Asian Journal of Basic Science & Research
Volume 8, Issue 1, Pages 59-69, January-March 2026

High-Resolution Crosshole Seismic Tomographic Imaging for Engineering Site Characterisation at a Gas Flow Facility in the Niger Delta, Southern Nigeria

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DOI: https://doi.org/10.38177/ajbsr.2026.8106

Article Received: 09 January 2026 *Article Accepted: 15 March 2026* *Article Published: 23 March 2026*

ABSTRACT

Crosshole seismic tomography was implemented at a gas flow facility in the Niger Delta to obtain a detailed image of subsurface velocity structure for engineering site characterization. Seismic energy was generated at 2 m depth intervals within a source borehole, while receivers were positioned at 4 m intervals in an adjacent borehole, allowing dense ray-path coverage between the boreholes. To enhance data quality, a four-shot stacking approach was adopted at each source location. The recorded waveforms were processed through amplitude correction, first-arrival travel-time picking, and iterative tomographic inversion based on a finite-element framework.

The inverted P-wave and S-wave velocity models reveal pronounced vertical and lateral heterogeneity within the subsurface to a depth of approximately 60 m. A low-velocity near-surface layer interpreted as weathered overburden thickens laterally from approximately 3 m near Borehole 1 to about 16 m toward Borehole 2. Beneath this zone, higher velocities corresponding to consolidated sandy units are observed, with the depth to the groundwater table increasing in the same direction. The geometry of the interface between unconsolidated and consolidated materials is clearly resolved, highlighting the capability of crosshole seismic tomography to image subsurface structures at a resolution unattainable by conventional one-dimensional seismic techniques. The study demonstrates the suitability of crosshole seismic tomography for detailed subsurface assessment in deltaic environments characterized by complex sedimentary architecture.

Keywords: Crosshole Seismic Tomography; Subsurface Velocity Modelling; Engineering Site Characterization; P-Wave Velocity Analysis; S-Wave Velocity Profiling; Seismic Tomography Inversion; Near-Surface Geophysics; Subsurface Heterogeneity; Deltaic Sedimentary Environment; Groundwater Table Delineation; Finite-Element Inversion; Niger Delta Geophysics.

1. Introduction

Accurate subsurface characterization is a fundamental requirement for engineering design, infrastructure development, and geotechnical risk mitigation. In heterogeneous sedimentary environments, traditional surface-based geophysical methods often provide limited resolution and may fail to capture lateral variations in material properties. Crosshole seismic tomography overcomes these limitations by enabling the direct measurement of seismic wave propagation between boreholes, thereby producing high-resolution images of subsurface velocity distributions.

The technique is particularly effective for determining compressional (P-wave) and shear (S-wave) velocities, which form the basis for evaluating dynamic elastic properties of subsurface materials. These parameters are essential for applications such as foundation design, soil–structure interaction analysis, and seismic site response assessment. In addition, crosshole surveys allow reliable identification of weathered zones, competent strata, and groundwater levels.

The Niger Delta is typified by rapid sedimentation, facies variability, and alternating layers of unconsolidated sands and clays, resulting in strong lateral and vertical heterogeneity. These characteristics present challenges for engineering investigations and necessitate the use of high-resolution subsurface imaging techniques. This study applies crosshole seismic tomography at a gas flow station within the Niger Delta to delineate subsurface layering, assess velocity contrasts, and characterize site conditions relevant to engineering development.

1.1. Study Objectives

The aim of this study is to utilize crosshole seismic tomography to obtain a high-resolution characterization of subsurface conditions in the Niger Delta, with a view to improving the understanding of geological structure and supporting engineering site assessment. The objectives are as follows:

1) To apply crosshole seismic tomography for high-resolution imaging of subsurface conditions at the study site.
2) To determine the spatial distribution of P-wave and S-wave velocities within the subsurface.
3) To identify and delineate subsurface layers, including weathered overburden and consolidated formations.
4) To evaluate lateral and vertical heterogeneity of subsurface materials in the Niger Delta environment.
5) To assess subsurface conditions relevant to engineering design, including groundwater variation and material competence.

2. Literature Review

Accurate subsurface characterization is fundamental to engineering design, geotechnical assessment, and infrastructure development, particularly in heterogeneous sedimentary environments. Traditional geophysical techniques, such as seismic refraction and surface-wave methods, often provide limited spatial resolution and may fail to adequately resolve lateral variations in subsurface properties. Consequently, advanced seismic imaging approaches, including crosshole seismic tomography, have gained increasing attention for high-resolution near-surface investigations (Malehmir et al., 2021; Chen et al., 2021).

