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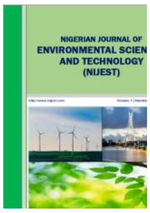

Compressive Strength and Deformation Behaviours in Quay Concrete Slabs Using Ultrasonic Pulse Velocity and Geodetic Analysis

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ABSTRACT

This study evaluates the compressive strength and deformation of a quay slab using ultrasonic pulse velocity (UPV) testing and geodetic deformation analysis. The slab, measuring 401.532 m in length and 29.644 m in width, was subjected to structural health monitoring techniques. The analysis revealed an overall compressive strength of 40 N/mm², with corresponding deformation parameters including deflection rates of 0.2 mm/year horizontally and 0.3 mm/year vertically. Furthermore, the analysis showed that the quay has an average rotation of 0.0000194 secs/year, and average velocity of 0.00000000000845 m/s². These results confirm that concrete structures with high compressive strength exhibit minimal deformation, supporting the role of UPV as a reliable indicator of structural integrity.

Keywords: *Structural health monitoring, Structural deformation, Least Squares Analysis, Quay, Verticality*

1.0 Introduction

Amidst numerous cases of building collapse and structural failure, the needs for structural health monitoring (SHM) have become more prominent in recent times. SHM is a critical process in engineering that utilizes sensors, data acquisition systems, and computational algorithms to assess the condition of structures in real-time or through periodic monitoring (Chang et al, 2003). The objective in SHM is to detect alarming movements and damages, such as cracks or corrosion, and thus, enable early interventions, improve safety and reduce maintenance costs (Farrar & Worden, 2012). Structural health monitoring involves a combination of structural integrity testing and deformation monitoring. While techniques such as vibration analysis, acoustic emission, and ultrasonic testing are commonly used to monitor changes in structural integrity (Sohn et al, 2004); geodetic measurements analyzed by either least squares (LS) or finite element method (FEM) are used to assess the state/rate of deformation of the structure. Invariably, continued cases of building collapse and structural failure continue to emphasize the need for effective SHM. While compressive strength is essential in maintaining structural stability, understanding its link to deformation behaviours is crucial, especially in large concrete slabs such as quay structures. This study aims to investigate the interrelationship between compressive strength and deformation parameters with a view to provide insight into the structural performance of concrete slabs under load.

Concrete is one of the most widely used construction materials due to its versatility, strength, and durability. Its compressive strength is a critical parameter, as it directly relates to the structural integrity of concrete components, including slabs, beams, and columns. Although, compressive strength test is traditionally tested using destructive test methods like core and cylinder tests (Neville, 2011); non-destructive testing (NDT) methods offer the advantage of testing the concrete slabs without damaging the structure. NDT methods such as rebound hammer and ultrasonic pulse velocity (UPV) are commonly used to estimate compressive strength indirectly. UPV testing (ASTM C597) involves measuring the velocity of ultrasonic waves traveling through the concrete, which can later be related to the material's strength.

Earlier studies have explored the relationship between compressive strength of concrete and building deformations, recognizing compressive strength as a fundamental factor in determining the behaviour of structures under load. One of such study by Neville (1995) highlighted the critical role of concrete compressive strength in resisting loads and preventing excessive deformations. The study showed that lowerstrength concrete increases the risk of cracking and deflection under service loads. Similarly, Mehta & Monteiro (2006) emphasized that inadequate compressive strength can lead to serviceability issues like excessive deflections, which can compromise structural integrity over time. Their work demonstrated that compressive strength is directly linked to the stiffness of concrete, which in turn governs the deformation characteristics of buildings. This relationship is particularly crucial in high-rise structures, where vertical deformations can lead to differential settlements and cause structural distress (Mindess et al, 2003)

Subsequent studies expanded on this understanding by investigating the effect of varying concrete strengths on deformation behaviours. For instance, Mukherjee and Joshi (2005) examined how compressive strength variations influenced structural performance under seismic loads, finding that structures built with higher strength concrete exhibited reduced lateral deformations during seismic activity. Additionally, Kwan and Ng (2013) studied the long-term effects of concrete strength on building deformations, concluding that high compressive strength reduced creep and shrinkage, which are the key factors contributing to deformation over time. Their research highlighted the importance of selecting appropriate concrete strength for different structural elements to mitigate time-dependent deformations.
Consequent upon the foregoing, this study presents a comparative analysis of the results of compressive strength testing and deformation analysis of a quay with a view to analyzing the spatial correlation and interrelationship between compressive strength and deformation parameters (strain, rotation, velocity and deflections) within the study area.

2.0 Materials and Methods

3.1 Study Area
The study was conducted on a jetty facility located at Apapa area of Lagos state. The jetty was constructed to serve as docking/anchor yard for vessels. It is located at 543688.39mE, 711258.131mN. Figure 1 shows the geographical location of the quay and its geometrical expanse.

