

# Seismic Refraction Tomography for Engineering Site Characterization in Awka, Southeastern Nigeria

Obiajulu, O. O; Olisah, N. C; Nneji, E. G

Department of Physics and Industrial Physics, Nnamdi Azikiwe University, Awka, Nigeria

DOI: <https://doi.org/10.51584/IJRIAS.2025.100900061>

Received: 11 September 2025; Accepted: 17 September 2025; Published: 16 October 2025

## ABSTRACT

Subsurface characterization is crucial for safe and cost-effective civil engineering design, particularly in regions underlain by weak or heterogeneous geological formations. This study employs seismic refraction tomography (SRT) to evaluate the engineering properties of near-surface materials in Awka, the capital of Anambra State, Southeastern Nigeria. Six seismic profiles were acquired using an ES-3000 seismograph with 24 geophones spaced at 2 m intervals. Data processing and interpretation were performed using ReflexW software, enabling delineation of three major subsurface layers with P-wave velocities ranging from 400–745 m/s, 589–1518 m/s, and 797–2826 m/s, respectively. Engineering parameters including shear modulus, Young's modulus, bulk modulus, oedometric modulus, and allowable bearing pressure were derived from the measured P- and S-wave velocities. Results show that seismic velocity and corresponding engineering parameters increase with depth, indicating progressive compaction and strength of subsurface materials. The calculated allowable bearing capacity ranges between  $1.36 \times 10^2$  and  $4.50 \times 10^2$  N/m<sup>2</sup>, consistent with regional geotechnical data. Findings demonstrate that SRT provides a reliable and cost-effective approach for evaluating foundation conditions in Awka, and can serve as an alternative or complement to conventional laboratory testing. These results are recommended for application in urban planning, construction projects, and subsurface resource management in Southeastern Nigeria.

**Keywords:** Seismic refraction tomography, engineering site characterization, Awka, P-wave velocity

## INTRODUCTION

Geophysical prospecting involves the study of subsurface materials by measuring their physical properties with appropriate instruments. These properties, when properly interpreted, provide information on subsurface structure and composition (Obiajulu, 2022). Among available techniques, geophysical methods have become indispensable tools in geotechnical and geo-environmental investigations due to their efficiency, cost-effectiveness, and non-destructive nature (Riwayat *et al.*, 2017; Ayolabi *et al.*, 2012).

Seismic refraction tomography (SRT) is particularly valuable for engineering site investigations, as it provides estimates of elastic parameters essential for evaluating foundation conditions. Compared to conventional seismic refraction, SRT performs well in complex near-surface environments, offering reliable subsurface velocity models even in areas with lateral heterogeneity, extreme topography, or limited spread lengths (Azwin *et al.*, 2013). Previous studies in Nigeria have demonstrated the utility of seismic methods for evaluating weathered layer thickness (Nwosu & Emujakporue, 2016), assessing foundation material strength (Agha *et al.*, 2006), and determining site vulnerability to structural collapse (Adewoyin *et al.*, 2017).

Despite these advances, there remains a need for detailed seismic-based site characterization in Awka and its environs, an area underlain by sedimentary formations known for their geotechnical challenges. This study therefore applies SRT to evaluate subsurface conditions and derive engineering parameters relevant to construction, with the aim of providing data that can inform safe and sustainable urban development.

## Study Area

Awka, the capital of Anambra State, lies within the Anambra Basin of Southeastern Nigeria. The area is situated between latitude 6°25'N and longitude 7°00'E, with elevations ranging from 150 to 300 m above sea level. The

topography gently slopes toward the Mamu River, with prominent *cuestas* trending north–south. The climate is tropical, marked by a wet season (April–October) and a dry season (November–March), with an average annual rainfall of ~1500 mm and mean daily temperatures ranging between 22–32 °C (Obiajulu and Okpoko, 2014 : NIMET, 2012).

Geologically, the study area is underlain predominantly by the Imo Shale Formation, consisting of dark-gray to bluish-gray clayey shale interbedded with thin sandstone bands (Ehirim & Ebeniro, 2010). The formation becomes progressively sandier toward the top, transitioning into alternating sandstone–shale sequences. These lithologies are associated with low bearing strength and high susceptibility to water infiltration, necessitating geophysical evaluation prior to engineering development.