Crosshole seismic tomography is a borehole-based geophysical technique that enables detailed imaging of subsurface velocity structures by measuring seismic wave travel times between closely spaced boreholes. This method provides direct estimates of compressional (P-wave) and shear (S-wave) velocities, which are critical parameters for evaluating the dynamic elastic properties of soils and rocks. Studies by Chen et al. (2021) and Zhang et al. (2020) demonstrate that crosshole tomography offers superior resolution compared to conventional one-dimensional seismic methods, particularly in complex geological settings. Similarly, Ghose (2020) highlights recent advances in borehole seismic techniques, emphasizing their effectiveness in resolving fine-scale heterogeneity and improving subsurface models for engineering applications.

The importance of P-wave and S-wave velocities in geotechnical and engineering investigations has been widely documented. P-wave velocity is highly sensitive to lithology, porosity, and fluid saturation, making it a useful indicator for identifying stratigraphic boundaries and groundwater conditions. Santamarina et al. (2017) explain that increases in P-wave velocity often correspond to higher degrees of saturation and compaction. In contrast, S-wave velocity is directly related to shear modulus and is therefore essential for assessing soil stiffness and dynamic response characteristics. Xia et al. (2019) and Foti et al. (2022) emphasize the role of S-wave velocity profiling in seismic site response analysis and soil–structure interaction studies.

In unconsolidated and heterogeneous sediments, such as those commonly found in deltaic environments, seismic velocities exhibit significant spatial variability. Huang et al. (2018) reported that crosshole seismic tomography effectively captures lateral heterogeneity in unconsolidated formations, providing improved delineation of subsurface layering. Similarly, Pazzi et al. (2023) demonstrated that high-resolution seismic velocity models are essential for engineering site characterization in complex geological terrains, where rapid changes in lithology can significantly influence foundation behavior.

The Niger Delta represents a classic example of a geologically complex sedimentary basin characterized by rapid deposition, facies variability, and alternating layers of sands and clays. Foundational studies on the geology of Nigeria (Reyment, 1965; Short and Stauble, 1967) describe the stratigraphic complexity of the region, while more recent investigations highlight the engineering implications of such variability. Aizebeokhai and Oyeyemi (2018) demonstrated the effectiveness of integrated geophysical methods for site characterization in Nigerian sedimentary terrains, emphasizing the need for high-resolution imaging techniques.

Near-surface deposits in the Niger Delta are predominantly composed of poorly consolidated sands with interbedded clays, often associated with the Benin Formation and related units (Nwajide, 2005). Additional lithological complexity is introduced by formations such as the Ogwashi–Asaba Formation, which contains alternating sandy and clayey layers with lignitic horizons (Onyekuru et al., 2018). These sediments are typically weakly cemented and exhibit irregular stratification, leading to significant variations in mechanical properties and seismic velocities. Obrike (2012) and Okoye and Obi (2011) further highlight the mineralogical and geotechnical variability of clay-rich deposits in southern Nigeria, which can influence subsurface stability and engineering performance. Groundwater conditions also play a critical role in subsurface characterization and engineering design. Akujieze (2004) investigated the impact of anthropogenic activities on groundwater systems in southern Nigeria, demonstrating how variations in groundwater levels can affect aquifer vulnerability and soil behavior. The sensitivity of seismic velocities, particularly P-wave velocity, to fluid content provides a reliable means of detecting groundwater variations in subsurface investigations (Santamarina et al., 2017; Ghose, 2020).

Recent developments in seismic data processing and inversion techniques have further enhanced the capabilities of crosshole tomography. Finite-element-based inversion methods allow for iterative refinement of velocity models, improving the accuracy and reliability of subsurface imaging (Zhang et al., 2020). These advancements, combined with improved data acquisition strategies such as multi-shot stacking, have significantly increased the resolution and applicability of crosshole seismic methods in engineering and environmental studies (Chen et al., 2021).

Overall, existing literature underscores the effectiveness of crosshole seismic tomography as a high-resolution tool for subsurface characterization, particularly in complex and heterogeneous environments such as the Niger Delta. The integration of P-wave and S-wave velocity analysis, along with advanced inversion techniques, provides a robust framework for evaluating subsurface conditions and supporting engineering decision-making (Malehmir et al., 2021; Pazzi et al., 2023).

