



Corrosion Evaluation of an Existing Bridge Exposed to the Orogodo River Environment in Delta State, Nigeria

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Abstract

Concrete structures in water-exposed environments are highly vulnerable to corrosion caused by chloride ingress, fluctuating water chemistry, and defective concrete cover. Corrosion damages steel reinforcement, concrete, and their bond, ultimately reducing service life and increasing maintenance expenses of structures. This study presents a non-destructive corrosion assessment of the Orogodo Composite Bridge exposed to the Orogodo River in Delta State, Nigeria. An integrated approach was adopted, combining physico-chemical water analysis with multiple non-destructive evaluation methods (visual inspection, concrete cover measurement, compressive strength using a rebound hammer, ultrasonic pulse velocity-UPV, and half-cell potential-HCP) to evaluate the bridge's corrosion condition. The physico-chemical analysis classified the Orogodo River as freshwater with a chloride concentration of 65.850 mg/L, indicating potential for reinforcement corrosion. Visual inspection revealed localised corrosion deterioration at section X of the bridge deck, while other RC elements and steel girders remained in visually good condition. The bridge deck's average concrete cover was approximately 75 mm, which is adequate for various exposure conditions. The average compressive strength (49.51 N/mm²) and UPV (5.57 km/s) of the bridge bottom deck indicated excellent concrete quality consistent with relevant codes and existing studies. The average HCP value of -290 mV at section X indicates a 50% probability of active corrosion, which aligns with the visual inspection findings. The findings highlight the need for adequate and defect-free concrete cover, continuous monitoring, and timely maintenance of RC structures in aggressive environments. The study recommends using multiple condition assessment methods for robust evaluation of existing structures and prioritising timely repairs on the Orogodo Bridge, especially at section X, in order to prevent further deterioration and performance loss.

Keywords: Bridge structures; Orogodo River environment; Corrosion deterioration; Condition assessments; Non-destructive testing methods

1. Introduction

Reinforced concrete (RC) and concrete are globally utilised in the construction sector due to their ease of usage, high strength, durability, economy and ability to withstand different environmental conditions (Wasiu and Osegbowa, 2022; Atashi and Einabadi, 2023; Liu and Shi, 2024). Reinforced concrete and concrete are extensively used in the construction of bridges, buildings, roads and pavements, dams, foundations, tunnels, water tanks and reservoirs (Majhi *et al.*, 2021) as well as marine structures in many countries of the world (Pratiwi *et al.*, 2021). Bridges are important components of the transportation network that support national economic growth (Ramdhani and Surnargo, 2020; Abdelhady and Moselhi, 2022) by providing routes for the movement of people, goods and services across natural or man-made obstacles to different locations within States and even beyond National boundaries (Adesanmi, 2017; Mlanga *et al.*, 2019). Bridges also serve as links in disaster control and management (Azam, 2015). Because of their critical roles, they need proper management to prevent disruption of traffic, economic losses and eventual failure over time.

Osumeje (2016), drawing on data obtained from the Federal Ministry of Works and the Federal Road Maintenance Agency, noted that by 2010, about 1,705 bridges were in service on Nigerian highways, but by 2016, over twenty had structural defects, while some were closed to traffic. Most of the existing RC bridges in operation in Nigeria are ageing and deteriorating due to different conditions they are exposed to (Olawale *et al.*, 2019). Relevant transport authorities across the globe are undertaking significant efforts to maintain transport infrastructure and ageing structures due to the increase in traffic volume and the adverse impact of environmental conditions on the structures, leading to their deterioration (Ellingwood *et al.*, 2009; Rashidi and Gibson, 2011). The deterioration of structures has been a serious concern as it relates to both safety and cost. Ede *et al.* (2019) revealed that there have been more than ninety (90) cases of bridge collapses in Nigeria due to different reasons such as extreme loadings, inadequate and scarce evaluation in addition to maintenance strategies, mistakes in design and implementation of designs. Bridges and other structures collapse, can lead to both loss of human lives and economic losses (Sule *et al.*, 2018; Uzodinma *et al.*, 2022).

Most existing bridges in highway transportation are usually exposed to various exposure conditions. Examples of such exposure conditions include severe environments (marine, industrial and other severe conditions) (Osuji *et al.*, 2020), brackish-water environments (moderate to severe conditions), and fresh water environments (mild conditions) coupled with different atmospheric conditions (temperature, humidity, rainfall, wind and air pressure). These exposure and atmospheric conditions of the structures, as well as the age of structures, excessive usage, acidic attacks, microbial actions, fire, excessive loads, material and construction defects, result in different kinds and degrees of

