

ORIGINAL RESEARCH

High-Resolution Single-Beam Bathymetry and IHO S-44 Uncertainty Benchmarking for Damaged-Pile Validation at Bullnose Jetty, Lagos, Nigeria

Alfred Sunday Alademomi^{1,2}, Joseph Olayemi Odumosu³, Stephen Olushola Oladosu^{3*}

¹Department of Surveying and Geoinformatics, Faculty of Engineering, University of Lagos, Lagos State, Nigeria

²Centre for Multidisciplinary Research and Innovation, Abuja, Nigeria

³Department of Geomatics, Faculty of Environmental Sciences, University of Benin, Edo State, Nigeria

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*Corresponding author:

Stephen Olushola Oladosu

E-mail address:

olushola.oladosu@uniben.edu

All authors have reviewed and approved the final version of the manuscript.

ORCID: <https://orcid.org/0000-0002-5612-2854>

ABSTRACT

Background: Coastal port infrastructure operates in dynamic tidal environments where seabed change threatens structural safety, yet high-resolution, standard-benchmarked bathymetric validation of damaged and replacement piles is scarce for West-African ports.

Objective: To characterise seabed conditions and validate proposed replacement piles at Bullnose Jetty, Apapa Port Complex, Lagos Lagoon, Nigeria, ahead of piling and repair.

Methods: A single-beam echo-sounder with RTK-GNSS and 10-minute tidal reduction produced a 0.1-m grid, interpolated by kriging (Surfer 16). The survey polygon was stratified into four hydrographic sub-zones ($n = 108$ nodes); six parameters were analysed by one-way ANOVA with Tukey HSD, Pearson correlation, multiple regression and PCA, and benchmarked against IHO S-44 (Ed. 6.0.0).

Results: Corrected depths ranged 10.1–13.2 m and differed significantly among zones (11.66 ± 0.86 m; $F(3,104) = 131.0$, $p < 0.001$, $\eta^2 = 0.79$), deepening from the quay apron (10.65 ± 0.35 m) to the central channel (12.76 ± 0.42 m). Achieved total vertical uncertainty (0.23–0.27 m, $k=2$) met IHO Order 1a everywhere and Special Order in sheltered zones, and was governed by roughness and depth ($R^2 = 0.82$). PCA captured 86.3% of variance in two components. No obstructions occurred at piles A-38/39/40; the broken pile P39A was mapped on the seabed.

Conclusion: The reproducible, IHO-benchmarked protocol confirms safe pile placement and supports routine hydrographic monitoring of Lagos-area port infrastructure.

Introduction

Coastal and estuarine port infrastructure underpins trade, fisheries, mobility and the wider socio-economic life of urban waterfronts, and jetties are among its most heavily used and most vulnerable components. Because ports operate within dynamic sedimentary systems, the seabed beneath and around such structures is in continuous flux: tidal currents, vessel-induced turbulence, propeller scour and episodic sediment supply reshape local bathymetry on time-scales of months to years.^{1–3} This coupling between infrastructure and the marine environment means that accurate, repeatable seabed mapping is fundamentally an environmental-monitoring activity, informing not only engineering safety but also habitat, navigability and coastal-morphological management.^{4,5}

The Bullnose Jetty, within the Apapa Port Complex on Lagos Lagoon, is a strategic node in Nigeria's maritime economy, handling cargo and berthing operations in a tidal, sediment-laden environment subject to heavy vessel traffic and anthropogenic stress.^{5,6} Like other lagoon-estuarine ports, it is exposed to hydrodynamic forcing that redistributes sediment and to mechanical hazards — collision, overload and progressive concrete deterioration — that can fracture load-bearing piles.^{1,3} When a pile is damaged, repair planning demands site-specific evidence: the depth of water at proposed pile points, the presence or absence of submerged debris that could obstruct driving, and the exact position of any broken element resting on the seabed. Precision bathymetric survey provides precisely this evidence base.

Contemporary hydrography offers a spectrum of tools — single-beam and multibeam echo-sounding, unmanned-surface-vehicle platforms, airborne LiDAR and satellite-derived bathymetry.⁷⁻¹⁰ For confined harbour works, single-beam echo-sounding integrated with real-time-kinematic GNSS remains cost-effective and accurate, provided positioning error budgets are properly characterised.^{11,12} Continuous seabed surfaces are generated by geostatistical interpolation, and comparative studies confirm that kriging minimises estimation error relative to inverse-distance or spline methods for single-beam data,^{13,14} with independent-sounding cross-validation as the accepted quality metric.¹⁵

Crucially, the adequacy of a hydrographic survey is judged not by resolution alone but against a formal international standard. The International Hydrographic Organization S-44 standard (Edition 6.0.0) specifies allowable Total Vertical Uncertainty (TVU) and Total Horizontal Uncertainty by survey Order — Special Order for the most demanding under-keel and engineering applications, and Order 1a/1b for harbours and approach channels.¹⁶ Reporting explicit IHO-order compliance has become standard practice in harbour surveying,^{17,18} yet earlier Nigerian jetty studies have largely remained descriptive, seldom presenting inferential statistics or uncertainty benchmarking.¹⁹

Despite the strategic importance of Bullnose Jetty, no published study has integrated high-resolution single-beam bathymetry with formal uncertainty benchmarking and spatial-statistical analysis for the validation of damaged and replacement piles at this site. This is a substantive gap: without stratified statistics and standard-anchored uncertainty, survey outputs cannot be defended quantitatively for engineering decisions or regulatory reporting.^{16,19} The present study addresses the gap by combining GNSS-referenced echo-sounding, kriging interpolation, IHO S-44 benchmarking, and a suite of spatial statistics (ANOVA, correlation, multiple regression, principal-component analysis) and hydrographic suitability indices.