## LITERATURE REVIEW

Traditional refraction analysis used travel-time picks and simple layer models (delay-time, intercept methods). SRT extends this by inverting first-arrival travel times for continuous 2-D (and increasingly 3-D) velocity fields, allowing lateral heterogeneity and complex interfaces to be imaged with higher resolution. Modern algorithms (travel-time tomography, ray-tracing, finite-difference and hybrid forward solvers) plus improvements in acquisition (multichannel recorders, denser receiver spacing) and inversion regularization have improved resolution for shallow engineering targets (meters to tens of meters). Practical reviews and evaluation studies highlight SRT’s advantages—better handling of dipping/irregular interfaces—and its limitations, notably non-uniqueness, dependence on good first-arrival picks, and difficulty imaging very low-velocity contrasts without complementary data. Recent methodological trends relevant to engineering applications include: optimized travel-time forward solvers for speed and accuracy, joint inversion with electrical resistivity tomography (ERT) and surface-wave methods to reduce ambiguity, and time-lapse SRT for monitoring moisture or seasonal changes. These advances increase the utility of SRT for site classification, slope monitoring, and locating weak layers or cavities.

Numerous Nigerian studies demonstrate SRT’s value for engineering and environmental problems. Obiajulu *et al.*, 2025 applied SRT specifically in Amawbia (Awka South) used multichannel acquisition and tomographic inversion to delineate three seismic layers, estimate velocities, and infer bearing capacity zones aimed at diagnosing building collapse issues and guiding foundation recommendations. This is directly relevant to Awka engineering practice and demonstrates the feasibility and local value of SRT surveys.

Studies across southeastern and other parts of Nigeria have applied SRT for 2-D geological modelling, depth to fresh basement, groundwater potential, and characterization of subgrade for highways. For example, SRT combined with geotechnical tests provided diagnostic information for failed and stable pavement sections on the Ajaokuta–Anyigba highway. Other work in Akwa Ibom and parts of the basement complex shows consistent use of SRT to map layer thicknesses and velocities for engineering interpretations. These studies show common outcomes—identification of weathered zones, estimation of depth to competent material, and derivation of conservative engineering parameters.

Multiple Nigerian case studies emphasize integrating SRT with ERT, MASW (surface-wave), VES, borehole logs and CPT/CPTu to overcome non-uniqueness and to translate velocity into engineering metrics (e.g., RQD, bearing capacity, dynamic shear modulus). Integrated surveys improve subsurface discrimination (e.g., separating saturated sands from clays) and better constrain the interpretation for engineering design.

## MATERIALS AND METHODS

### Theoretical Background

The seismic refraction method is governed by Snell’s law, which describes the refraction of seismic energy at interfaces of contrasting velocity. At the critical angle of incidence, waves become refracted along subsurface interfaces and return to the surface as head waves. The first arrivals of these waves, recorded by geophones, are used to calculate velocity distributions within the subsurface (Dutta, 1984). SRT extends this principle by

inverting first-arrival times to generate continuous velocity tomograms.

