuku	3.07	4
Nyahua	3.04	4

The results in Table 16 indicate that the soil at Kikwete Bridge had high resistance to erosion by the action of flowing water, having a scouring index (SI) of 2.94, followed by Nyahua Bridge having a scouring index of 3.04, then Unkuku Bridge having a scouring index of 3.07, and the last was Mvomero Bridge having a scoring index of 3.27. The scoring ratings (SR) obtained for each bridge were 3 for the Kikwete Bridge and 4 for the Nyahua, Unkuku, and Mvomero bridges.

4.3 Seismic Damaging Index (SDI)

Data from the Geological Survey of Tanzania (GST) indicated that the earthquake with a magnitude of more than 4 within an epicentre of 50 km radius from the bridge location occurred within five years, from 2017 to 2021, as indicated in Tables 17 and Table 18 for Kikwete and Unkuku bridges respectively. There were no earthquakes recorded of more than 4 magnitude at Mvomero and Nyahua bridges within the specified time. The maximum magnitude of the earthquake and the number of occurrences within a specified distance and time were determined and summarised in Table 1

Table 17
Earthquake Records at Kikwete Bridge

S/N	Date	Time	Coordinates		Depth (Km)	Magnitude (Richter)
			Latitude (S)	Longitude (E)		
1	22-Oct-17	6:05:12	-6.0932	30.7397	10	5.1
2	18-Jun-17	13:54:26	-4.2347	30.4912	10	4.4
3	29-Apr-17	10:53:22	-6.1295	29.927	10	5.3

Table 18
Earthquake Records at Unkuku Bridge

S/N	Date	Time	Coordinates		Depth (Km)	Magnitude (Richter)
			Latitude (S)	Longitude (E)		
1	25-Feb-21	5:46:51	-3.547	35.907	10	4.1
2	8-Jun-20	6:44:20	-6.08965	35.84514		4.5
3	2-Jun-20	5:44:13	-4.64	35.85	10	4.5
4	31-Mar-20	2:36:59	-6.0576	35.7926	15	4.5
5	8-Aug-18	21:07:22	-3.7282	35.6252	10	4.2
6	30-Oct-17	12:14:33	-5.5061	35.9183	10	4.5

Table 19
Maximum Magnitudes and Number of Earthquakes Occurrences

Bridge Name	Maximum Magnitude	Occurrence
Kikwete	5.3	3
Mvomero	0	0
Unkuku	4.5	6
Nyahua	0	0
Total		**9**

The values in Table 19 were converted to obtain the seismic index by using Equation 5. The obtained seismic indices were rated to obtain their corresponding rating as per Table 4, and the results were as shown in Table 20. According to the results obtained (Table 20), the seismic damaging rating was 1 for all four bridges, which signifies that the effects of earthquakes at all four locations are minimal.

Table 20
Seismic Factor (SF) and their Corresponding Ratings

Bridge Name	Seismic factor (SF)	Seismic damaging rating (SDR)
Kikwete	0.650	1
Mvomero	0.000	1
Unkuku	0.408	1
Nyahua	0.000	1

4.4 Traffic Index (TI)

The traffic count data were used to obtain the ADT of vehicles crossing the bridges, and the axle survey data were converted into the Axle Equivalent Factor (AEF) of vehicles crossing the bridges using Equation 6. Table 21 shows the average daily traffic and axle equivalent factor for each bridge.

Table 21
Average Daily Traffic (ADT) and Axle Equivalent Factors (AEF) for Each Bridge

Vehicle Category (No. of Axles)	**Kikwete**		**Mvomero**		**Unkuku**		**Nyahua**	
	ADT	**AEF**	**ADT**	**AEF**	**ADT**	**AEF**	**ADT**	**AEF**
2 axles	51.00	2.02	145.00	1.51	75.00	1.81	41.00	2.66
3 axles	48.00	12.82	71.00	16.78	148.00	17.49	55.00	16.59
4 axles	24.00	40.27	34.00	31.57	52.00	29.50	32.00	36.47
5 axles	0.00	0.00	3.00	44.05	1.00	44.05	0.00	0.00
6 axles	37.00	93.37	18.00	110.42	28.00	114.36	127.00	104.36
7 axles or more	8.00	54.82	17.00	58.11	13.00	60.43	35.00	65.78

The ADT and AEF values in Table 21 were used to obtain the ESAL of each vehicle category per day, as shown in Table 22, and were calculated as illustrated in Equation 8. The calculation of ESAL per day involved the projected rate of traffic growth (i) per year and the designated design life (n). On the traffic study projection of the baseline year, (i) and (n) were all zeros.

$$\begin{aligned}\mathrm{ESAL} &= \mathrm{AEF\ x\ ADT}(1+\mathrm{i})^{\mathrm{n}} && (8)\\ &= 104.36\ \mathrm{x}\ 127(1+0)^{0}\\ &= 13253.72\end{aligned}$$

Table 22
Equivalent Standard Axle Load (ESAL) of each Vehicle Category

Vehicle Axles (No.)	**ESAL**			
	Kikwete	**Mvomero**	**Unkuku**	**Nyahua**
2 axles	103.02	218.95	135.75	109.06
3 axles	615.36	1191.38	2588.52	912.45
4 axles	966.48	1073.38	1534.00	1167.04
5 axles	0.00	132.15	44.05	0.00
6 axles	3454.69	1987.56	3202.08	**13253.72**
7 axles or more	438.56	987.87	785.59	2302.30
Total (ESAL per Day)	5578.11	5591.29	8289.99	17744.57

The summation of the ESAL of all vehicle categories at a bridge shows the ESAL per day as indicated in Table 23. The ESAL per day was used to calculate the ESAL per year at each respective bridge as illustrated using Equation 9 and the results are shown in Table 23. The obtained ESAL per year was also the Cumulative Equivalent Standard Axle Load (CESAL) of the baseline year.

$$\begin{aligned}\mathrm{ESAL\ per\ year} &= {}^{\mathrm{ESAL}}/_{day}\ \mathrm{x}\ 365 && (9)\\ &= 17744.57\ \mathrm{x}\ 365 = 6{,}476{,}768.05\end{aligned}$$

Table 23 shows the Traffic index ratings obtained using ESAL per year as per Table 6.