deterioration, which are the principal issues affecting existing structures (Alsharqawi *et al.*, 2017; Omar, 2018; Omar and Nehdi, 2018). It is vital to have proper knowledge of the different deterioration mechanisms due to the fact that different deterioration mechanisms lead to different defects such as corrosion of steel reinforcement, cracking, spalling, scaling, concrete delamination and disintegration (Alsharqawi *et al.*, 2017). Some of these deterioration mechanisms mainly affect the steel reinforcement, some affect the concrete, and some affect both. In all the deterioration mechanisms reduce the integrity and performance of the concrete structures (Gucunski and Nazarian, 2010). The majority of deterioration in existing bridges is associated with the bridge deck because it carries traffic and is directly affected by environmental conditions (Mac *et al.*, 2019; Abdelhady and Moselhi, 2022). Also, bridge deck can either be in the atmospheric zone or splash zone depending on its elevation relative to the tide or wave action in the situation where the bridge is subjected to a marine environment. Different researchers (Imani *et al.*, 2013; Omar, 2018; Abdelhady and Moselhi, 2022) have suggested corrosion, alkali-silica reaction (ASA), leaching, salt and acid actions, creep, fatigue, shrinkage, deck delamination, cracking, concrete deterioration, spalling, scaling, disintegration, abrasion, cavitation and scour as the common defects in RC structures.

Nevertheless, corrosion has been recognised as the major cause of about 70 – 90% deterioration in structures (Evzen *et al.*, 2025) built with reinforced concrete and pre-stressed concrete (Rinaldi *et al.*, 2022; Liu *et al.*, 2024). Corrosion is a chemical change (in the existence of oxygen) or electrochemical process (in the presence of electrolyte) causing deterioration to the properties of metals (e.g steel reinforcements) due to their interactions with the environment (Sheela and Kapil, 2020; Amirhossein *et al.*, 2023). Corrosion occurs due to redox (reduction and oxidation) reactions which take place simultaneously at the anodic and cathodic sites on the steel reinforcement surface (Nayak and Thakare, 2017). The combination of the two half-cell equations from the redox reactions leads to the production of corrosion product (rust), i.e., iron(II) hydroxide [Fe(OH)₂]. The corrosion of steel reinforcement in concrete structures can be due to either carbonation of concrete or ingress of chloride in concrete structures (Dubala *et al.*, 2015; Zheng *et al.*, 2020). However, corrosion generated by ingress of chlorides has been the main cause of deterioration of RC structures opened to marine environments (Zeng *et al.*, 2022; Darmawan *et al.*, 2024). Corrosion in RC structures negatively affects the steel reinforcement properties (Osmolska *et al.*, 2020; Amirhossein *et al.*, 2023), the concrete material and the bond between the concrete and steel reinforcement, resulting in the overall reduction of the structural efficiency of the structures (Mak *et al.*, 2019; Nour and Abo, 2021), a decrease in the structures' service life (Mahima *et al.*, 2018) and also economic losses (Nagande *et al.*, 2020) due to repair (Zhao *et al.*, 2023) and replacement in addition to structural failure over time. Corrosion makes up about one-fourth of

the world's annual production (Juspher *et al.*, 2018).

Furthermore, due to the negative effects and consequences of corrosion, it has become of great interest to researchers globally (Ogirigbo and Black, 2017; Yupeng *et al.*, 2022). To ensure effective management of all existing bridges, it is essential to conduct comprehensive condition assessments. Such assessments provide critical information on the extent of corrosion and other forms of deterioration, thereby enabling stakeholders and highway authorities to reliably predict the service life, estimate the residual service life and evaluate future performance, as well as make informed decisions regarding maintenance planning and life cycle cost (LCC) analysis. A reliable condition assessment of existing bridges is vital in optimising the structure intervention strategies (maintenance, replacement and rehabilitation) and also helps in reducing the social-economic implications associated with the structure's distress or collapse. Existing bridge condition assessment also acts as a source of information for management systems of structure such as the bridge management system (BMS) (Ahmed *et al.*, 2015). The assessment of the conditions of existing bridges has become a frequent task for engineers, due to the increasing age and deteriorating conditions of the structures (Olawale *et al.*, 2019). Condition assessment of existing RC bridges can be done with different methods such as visual inspection (VI), non-destructive testing (NDT), load testing, structural health monitoring (SHM), and finite element modeling (FEM) (Omar and Nehdi, 2018). These methods of assessments have their associated merits and limitations. The visual inspection (VI) method is the most frequently used method in the assessment of structures' components (Ahmad, 2015), and it can only be used to assess visible defects or surface defects in structures (Ayswarya *et al.*, 2016; Alhaj, 2018), such as cracks, spalling, patches, potholes, concrete deterioration (Osuji *et al.*, 2020) and rust stains (Dousti *et al.*, 2013). The non-destructive testing (NDT) method has been identified as a group of techniques commonly deployed in accessing the conditions of RC structures without causing any destruction to the structures (More and Bogar, 2017). The advanced NDT methods such as Electrical Resistivity (ER), Ground Penetrating Radar (GPR), Half-Cell Potential (HCP) and Impact Echo (IE) are used to obtain corrosion data regarding concrete structures' components as well as the whole structures.

