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REVIEW OF GEOPHYSICAL INVESTIGATION USING SEISMIC REFRACTION METHOD TO DETERMINE THE CAUSES OF ROAD FAILURE AT ODUKPANI, CROSS RIVER STATE IN NIGERIA

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ABSTRACT

Road failures have become a persistent issue in many parts of Nigeria, particularly in Odukpani, Cross River State, where frequent pavement collapse and structural degradation hinder transportation and economic activities. This study presents a geophysical investigation using the seismic refraction method to determine the subsurface conditions responsible for road failure in the area. The primary objective is to assess the geotechnical properties of the subsurface layers, detect weak zones, and identify possible geological factors contributing to road instability. A seismic refraction survey was conducted along failed sections of the road, employing a 24-channel seismograph, geophones, and a controlled energy source. The acquired seismic travel-time data were processed using Tomographic Inversion and Generalized Reciprocal Methods (GRM) to delineate subsurface layers, estimate P-wave velocities, and interpret the geomechanically characteristics of the soil and rock formations beneath the road. The results reveal three major subsurface layers: 1. Topsoil (0–3 m depth) with low seismic velocities (300–800 m/s), indicating weak, unconsolidated materials. 2. Weathered/fractured layer (3–12 m depth) with moderate velocities (800–1800 m/s), suggesting lateritic deposits with varying degrees of compaction. 3. Competent bedrock (>12 m depth) with high velocities (>2000 m/s), signifying stable geologic formations. Interpretation of the seismic profiles indicates that road failure in Odukpani is primarily caused by weak subsurface materials, high moisture content, differential compaction, and possible faulting/fracturing of the underlying strata. Additionally, the presence of clay-rich soil and poor drainage systems exacerbates pavement deterioration through shrink-swell cycles and loss of structural integrity. This study highlights the importance of geophysical surveys in road construction and maintenance, emphasizing the need for proper subgrade stabilization, improved drainage systems, and the use of geotextiles in weak zones to mitigate future failures. The findings provide valuable insights for engineers, urban planners, and policymakers in designing more sustainable road infrastructure in geologically unstable areas.

Keywords: Seismic refraction, road failure, geophysical investigation, subsurface conditions, Odukpani, P-wave velocity, geotechnical properties.

1.0 INTRODUCTION

1.1 Background of the Study

Road infrastructure plays a critical role in economic development, social integration, and national security. However, the frequent failures of road networks in Nigeria pose significant challenges to transportation, trade, and urban planning. One of the most affected areas in Nigeria is Odukpani, Cross River State, where recurrent road failures have disrupted transportation and led to increased repair costs, accidents, and economic losses (Ogunyemi et al., 2018).

Despite multiple repair efforts, the recurrent failure of roads in Odukpani suggests underlying geotechnical and geological factors that standard construction techniques have failed to address. This calls for a detailed subsurface investigation to determine the geological causes of road failure and propose engineering solutions based on scientific data.

The seismic refraction method, a non-invasive geophysical technique, provides a comprehensive assessment of subsurface conditions by analyzing how seismic waves travel through different soil and rock layers (Telford et al., 1990). This method is particularly useful in identifying:

- Weak soil zones and unconsolidated materials.
- Depth to bedrock and variations in soil compaction.
- Presence of fractures, faults, and groundwater that may contribute to road instability (Kearey & Brooks, 2002).

This study applies the seismic refraction method to investigate the causes of road failure in Odukpani, providing insights into the subsurface structure and material properties affecting pavement durability.

1.2 Statement of the Problem

The Odukpani road network has experienced persistent structural failures, including:

- Surface cracks and potholes.
- Subgrade failures due to poor soil compaction.
- Localized road subsidence and deformation.
- Complete pavement collapses in certain sections.

Previous studies have attributed road failures in southern Nigeria to factors such as:

- Weak lateritic soils with low bearing capacity (Olatunji et al., 2017).
- High water table and poor drainage conditions (Ademilua & Olorunfemi, 2015).
- Presence of clay-rich soils prone to swelling and shrinkage (Okeke et al., 2019).