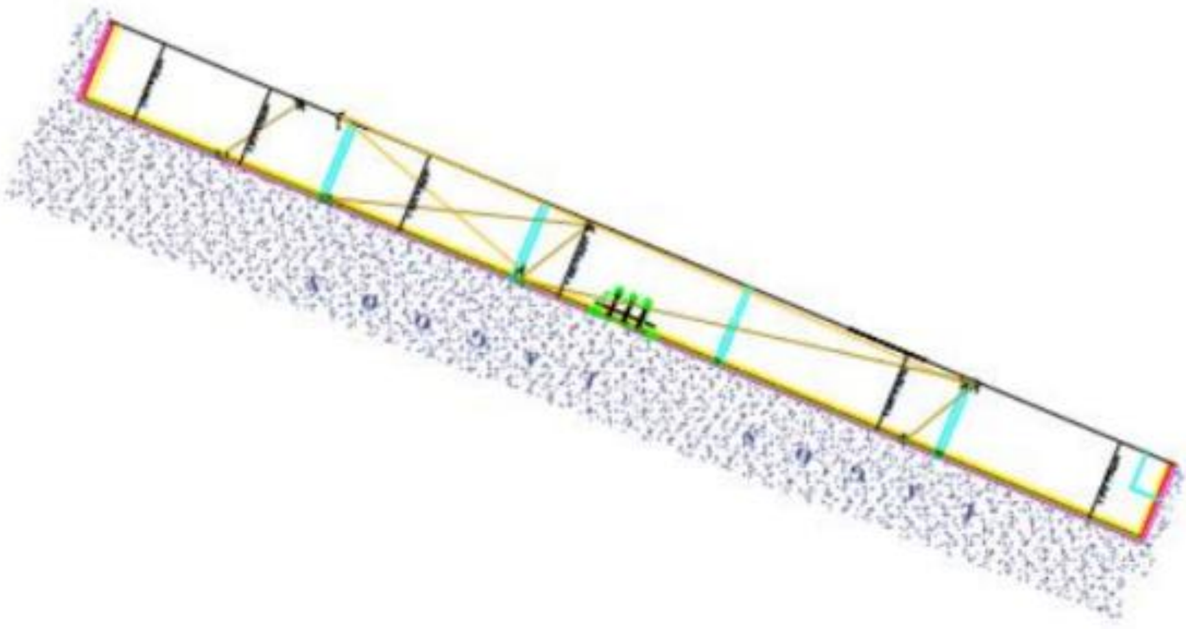


Figure 1: The study area

2.2 Overview of Methods
Theoretical overview of compressive strength testing by Ultrasonic pulse velocity measurement and deformation analysis by the MINQUE-LS estimation approach is presented below;

2.3 Compressive Strength from Ultrasonic Pulse Velocity Measurement

Ultrasonic Pulse Velocity (UPV) measurement is a widely used non-destructive testing (NDT) takes for ultrasonic waves to travel through a concrete specimen, providing indirect information about its density, elasticity, and internal structure. According to ASTM C597 and BS 1881-203, the wave velocity is affected by the concrete's mechanical properties and internal conditions, such as voids, cracks, and aggregate distribution (Malhotra & Carino, 2004). The relationship between pulse velocity V (m/s) and compressive strength fc can be mathematically expressed as:

$$V = \frac{L}{T} \quad (1)$$

Where
L is the path length (m), and
T is the travel time (seconds).

High pulse velocities often correlate with higher compressive strength, as denser concrete allows waves to propagate more rapidly. Studies such as those by Demirboğa, Türkmen, and Karakoc (2004) have established empirical correlations between UPV and compressive strength, which is often used to estimate the latter without damaging the concrete structure.

UPV's advantage lies in its ability to assess in-situ concrete, making it useful for evaluating structures without the need for destructive core extraction. The correlation between velocity and strength can be improved by considering factors like moisture content, aggregate size, and curing conditions (Neville, 2011). A commonly used empirical relationship for estimating compressive strength is:

$$fc = aV^b \quad (2)$$

Where
a and b are constants determined from experimental calibration (Popovics, 2001).

2.4 Determination of Deformation parameters by Minimum Quadrature Unbiased Estimation Lease Squares (MINQUE-LS)

Deformation analysis is a critical process in engineering, geodesy, and structural health monitoring, where the movement or deformation of structures is evaluated based on observational data. The least squares method (LSM) is widely employed in deformation analysis to provide optimal estimations by minimizing the sum of the squared residuals between observed and modeled values (Mikhail and Ackermann, 1976). In its simplest form, LSM estimates unknown parameters in a linear model by solving the normal equations derived from the condition of minimal squared errors. This method is robust for geodetic networks, where coordinate changes over time are used to infer deformation patterns (Teunissen, 2000). Despite its broad applications, traditional least squares can be sensitive to the assumptions of equal precision in the data. When observations have unequal variances, the weighted least squares (WLS) method, which incorporates variances into the estimation process, offers a more refined solution (Koch, 1999).