It is worthy of note that most of the assessments of bridges that have been done in the past in Nigeria were mainly done with conventional non-destructive testing (NDT) methods like visual inspection (VI) and chain dragging/hammer sounding (Sule *et al.*, 2018; Olawale *et al.*, 2019; Mlanga *et al.*, 2019; Petri, 2020; Ibrahim *et al.*, 2021). Ajjagbe *et al.* (2012) used both conventional and advanced NDT methods while Afolabi *et al.* (2020) used advanced NDT method in their respective studies. Also, most of the existing condition assessments that have been conducted on different bridges in Nigeria did not focus on corrosion deterioration, and also studies regarding the impact of the Orogodo River environment on existing structures are as well scarce. Thus this study provides a distinctive contribution by delivering the corrosion assessment of a steel-concrete composite bridge exposed to the Orogodo River environment using an integrated approach that combines physico-chemical water analysis with multiple non-destructive evaluation methods (visual inspection, concrete cover measurement, rebound hammer, ultrasonic pulse velocity-UPV, and half-cell potential-HCP). This integrated framework addresses a significant gap in existing literature, where such comprehensive, multi-method corrosion diagnosis for Nigerian river-exposed composite bridges is largely absent.

2. Materials and Methods

2.1 Material

2.1.1 Collected Water Sample for Analysis

Water samples were collected from different points along the Orogodo River, located along Benin-Asaba Road, Agbor, Delta State, Nigeria. The collected water samples were analysed in the laboratory to determine the different corrosion-causing agents.

2.2 Methods

2.2.1 Description of the Study Area and the Orogodo Composite Bridge

The Orogodo River is located in Agbor, in the Ika South Local Government Area of Delta State, Nigeria and Agbor experiences an annual rainfall of about 2000 mm (Aghogho *et al.*, 2023). The river is about 50 km in length and lies between latitude $5^{\circ}00' - 6^{\circ}02' N$ and longitude $6^{\circ}10' - 6^{\circ}26' E$ (Iwegbue *et al.*, 2012) as shown in Figure 1. The source of the river is from Mbiri village at an elevation of 150 m above the level of the sea (Rim-Rukeh *et al.*, 2006; Edjere *et al.*, 2015), and it flows through the major towns in Agbor and then empties into the River Ethiope in Southern Nigeria (Iwegbue *et al.*, 2012). The river serves as the major source of water for domestic use, fishing and recreational needs for the people living in the environs (Edjere *et al.*, 2015; Olomukoro *et al.*, 2022), while agricultural waste disposal has been contributed to its pollution (Rim-Rukeh *et al.*, 2006). The water samples used for this study were collected from different points around the steel-concrete composite Orogodo Bridge in the Orogodo River.

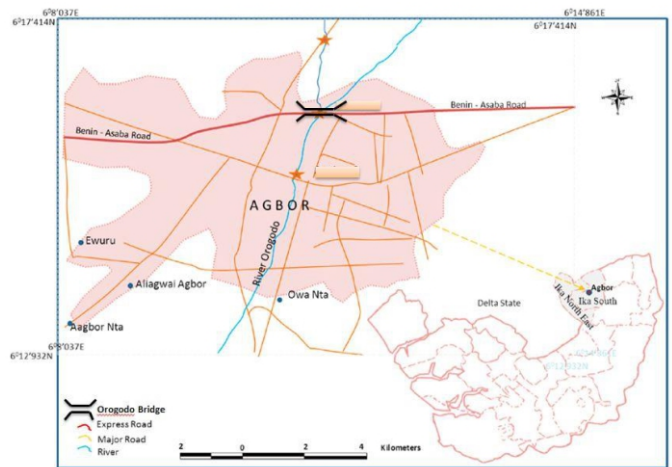


Figure 1: Modified map showing Orogodo River (Olomukoro *et al.*, 2022)

The Orogodo Bridge is a steel-concrete composite bridge located along the Benin-Asaba Road in Agbor, in the Ika South Local Government Area of Delta State, Nigeria, as shown in Figure 1 and Figure 2. The bridge lies between latitudes $06^{\circ}16.035' N$ and $06^{\circ}16.029' N$ and between longitudes $006^{\circ}11.580' E$ and $006^{\circ}11.604' E$. It was constructed around 1970, and it is a crucial part of the expressway, facilitating transportation between Benin City in Edo State and Asaba in Delta State. The bridge is about 43.575 m in length and 8.850 m in width. The bridge deck is made of reinforced concrete supported by 5 No. universal girder steel beams resting on reinforced concrete piers and abutments. The average vertical distance between the deck soffit of the bridge and the surface of the Orogodo River, which the bridge spans over, is about 1.950 m. The transverse arrangement of the Orogodo Bridge is depicted in Figure 3, while the different sections (V, W, X, and Y) in which the bridge deck was sectioned for field assessment purposes are illustrated in Figure 4.