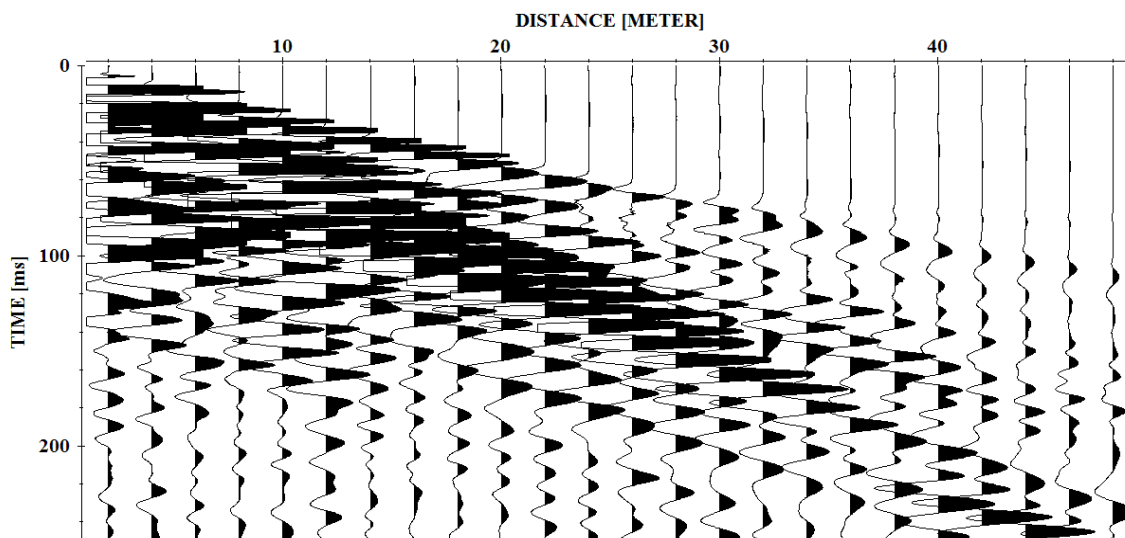
## Data Acquisition

Six seismic profiles were conducted across Awka using an ES-3000 seismograph with 24 geophone channels. Geophones were deployed at 2 m spacing, while a sledgehammer and striker plate served as the seismic energy source. Multiple shots were recorded per spread to ensure data redundancy.

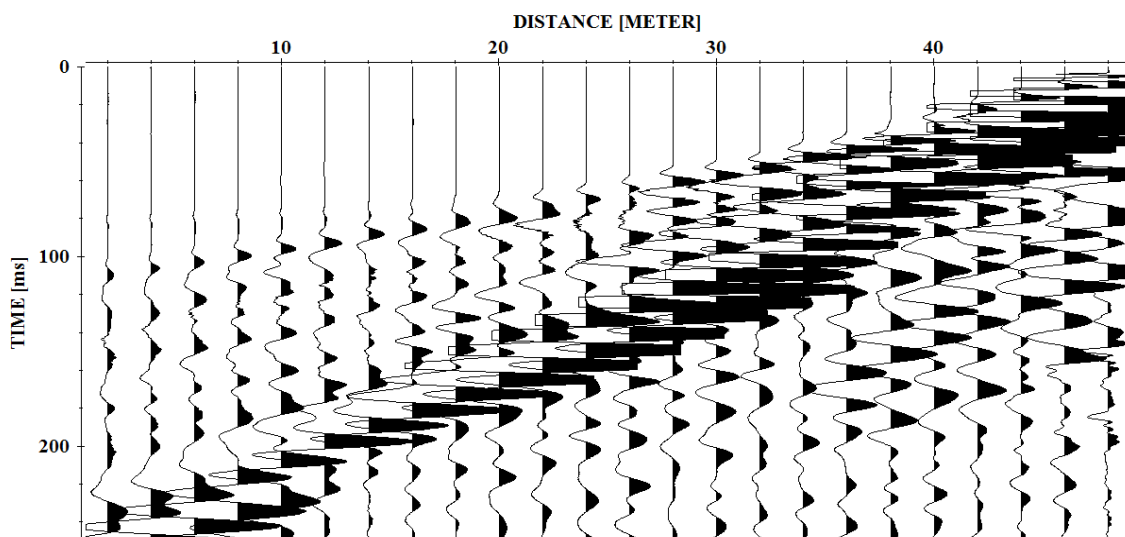
## Data Processing and Interpretation

Field data were processed with ReflexW software (Sandmeier, 2002). Signal enhancement was achieved through band-pass and gain filtering. The data collected from the field was subjected to different stages of processing to enhance the signal-to-noise ratio. The data were first filtered by applying a bandpass filter and then gain filter to enhance the quality of the real signal. The next step is to pick the first arrival times, this arrival time picks were used to plot the travel time curves from where the velocity layers can be estimated from the reciprocal of the slopes obtained. (i.e wave form inversion). Fig 3.1 to Fig 3.6 are different stages involved in the processing of data