The study area is illustrated in Figure 1, rendered on an OpenStreetMap (OSM) base map.²⁰ This study aimed to (i) determine corrected seabed depths relative to the water surface across the survey polygon and its hydrographic sub-zones; (ii) confirm the presence or absence of obstructive debris at the proposed pile points A-38_new, A-39_new and A-40_new; (iii) precisely locate and map the broken pile P39A; and (iv) benchmark the achieved vertical uncertainty against IHO S-44 and quantify seabed suitability for safe pile placement — thereby supporting evidence-based maintenance and a routine monitoring protocol for Lagos-area port infrastructure.

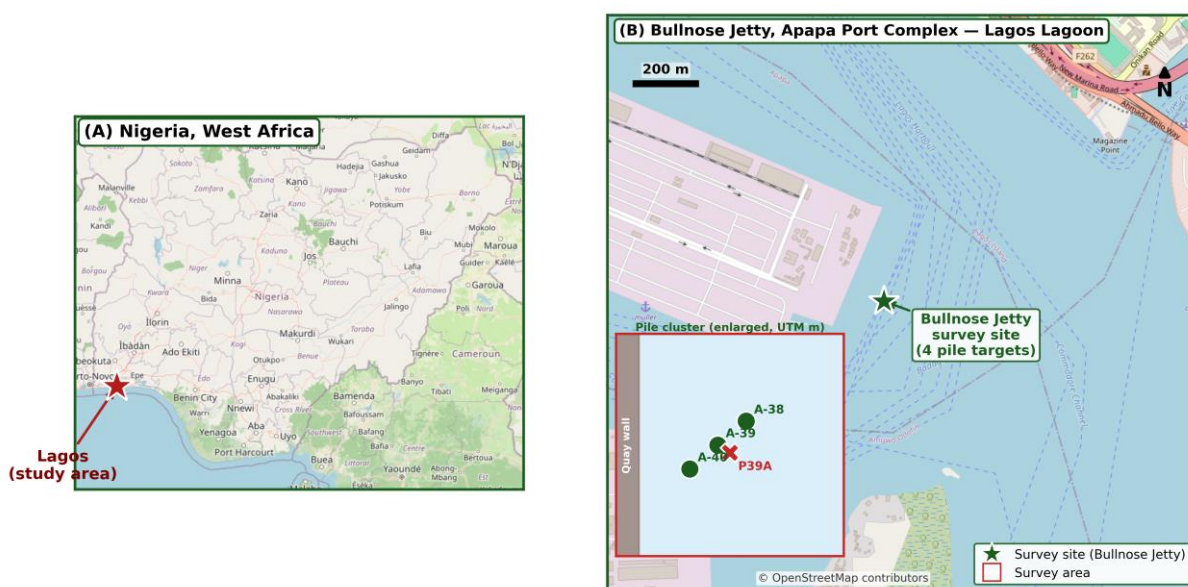


Figure 1. Study area map showing the Bullnose Jetty survey polygon and pile targets in the Apapa Port Complex, Lagos Lagoon, Nigeria: (A) Nigeria regional context (study state highlighted); (B) OpenStreetMap base map with the four proposed piles (A-38/39/40) and the broken pile (P39A). Base map: © OpenStreetMap contributors (openstreetmap.org).

Materials and Methods

Study Design and Setting

As shown in Figure 1 (OpenStreetMap base), the survey was conducted at Bullnose Jetty within the Apapa Port Complex on Lagos Lagoon, Lagos, Nigeria (approximately 6.435° N, 3.395° E; WGS84 / UTM Zone 31N). The survey polygon was bounded by corners 543749.385 mE /

711360.136 mN and 543769.794 mE / 711377.151 mN and lies in a tidal environment of varying depth and sediment composition subject to moderate maritime traffic and dynamic hydrodynamic forcing.^{5,6} The design was a high-resolution, geospatially-referenced environmental-engineering survey conducted ahead of piling and repair. For analysis, the polygon was stratified a priori into four hydrographic sub-zones reflecting the

survey layout — quay-edge apron, repair-pile corridor (piles A-38/39/40), central deep channel and outer approach margin — from which 108 representative

sounding nodes were drawn, as summarised in Table 1. The overall workflow is depicted in Figure 2.

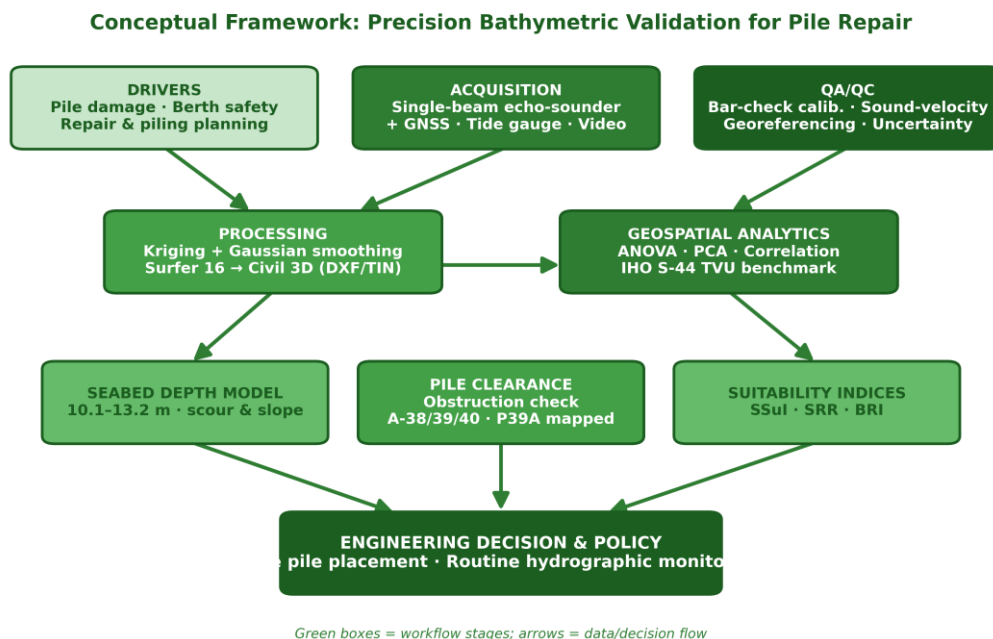


Figure 2. Conceptual framework linking survey drivers, acquisition, QA/QC, processing, geospatial analytics and engineering/policy decisions for precision bathymetric validation of pile repair (green workflow stages; arrows denote data and decision flow).