An advanced extension of the least squares method, particularly suitable for deformation analysis, is the

Minimum Norm Quadratic Unbiased Estimation (MINQUE) approach. MINQUE, first introduced by Rao (1971), is a statistical method used to estimate variance and covariance components in linear models without assuming prior knowledge of these components. This makes it particularly useful in situations where the variances of the observations are unknown or heterogeneous. In deformation analysis, the MINQUE method is applied to estimate not only the deformation parameters but also the variances of the observed points, allowing for more reliable detection of structural displacements or movements (Koch, 1999). MINQUE minimizes the quadratic form of the residuals while ensuring unbiased estimates of the variance components, which provides a significant advantage over traditional weighted least squares methods, especially in cases with complex error structures.

The effectiveness of the MINQUE method in deformation analysis lies in its ability to handle correlated observations, which are common in practical applications where multiple points in a structure or network may deform simultaneously under similar loads or environmental conditions. By estimating the variance-covariance matrix of the observations, MINQUE offers more flexibility and accuracy in deformation modeling, making it ideal for geodetic networks, structural monitoring, and civil engineering projects (Rao, 1971; Amiri-Simkooei, 2007). The method's unbiasedness and efficiency have been demonstrated in several studies, such as those by Amiri-Simkooei (2007), where the variance component estimation in geodetic networks showed superior performance compared to traditional LSM approaches. The MINQUE method is also computationally feasible for large datasets, which is crucial in real-time structural health monitoring and geospatial applications.

According to the MINQUE approach, the deformation parameters are directly related to measured coordinates using the following mathematical formulations as shown in equations 3a-7;
Let point ''i '' be the fixed point of the structure, then;

$$d_{x_{ij}} + v_{x_{ij}} = \varepsilon_x X_j + \varepsilon_{xy} Y_j + 0 - \omega Y_j \tag{3a}$$

$$d_{y_{ij}} + v_{y_{ij}} = 0 + \varepsilon_{xy} X_j + \varepsilon_y Y_j - \omega X_j \tag{3b}$$

Where;

$d_{x_{ij}}$ = difference in displacement (distance) between i and j in the "x-direction" $[(X_i - X_j)_{t1}$ - $(X_i - X_j)_{t2}]$

$d_{y_{ij}}$ = difference in displacement (distance) between i and j in the "y-direction"

$d_{z_{ij}}$ = difference in displacement (distance) between i and j in the "z-direction"

v = observational residual

$\varepsilon_x, \varepsilon_y$ = strain in the ''x'' and ''y'' directions

X_j, Y_j = X and Y coordinates of point ''j''

ω = rotation

$$\begin{bmatrix} \Delta_{x_{ij}} \\ \Delta_{y_{ij}} \\ \Delta_{z_{ij}} \end{bmatrix} = \begin{bmatrix} \sqrt{[(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,]} \\ \sqrt{[(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,]} \\ \sqrt{[(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,]} \end{bmatrix} \times \begin{bmatrix} \cos\beta & \cos\alpha \\ \cos\beta & \sin\alpha \\ \sin\beta & 1 \end{bmatrix} \tag{4a}$$

$$\begin{bmatrix} {\Delta_{x_{ij}}}^2 \\ {\Delta_{y_{ij}}}^2 \\ {\Delta_{z_{ij}}}^2 \end{bmatrix} = \begin{bmatrix} (X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,] \\ [(X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,] \\ (X_i - X_j)^2 + (Y_i - Y_j)^2 + (Z_i - Z_j)^2\,] \end{bmatrix} \times \begin{bmatrix} \cos\beta^2 & \cos\alpha^2 \\ \cos\beta^2 & \sin\alpha^2 \\ \sin\beta^2 & 1 \end{bmatrix} \tag{4b}$$

Where
$\Delta_{x_{ij}} = (X_i - X_j)$
all other parameters are as earlier defined
β = Vertical Angles
α = Horizontal Angles

$$\begin{bmatrix} \Delta_{x_{ij}} \\ \Delta_{y_{ij}} \\ \Delta_{z_{ij}} \end{bmatrix} \times [\Delta t^{-1}] = \begin{bmatrix} \boldsymbol{V_x} \\ \boldsymbol{V_y} \\ \boldsymbol{V_z} \end{bmatrix} \tag{5}$$

Putting equations 3 – 5 together to satisfy the conventional least squares MINQUE condition as given in (6) yields a simplified generalized least squares observation equation for 3D building model deformation modeling.

$$\begin{bmatrix} d_{x_{ij}} \\ d_{y_{ij}} \\ d_{z_{ij}} \\ \Delta_{x_{ij}}{}^2 \\ \Delta_{y_{ij}}{}^2 \\ \Delta_{z_{ij}}{}^2 \\ \Delta_{x_{ij}} \\ \Delta_{y_{ij}} \\ \Delta_{z_{ij}} \end{bmatrix} = \begin{bmatrix} X_j & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_j & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_j & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{ij}{}^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{ij}{}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Delta t \end{bmatrix} \times \begin{bmatrix} \boldsymbol{\varepsilon_x} \\ \boldsymbol{\varepsilon_y} \\ \boldsymbol{\varepsilon_z} \\ \cos\beta^2 \\ \cos\alpha^2 \\ \cos\beta^2 . \cos\alpha^2 \\ \boldsymbol{V_x} \\ \boldsymbol{V_y} \\ \boldsymbol{V_z} \end{bmatrix} + [\bar{v}] \qquad (6)$$