Table 23
Traffic index rating (TIR)

Bridge Name	ESAL per Day	ESAL per Year	Rating (TIR)
Kikwete	5578.11	2,036,010.15	2
Mvomero	5591.29	2,040,820.85	2
Unkuku	8289.99	3,025,846.35	3
Nyahua	17744.57	6,476,768.05	3

4.5 Bridge Prioritization

The bridge prioritisation indices (BPI) of the four bridges for this study were computed using Equation 7. Table 24 indicates the indices of each parameter for bridge prioritisation of the Kikwete, Mvomero, Unkuku, and Nyahua bridges, as well as the results of parameter ratings (PR) and bridge prioritisation indices (BPI) for each bridge.

Table 24
Bridge Prioritization Index for each Bridge

Bride Name	Bridge condition rating (BCR)	Traffic index rating (TIR)	Seismic damaging rating (SDR)	Scouring Rating (SR)	BPI
Kikwete	1	2	1	3	1.41
Mvomero	2	2	1	4	2.08
Unkuku	2	3	1	4	2.19
Nyahua	1	3	1	4	1.67

The results indicated in Table 24 show the Unkuku bridge had more priority in maintenance, having a BPI of 2.19, followed by the Mvomero bridge with a BPI of 2.08, the Nyahua bridge with a BPI of 1.67, and lastly, the Kikwete bridge with a BPI of 1.41.

4.6 Bridge Prioritisation

The maintenance actions required for this study were obtained using BPI and categorised using Table 8. Therefore, based on the BPI obtained, the required maintenance actions for each bridge are shown in Table 25.

Table 25
Maintenance Action

Bride Name	BPI	Action Required
Kikwete	1.41	Routine
Mvomero	2.08	Preventive
Unkuku	2.19	Preventive
Nyahua	1.67	Preventive

Table 25 indicates the maintenance action required for each bridge at which Mvomero, Unkuku, and Nyahua bridges required preventive maintenance while the Kikwete Bridge required routine maintenance.

5.0 Conclusion and Recommendation

The financial shortage makes it difficult to maintain the bridges at good standard conditions to perform as intended for their remaining lifetime. The funds required for bridge rectification are most of the time higher than the available budget, which results in some bridges being left without being maintained even though they are defective. Therefore, selecting bridges to be rectified among the defective bridge population has not been an easy task. In this paper, a method of prioritisation has been introduced composed of different parameters, which are bridge condition, scour potential, seismic, and traffic actions.

The bridge condition index (BCI) indicates that Unkuku Bridge is more highly damaged than other bridges, having a BCI of 1.42, followed by the Mvomero Bridge with a BCI of 1.18, the Nyahua Bridge with a BCI of 0.78, and the Kikwete Bridge with a BCI of 0.65. The Bridge Condition Rating (BCR) for Unkuku and Mvomero bridges is 2, while the BCR for Kikwete and Nyahua bridges is 1.

The soil investigation on scouring potential shows that Mvomero Bridge is composed of soil that is easy to erode, with a scouring index (SI) of 3.27, followed by Unkuku with a SI of 3.07, Nyahua with a SI of 3.04, and Kikwete with a SI of 2.94. The scouring ratings (SR) of the bridges obtained are 4 for the Unkuku, Nyahua, and Mvomero bridges and 3 for the Kikwete Bridge.

The earthquake-damaging effects on bridges show that the Kikwete bridge is located in an area more prone to earthquake damage than other bridges, having a seismic factor (SF) of 0.65, followed by the Unkuku bridge with a SF of 0.41. Mvomero and Nyahua bridges are located in areas that are less likely to be affected by earthquakes, both having SFs of 0. The seismic damaging rates (SDR) obtained for all bridges are 1.

Traffic volumes and axle load surveys show that the Nyahua bridge is composed of more traffic volume than other bridges, having an Equivalent Standard Axle Load (ESAL) of 6.476 million, followed by the Unkuku bridge with an ESAL of 3.025 million, the Mvomero bridge with an ESAL of 2.040 million, and lastly, the Kikwete bridge with an ESAL of 2.036 million. Traffic Index Rating (TIR) was 3 for Unkuku and Nyahua bridges and 2 for Mvomero and Kikwete bridges.

From the parameter ratings, the Bridge Prioritisation Indices (BPI) for each bridge show that the Unkuku bridge has a higher priority in maintenance than other bridges, having a BPI of 2.19, followed by the Mvomero bridge with a BPI of 2.08, the Nyahua bridge with a BPI of 1.67, and lastly, the Kikwete bridge with a BPI of 1.41.

According to the results of the BPI obtained, the proposed maintenance option is preventive maintenance for the Unkuku, Nyahua, and Mvomero bridges, while the Kikwete bridge requires routine maintenance.

This study can assist engineers and road authorities in prioritising maintenance and selecting maintenance options (routine or preventive) based on multi-parameters that affect bridge function. It is recommended that other studies be done to incorporate the amplitude of earthquakes into the prioritisation of bridge maintenance.

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