2.1. Geological Background

The study area lies within the Niger Delta sedimentary basin, a major Tertiary depocenter characterized by thick accumulations of clastic sediments deposited in fluvial, deltaic, and shallow marine environments. The stratigraphy of the basin is broadly divided into the Akata Formation (marine shales), the Agbada Formation (interbedded sands and shales), and the Benin Formation, which consists predominantly of continental sands (Reyment, 1965; Short and Stauble, 1967).

Near-surface sediments in the region are mainly associated with the Benin Formation and are composed of poorly consolidated sands with minor clay intercalations. Additional lithological variability is introduced by units such as the Ogwashi–Asaba Formation, which comprises alternating sandy and clayey layers with occasional lignite horizons (Nwajide, 2005; Onyekuru et al., 2018). These sediments are typically weakly cemented and exhibit irregular stratification, resulting in significant lateral and vertical heterogeneity.

Such geological complexity is characteristic of deltaic environments and presents challenges for engineering site characterization, as rapid facies changes and variable sediment properties can significantly influence subsurface behaviour and stability (Aizebeokhai and Oyeyemi, 2018).

░ 3. Methodology

3.1. Survey Design

The crosshole seismic survey was conducted using two vertical boreholes spaced approximately 38 m apart. Seismic sources were positioned at regular 2 m depth intervals in one borehole, while receivers were installed at 4 m intervals in the adjacent borehole to ensure adequate ray-path coverage. To enhance data quality and improve signal-to-noise ratio, multiple recordings were acquired at each source depth and subsequently stacked. This acquisition geometry enabled high-resolution imaging of the subsurface between the boreholes.

3.2. Data Processing and Inversion

Recorded seismic data were processed using specialized geophysical software. Initial processing involved amplitude compensation to correct for geometric spreading and attenuation effects. First-arrival travel times for both P-waves and S-waves were manually picked to ensure consistency and accuracy.

Tomographic inversion was performed using a finite-element approach. An initial velocity model was progressively updated through iterative inversion until convergence was achieved, resulting in two-dimensional velocity models that represent the spatial distribution of seismic velocities within the inter-borehole region.

░ 4. Result & Discussion

The tomographic models reveal clear velocity contrasts corresponding to different subsurface units (Figure 1 and Figure 2). Near-surface P-wave velocities range from approximately 400 to 900 m/s, indicative of loose, weathered materials, as illustrated in Figure 1. At greater depths, velocities increase to values exceeding 2000 m/s, consistent with more competent sandy formations. Similarly, the S-wave velocity model (Figure 2) shows an increase from about 200 m/s near the surface to over 1000 m/s in deeper consolidated units. These trends are consistent with established relationships between seismic velocity, lithology, and degree of compaction (Santamarina et al., 2017; Xia et al., 2019).

The thickness of the low-velocity overburden increases laterally from Borehole 1 toward Borehole 2, as clearly observed in both tomographic sections (Figure 1 and Figure 2). This suggests a dipping stratigraphic interface between the weathered overburden and the underlying competent formation. Such lateral variability is characteristic of deltaic depositional systems, where rapid sedimentation and facies changes occur over short distances (Malehmir et al., 2021; Pazzi et al., 2023).

The groundwater table is inferred from a marked velocity transition around 1400 m/s in the P-wave model (Figure 1), reflecting the sensitivity of compressional-wave velocity to pore-fluid saturation (Santamarina et al., 2017; Ghose, 2020).

The interface between unconsolidated and consolidated materials is distinctly undulatory, reflecting depositional and post-depositional processes typical of deltaic environments. These structural variations are well resolved in the tomograms (Figure 1 and Figure 2), demonstrating the high spatial resolution capability of crosshole seismic tomography compared to conventional surface-based methods (Chen et al., 2021; Zhang et al., 2020).

Quantitative validation of the tomographic models is provided by the extracted velocity data presented in Table 1. The table shows a systematic increase in both P-wave and S-wave velocities with depth for Borehole 1 and Borehole 2. For instance, P-wave velocities increase from about 609 m/s at the surface to over 2000 m/s at depths greater than 20 m, while S-wave velocities increase from approximately 315 m/s to over 1000 m/s within the same depth range (Table 1).

This trend confirms progressive compaction and increasing stiffness of subsurface materials with depth, consistent with findings from previous crosshole studies in unconsolidated sediments (Huang et al., 2018; Zhang et al., 2020).