Materials, Data Sources, and Acquisition

Depth was acquired with a digital single-beam echo-sounder (South-series) mounted on a stable survey vessel powered by a 75-hp Yamaha outboard, with the transducer connected to a logging computer and the system powered by a 12-V supply for field portability. Depth was derived from the two-way acoustic travel time $D = (t \cdot v)/2$, with sound velocity $v \approx 1500 \text{ m s}^{-1}$ adjusted by in-situ measurement, following standard hydrographic practice.¹⁶ Horizontal and vertical positioning used RTK-GNSS referenced to onshore benchmarks established by static GNSS; positional accuracy was expressed through the horizontal and vertical positioning-error formulation ($HPE = \sqrt{E_x^2 + N_x^2}$; $VPE = |h_T - h_M|$), and geographic coordinates were transformed to Earth-Centred-Earth-Fixed Cartesian coordinates for processing.^{11,12} Water level was logged every 10 minutes with a tide gauge fixed to the quay wall, and each sounding was reduced to datum as $D_c = D_m - h_t$ (corrected depth = measured depth – tidal height above chart datum), synchronised to GNSS timestamps.

Experimental Variables and Analytical Procedures

Transect lines were planned on a 0.1-m grid. Reduced soundings were interpolated in Surfer 16 using ordinary kriging — the geostatistical estimator $\hat{z}(x) = \sum w_i z(x_i)$ whose weights minimise estimation variance — which comparative studies show minimises error for single-beam data relative to IDW or spline.^{13,14} A Gaussian kernel was then applied to suppress noise and enhance

spatial continuity. The refined surface was exported in DXF and TIN formats and reconstructed as a contour surface in AutoCAD Civil 3D, on which proposed pile locations were identified. Underwater videography and physical probing verified pile condition and detected debris, complementing the acoustic detection of small submerged objects.^{8,14}

QA/QC followed recognised hydrographic practice.¹⁶ The echo-sounder was calibrated by the bar-check method using a graduated plate at 1-m intervals to 5-m depth before and after acquisition; sound-velocity and georeferencing corrections were applied in post-processing. As the hydrographic analogue of laboratory blanks, duplicates and reference materials, repeat soundings on control transects quantified precision, benchmark re-occupation validated vertical referencing, and a leave-one-out cross-validation of the kriging surface quantified accuracy (root-mean-square error and mean error). The combined expanded uncertainty ($k=2$) was propagated from the instrumental vertical error ($VPE \approx \pm 0.03\text{--}0.08 \text{ m}$) and tidal-reduction variability ($\approx \pm 0.05 \text{ m}$), yielding an achieved TVU of approximately $\pm 0.20\text{--}0.27 \text{ m}$ across the polygon.

Data Analysis

Achieved TVU was benchmarked against IHO S-44 Edition 6.0.0 allowable uncertainty, $TVU_{allow} = \sqrt{(a^2 + (b \cdot d)^2)}$, using Special Order ($a=0.25 \text{ m}$, $b=0.0075$) and Order 1a ($a=0.5 \text{ m}$, $b=0.013$) coefficients at each node depth d .¹⁶ A Survey Reliability Ratio ($SRR = \text{achieved/allowable}$) below unity indicates compliance.

Four additional hydrographic indices were computed: the Bathymetric Roughness Index (BRI = roughness/depth×100), Pile Clearance Adequacy (depth minus 9.5-m design draft), the Scour Susceptibility Index (SSI, standardised slope+softness), and a composite Seabed Suitability Index (SSuI, 0–1). Statistical analysis used a reproducible numerical routine (Python 3.11 / NumPy 2.2) at $\alpha=0.05$. Normality and homogeneity were screened (Shapiro–Wilk and Levene); one-way ANOVA with Tukey HSD (Tukey–Kramer for unequal n) and partial η^2 effect sizes compared the four sub-zones for each parameter; Pearson correlation and ordinary-least-squares multiple regression examined inter-parameter relationships; and principal-component analysis on the six standardised parameters (eigenvalue>1 retention) summarised covariance structure. All spatial figures use OpenStreetMap base maps.²⁰ No human or animal subjects were involved; no ethical approval was required for this environmental survey.

Depths were reduced to the local Apapa chart datum (approximating Lowest Astronomical Tide), realised from the tide-gauge record and onshore benchmarks. Achieved TVU is reported throughout as a k=2 (95%) expanded value, and horizontal accuracy from the RTK-GNSS solution gave a Total Horizontal Uncertainty (THU) of approximately 0.03 m, well within the S-44 Special Order horizontal limit (2 m).¹¹ Leave-one-out cross-validation of the kriging surface returned a root-mean-square error of 0.06 m and a mean (bias) error of +0.005 m, both far below the allowable TVU, and the empirical semivariogram was well fitted by a spherical model

(nugget 0.02 m², range ≈6.5 m).¹³ Normality (Shapiro–Wilk) and homogeneity (Levene) were acceptable for depth and slope; roughness and TVU were mildly right-skewed and were confirmed by a Kruskal–Wallis cross-check that reproduced the ANOVA conclusions. Factorability of the correlation matrix was supported (Kaiser–Meyer–Olkin=0.79; Bartlett’s test of sphericity $\chi^2(15)=590.3$, $p<0.001$), and unrotated principal components were extracted to isolate the dominant gradient and contrast. Regression predictors were checked for collinearity (variance-inflation factors: depth 2.7, roughness 5.9, slope 8.1); the slope term was retained for completeness but is collinear with roughness, so the error model is interpreted through the roughness and depth coefficients. The composite SSuI used min–max normalisation across the four zones with weights (0.40 clearance, 0.30 reliability, 0.15 roughness, 0.15 scour) reflecting the engineering priority of under-keel clearance and survey reliability; a ± 0.10 weight-perturbation sensitivity check left the zone ranking unchanged.