This study involves comparative analysis through two primary tests: integrity testing and deformation analysis. Table 1 summarizes the methods and materials used for these tests;

Table 1: Summary of materials and methods

S/No	Structural Health Component	Method	Materials
1	Integrity Test	Ultrasonic Pulse Velocity measurement	Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT), and the jelly-like lubricating substance
2	Deformation analysis	Baseline study by GNSS	Differential GNSS receiver linked to CORS by NRTK
		Routine monitoring by Total station	Total station and its accessories
		Horizontal deflection measurement	Total station and its accessories
		Vertical deflection measurement	Dumpy level

The integrity tests were performed using a Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) following BS EN 12504-4:2004 and BS EN 12504-2:2001 standards. These tests involved measuring the transit time of ultrasonic pulses through concrete using jelly-like grease as a coupling agent. Upon generation of the pulse, longitudinal vibrations were reflected at material phase boundaries, and the arrival time of these waves was captured by a receiving transducer to calculate the transit time TTT (Figure 2).

Figure 2(a): PUNDIT sensors (b) Calibration of US meter (c) US scan on-going

Deformation monitoring on the other hand was conducted in three stages being;

(i) **Baseline Establishment**: Three geodetic control points were established around the site to serve as reference for deformation monitoring. These points, placed in zero-deformation zones (near expansion joints), were subjected to a 1-hour static GNSS observation using NRTK linked to local CORS networks. The OSCAR NRTK GNSS receiver was employed to achieve precise geodetic coordinates and accuracy metrics.

Figure 3(a) Static NRTK 3(b) Geodetic BM's

(ii) **Routine Monitoring:** Daily monitoring over two weeks was conducted at 20 deformation monitoring points (DMP001–DMP020) placed across the quay. Measurements were taken using a Total Station set up on one of the established geodetic points, with references to others.

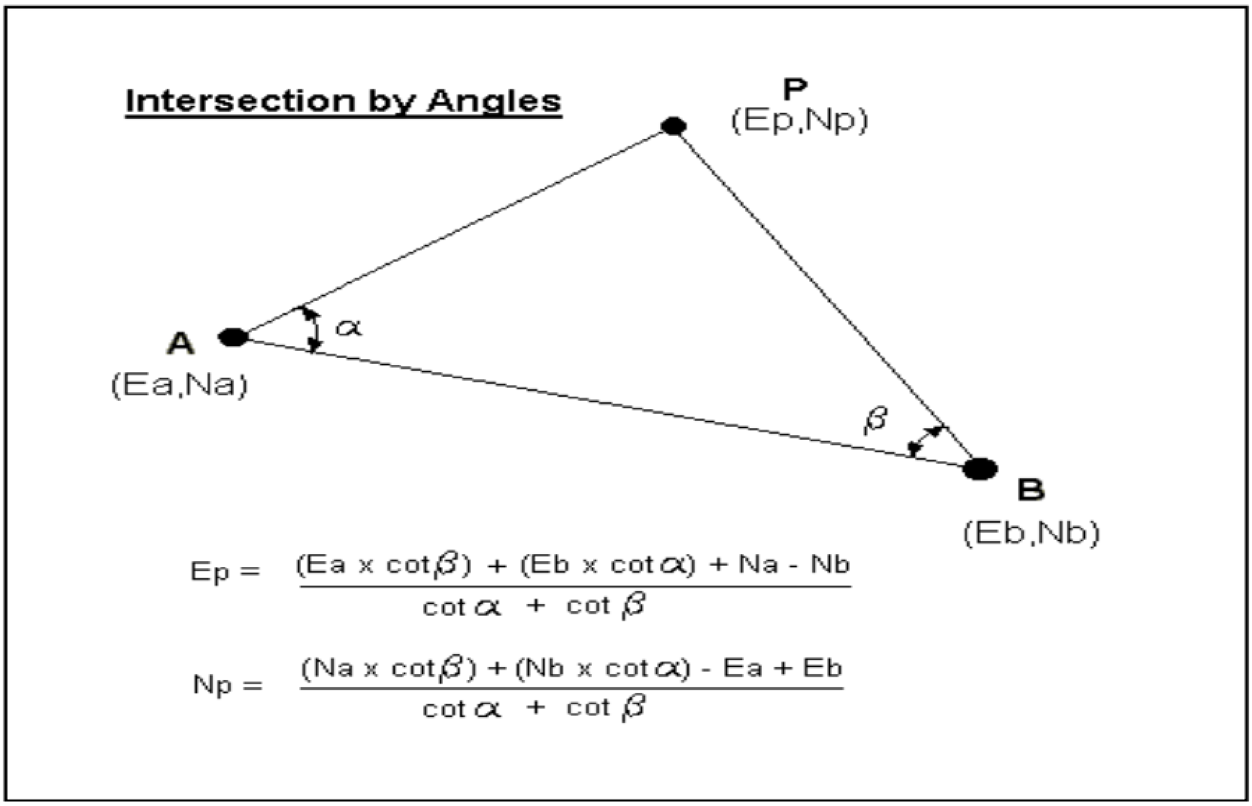


Figure 4. Description of the 2-point resection problem
The observation times for the daily monitoring observations were as follows;