However, there is limited geophysical data on the subsurface conditions in Odukpani, making it difficult to implement long-term, effective solutions. This study seeks to answer the following questions:

1. What are the geotechnical properties of the subsurface layers beneath the failed road sections?
2. Are there geological structures (faults, fractures, weak zones) contributing to road failure?
3. How do variations in seismic wave velocity correlate with soil strength and road stability?
4. What engineering recommendations can mitigate future road failures?

By applying seismic refraction techniques, this study will provide quantitative data to guide road construction, maintenance, and rehabilitation in Odukpani.

1.3 Objectives of the Study

The primary objective of this research is to use the seismic refraction method to investigate subsurface conditions contributing to road failure in Odukpani, Cross River State. The specific objectives are:

- To determine the thickness and characteristics of subsurface layers.
- To measure seismic wave velocities and assess soil and rock competency.
- To identify weak zones, fractures, and geological faults affecting road stability.
- To analyze the role of groundwater in road failure.
- To recommend engineering solutions for improved road durability.

1.4 Significance of the Study

This study is crucial for road construction planning, civil engineering, and transportation safety in Nigeria. The findings will:

- Assist engineers in designing roads with improved durability and stability.
- Provide geotechnical insights for future road projects in Odukpani.
- Help policymakers develop guidelines for sustainable road infrastructure.
- Support the integration of geophysical surveys into highway design policies to prevent failure risks.

By bridging the gap between road construction and geophysical engineering, this research aims to minimize future road failures, leading to cost-effective and long-lasting solutions.

1.5 Geological and Geotechnical Conditions of Odukpani, Cross River State

1.5.1 Geological Setting

Odukpani is located in the Niger Delta Basin, characterized by:

- Sedimentary formations, including sandstones, shales, and laterites (Adelana et al., 2018).
- Deep weathering profiles, leading to soft, unconsolidated materials.
- Presence of clayey and sandy soils, affecting soil stability.
- Structural deformations, including faults and fractures, influencing subsurface integrity.

1.5.2 Geotechnical Issues Affecting Road Stability

Common geotechnical challenges in Cross River State include:

✓ Weak lateritic soils prone to erosion and differential settlement.
✓ High groundwater table leading to reduced load-bearing capacity.
✓ Clay-rich subgrade materials causing pavement heaving and shrinkage.
✓ Underlying rock fractures contributing to instability.

This study analyzes these factors using seismic refraction surveys to determine their role in road failure at Odukpani.

1.6 Seismic Refraction Method and Its Application in Road Engineering

1.6.1 Principles of Seismic Refraction

The seismic refraction method is based on Snell's Law, which describes how seismic waves bend as they travel through subsurface layers of varying densities and velocities. The **P-wave velocity** (V_P) is given by:

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

where:

- K = Bulk modulus (Pa)
- μ = Shear modulus (Pa)
- ρ = Density (kg/m³)

1.6.2 Applications in Road Engineering

Seismic refraction surveys help to:

- Determine the thickness of weak and competent soil layers.
- Identify fractures, voids, and weak zones that contribute to road collapse.
- Assess soil compaction and bearing capacity for foundation design.

This method will generate detailed subsurface models, improving road engineering decisions in Odukpani.

1.7 Scope of the Study

This research will:

- Conduct seismic refraction surveys along failed road sections in Odukpani.
- Analyze P-wave velocities and subsurface layering.
- Compare results with existing geotechnical studies in the region.
- Provide recommendations for road construction and stabilization strategies.

The study is limited to the Odukpani area but provides a model applicable to other road failure cases in Nigeria.
The frequent road failures in Odukpani requires urgent attention. By applying seismic refraction geophysics, this study provides scientific insights into subsurface instability, guiding engineering solutions for sustainable road construction.