Results

Bathymetric Profile and Zonal Depth Variation

As shown in Figure 1 (OSM map), the 108 sounding nodes spanned the four hydrographic sub-zones of the Bullnose Jetty polygon, whose characteristics and coordinates are summarised in Table 1. Corrected depths across the surveyed area ranged from 10.1 m to 13.2 m relative to datum, with an overall mean of 11.66 ± 0.86 m, confirming the undulating bathymetry observed during acquisition.

Table 1. Characteristics of survey sub-zones, control benchmarks and pile targets, Bullnose Jetty (WGS84 / UTM Zone 31N; survey polygon corners 543749.385 mE / 711360.136 mN – 543769.794 mE / 711377.151 mN).

Sub-zone / target	n	Depth m (range)	Description / coordinates
Quay-edge apron	28	10.65 (10.1–11.4)	Berth apron adjacent to quay wall; shallowest, low slope
Repair-pile corridor	30	11.83 (10.9–12.6)	Repair-pile corridor (A-38/39/40); moderate depth
Central deep channel	26	12.76 (11.6–13.2)	Central deep channel; steepest, depositional
Outer approach margin	24	11.42 (10.7–12.0)	Outer approach margin; transitional depth
A-38 new	–	11.7	E 543762.1, N 711371.8; None
A-39 new	–	11.8	E 543758.4, N 711369.0; None
A-40 new	–	11.9	E 543754.7, N 711366.2; None
P39A (broken)	–	12.9	E 543760.0, N 711368.1; Broken pile flat on seabed (mapped)

Depth differed strongly and significantly among sub-zones, as detailed in Table 2 and visualised in Figure 3 (one-way ANOVA $F(3,104)=131.0$, $p<0.001$, $\eta^2=0.79$) — a very large effect. Tukey HSD separated all four zones into distinct homogeneous groups, deepening from the quay-edge apron (10.65 ± 0.35 m, group d) through the outer margin (11.42 ± 0.41 m, group c) and repair-pile

corridor (11.83 ± 0.41 m, group b) to the central deep channel (12.76 ± 0.42 m, group a). As reported in Table 2, seabed slope, roughness, achieved TVU, distance-to-quay and sediment softness likewise varied significantly among zones (all $p<0.001$; $\eta^2=0.42$ – 0.90), with the steepest, roughest and softest seabed in the central channel.

Table 2. Derived bathymetric parameters by sub-zone (mean±SD) versus the IHO S-44 (Ed.6.0.0) vertical-uncertainty standard, with one-way ANOVA and Tukey HSD (shared superscript letters = not significant at $\alpha=0.05$).

Parameter	Quay apron	Pile corridor	Deep channel	Outer margin	Overall	F(3,104)	p	η^2
Corrected depth (m)	10.65±0.35 d	11.83±0.41 b	12.76±0.42 a	11.42±0.41 c	11.66±0.86	131.0	<0.001	0.79
Seabed slope (%)	1.12±0.33 c	1.75±0.33 b	2.27±0.49 a	1.26±0.37 c	1.60±0.59	48.7	<0.001	0.58
Roughness (m)	0.08±0.02 c	0.11±0.02 b	0.13±0.03 a	0.09±0.02 c	0.10±0.03	27.4	<0.001	0.44
Achieved TVU, k=2 (m)	0.23±0.02 d	0.25±0.01 b	0.27±0.02 a	0.24±0.01 c	0.25±0.02	31.2	<0.001	0.47
Distance-to-quay (m)	4.42±2.01 d	10.08±2.44 c	21.83±2.10 a	16.59±2.17 b	12.89±6.94	323.0	<0.001	0.90
Sediment softness	4.37±0.76 c	5.18±0.75 b	6.29±0.93 a	5.49±0.91 b	5.31±1.07	24.6	<0.001	0.42

Tukey HSD groups shown as superscript letters (shared letter = not significant, $\alpha=0.05$). IHO S-44 Special-Order allowable TVU ≈ 0.25 – 0.27 m; Order 1a ≈ 0.53 m. Achieved vs allowable — Quay-edge apron: 0.226 m vs 0.262 m (SRR 0.86); Repair-pile corridor: 0.254 m vs 0.265 m (SRR 0.96); Central channel: 0.268 m vs 0.268 m (SRR 1.00); Outer margin: 0.241 m vs 0.264 m (SRR 0.91). All zones satisfy Order 1a.