Morning observation: 8am – 10am
Mid-day observation 12noon – 2pm
Evening observation 4pm – 6pm

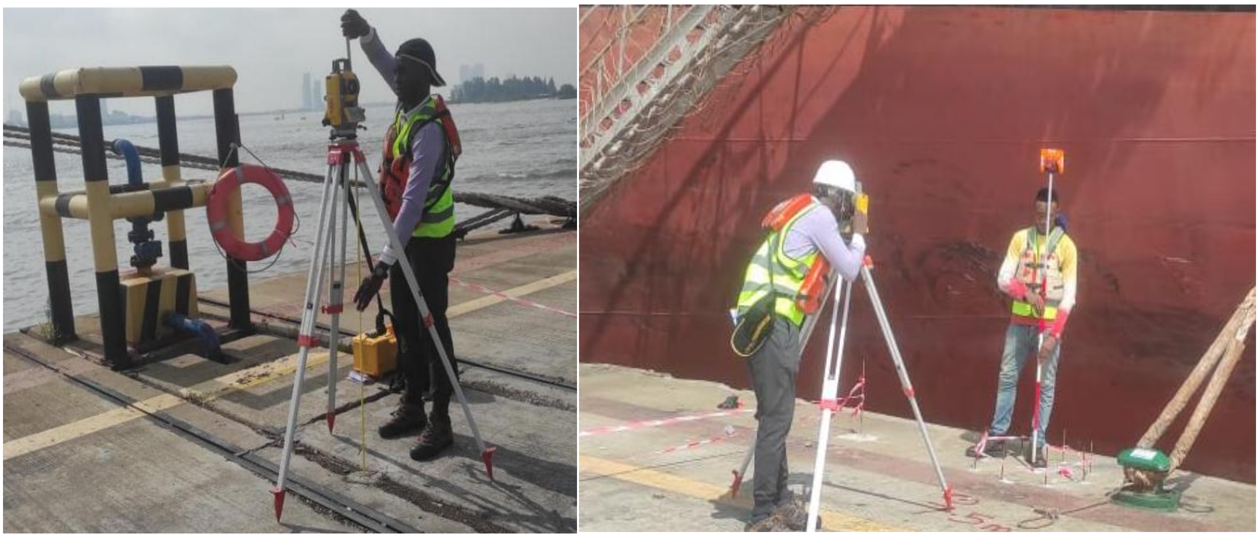


Figure 5(a) Setting up the Total station (b) coordinating the DMP's

(iii) *Deflection monitoring*: Elevation levels at 40m grid intervals were measured using a Dumpy level to assess vertical displacements across the deck, particularly focusing on slope deviations. On the other hand, the horizontal deflections were determined from the coordinate changes.

3.0 Results and Discussion

The fieldwork yielded two sets of results; compressive strength analysis and deformation monitoring. Both sets of data show a high correlation, confirming the reliability of the tests.

3.1 *Compressive strength analysis*:

Compressive strength was evaluated at multiple points across the quay at 20m grid intervals. Table 2 summarizes the average compressive strength measurements. Results indicate an average strength of 40 N/mm², consistent with the design specification. This result indicates that the quay slab remains capable of supporting its designed loads.

Although the compressive strength of concrete is expected to increase with age (although significant increase in strength reduces after curing); it might as well reduce with time due to a number of factors. Such factors include; environmental exposure consequent upon freeze-thaw cycles (Neville, 1995), chemical attacks by sulfates, acid substances, carbonation, or chloride penetration (Neville, 1995; Papadakis, 2000; Mehta and Monteiro, 2014), improper mix design or curing due to poor workmanship, and excessive loading conditions (Bazant and Planas, 1998; Mindess et al, 2003). The results from Table 2 indicate that such deterioration has been minimal, further suggesting regular maintenance practices are effective.

The graphical plot (Figure 6) shows the relationship between transmission time, pulse velocity, and compressive strength. The consistency of transmission time across columns suggests uniformity in material properties, while variations in pulse velocity indicate differences in concrete richness and rebar distribution.