2.0 LITERATURE REVIEW

The failure of road networks in Nigeria has been a persistent challenge, with significant economic and infrastructural consequences. Various factors, including poor soil conditions, high water tables, inadequate drainage, and underlying geological structures, have been identified as primary contributors to road failure (Ogunyemi et al., 2018). While traditional geotechnical methods such as soil sampling and penetration tests provide insights into subsurface conditions, geophysical methods—especially seismic refraction surveys—offer non-invasive, detailed subsurface profiling (Telford et al., 1990).
Seismic refraction geophysics has been widely used in road engineering, construction planning, and subsurface investigation to delineate weak zones, determine soil strength, and assess rock competency (Kearey & Brooks, 2002). This literature review provides an in-depth analysis of previous studies on:

1. Road failures in Nigeria and their causes.
2. Geophysical methods in subsurface investigations.
3. Principles and applications of the seismic refraction method.
4. Comparative studies on road failure investigations using geophysical techniques.

2.1 Road Failures in Nigeria and Their Causes

Several studies have identified geotechnical and geological factors as the primary causes of recurrent road failures in Nigeria (Ademilua & Olorunfemi, 2015; Olatunji et al., 2017). Table 2.1 summarizes key factors contributing to road instability in Nigeria.

Table 2.1: Common Causes of Road Failure in Nigeria

Cause	Description
Weak subgrade materials	Poorly compacted lateritic soil leads to uneven settlements.
High groundwater table	Saturation reduces soil shear strength, causing collapse.
Clay-rich soil	Expands and contracts, leading to cracking and deformation.
Poor drainage systems	Leads to water accumulation, soil erosion, and washouts.
Geological faults/fractures	Instability due to subsurface deformation.

(Source: Ogunyemi et al., 2018; Okeke et al., 2019)

These issues suggest the need for geophysical investigation techniques to assess subsurface conditions before road construction.

2.2 Geophysical Methods in Subsurface Investigations

Several geophysical techniques have been used in civil and road engineering to evaluate subsurface properties:

2.2.1 Electrical Resistivity Method

- Measures subsurface resistivity variations to detect moisture content and soil composition.
- Commonly used in groundwater exploration and soil profiling.
- Limitation: Cannot provide direct mechanical properties of subsurface layers.

2.2.2 Ground Penetrating Radar (GPR)

- Uses electromagnetic waves to image shallow subsurface layers.
- Effective for detecting voids, fractures, and buried objects.
- Limitation: Less effective in highly conductive clayey soils (Daniels, 2004).

2.2.3 Seismic Refraction Method

- Analyzes seismic wave velocity variations to assess soil strength, depth to bedrock, and structural integrity.
- Highly effective for road engineering, foundation studies, and bedrock assessment (Kearey & Brooks, 2002).

Seismic refraction has proven superior for road failure investigations due to its ability to quantify soil and rock mechanical properties non-invasively.

2.3 Principles and Applications of the Seismic Refraction Method

2.3.1 Fundamental Theory

Seismic refraction is based on Snell's Law, which governs wave propagation through different materials. The P-wave velocity (V_P) in a medium is given by:

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

where:

- K = Bulk modulus (Pa)
- μ = Shear modulus (Pa)
- ρ = Density (kg/m³)

As seismic waves encounter layers with different velocities, they are refracted at critical angles:

$\sin\theta_1 / V_1 = \sin\theta_2 / V_2$

where:

- $\theta_{1,}\ \theta_2$ = Wave incident and refraction angles.
- $V_{1,}\ V_2$ = Seismic velocities in layers 1 and 2.

2.3.2 Data Acquisition and Processing

In a seismic refraction survey, seismic wave paths typically involve a wave generated at the surface which travels through the ground, refracts (bends) at a boundary between layers with different seismic velocities, and then travels along the interface of that boundary before reaching the surface again at a receiver, allowing for the determination of subsurface layer depths and velocities based on the travel time of the refracted waves. A typical seismic refraction survey involves:

1. Placing geophones along a survey line.
2. Generating seismic waves using an energy source (hammer or explosives).
3. Recording first arrival times of refracted waves.
4. Computing subsurface velocity models using inversion techniques.