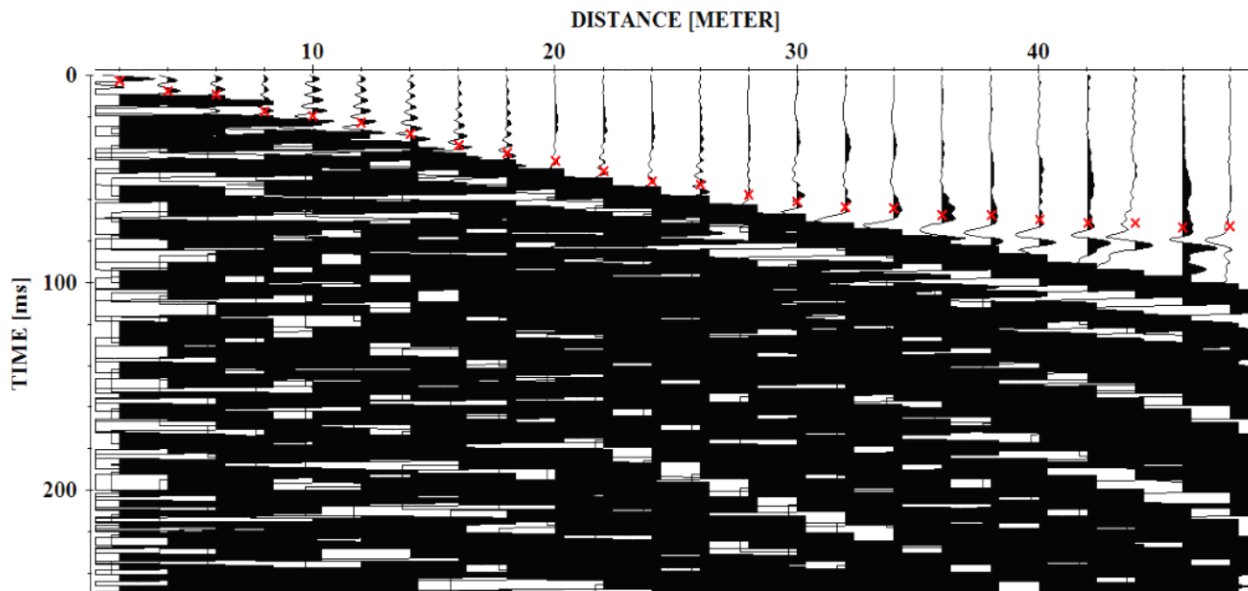
**Fig 4.1:** Raw data for forward shooting



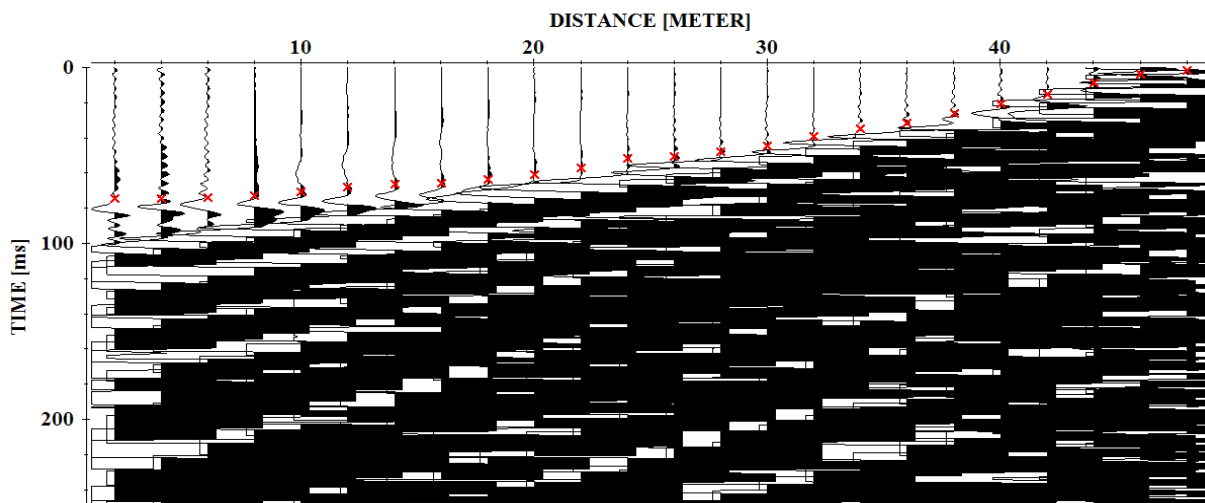
**Fig 4.2:** Raw data for reverse shooting