Table 2: Average compressive strength test for quay slab

Structural Element	Transmission Time (µs)	Path Length (mm)	Pulse Velocity (km/s)	Ave. Equivalent compressive strength (N/mm2)	Remark
SlabPT 01	26.84	120	4.6938	43.6	Good
SlabPT 02	26.46	120	4.763	45.2	Good
SlabPT 03	26.6	120	4.7436	44.8	Good
SlabPT 04	26.6	120	4.7436	44.8	Good
SlabPT 05	26.56	120	4.745	44.8	Good
SlabPT 06	26.18	120	4.811	46	Good
SlabPT 07	26.68	120	4.724	44.4	Good
SlabPT 08	27.04	120	4.658	42.8	Good
SlabPT 09	26.7	120	4.7178	44	Good
SlabPT 10	26.54	120	4.7516	44.4	Good
SlabPT 11	26.42	120	4.7696	45.2	Good
SlabPT 12	26.74	120	4.716	44.4	Good
SlabPT 13	26.8	120	4.707	44	Good
SlabPT 14	26.42	120	4.7702	45.2	Good
SlabPT 15	26.56	120	4.7448	44.8	Good
SlabPT 16	26.6	120	4.7402	44.4	Good
SlabPT 17	27.08	120	4.6526	42.4	Good
SlabPT 18	26.8	120	4.7038	44	Good
SlabPT 19	26.58	120	4.736	44.8	Good
SlabPT 20	27.12	120	4.6438	42.4	Good
SlabPT 21	26.76	120	4.7074	44	Good

The results presented in Table 2 are further represented by the graphical plot shown in Figure 6.

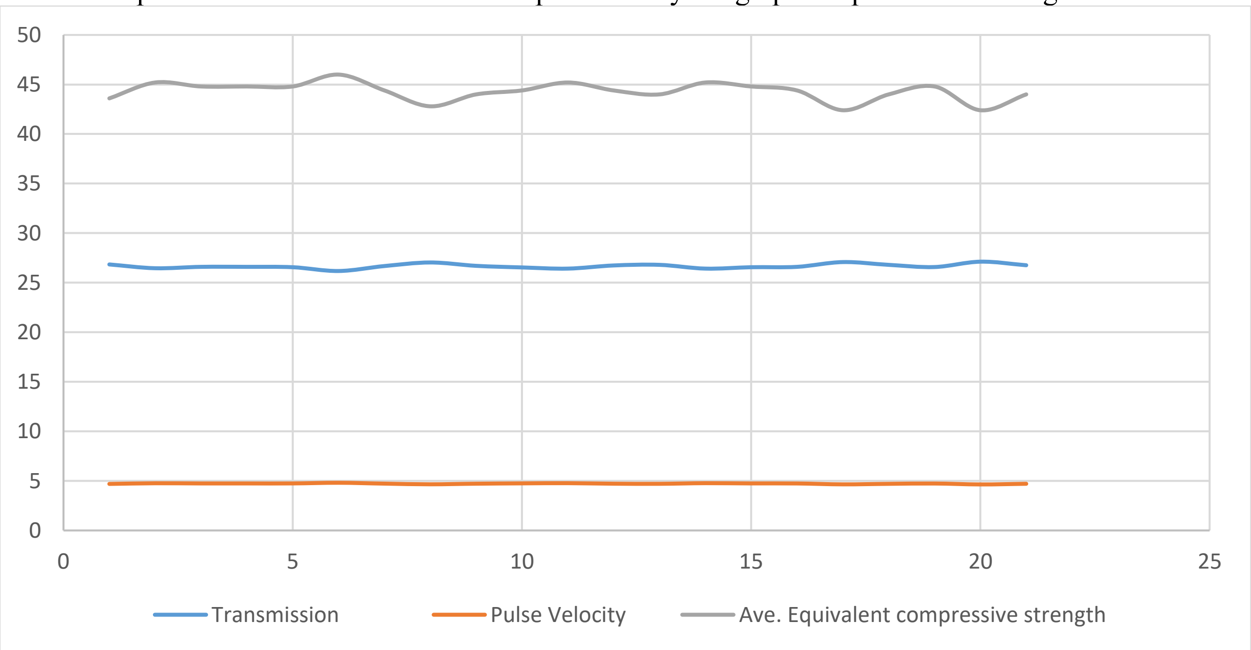


Figure 6: overlay plot of transmission time, pulse velocity and average compressive strength across the quay

3.2 *Deformation monitoring*:

Analysis using MINQUE-LS reveals minimal strain in the horizontal and vertical directions. As shown in Table 3, horizontal strain remained at zero for the first 10 days, while vertical strain values, though minimal, correlated with increased vehicular traffic on the quay.

Table 3: Summary of observed displacements along and across the quay

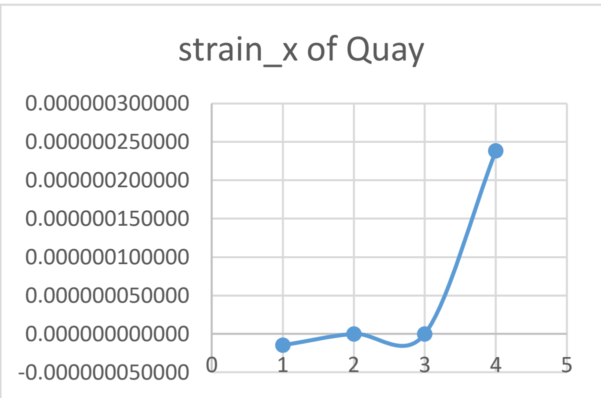
	Day01 - 03	**Day01 - 07**	**Day01 - 10**	**Day01 - 14**
strain_z	-0.0000000447	0.00000012	0.00000003	0.0000000119
strain_x	0	0	0	0.00000024
rot	0.00000427	0.00000513	0.00004515	0.00002304
vel_x	0.000000000002593	0.000000000002422	0.000000000002056	-0.000000000005384
vel_y	-0.000000000000033	-0.000000000000457	0.000000000002894	0.000000000003497
vel_z	-0.000000000000155	0.000000000008646	-0.000000000010061	0.000000000009600