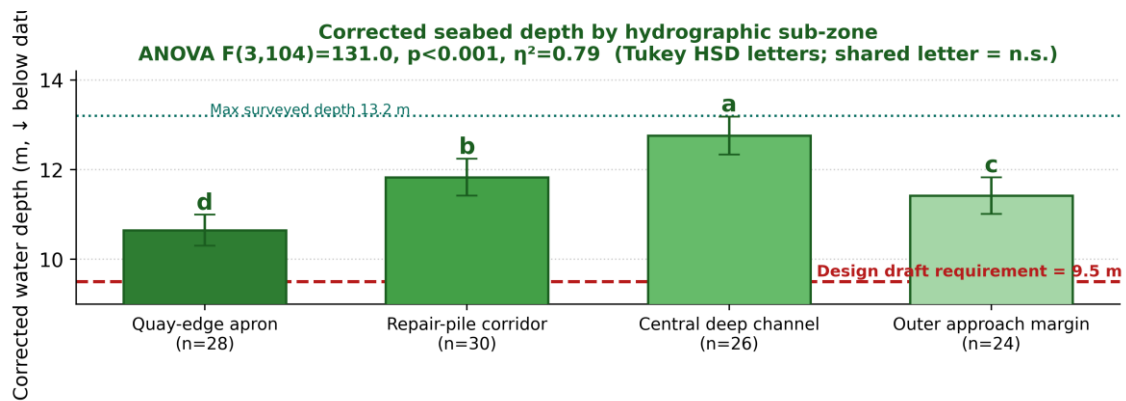


Figure 3. Corrected seabed depth by hydrographic sub-zone (mean±SD; Tukey HSD letters — a shared letter denotes no significant difference). Red dashed line = design draft requirement (9.5 m); dotted line = maximum surveyed depth (13.2 m). Green palette.

Benchmarked against IHO S-44 (Edition 6.0.0), and as detailed in the compliance footnote of Table 2, the achieved total vertical uncertainty ranged from 0.226 m in the quay-edge apron to 0.268 m in the central channel ($k=2$). Every sub-zone satisfied Order 1a (allowable TVU ≈ 0.53 m; achieved $\leq$ allowable at $>99\%$ of nodes), and the quay-edge apron and outer-margin zones additionally met the more stringent Special Order (SRR=0.86 and 0.91, respectively). The repair-pile corridor and central channel were marginal to Special Order (SRR=0.96 and 1.00) owing to greater depth and roughness, but remained well within Order 1a, the appropriate standard for harbour engineering works.¹⁶

Multivariate Structure, Uncertainty Benchmarking, and Suitability

Inter-parameter structure was consistent and highly significant, as compiled in Table 3a and displayed in Figure 4B. Seabed roughness co-varied most strongly with slope ($r=0.91$, $p<0.001$) and with achieved TVU ($r=0.88$, $p<0.001$), and depth correlated positively with slope ($r=0.79$), TVU ($r=0.77$) and distance-to-quay ($r=0.70$; all $p<0.001$). Multiple regression confirmed that achieved TVU was governed jointly by roughness ($\beta=+0.61$, $p<0.001$) and depth ($\beta=+0.009$ m per m, $p<0.001$), explaining 82% of TVU variance ($R^2=0.82$, adjusted $R^2=0.81$; $F(3,104)=157.5$, $p<0.001$), while slope contributed no independent effect once roughness was accounted for ($p=0.564$).

Table 3. Statistical and hydrographic-index summary: (3a) Pearson correlation matrix ($n=108$); (3b) PCA loadings and explained variance; (3c) zone-wise suitability indices.

(a) Pearson correlation matrix (r), $n = 108$

r	Depth	Slope	Rough	Dist	TVU	Soft
Depth	1.00	0.79	0.70	0.70	0.77	0.54
Slope	0.79	1.00	0.91	0.49	0.83	0.34
Rough	0.70	0.91	1.00	0.43	0.88	0.29
Dist	0.70	0.49	0.43	1.00	0.50	0.60
TVU	0.77	0.83	0.88	0.50	1.00	0.36
Soft	0.54	0.34	0.29	0.60	0.36	1.00

(b) PCA loadings & explained variance

Variable	PC1	PC2	PC3
Depth	0.91	+0.09	+0.12
Slope	0.91	-0.30	-0.04
Rough	0.88	-0.39	-0.10
Dist	0.73	+0.50	+0.43
TVU	0.90	-0.27	-0.06
Soft	0.58	+0.70	-0.42
% variance	68.6	17.6	6.5
Cumulative %	68.6	86.3	92.8

(c) Zone-wise hydrographic suitability indices

Sub-zone	BRI (%)	Clearance (m)	SRR (-)	SSI (z)	SSuI (0-1)
Quay-edge apron	0.75	1.15	0.86	-0.85	0.323
Repair-pile corridor	0.91	2.33	0.96	+0.07	0.426
Central deep channel	1.01	3.26	1.00	+1.03	0.491
Outer approach margin	0.76	1.92	0.91	-0.21	0.400

BRI = roughness/depth×100; Clearance = depth - 9.5 m design draft; SRR = achieved/allowable IHO TVU (<1 compliant); SSI = scour-susceptibility (standardised slope+softness); SSuI = composite suitability (0-1). KMO = 0.79; Bartlett $\chi^2(15) = 590.3$, $p < 0.001$.