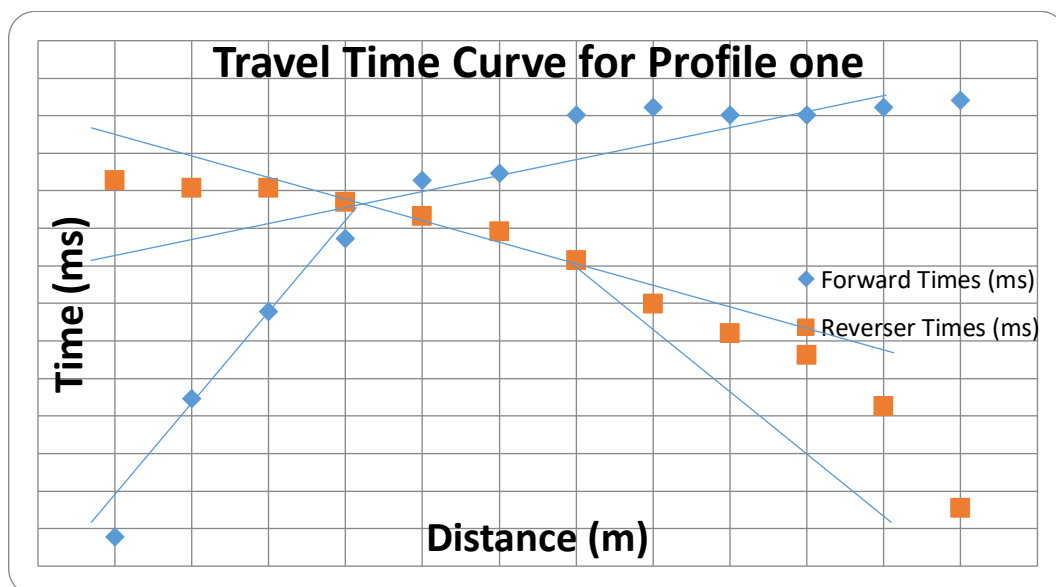
**Fig 4.3:** Data for forward shooting after gain and band pass filter has being applied



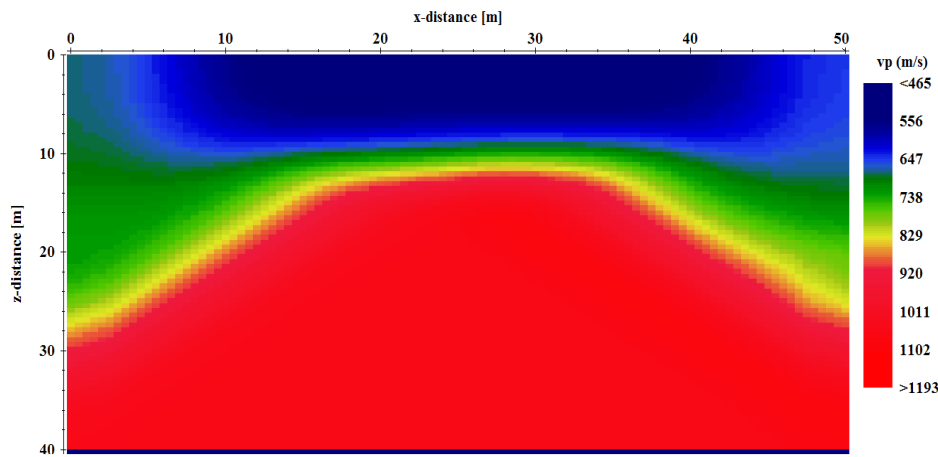
**Fig 4.4:** Data for reverse shooting after gain and band pass filter has being applied



**Fig 4.5:** Travel time curve



**Fig 4.6:** Interpreted data



## Calculation of Engineering Parameters

Seismic refraction tomography method is in high demand lately because of their relevance in engineering studies. The fundamental principle of the application of the method in engineering studies is the utilization of the seismic waves. Many engineering properties can be measured by the propagation of seismic waves. Some of the engineering properties that can be obtained by this method include Young's modulus, Modulus of elasticity, Bulk modulus, Poisson's ratio and Allowable bearing pressure etc. All these parameters require the knowledge of both P and S waves to determine their values. Tezcan *et al*, 2009 derived expressions used to calculate engineering properties. Table 1 is the summary of the formula developed by Tezcan *et al*, 2009.