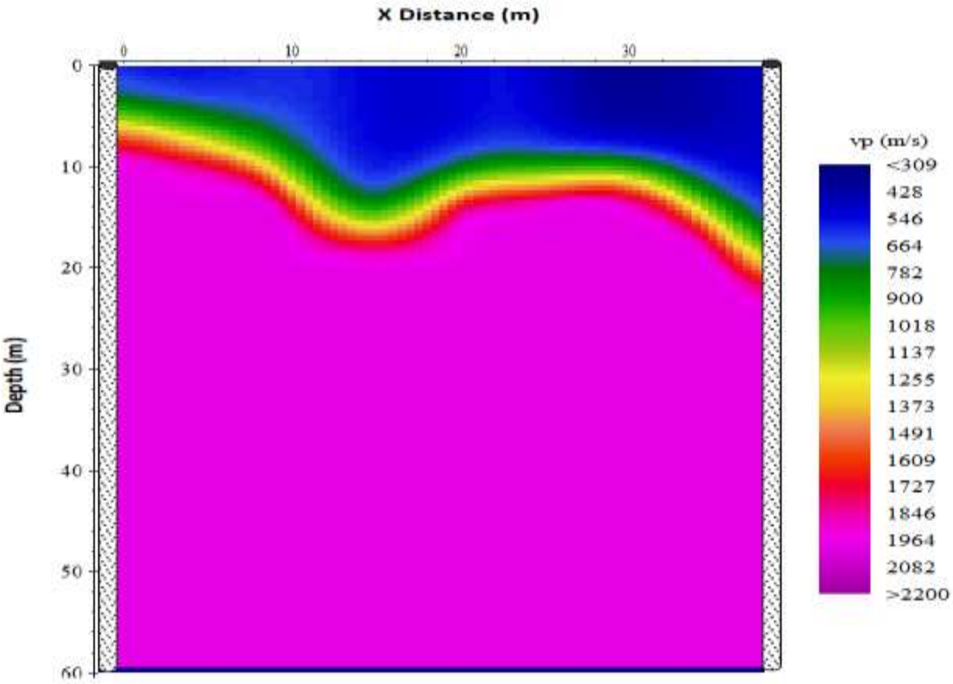

Figure 1. Crosshole seismic tomogram showing the distribution of P-wave velocity within the subsurface between Borehole 1 and Borehole 2.

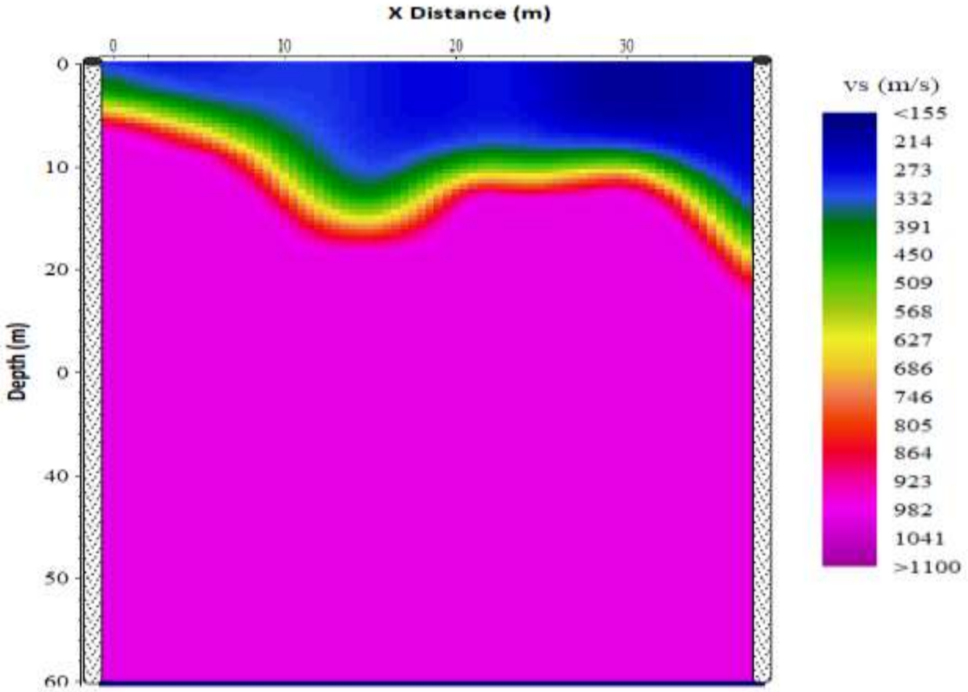

Figure 2. Crosshole seismic tomogram showing the distribution of S-wave velocity within the subsurface between Borehole 1 and Borehole 2.