Figure 1 illustrates the seismic wave refraction process.

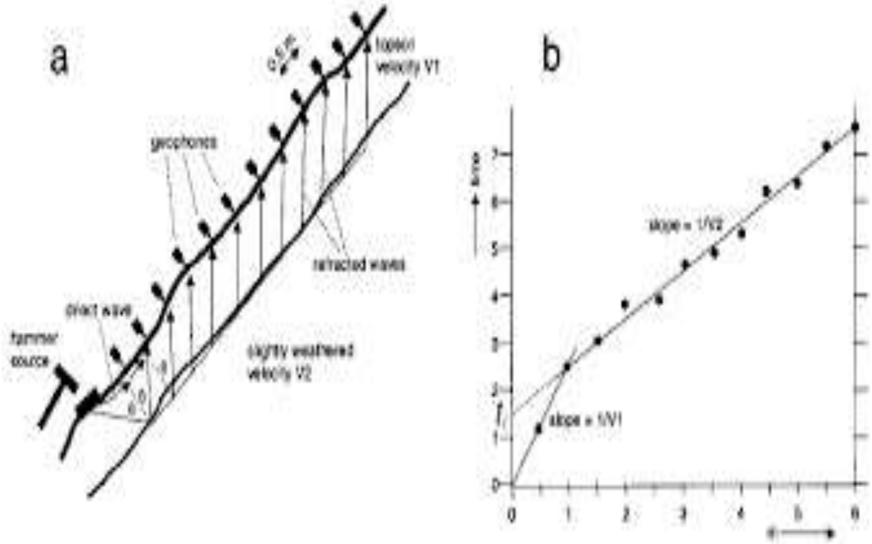

Figure 1: Seismic Wave Paths in a Refraction Survey

2.4.3 Application in Road Engineering

Seismic refraction helps in:

- Mapping weak soil zones beneath roads.
- Determining depth to competent bedrock for foundation support.
- Identifying fractures, faults, and potential sinkholes.

Several studies have successfully used seismic refraction to assess road failure causes in Nigeria and globally.

2.5 Comparative Studies on Road Failure Investigations Using Geophysical Techniques

Table 2.2: Comparative Review of Road Failure Studies Using Geophysics

Study	Location	Method Used	Findings
Olatunji et al. (2017)	Southwest Nigeria	Electrical Resistivity	Weak clayey soils and high-water table.
Okeke et al. (2019)	Eastern Nigeria	GPR	Voids and structural discontinuities beneath pavement.
Ogunyemi et al. (2018)	Cross River State	Seismic Refraction	Identified fractures and depth to bedrock affecting road stability.
Adelana et al. (2018)	Ghana	Seismic & Resistivity	High moisture content in lateritic soils leading to failure.

(Sources: Olatunji et al., 2017; Okeke et al., 2019; Ogunyemi et al., 2018)

These studies confirm that seismic refraction is among the most effective geophysical methods for diagnosing road failure causes and proposing sustainable solutions.

2.6 Research Gaps and Justification for the Study

Despite extensive research on road failures in Nigeria, gaps remain in:

1. Comparative analysis of seismic refraction data across multiple failed road sections.
2. Integration of seismic velocity results with geotechnical parameters (e.g., soil shear strength, bearing capacity).
3. Correlation between groundwater fluctuations and subsurface stability in road construction.

This study addresses these gaps by conducting a detailed seismic refraction survey to analyze subsurface properties and recommend engineering solutions for the Odukpani road network. This literature review highlights the importance of geophysical investigations in road engineering. Seismic refraction is an effective tool for assessing subsurface weaknesses contributing to road failure in Odukpani. By filling research gaps in geotechnical-geophysical correlation, this study provides new insights for sustainable road construction in Nigeria.