**Table 1:** Summary of the Formula for Engineering Parameters in terms of  $V_p$  and  $V_s$  (Tezcan et al., 2009; Atat et al., 2013)

| Parameter                       | Formula                                                                       |
|---------------------------------|-------------------------------------------------------------------------------|
| Shear Modulus                   | $G = \gamma V_s^2 / g$                                                        |
| Poisson's ratio                 | $\nu = (\alpha - 2) / 2(\alpha - 1)$                                          |
| Modulus of Elasticity (Young's) | $E = 2(1 + \nu)G$                                                             |
| Bulk Modulus                    | $K = 2(1 + \nu)G / 3(1 - 2\nu)$                                               |
| Oedometric Modulus              | $E_c = (1 - \nu)E / (1 + \nu)(1 - 2\nu)$<br>$E_c = \alpha E / 2(3\alpha - 4)$ |
| Subgrade Coefficient            | $k_s = 4\gamma V_s$                                                           |
| Allowable bearing pressure      | $q_a = 0.1 \gamma V_s / n$                                                    |

Where  $g$  is the acceleration due to gravity =  $9.81 \text{ m/s}^2$ ,  $\alpha = (V_p / V_s)^2$ ,  $\gamma$  is the unit weight of the soil in  $\text{N/m}^3 = \gamma_0 + 0.002V_p$ ,  $\gamma_0$  is the reference unit weight values in  $\text{N/m}^3$ , for soil  $\gamma_0 = 16$ ,  $n$  is factor of safety, for soil  $n = 4.0$ ,  $V_p$  is the compressional wave velocity and  $V_s$  is the shear wave velocity

## RESULTS AND DISCUSSION

### Calculated Engineering Parameters

From the velocity models, P-wave ( $V_p$ ) and S-wave ( $V_s$ ) velocities were extracted for calculation of engineering parameters including shear modulus ( $G$ ), Young's modulus ( $E$ ), bulk modulus ( $K$ ), Poisson's ratio ( $\nu$ ),

oedometric modulus ( $E_c$ ), subgrade coefficient ( $k_s$ ), and allowable bearing capacity ( $q_a$ ) using established empirical relations (Tezcan et al., 2009).