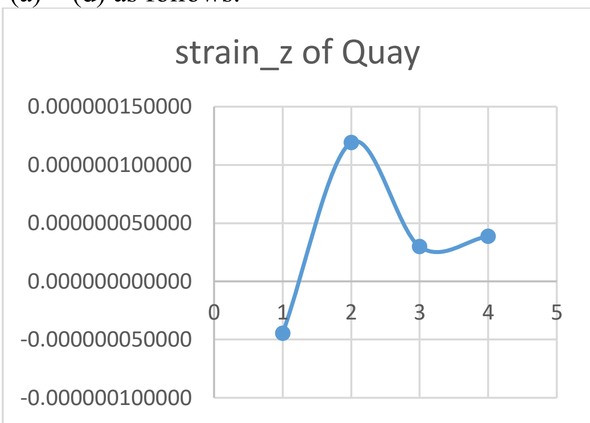
From Table 2, it is observed that the quay is experiencing very minimal strain in the horizontal direction as we see that there was completely no horizontal strain (strain_x = 0) between day 1 – day 10. Also, as expected, we observe that the strain in the vertical direction (strain_z) has the highest value amongst all the parameters. This vertical strain is supposedly caused by the high volume of traffic, vehicular flow and heavy machines that operate on the quay. Nevertheless, the maximum vertical strain value is minimal (0.000000019m) can be considered completely negligible. Further validating the assumption is the fact that the maximum strain as observed occurred between October 17th – 19th. This period was very busy on the Jetty and it is reflected with the highest vertical strain occurring at that observational epoch. Therefore, Table 3 shows that the quay is apparently stable and undisturbed. These can be further interpreted to correspond to annual deflection values of 0.2mm/yr, and 0.3mm/yr in the horizontal and vertical directions. This value corroborates the compressive strength (integrity test) results which confirms that the quay is very stable and undisturbed. A summary of the results shown in Table 2 is presented in Table 3.

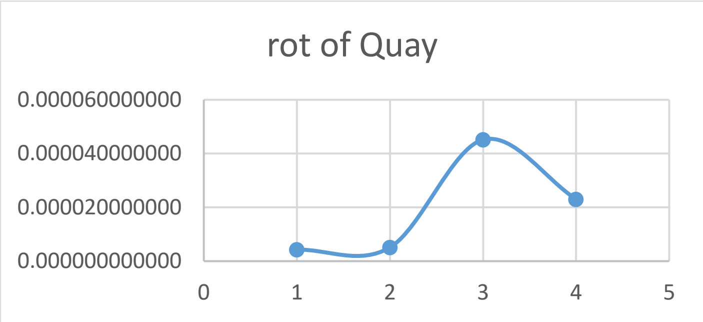
Table 3: Summary of deformation parameters

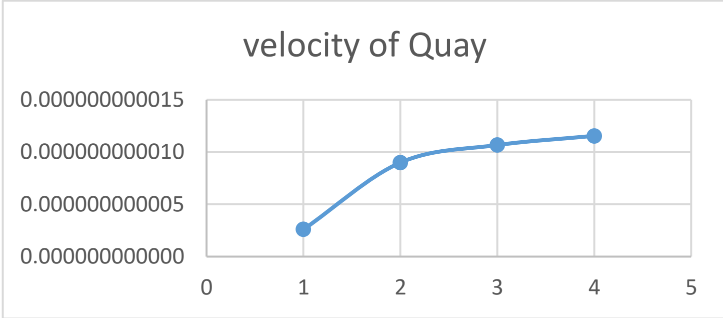
parameter	**strain_z (m)**	**strain_x (m)**	**Rot (secs)**	**Vel (m/s^2)**
Ave	0.000000056	0.000000036	0.000019396	0.000000000008451
min	-0.000000045	-0.000000015	0.000004274	0.000000000002598
max	0.000000119	0.000000238	0.000045148	0.000000000011549
range	0.000000164	0.000000253	0.000040874	0.000000000008951

As seen, the average horizontal and vertical strain are 0.000000036m and 0.000000056m respectively. These values are very minute and completely insignificant. Furthermore, the average rotation of the quay is 0.0000194secs while the average velocity is 0.00000000000845m/s^2 which translates into a motion of about 0.2mm/year. These negligible deformation values were plotted in a bid to establish the trend of the observed movements. The trend of movements is seen in Figures 7 (a) – (d) as follows.









Figures 7: Graphical plot of trend of; (a) horizontal strain (b) vertical strain (c) rotation (d) velocity

Graphical plots of trends in horizontal strain, vertical strain, rotation, and velocity (Figure 7) reveal elastic behavior, with fluctuations revolving around central values. This is consistent with normal structural responses to external forces and environmental factors.