Table 1. Extracted digital values of P-wave and S-wave velocities at Borehole 1 and Borehole 2.

Depth (m)	P waves velocity (m/s) at borehole 1	P waves velocity (m/s) at borehole 2	s wave velocity (m/s) at borehole 1	s wave velocity (m/s) at borehole 2
0	609	500	315	274
1	704	501	350	278
2	784	503	394	230
3	921	505	462	231
4	1112	507	576	233
5	1346	509	728	236
6	1567	513	895	239
7	1769	518	980	241
8	1918	522	984	244
9	1982	543	998	249
10	2016	553	1010	255
11	2019	578	1013	263
12	2020	613	1014	275
13	2020	662	1014	291
14	2020	727	1014	314
15	2021	813	1015	343
16	2021	927	1015	383
17	2021	1070	1015	436
18	2021	1236	1015	503
19	2022	1429	1016	584
20	2022	1621	1016	683
21	2022	1788	1016	784

22	2023	1909	1017	877
23	2023	1980	1017	946
24	2023	1999	1017	988
25	2024	2000	1018	1000
26	2024	2028	1018	1020
27	2024	2028	1018	1020
28	2024	2028	1018	1020
29	2025	2028	1019	1020
30	2025	2029	1019	1021
31	2025	2029	1019	1021
32	2026	2029	1020	1021
33	2026	2030	1020	1022
34	2026	2030	1020	1022
35	2027	2030	1021	1022
36	2027	2031	1021	1023
37	2027	2031	1021	1023
38	2027	2031	1021	1023
39	2028	2031	1022	1023
40	2028	2032	1022	1024
41	2028	2032	1022	1024
42	2029	2032	1023	1024
43	2029	2033	1023	1025
44	2029	2033	1023	1025
45	2030	2033	1024	1025
46	2030	2034	1024	1026
47	2030	2034	1024	1026
48	2030	2034	1024	1026
49	2031	2034	1025	1026
50	2031	2035	1025	1027
51	2031	2035	1025	1027
52	2032	2035	1026	1027
53	2032	2036	1026	1028
54	2032	2036	1026	1028
55	2033	2036	1027	1028
56	2033	2037	1027	1029
57	2033	2037	1027	1029
58	2033	2037	1027	1029
59	2034	2037	1028	1029
60	2034	2038	1028	1030

4.1. Discussion

The crosshole seismic tomograms (Figure 1 and Figure 2) provide a clear representation of subsurface conditions between the two boreholes and confirm that the shallow section of the site is heterogeneous both vertically and laterally. Such variability is typical of deltaic sedimentary environments, where rapid deposition and channel migration produce irregular layering and short-distance changes in material properties (Malehmir et al., 2021; Pazzi et al., 2023). High-resolution inter-borehole imaging techniques have increasingly been recommended for these complex near-surface conditions (Chen et al., 2021).

The P-wave velocity distribution shown in Figure 1 indicates that velocities within the upper few meters range from approximately 400 to 900 m/s, which is characteristic of loose and partially consolidated sediments. Comparable velocity ranges for weathered sandy overburden have been reported in engineering seismic investigations of unconsolidated terrains (Huang et al., 2018; Zhang et al., 2020). The tomographic image further reveals that this low-velocity layer thickens laterally toward Borehole 2. This observation is consistent with the extracted numerical values presented in Table 1, where lower velocities persist to greater depths in Borehole 2 compared to Borehole 1.

A pronounced increase in P-wave velocity below the weathered zone is clearly visible in Figure 1, where values exceed 2000 m/s. This sharp transition marks the boundary between unconsolidated materials and more competent sandy formations. Similar velocity contrasts marking competence boundaries have been documented in recent crosshole and borehole seismic studies (Chen et al., 2021; Pazzi et al., 2023). The depth of this transition varies laterally, further confirming the inclined nature of the subsurface interface, which is typical of fluvial–deltaic depositional settings (Malehmir et al., 2021).

The S-wave velocity structure (Figure 2) exhibits a similar trend, with velocities increasing from approximately 200–300 m/s near the surface to over 1000 m/s at depth. This trend is also supported by the data in Table 1, where S-wave velocities progressively increase with depth in both boreholes. Since S-wave velocity is directly related to shear modulus, this increase reflects enhanced stiffness and compaction of subsurface materials (Xia et al., 2019; Foti et al., 2022).