**Table 2** is the calculated engineering parameters

| Profile | Location          | $V_p$ | $V_s$ | $\alpha$ | $v \cdot 10^{-1}$ | $\gamma \cdot 10^1$ | $G \cdot 10^5$      | $E \cdot 10^5$      | $K \cdot 10^5$      | $E_c \cdot 10^5$    | $K_s \cdot 10^4$    | $q_a \cdot 10^2$    |
|---------|-------------------|-------|-------|----------|-------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
|         |                   |       |       |          |                   | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) | (N/m <sup>2</sup> ) |
| 1       | Comm. Pri. Sch.   | 556   | 318   | 3.06     | 0.26              | 1.71                | 1.76                | 4.43                | 3.04                | 1.31                | 2.18                | 1.36                |
|         |                   | 738   | 436   | 2.87     | 2.32              | 1.75                | 3.39                | 8.34                | 5.19                | 2.60                | 3.05                | 1.90                |
|         |                   | 1011  | 612   | 2.73     | 2.11              | 1.80                | 6.88                | 16.7                | 9.60                | 5.43                | 4.41                | 2.76                |
| 2       | Amaenyi Girls     | 626   | 356   | 3.09     | 2.61              | 1.73                | 2.23                | 5.62                | 3.92                | 1.65                | 2.46                | 1.54                |
|         |                   | 795   | 464   | 2.94     | 2.42              | 1.76                | 3.86                | 9.59                | 6.19                | 2.93                | 3.26                | 2.04                |
|         |                   | 1048  | 625   | 2.81     | 2.24              | 1.81                | 7.21                | 17.6                | 10.7                | 5.59                | 4.52                | 2.83                |
| 3       | All Saints Church | 538   | 358   | 2.26     | 1.03              | 1.71                | 2.23                | 4.92                | 2.06                | 2.00                | 2.45                | 1.53                |
|         |                   | 641   | 470   | 1.86     | 0.81              | 1.73                | 3.89                | 7.15                | 2.05                | 4.21                | 3.25                | 2.03                |
|         |                   | 797   | 626   | 1.62     | 3.05              | 1.76                | 7.03                | 9.77                | 2.02                | 9.17                | 4.41                | 2.75                |
| 4       | Paul University   | 854   | 353   | 5.85     | 3.97              | 1.77                | 2.25                | 6.28                | 10.2                | 1.36                | 2.50                | 1.56                |
|         |                   | 1398  | 609   | 5.27     | 3.83              | 1.88                | 7.11                | 19.7                | 28.0                | 4.39                | 4.58                | 2.86                |
|         |                   | 2214  | 865   | 6.55     | 4.10              | 2.04                | 15.6                | 43.9                | 81.3                | 9.19                | 7.07                | 4.42                |
| 5       | Ukwuorji          | 833   | 355   | 5.51     | 3.89              | 1.77                | 2.27                | 6.30                | 9.47                | 1.39                | 2.51                | 1.57                |
|         |                   | 1238  | 611   | 4.11     | 3.39              | 1.85                | 7.03                | 18.8                | 19.5                | 4.65                | 4.52                | 2.82                |
|         |                   | 1845  | 866   | 4.54     | 3.59              | 1.97                | 15.1                | 40.9                | 48.3                | 9.65                | 6.84                | 4.26                |
| 6       | Obunagu           | 957   | 358   | 7.15     | 4.19              | 1.79                | 2.34                | 6.64                | 13.6                | 1.36                | 2.57                | 1.60                |
|         |                   | 1524  | 609   | 6.26     | 4.05              | 1.90                | 7.20                | 20.2                | 35.5                | 4.28                | 4.64                | 2.90                |
|         |                   | 2375  | 867   | 7.50     | 4.23              | 2.08                | 15.9                | 45.3                | 98.1                | 9.17                | 7.20                | 4.50                |

## Seismic Velocity Structure

The interpreted velocity models delineate three major seismic layers across the study area. P-wave velocities range from 400–745 m/s in the topsoil, 589–1518 m/s in the intermediate layer, and 797–2826 m/s in the deeper layer. The progressive increase in velocity with depth reflects compaction and lithological transition from weathered shale to competent sandstone-shale sequences.

## Engineering Parameters

Derived engineering parameters show that shear modulus varies between  $1.76 \times 10^5$  and  $1.59 \times 10^6$  N/m<sup>2</sup>, while Young's modulus ranges from  $4.36 \times 10^5$  to  $4.53 \times 10^6$  N/m<sup>2</sup>. Bulk modulus values lie between  $2.02 \times 10^5$  and  $9.81 \times 10^6$  N/m<sup>2</sup>, and the calculated allowable bearing capacity spans from  $1.36 \times 10^2$  to  $4.50 \times 10^2$  N/m<sup>2</sup>. These values indicate that near-surface materials in Awka are generally suitable for shallow foundations, though variability across locations highlights the importance of site-specific evaluation.

The results are consistent with cone penetration test data obtained from the Anambra State Materials and Testing Laboratory (2018), reinforcing the reliability of SRT as an alternative to conventional geotechnical methods.

## Implications for Engineering Development

The findings demonstrate that SRT can effectively characterize subsurface engineering properties in sedimentary environments where traditional borehole testing may be costly or spatially limited. In Awka, where rapid

urbanization increases demand for construction, such data are critical for minimizing risks of foundation failure, structural collapse, and groundwater contamination.

## CONCLUSION

This study applied seismic refraction tomography to evaluate the engineering properties of subsurface materials in Awka, Southeastern Nigeria. Three seismic layers were identified, with velocities and engineering parameters increasing with depth, consistent with progressive compaction. The derived shear modulus, Young's modulus, bulk modulus, and allowable bearing capacity values show that the area generally supports shallow foundations, though localized variations warrant detailed site-specific assessments.