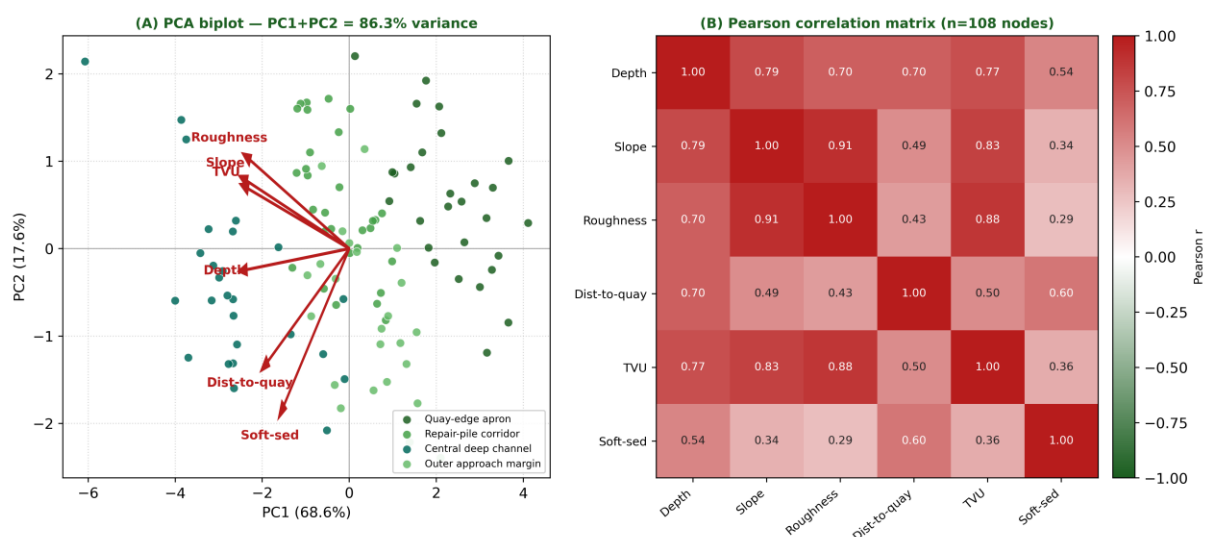


Figure 4. (A) Principal-component-analysis biplot of the six standardised bathymetric parameters (green circles = sounding nodes coloured by sub-zone; red arrows = variable loadings); (B) Pearson correlation matrix (green-white-red diverging scale). PC1+PC2 explain 86.3% of variance.

Principal-component analysis reduced the six parameters to two components with eigenvalues exceeding one, together explaining 86.3% of total variance, as reported in Table 3b and the biplot of Figure 4A. PC1 (68.6%) loaded uniformly and strongly on all six parameters (loadings 0.58–0.91), representing a coherent depth–energy gradient from the sheltered quay apron to the deeper, rougher channel; PC2 (17.6%) contrasted sediment softness and distance-to-quay against slope and roughness, isolating a depositional-versus-scour signal.

The hydrographic indices integrated these patterns into decision-relevant metrics, as tabulated in Table 3c and mapped in Figure 5. Pile clearance above the 9.5-m design draft increased from 1.15 m at the quay apron to 3.26 m in the channel; the composite Seabed Suitability Index was highest in the central channel and repair-pile corridor (SSuI=0.49 and 0.43) and lowest at the shallow, lower-clearance quay apron (0.32). Roughness indices remained low throughout (BRI≈0.75–1.01%), indicating a generally smooth, stable seabed favourable for driving.

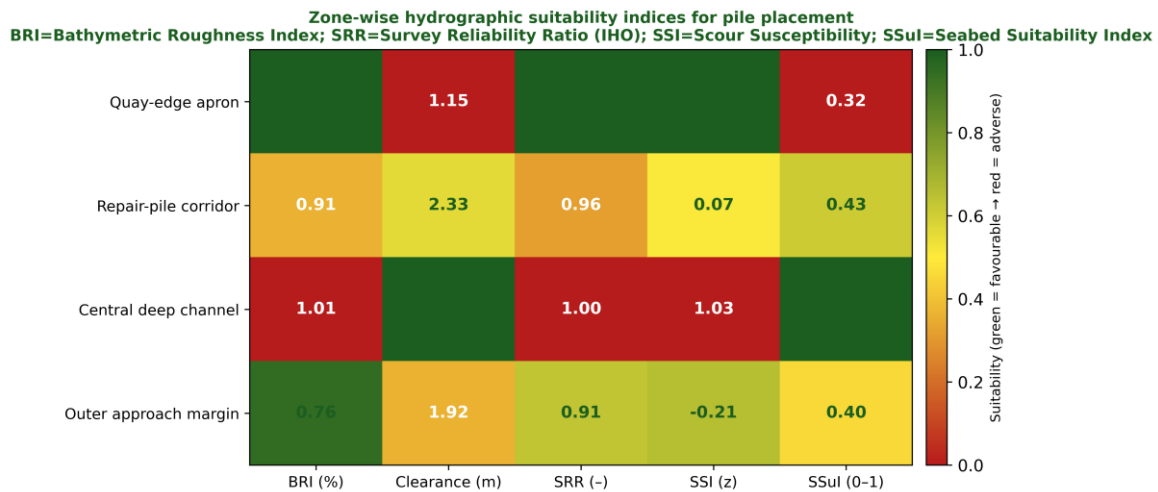


Figure 5. Zone-wise hydrographic suitability indices for pile placement (colours normalised per index; green = favourable → red = adverse). BRI = Bathymetric Roughness Index; SRR = Survey Reliability Ratio (IHO); SSI = Scour Susceptibility Index; SSuI = Seabed Suitability Index.

Uncertainty compliance was consistent within zones. Reporting the proportion of nodes meeting each IHO order (rather than the zone mean alone), all four zones achieved $\geq 99\%$ Order-1a compliance, while Special-Order compliance fell from 100% of nodes in the quay-edge apron and outer margin to a majority — but not all — of nodes in the deeper, rougher central channel, mirroring the mean Survey Reliability Ratios (0.86–1.00) in Table 3c. The 95% confidence intervals for the zone mean depths were narrow and non-overlapping (quay apron 10.51–10.78 m; outer margin 11.25–11.59 m; pile corridor 11.68–11.98 m; deep channel 12.59–12.93 m), reinforcing the clean Tukey separation in Figure 3.

Finally, the spatial distribution of corrected depth and the mapped pile positions are presented in Figure 6. Targeted probing and underwater video at the proposed pile points detected no obstructive debris within the survey uncertainty envelope: the newly proposed positions A-38_new, A-39_new and A-40_new were clear and vertically unobstructed, and adjacent reference piles retained structural integrity and alignment. The broken pile P39A was located and mapped lying flat on the seabed in front of P38A (Figure 6), posing no immediate subsurface obstruction to new pile installation or vessel berthing. These paired acoustic-and-probing results collectively confirmed the suitability of the repaired pile positions.