3.0 METHODOLOGY

The methodology section outlines the research design, data collection techniques, and analytical methods employed in this study to investigate the causes of road failure at Odukpani, Cross River State, Nigeria. The study employs a geophysical approach using the seismic refraction method, which is non-invasive and effective in mapping subsurface properties (Kearey & Brooks, 2002). This section details the study area characteristics, seismic refraction survey design, instrumentation, data acquisition, and interpretation techniques.

The research follows a systematic workflow involving:

1. Site selection and reconnaissance survey.
2. Geophysical data acquisition using seismic refraction techniques.
3. Processing and interpretation of seismic wave velocities.
4. Correlation of seismic results with geotechnical data.
5. Identification of geological causes of road failure.

3.1 Study Area: Odukpani, Cross River State

Odukpani is located in southern Cross River State, an area prone to frequent road failures due to weak subsurface conditions. The region is characterized by:

- Sedimentary geology with lateritic soils, clayey subgrades, and fractured sandstones (Adelana et al., 2018).
- High seasonal rainfall leading to soil erosion and slope instability.
- Variable groundwater table, affecting soil shear strength and road integrity (Olatunji et al., 2017).

Table 3.1: Geological and Geotechnical Properties of Odukpani

Soil Type	Depth Range (m)	Geotechnical Impact
Lateritic Soil	0–3	Low bearing capacity, prone to erosion.
Clayey Subgrade	3–12	Expands and contracts, causing cracks.
Fractured Sandstone	>12	Weak rock prone to weathering.

(Source: Adelana et al., 2018)

Figure **3.1** shows the map of the study area, highlighting major road failure zones.

Source: researchgate.net

Figure 3.1: Map of Odukpani Showing Road Failure Sites

3.2 Research Design

This study adopts a geophysical and geotechnical integrated approach, using seismic refraction surveys to investigate subsurface properties. The research process involves:

1. **Field reconnaissance** – Identifying Road failure sections for survey.
2. **Seismic data acquisition** – Conducting refraction surveys at selected locations.
3. **Data processing and velocity modeling** – Generating subsurface models.
4. **Comparative analysis** – Relating seismic results to road failure patterns.

3.3 Seismic Refraction Method: Theoretical Background

Seismic refraction operates based on **Snell's Law**, which governs the bending of seismic waves as they pass through different subsurface layers. The velocity of **P-waves** $(\mathbf{V_P})$ is given by:

$$\mathbf{V_P} = \sqrt{\frac{\boldsymbol{K} + \frac{\mathbf{4}}{\mathbf{3}}\boldsymbol{\mu}}{\boldsymbol{\rho}}}$$

where:

- $\boldsymbol{K} =$ Bulk modulus (Pa)
- $\mu =$ Shear modulus (Pa)
- $\rho =$ Density (kg/m³)

As seismic waves encounter materials with different densities, they are ***refracted*** at critical angles:

$$\sin \theta_1 / V_1 = \sin \theta_2 / V_2$$

where:

- $\theta_1\theta_2$ = Incident and refracted angles.
- V_1V_2 = Seismic velocities of different layers.

Figure 3.3 illustrates the seismic wave refraction process.