Seismic refraction tomography has proven to be a cost-effective, reliable, and non-invasive method for geotechnical site characterization in Awka. The method is recommended for government agencies, urban planners, estate developers, and engineers prior to construction projects such as buildings, roads, and boreholes. Future work should integrate SRT with electrical resistivity and borehole testing to further constrain subsurface models and improve engineering risk assessment.

## REFERENCES

1. Adewoyin, O. O., Joshua, E., Akinyemi, M.L., Omeje, M. & Joel, E. S. (2017). Investigation to determine the vulnerability of reclaimed land to building collapse using near surface geophysical method. *Journal of Physics Conf. Series* 852.
2. Agha, S. O., Okwueze, E. & Akpan, A.E. (2006). Assessment of the Strength of foundation materials in some parts of Afikpo, Nigeria using seismic refraction. *Nigerian Journal of Physics* 18 (1).
3. Anambra State Materials and Testing Laboratory (2018). Ministry of Works, 1-3 Works Road, Awka, Anambra State, Nigeria.
4. Atat, J. G., Akpabio, I. O. & George, N. J. (2013). Allowable bearing capacity for shallow foundation in Eket Local Government Area, Akwa Ibom State, Southern Nigeria. *International Journal of Geosciences* (4) 1491-1500.
5. Ayolabi, E. A., Adeoti, L., Oshinlaja, N. A., Adeosun, I. O & Idowu, O. I, (2012). Seismic refraction and resistivity studies of parts of Igbogbo Township, Southwest, Nigeria. *Journal Science and Research Development* (2) 42 – 61.
6. Azwin, I. N., Rosli. S & Nordiana. M (2013). Applying the Seismic refraction tomography for site characterization. *APCBEE Procedia*(5) 227-231.
7. Dutta, P. N. (1984). Seismic refraction method to study the foundation rock of a dam. *Geophysical Prospecting*, 32, 1103-1110.
8. Ehirim, C. N. & Ebeniro, J. O. (2010). Evaluation of aquifer characteristics and groundwater potentials in Enugwu-Agidi, Awka, Nigeria Using vertical electrical sounding. *Asian Journal of Earth Sciences* 3(2) 73-81.
9. NIMET. (2012). Nigeria Climatic data, Abuja, Nigeria
10. Nwosu, L. I. & Emujakporue, G. O (2016). Seismic refraction investigation of thickness and velocity of the weathered layer in Emuoha town, Rivers State, Nigeria. *IOSR Journal of Applied Geology and Geophysics* 4 (6) 52 – 57.
11. Obiajulu, O. (2012). Geoelectric investigation of groundwater potentials in Ihiala, Anambra State, Nigeria. Unpublished M.Sc Thesis, Nnamdi Azikiwe University, Awka.
12. Obiajulu, O. O & Okpoko, E. I. (2014). Geoelectric investigation of groundwater potentials of Ihiala and its environs, Anambra State, Nigeria. *IOSR Journal of Applied Geology and Geophysics* 3 (6) 14 – 20.
13. Obiajulu, O. O., Olisa, N. C., Obiabunmo, O. C and Nwaka, E. G. (2025). Application of Seismic Refraction Tomography to proffer solution to building collapse in Amawbia and its environs, South East, Nigeria. *Journal of Basic Physical Research* 14 (1) 1 – 8.
14. Riwayat, A. I., Nazri, M .A. & Abidin, M .H. (2017). Application of electrical resistivity method (ERM) in groundwater exploration. *Journal of physics: Conference series*, vol 995, International Seminar on Mathematics and Physics in Sciences and Technology.28-29.

15. Sandmeier, K. J. (2002). Reflexw 6.0, Manual, Sandmeier software, Zipser Strabe 1, D-76227 Karlsruhe, Germany.
16. Tezcan, S. S., Ozdemir, Z. & Keceli, A. (2009). Seismic technique to determine the allowable bearing pressure for shallow foundations in soils and rocks. *Acta geophysica* 57, 400-412.