Figure 2: The Existing Orogodo Composite Bridge

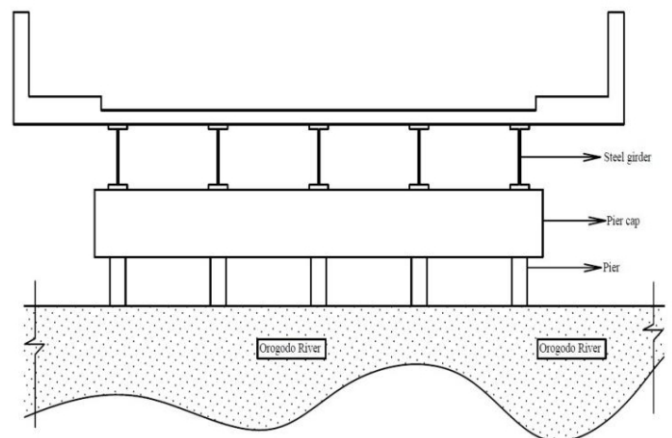


Figure 3: Transverse layout of existing Orogodo Bridge

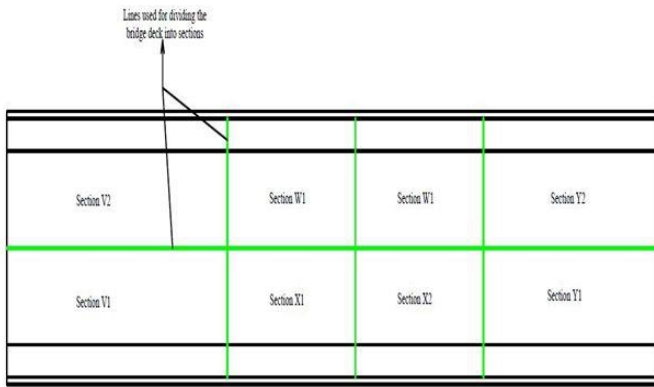


Figure 4: Orogodo Bridge deck showing different sections used for Field Assessments



Figure 5: Visual inspection of the Orogodo Composite Bridge

2.2.2 Physico-Chemical Analysis of the Orogodo River Water Sample

The Orogodo River water samples were collected from four (4) different points (a, b, c, and d) at the bottom of the existing Orogodo Composite Bridge located in the Orogodo River environment. The water samples were collected in clean transparent plastic containers, labelled and analysed in the laboratory. The transparent plastic sample containers were pre-treated by washing with 0.05 M dilute hydrochloric acid, rinsed with distilled water, and then sun-dried. At the sampling points, the containers were again rinsed twice with the water samples before being filled with the Orogodo River water samples and tightly sealed. This aligns with the method used by Rim-Rukeh *et al.* (2006) for water sample collection. The pH, conductivity and salinity of the water sample were determined with a multiparameter device after stirring the water sample with a constant-temperature magnetic stirrer.

The chloride concentrations in the Orogodo River water samples were determined by Argentometric titration. Argentometric titration involves reacting silver nitrate (AgNO_3) with chlorides in the water samples to form an insoluble white precipitate of silver chloride (AgCl). Once all the chloride ions are used up, excess silver ions react with chromate ions (CrO_4^{2-}) from the potassium chromate indicator to produce a brick-red silver chromate (Ag_2CrO_4) precipitate, marking the end point. The chloride ion concentration was then calculated using Equation 1.

$$\text{Chloride ion concentration (mg/L)} = \frac{V \times N \times 35.5 \times 1000}{\text{Volume of water sample (mL)}} \quad (1)$$

where V = Volume of AgNO_3 used in litres (L), N = Normality of AgNO_3 (mol/L); 35.5 = Molar mass of chloride ion; 1000 = conversion factor.

The sulphate concentrations in Orogodo River water were determined using the turbidimetric method-where sulphate ions in the Orogodo River water react with barium chloride (BaCl_2) to form a fine white precipitate of barium sulphate (BaSO_4). The resulting turbidity was measured with a spectrophotometer and the sulphate concentration was obtained by comparing with a standard calibration curve.

2.2.3 Field Condition Assessment Methods

The following five (5) methods, visual inspection (VI), concrete cover testing using a covermeter or profometer, rebound hammer testing, ultrasonic pulse velocity (UPV) testing and half-cell potential (HCP) testing, were separately used in assessing the Orogodo Bridge.

(i) Visual Inspection (VI)

Visual inspection (VI) has been described as the fundamental method used for assessing structural conditions of structures, and it guides the assessors on the need for further evaluation and the appropriate method to use (Osuji *et al.*, 2020). In this study, VI was performed in accordance with ACI 201.1R-08 using a digital camera, measuring tape, marker, personal protective equipment (PPE) and a recording notebook. The VI was used to document the dimensions and surface defects-cracks, spalling, exposed reinforcement corrosion and rust stains- on the different elements of the Orogodo composite bridge. Figure 5 shows the VI assessment operation of the Orogodo composite bridge. Based on the observation from the VI and its importance in condition assessments of existing structures, the Orogodo composite bridge's deck was selected for further assessment using a covermeter or profometer, rebound hammer test, ultrasonic pulse velocity (UPV) test and half-cell potential (HCP) test, respectively.