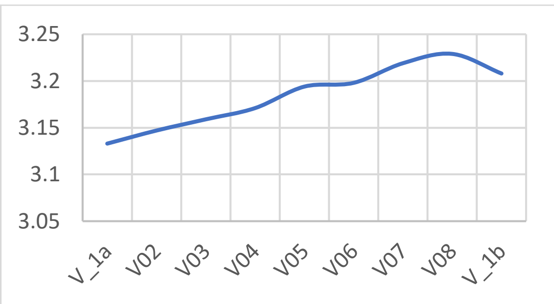
As seen in Figures 8.1(b) – (d), the movements (vertical, rotation and velocity) are elastic as they increase and decrease about their central value. This is normal for all structures as the structure is expected to make linear and non-linear responses to load, environmental conditions, heat and other forms of stress imposed on it. Being elastic movements, we notice that they revolve around their mean value within fourteen days of observation. This means that the structure is performing optimally and is able to self-compensate for the load and stresses imposed on it. The departure from this trend which we observe in Figure 7(a) is however not worrisome because the value is grossly insignificant and for two consecutive measurement epochs, there was no movement at all on the structure.

In line with the deformation results, the vertical alignment surveys also show very minimal vertical deflections of the structure from the designed slope level. Result from 4 of the 20 lines checked is provided in Table 4. The results show that the maximum vertical deflection requires a cut value of 20mm and a fill value of about 5mm across the quay, signifying that the quay is very stable with very minimal vertical deflections. Results for the vertical alignment show that the lagoon-ward slope of the quay is about 2.7% (0.0027).

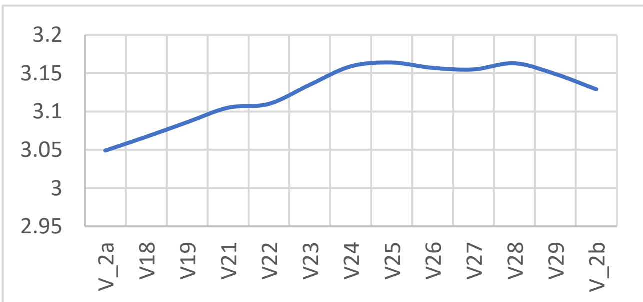
Table 4: summary of vertical displacements of the quay

Line	Slope	Cut (mm)	Fill (mm)
1	0.0025	20	
2	0.0027		
3	0.0029		5
4	0.0027		

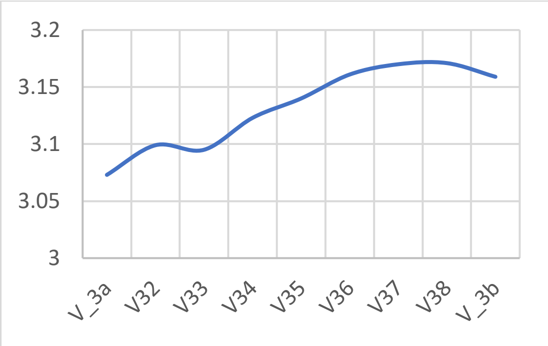
The maximum vertical deviation (being 20mm) is considered allowable given the gentle nature of the slope of the study area. Graphical plots of this observed deviation are shown in Figure 8).



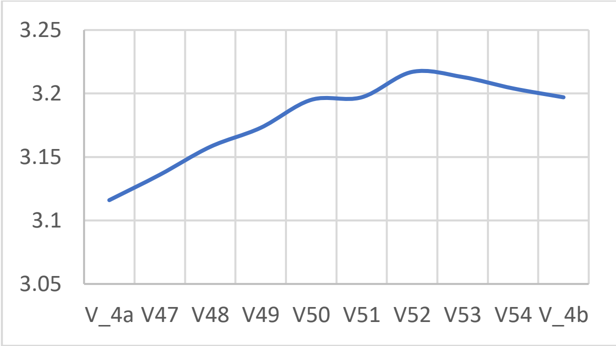
(a) Line 01



(b) Line 02



(c) Line 03



(d) Line 04

Figure 7(a) – (d): observed slope along vertical alignment survey for some lines

4.0 Conclusion

This study analyzed the compressive strength and deformation characteristics of a quay slab using ultrasonic pulse velocity and GNSS-based deformation monitoring. The results from both tests indicate that the structure remains stable and capable of carrying its design loads, with minimal vertical and horizontal strain observed during the 14-day monitoring period.

The findings suggest that the quay has been well-maintained, with no significant deterioration in compressive strength due to environmental or anthropogenic factors. The minimal deformation values further corroborate the integrity test results, indicating that both methodologies provide complementary data for monitoring concrete slabs.

Future studies should focus on long-term monitoring to assess potential seasonal effects on deformation and structural integrity. Additionally, incorporating more advanced monitoring techniques, such as fiber optic sensors, could provide real-time deformation data for more precise assessments.

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