The tomographic results also indicate lateral variation in groundwater depth. In Figure 1, a noticeable increase in P-wave velocity—interpreted as the onset of full saturation—occurs at greater depths toward Borehole 2. The sensitivity of compressional-wave velocity to pore-fluid content is well established (Santamarina et al., 2017; Ghose, 2020), and this interpretation is consistent with the velocity trends observed in Table 1.

From an engineering perspective, the spatial variation in overburden thickness and sediment stiffness identified in Figure 1, Figure 2, and Table 1 has significant implications for foundation design. Zones characterized by thicker low-velocity materials (as seen toward Borehole 2) may exhibit reduced stiffness and higher compressibility, increasing the risk of differential settlement. High-resolution seismic imaging methods such as crosshole tomography have been shown to provide more reliable subsurface models for infrastructure planning in heterogeneous environments (Malehmir et al., 2021; Pazzi et al., 2023).

Overall, the integration of tomographic imaging (Figure 1 and Figure 2) with quantitative velocity data (Table 1) confirms that crosshole seismic tomography provides a detailed and reliable characterization of subsurface conditions in complex sedimentary environments such as the Niger Delta, consistent with previous studies (Chen et al., 2021; Pazzi et al., 2023).

░5. Conclusion

This study applied crosshole seismic tomography to investigate the shallow subsurface conditions at a gas flow facility in the Niger Delta. The method provided detailed images of the P-wave and S-wave velocity structure between two boreholes and allowed the identification of important geological and geotechnical features within the upper 60 m of the subsurface.

The results reveal a distinct low-velocity near-surface layer corresponding to weathered and unconsolidated sediments. The thickness of this layer varies laterally across the site, increasing from Borehole 1 toward Borehole 2. Beneath this zone, seismic velocities increase markedly, indicating the presence of more consolidated sandy formations with greater mechanical strength. The interface separating these units is clearly defined in the tomographic models, highlighting the ability of crosshole seismic tomography to resolve subsurface stratigraphy with high spatial resolution.

The combined interpretation of P-wave and S-wave velocity models also enabled the identification of variations in groundwater level across the site. The inferred groundwater table deepens laterally, following the same general trend as the increasing thickness of the weathered overburden. This information is important for engineering design because groundwater conditions influence soil behavior, settlement characteristics, and long-term structural stability.

Overall, the study confirms that crosshole seismic tomography is a reliable technique for detailed subsurface characterization in heterogeneous sedimentary environments. The high-resolution velocity models obtained in this work provide valuable information for engineering site assessment and demonstrate the usefulness of the method for infrastructure development in deltaic terrains. Future investigations could further improve subsurface characterization by integrating crosshole seismic data with borehole logging and geotechnical laboratory testing.

░6. Recommendations

To further enhance subsurface characterization and improve the reliability of engineering interpretations, future studies should integrate crosshole seismic tomography with complementary geotechnical and geophysical methods. The inclusion of borehole logging techniques, such as gamma-ray, resistivity, and density logs, alongside laboratory testing of soil samples, would provide ground-truth data for validating seismic velocity models and refining lithological interpretations.

In addition, the application of three-dimensional (3D) crosshole seismic tomography is recommended to better capture complex subsurface geometries and lateral heterogeneity that may not be fully resolved in two-dimensional models. Expanding the survey to include additional boreholes would improve spatial coverage and increase the accuracy of velocity distribution mapping across the site.

Advanced data processing and inversion techniques, including joint inversion of P-wave and S-wave data, should also be explored to enhance model resolution and reduce uncertainties. The integration of crosshole seismic data with other near-surface geophysical methods, such as electrical resistivity tomography (ERT) and surface-wave analysis, would provide a more comprehensive understanding of subsurface conditions.

Furthermore, time-lapse (4D) seismic monitoring is recommended for assessing temporal variations in subsurface properties, particularly in relation to groundwater fluctuations and seasonal changes. This approach would be valuable for long-term infrastructure monitoring and risk assessment.

Finally, future research should focus on developing site-specific empirical relationships between seismic velocities and geotechnical parameters in Niger Delta environments. Such correlations would improve the practical application of seismic data in engineering design, particularly for foundation analysis, settlement prediction, and soil–structure interaction studies.

Declarations

Source of Funding

This study did not receive any grant from funding agencies in the public, commercial, or not–for–profit sectors.

Competing Interests Statement

The authors have not declared any conflict of interest.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis and manuscript writing equally.

Informed Consent

Not applicable for this study.

Availability of data and material

All supplementary documentation can be provided for the purpose of academic inquiry or verification.

Institutional Review Board Statement

Not applicable for this study.

Ethical Approval

Not applicable for this study.

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