(ii) Determination of Concrete Cover using Covermeter

Concrete cover in RC structures protects the steel reinforcement, enhances durability and extends the service life of the structures. The concrete cover of the RC Orogodo Bridge deck was measured with a covermeter (Profometer) (Bosch, D-TECT 150 SV), as depicted in Figure 6, and the test was conducted in line with BS 1881-204 (1988). The concrete cover of the different sections of the bridge deck, as illustrated in Figure 4, was measured with the covermeter instrument.



Figure 6: Covermeter device used for the study

Prior to the assessment, the instrument was calibrated in the field with the manufacturer-provided calibration block. Care was taken to ensure that the concrete surfaces of the bridge deck that were assessed were clean, dry and free from debris. A systematic scan was conducted along defined sections of the bridge deck, maintaining consistent contact between the covermeter probe and the concrete surface. Multiple readings were taken, and the average value was calculated, especially in areas with variable concrete covers.

(iii) Compressive Strength Test using Rebound Hammer

The rebound hammer test is a non-destructive testing (NDT) method used to measure the compressive strength of hardened concrete, and it can be deployed both in the field and in laboratory settings. The digital rebound hammer (Control Group, 58-C0181/DGT, 16008269), as shown in Figure 7, was deployed in accordance with BS 1881-202 (1986) for the assessment of the bridge deck. The test was conducted on a neat, non-moist, flat and smooth concrete deck of the bridge. Light pressure was applied to release the rebound hammer's plunger from its locked position, as shown in Figure 8.



Figure 7: Digital Rebound Hammer test kit used for the study



Figure 8: Digital Rebound Hammer test on Orogodo Composite Bridge

The device was positioned perpendicular (90°) to the concrete surface of the bridge deck, and the plunger was gradually pressed until it impacted. The rebound reading was recorded while ensuring no two points were closer than 25 mm or within 25 mm of an edge. Nine readings were taken per area, and the average compressive strength was calculated.

(iv) *Ultrasonic Pulse Velocity (UPV) Test*

The ultrasonic pulse velocity (UPV) test is used to assess concrete quality (Zaid et al., 2023), and its relationship with compressive strength is well established and reported (Said and Ali, 2021). The measurement of the propagation velocity of the ultrasonic pulse of the Orogodo Bridge deck was conducted in accordance with BS 1881-203 (1986), and Figure 9 depicts the UPV device (Control brand, 58 – E4900) that was used for the assessment. The indirect (surface method) of transducer arrangement (transmitter-T and receiver-R) – which involves positioning both the transmitter (T) and receiver (R) on the same surface of the bridge deck – was utilised, as seen in Figure 10. This approach was used due to the asphalt overlay on the top deck of the bridge and in order not to interrupt traffic flow on the bridge, in addition to safety concerns. Measurements were only taken on the bottom of the bridge deck, and none were taken on the top of the deck due to asphalt overlay. The value of the longitudinal pulse velocity obtained from the test was interpreted using the criteria given by Song and Saraswathy (2007), as shown in Table 1.



Figure 9: Ultrasonic pulse velocity device used for the study



Figure 10: Determination of UPV values of the Orogodo Bridge deck

Table 1: Longitudinal pulse velocity and concrete quality

Longitudinal pulse velocity (km/sec)	Approximate compressive strength (N/mm ²)	Quality of concrete
Below 2.0	-	Very poor
2.0 to 3.0	4.0	poor
3.0 to 3.5	up to 10	Fairly good
3.5 to 4.0	Up to 25	Good
4.0 to 4.5	up to 40	Very Good
Above 4.5	up to 40	Excellent

(Song & Saraswathy, 2007)

(v) *Half-Cell Potential (HCP) test*

The HCP test for the Orogodo Bridge deck was done in line with ASTM C876 (1999). The test was performed with the use of a portable corrosion meter, James instrument brand, C-CM-4000, as depicted in Figure 11, and a copper/copper sulphate electrode (CSE) was deployed as the reference electrode. The CSE was linked to the positive port of the voltmeter, while the negative port was linked to the steel reinforcement, as shown in Figure 12 and Figure 13.



Figure 11: Half- Cell Potential Equipment Kit used for the Study

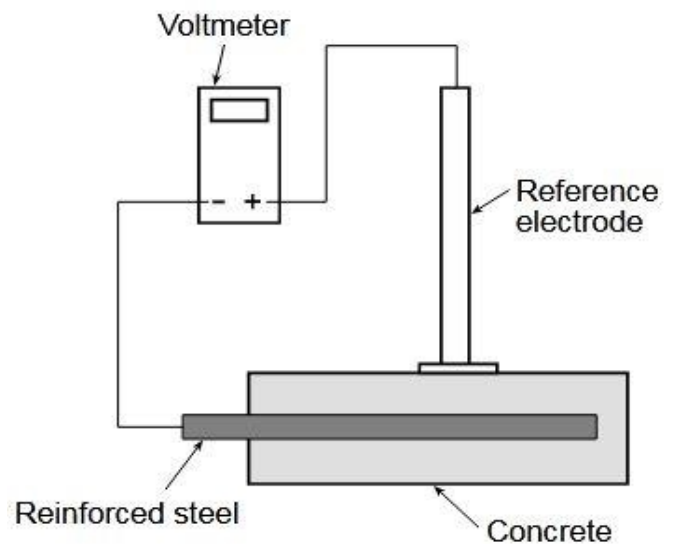


Figure 12: Schematic HCP test setup (Gu & Beaudoin, 1998)