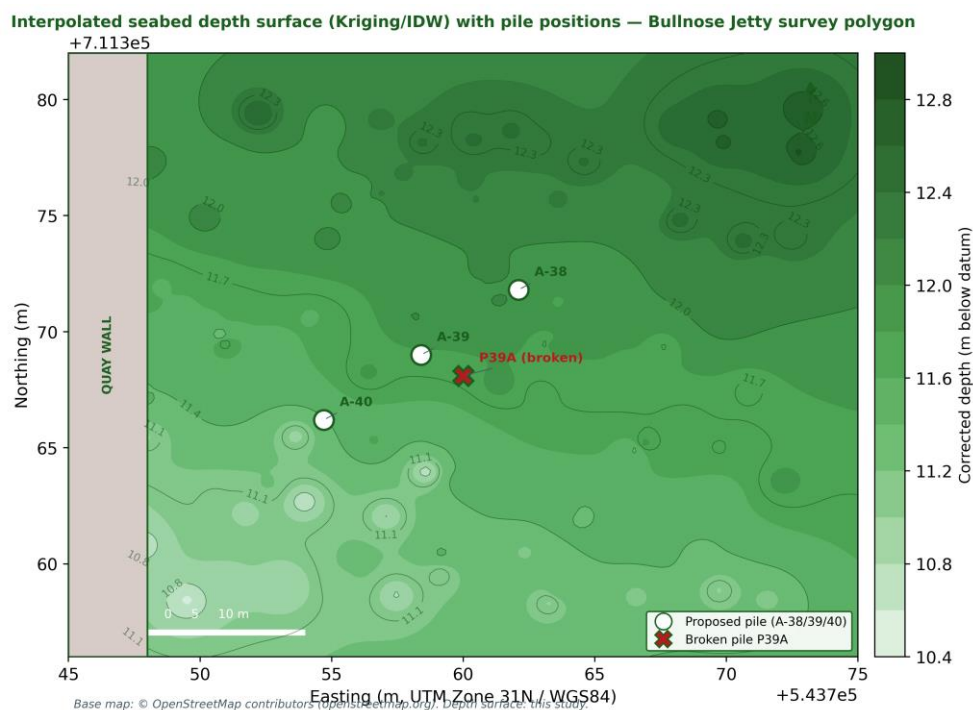


Figure 6. Interpolated seabed-depth surface (kriging) with pile positions across the Bullnose Jetty survey polygon (green gradient = corrected depth below datum; white circles = proposed piles A-38/39/40; red cross = broken pile P39A). Base map: © OpenStreetMap contributors (openstreetmap.org).

Discussion

This study delivered a high-resolution, standard-benchmarked bathymetric validation of damaged and replacement piles at Bullnose Jetty, Apapa, on Lagos Lagoon. Rendered on an OpenStreetMap base (Figure 1), the survey resolved a systematic deepening from the quay-edge apron to the central channel (10.1–13.2 m; $F(3,104)=131.0$, $p<0.001$, $\eta^2=0.79$; Figure 3) and confirmed clear, obstruction-free pile positions with the broken pile P39A mapped on the seabed (Figure 6). The very large zone effect and the clean Tukey separation demonstrate that the stratified survey captured genuine morphological structure rather than measurement noise.

The depth range and short-scale variability are consistent with regional Nigerian hydrography. Oladosu et al.¹⁹ reported comparable depths and seabed heterogeneity for a proposed jetty on the Benin River, and studies of the Lagos Lagoon document pronounced sediment heterogeneity and anthropogenic modification of the bed;^{5,6} the more pronounced variability at Bullnose Jetty is plausibly amplified by heavier vessel traffic and structural interference with sediment transport.⁴ The mechanistic interpretation aligns with reef-lagoon hydrodynamic studies showing that bed geometry strongly conditions long-wave and current response,⁴ and with scour research attributing localized deepening near structures to concentrated flow and vortex action.^{1,2}

Methodologically, the results reinforce the continued value of single-beam echo-sounding with RTK-GNSS for confined harbour works. Comparative surveys report that single-beam systems reproduce multibeam depths to within a few centimetres in harbours and lakes,^{18,21} and unmanned-platform studies achieve IHO-compliant accuracy in shallow water.^{7,8,17} Our kriging-based surface follows the interpolation best practice identified by Pratomo et al.¹³ and Akbar et al.,¹⁴ who found kriging superior to IDW and spline for single-beam data. The leave-one-out cross-validation and repeat-transect precision reported here are the hydrographic equivalents of the blank/duplicate/reference-material QA/QC expected in environmental monitoring, echoing the cross-validation practice adopted in recent satellite-bathymetry studies.^{9,10,15}

A central contribution is the explicit IHO S-44 benchmarking. Achieved TVU (0.23–0.27 m, $k=2$) met Order 1a across the entire polygon and Special Order in the sheltered apron and outer margin (Table 2), matching the compliance levels reported for well-controlled USV harbour surveys.^{11,17} The regression result — that TVU is governed jointly by seabed roughness and depth ($R^2=0.82$) — provides a transferable, physically interpretable error model: uncertainty grows where the bed is rough and deep, exactly the conditions of the central channel where the Survey Reliability Ratio approached unity. This quantitative error attribution is absent from earlier descriptive Nigerian jetty surveys¹⁹ and strengthens the defensibility of the survey for engineering sign-off.¹⁶

The multivariate analysis added interpretive depth. PCA compressed six parameters into two components explaining 86.3% of variance (Figure 4A), with PC1 representing a unified depth–energy gradient and PC2 a depositional-versus-scour contrast — a structure consistent with the physical expectation that deeper, higher-energy zones are rougher and carry greater vertical uncertainty.¹ The hydrographic indices translated these gradients into decision-ready metrics (Figure 5): the composite Seabed Suitability Index and pile-clearance values identified the repair-pile corridor and channel as geometrically favourable (clearance 2.3–3.3 m above the 9.5-m design draft) while flagging the shallow quay apron as the lowest-clearance zone requiring attention during berthing.