During the assessment, a moist sponge was placed between the CSE and the concrete in order to improve the electrical coupling between the HCP device and the bridge deck. The obtained values of the potential difference from the HCP assessment were compared with standard values stipulated in code as documented in the study conducted by Osuji et al. (2020) and presented in this study as Table 2.



Figure 13: HCP Test Connection on the Orogodo Bridge Deck

Table 2: Probability of Corrosion for CuSO₄ in accordance with ASTM C 876 (2015)

S/ N	Half-cell potential (mV) relative to Cu/CuSO ₄ reference electrode (mV)	Interpretation
1	> -200	> 90% probability that no corrosion is occurring. (10% chance of active corrosion)
2	-200 to -350	Corrosion activity is uncertain. (50% chance of active corrosion)
3	< -350	> 90% probability that corrosion is occurring. (90% chance of active corrosion)

(Osuji *et al.*, 2020)

3. Results and Discussion

3.1 Water Constituents and Quality Analysis

The physico-chemical properties of the Orogodo River water sample are presented in Table 3. The results of the water samples showed that the Orogodo River water, with an average conductivity of 119.375µs/cm, is fresh water. It aligned with the criteria given by Ferdiansyah *et al.* (2023) for the conductivity of fresh water (<1,500 µs/cm). The results also revealed that the Orogodo River water contained an average chloride concentration of 65.850 mg/l and a sulphate concentration of 8.718 mg/l.

The average chloride was within the range (56.59 mg/l - 87.64 mg/l) in the physico-chemical properties analysis of the Orogodo River water conducted by Rim-Rukeh *et al.* (2006). The results also revealed that the Orogodo River water contains aggressive agents (chloride ions and sulphate ions) that are corrosion causative agents in steel reinforcements embedded in concrete. This aligned with the opinions of researchers (Mak *et al.*, 2019; Taheri-Shakib and Al-Mayah, 2025). The results also revealed that the concentration of the chlorides was higher compared to the concentration of the sulphates. This showed that the chlorides were the major corrosion-causing agent of the steel reinforcing bars in the Orogodo composite bridge's elements.

Table 3: Orogodo River water constituents

Physico-chemical parameters	Points of water sample collections				Average Values
	a	b	c	d	
pH	5.41	5.23	5.39	5.45	5.370
Conductivity (µs/cm)	117.00	105.00	131.50	124.00	119.375
Salinity (ppt)	0.119	0.106	0.132	0.125	0.121
Chloride ion (Cl ⁻) (mg/l)	65.00	58.00	72.15	68.25	65.850
Sulphate ion (SO ₄ ²⁻) (mg/l)	8.97	8.55	8.70	8.65	8.718

3.2 Visual Inspection Result of Orogodo Composite Bridge

The results of the visual inspection are outlined in Table 4. The findings showed that the bridge RC elements – piles, piers and pier caps, abutment and wing walls – as well as the steel girders, were visually in good condition. However, there are different degrees of deterioration, broken concrete from the parapet in the section

of the deck marked X, as well as cracking, spalling, exposed and corroded steel reinforcements, in addition to visible rust stains, as shown in Figure 14 and Figure 15. The broken concrete sections on the bridge deck and parapet might be due to human activities, accidents, and overloading on the bridge, as well as poor construction and inadequate maintenance. The broken concrete sections and the spalling of the concrete cover served as channels through which the aggressive agents (chloride ions, moisture and oxygen) easily get to the steel reinforcing bars, thus leading to corrosion. This finding aligned with the VI result in the investigation conducted by Osuji *et al.* (2020) on a quay structure located in the Niger Delta Region of Nigeria. In a nutshell, the VI results of the Orogodo Bridge revealed that the section labelled X on the bridge deck located in a spray and splash zone showed more visible signs of deterioration than other sections (V, W, and Y), respectively. The VI results also revealed the need for further assessment for the bridge deck, with more attention on the section marked X. This will help to determine other variables (level of corrosion and strength parameter), which will be useful in determining the bridge deck's condition for proper recommendation of appropriate strategy(ies) among repair, maintenance, replacement and rehabilitation.