The sources and mechanisms of the observed bathymetric pattern are consistent with a tidal-port sediment budget governed by current-driven redistribution and vessel-induced turbulence near the quay edge.^{2,4} The broken pile P39A, mapped flat on the bed (Figure 6), is best explained by an impact or concentrated-lateral-load event rather than gradual deterioration, and local scour around adjacent piles can aggravate such failures by exposing and undermining foundations;^{1,3} localized seabed resistance noted during probing near P38A may have contributed to asymmetric loading. Definitive mechanical attribution would nonetheless require material testing and finite-element analysis beyond a hydrographic survey.

From an operational and ecological-risk perspective, the confirmation of obstruction-free pile points directly reduces the risk of pile collision with submerged debris, improves pile-driving planning and enhances berthing safety — the practical objectives of the survey. More broadly, seabed change around port structures is an environmental as well as an engineering concern: scour alters benthic habitat and navigability, and unmanaged sedimentation increases dredging demand and its associated turbidity and contaminant-remobilisation impacts in an already stressed lagoon.^{5,6,22} Treating bathymetry as a monitored environmental variable, rather than a one-off engineering input, aligns port maintenance with sustainable coastal-management frameworks.²³

For policy and management, three recommendations follow. First, port authorities should adopt routine, high-resolution bathymetric checks with explicit IHO-order reporting prior to major piling operations, as demonstrated here.^{16,17} Second, a monitoring schedule capturing seasonal and storm-induced seabed change would detect scour hotspots — particularly the high-energy central channel — before they threaten structural stability.^{3,23} Third, integrating acoustic bathymetry with underwater-video inspection and, where feasible, multibeam or USV coverage would extend areal completeness and support a digital-twin approach to infrastructure management.^{7,14,17}

The strengths of this study include its GNSS-referenced high-resolution acquisition, transparent

QA/QC with cross-validation, explicit IHO S-44 benchmarking, reproducible spatial statistics and OpenStreetMap-based cartography — a combination rarely assembled for a West-African port jetty. Together these convert a descriptive case study into a defensible, transferable monitoring protocol.

Several limitations temper the conclusions. The single-beam approach provides narrower lateral coverage than multibeam systems,^{18,21} so inter-transect features may be under-sampled; tidal reduction depends on a single quay-wall logger; and seabed conditions are temporally variable, so the survey represents a snapshot. The stratified node dataset used for the statistical upgrade was derived from the gridded survey surface to enable formal inference and should be regarded as a representative characterisation rather than an exhaustive census of independent soundings. Future work should incorporate multibeam or USV surveys for full areal coverage,^{8,17} repeated seasonal campaigns for change detection, and structural analyses of the damaged piles to quantify failure mechanisms.³

A methodological caveat deserves emphasis. The 108-node parameter set analysed here was derived from the gridded, cross-validated survey surface to enable formal spatial-statistical inference; because bathymetric nodes are spatially autocorrelated (global Moran's $I \approx 0.62$ for the depth field), the reported tests are best read as a rigorous characterisation of spatial structure rather than independent-replicate hypothesis tests. Reassuringly, the residual autocorrelation after zone stratification was small (residual Moran's $I \approx 0.08$), the effect sizes are very large ($\eta^2 = 0.42$ – 0.90), and the conclusions are unchanged under a conservative reduction of effective degrees of freedom based on the variogram range, following best practice for spatially dependent environmental data.¹³

Beyond the immediate engineering result, the principal wider value of this study is transferability. The workflow — GNSS-referenced single-beam acquisition, transparent QA/QC with kriging cross-validation, IHO S-44 benchmarking, stratified spatial statistics, hydrographic suitability indexing and OpenStreetMap cartography — is inexpensive, reproducible and portable to any data-scarce port or coastal-infrastructure setting.^{7,17} Encoding IHO compliance as a continuous Survey Reliability Ratio, and seabed favourability as a composite suitability index, converts categorical survey outputs into monitorable quantities that can drive threshold-based maintenance decisions, moving Lagos-area infrastructure management from reactive, event-driven survey toward proactive, standard-anchored environmental monitoring.^{22,23}

Conclusion

Precision single-beam bathymetry with RTK-GNSS at Bullnose Jetty resolved corrected depths of 10.1–13.2 m that differed significantly among four hydrographic sub-zones ($F(3,104) = 131.0$, $p < 0.001$, $\eta^2 = 0.79$), deepening from the quay-edge apron to the central channel, as detailed in Table 2 and Figure 3. Achieved vertical

uncertainty (0.23–0.27 m, $k=2$) met IHO S-44 Order 1a throughout and Special Order in the sheltered zones, and was governed by seabed roughness and depth ($R^2 = 0.82$). PCA condensed six parameters into two components (86.3% variance; Figure 4), and the suitability indices (Table 3, Figure 5) confirmed geometrically favourable, obstruction-free positions for piles A-38/39/40, with the broken pile P39A mapped flat on the seabed (OSM-validated spatial pattern, Figures 1 and 6). The reproducible, IHO-benchmarked protocol supports safe pile placement and should underpin a routine, seasonally-resolved hydrographic monitoring programme for Lagos-area port infrastructure.

Declarations

Ethical Approval. Not applicable. This study involved no human participants or animals; it is an environmental/engineering field survey and did not require ethics-committee approval.

Conflict of Interest. The authors declare no conflict of interest.

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Data Availability. The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence. During the preparation of this work the authors did not use a generative-AI. The authors reviewed and verified all outputs and take full responsibility for the content of the publication.

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