Figure 14: Visible signs of severe deteriorations on the section X of the Orogodo Bridge Deck



Figure 15: severe broken concrete section with dried vegetation an exposed corroded steel rebar

3.3 Concrete Cover Result of Orogodo RC Bridge Deck

The average concrete cover result for the bridge deck was found to be 74.50 mm, as seen in Table 5. The average concrete cover satisfied the BS 8110-1 (1997) minimum concrete cover requirements: 20 mm for 40 N/mm² and 45 N/mm² in mild environments; 40 mm and 30 mm for 40 N/mm² and 45 N/mm² in severe environments; and 50 mm and 40 mm for 40 N/mm² and 45 N/mm² in very severe environments. The concrete cover for the bridge deck also met the minimum cover requirement of 75 mm prescribed in the AASHTO LRFD Bridge Specification (1998) for concrete in coastal environments, as reported by Kepler *et al.* (2000). The adequate concrete cover provided adequate protection for the embedded steel reinforcements on the bridge deck against aggressive agents such as chloride ions. However, the broken concrete sections and the concrete cover spalling on the section marked X on the bridge deck served as channels through which aggressive agents (chloride ions, moisture and oxygen) got to the steel reinforcements. This resulted in the corrosion that was seen on the steel reinforcements on the section marked X of the bridge deck.

Table 4: Elements of Orogodo Composite Bridge, Exposure Zone & Level of Deterioration using Visual Inspection and Existing Literatures

Bridge Element	Exposure zone/class	Level of deteriorations using visual inspection/existing literature	The need for further assessment	Alignment with existing studies
Piles	Submerged zone; Continuously immersed in the Orogodo River water.	There is possibility of chloride ingress, however with low oxygen and slow /low corrosion.	No, due to difficulties in carrying out assessment.	Moore <i>et al.</i> , (2022); Sannasiraj <i>et al.</i> , (2025)
Piers and piers caps	Tidal/splash zone; The zone is aggressive due to surplus oxygen supply from the environment.	There was no visible defects (corrosion, and cracks) on the section of the pile even when the section is subjected to wet – drying cycling. This might be due to the concrete quality and the level of aggressive agents in the Orogodo River water.	No, due to no visible deteriorations	Moore <i>et al.</i> , (2022); Yu <i>et al.</i> , (2023)
Bridge deck (Top surface)	Atmospheric zone; Exposed to air borne Orogodo River water	There were no; rust stains, cracks, broken/spalled concrete cover, exposed and corroded steel rebars on any section of the top deck of the bridge.	Yes, due to the condition of the bottom deck	Li <i>et al.</i> , (2022); Sannasiraj <i>et al.</i> , (2025)
Deck (Bottom and sides)	Spray/splash zone; Wetting and drying cycles and aeration (continuous oxygen supply).	It showed severed signs of deterioration (cracking, spalling, exposed and corroded steel rebars, as well as visible rust stains) on section marked X.	Yes, it showed severe deterioration on section X.	Sannasiraj <i>et al.</i> , (2025)
Steel girders	Spray zone; Wetting and drying cycles and aeration.	There were no signs of any defects on the steel girders.	No, due to no deterioration	Yu <i>et al.</i> , (2023)
Abutment and wing walls	Atmospheric zone; Exposed to air borne Orogodo River water	There were no signs of any defects on the abutment and wing walls.	No, due to no visible defects	Li <i>et al.</i> , (2022)

Table 5: Concrete Cover Results of the Bridge (Bottom Deck)

Parameter	Different Sections on the Bridge Deck							
	V		W		X		Y	
Cover thickness (mm)	V1	V2	W1	W2	X1	X2	Y1	Y2
Cover thickness (mm)	75	74	75	74	75	75	74	74
Average cover thickness (mm)	74.50							

3.4 Rebound Hammer Test Results of Orogodo RC Bridge Deck

The compressive strength results obtained from the rebound hammer test conducted on different sections (V, W, X and Y) of the Orogodo composite bridge deck are presented in Table 6. There were no results for the top sections of the bridge deck due to the fact that no strength test was conducted on the deck of the bridge. This was due to the non-accessibility of the concrete section at the top deck owing to the asphalt overlay at the top deck of the bridge. The bottom deck compressive strength ranged from 49.3 to 50.5 N/mm², with an average of 49.51 N/mm². All values exceeded the minimum requirements: 30 N/mm² for mild exposure and 40 N/mm² for severe environments as prescribed by BS 5328-1 (1997), as well as the 35 N/mm² minimum for corrosion protection in chloride-exposed concrete specified in ACI 305-01 (2001). The compressive strength results also showed that section X - despite corrosion, broken concrete, cracks, and vegetation-still met the minimum strength requirements for various exposure conditions specified in different codes (BS 5328-1, 1997; ACI 305-01, 2001). This is regardless of the fact that some compressive strength values obtained at some points of section X were lower compared to other deck sections of the bridge. The adequacy of the compressive strength of the deck section of the bridge with respect to minimum relevant provisions might be due to adequate design and construction of the bridge as well as the less aggressiveness of the exposure condition, i.e., the Orogodo River.

Table 6: Compressive Strength Results of Orogodo RC Bridge Deck

Parameter	Different Sections on the Bridge Deck							
	V		W		X		Y	
	V1	V2	W1	W2	X1	X2	Y1	Y2
Compressive strength (N/mm ²) (from top side of the deck)	NA	NA	NA	NA	NA	NA	NA	NA
Compressive strength (N/mm ²) (from bottom side of the deck)	50.2	50.5	49.5	49.7	48.8	48.6	49.3	49.5

Note; NA means not accessible

3.5 UPV results of Orogodo RC Bridge Deck

There were no UPV results for the top deck section of the bridge due to the fact that no UPV test was carried out on the top deck of the bridge. This was due to the asphalt overlay on the deck of the bridge. However, the UPV results of the bridge bottom deck ranged from 5.47 km/s to 5.69 km/s with an average value of 5.57 km/s, as seen in Table 7. All the UPV results of the different sections as well as the average magnitude met the requirement (≥ 4.5 km/s) for “Excellent” concrete contained in the studies conducted by the researchers (Song and Saraswathy, 2007; Hasbullah *et al.*, 2017). It also met the standard of > 4.0 km/s for “Very good” concrete as reported in the study conducted by Rehman and Paliwal (2019). The UPV results also revealed that the corrosion on the different sections of the bridge bottom deck was in the order $X > Y > W > V$. This corroborated the findings of the visual inspection evaluation of the bridge structure. Additionally, it supported the findings of Othman and Ayop (2019) and the view of Mayakuntla *et al.* (2022) that UPV results decrease as corrosion increases over time. However, the corrosion at section X, despite adequate UPV results, was caused by broken concrete that allowed river water, oxygen, and moisture to reach the steel. If not addressed, it will progress to severe corrosion, cracking, spalling, loss of steel-concrete bond, and reduced bridge performance.

Table 7: UPV Results of Orogodo RC Bridge Deck

Parameter	Different Sections on the Bridge Deck							
	V		W		X		Y	
	V1	V2	W1	W2	X1	X2	Y1	Y2
Pulse velocity (km/s) (from top of the deck)	NA	NA	NA	NA	NA	NA	NA	NA
Pulse velocity (km/s) (from bottom of the deck)	5.66	5.69	5.57	5.59	5.49	5.47	5.54	5.57

Note; NA means not accessible

3.6 HCP Results of Orogodo RC Bridge Deck

There was no HCP test results for the top deck of the bridge deck due to a lack of exposed steel reinforcement needed to conduct and complete the test. The HCP results of the different sections (V, W, X and Y) of the Orogodo bridge bottom deck ranged from -150 mV to -295 mV with an average value of -202.50 mV, as shown in Table 8. The HCP results showed that the corrosion possibility in the different sections of the bridge deck was in the order $X > Y > V > W$. The HCP results of the sections (V, W, and Y) of the bridge bottom deck showed that more than 90% of the sections have no corrosion taking place in accordance with ASTM C876 (2015) and Tenli *et al.* (2020). Also the average HCP result (-290 mV) of section X of the bridge deck conformed to the stipulation (-200 mV to -350 mV) (Osuji *et al.*, 2020) - which depicted that there was about a 50% possibility that corrosion might be occurring in the section marked X of the bridge deck. However, visual inspection results showed that there were corrosion

signs on the section X of the bridge deck – which means that there was a possibility that corrosion was occurring on the bridge deck section marked X.

Table 8: HCP results of Orogodo Bridge deck

Parameter	Different Sections on the Bridge Deck									
	V		W		X		Y			
	V1	V2	W1	W2	X1	X2	Y1	Y2		
HCP (mV) (from top side of the deck)	NA	SNA	SNA	SNA	SNA	SNA	SNA	SNA	SNA	
HCP (mV) (from bottom side of the deck)	-175	-160	-170	-150	-295	-285	-195	-190		

Note: SNA means steel reinforcement not accessible

4. Conclusions

This study shows that the Orogodo River, though a freshwater system, mainly contains chloride concentration (65.850 mg/L) capable of accelerating corrosion in the Orogodo Composite Bridge. Visual inspection identified a localised deteriorated area (section X) with cracking, spalling, and exposed/corroded reinforcements, while other elements remained in good condition. Although the average compressive strength (49.51 N/mm²) and UPV (5.57 km/s) results of the bridge bottom deck confirmed excellent concrete quality and adequate concrete cover (approximately 75 mm) across the bridge bottom deck sections (X, Y, V and W). Section X exhibited an average HCP value of -290 mV, indicating a 50% probability of active corrosion. This was due to the broken concrete and the spalled concrete cover of the section leading to corrosion due to the easy access of the Orogodo River water-which contains chloride. Thus the HCP and VI results revealed active corrosion on section X of the bridge deck. This further shows the importance of concrete cover to RC structures and the need for its preservation. In a nutshell, the findings further reinforced the importance of sufficient and non-defective concrete cover, continuous monitoring, and timely maintenance of RC structures exposed to aggressive environments. The study recommends the multiple condition assessment methods for corrosion assessment of RC structures and timely maintenance of the Orogodo Bridge to prevent further deterioration and performance loss in the bridge, with emphasis on the section marked X.

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