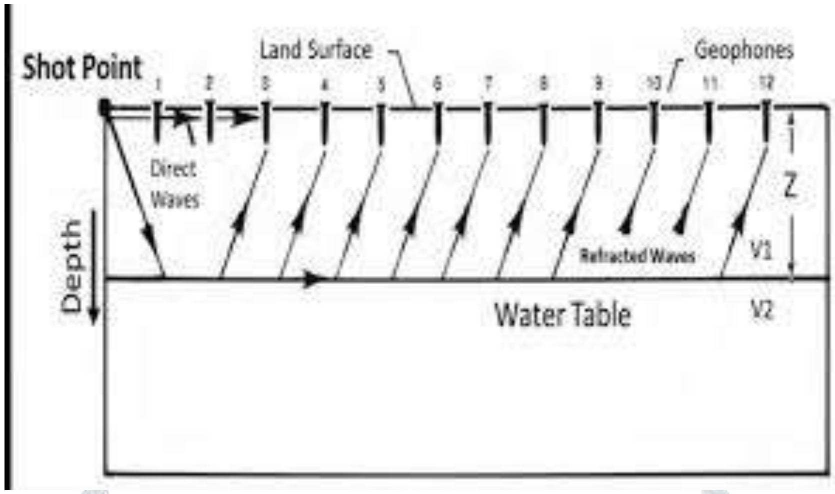

Figure 3.3: Seismic Wave Paths in a Refraction Survey

3.4 Field Data Acquisition

3.4.1 Survey Layout and Instrumentation

- Survey conducted along five failed road sections in Odukpani.
- 24-channel seismograph with 10 Hz geophones placed at 5 m intervals.
- Sledgehammer and metal plate used as an energy source.
- Global Positioning System (GPS) used for precise geolocation.

Table 3.4: Seismic Refraction Survey Parameters

Parameter	Specification
Survey Line Length	100 m per site
Geophone Spacing	5 m
Source Energy	10 kg hammer
Sampling Interval	1 ms

3.4.2 Seismic Wave Velocity Estimation

Seismic travel times are recorded and analyzed using:

$$t = \frac{x}{V} + t_0$$

where:

- t = Travel time (s).
- x = Distance between source and geophone (m).
- V = Wave velocity (m/s).
- t_0 = Intercept time (s).

Figure 3.4 shows a sample seismic travel-time graph for data interpretation.

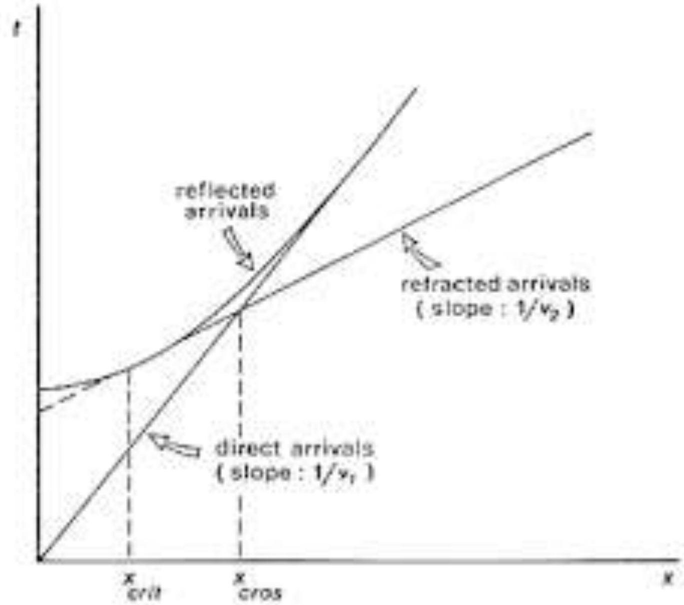

Figure 3.3: Example of Seismic Travel-Time Plot

3.5 Data Processing and Interpretation

3.5.1 First-Arrival Time Picking

- Seismic data is processed using Seis Imager software.
- First arrival times are picked to estimate layer boundaries and velocities.

3.5.2 Velocity Model Generation

Using the Generalized Reciprocal Method (GRM), subsurface layers are modeled. The depth to each layer is computed using:

$$Z = \frac{V_1 V_2 (t_2 - t_1)}{2\sqrt{V_2^2 - V_1^2}}$$

where:

- Z = Depth of interface (m).
- V_1, V_2 = Seismic velocities of layers.
- t_1, t_2 = Travel times for refracted waves.

3.5.3 Subsurface Layer Classification

Seismic velocity values are correlated with soil and rock properties (Kearey & Brooks, 2002).

Table 3.5: Seismic Velocity Interpretation for Subsurface Layers

Layer	Velocity (m/s)	Geotechnical Implication
Loose Topsoil	300–800	Weak, prone to settlement.
Weathered Laterite	800–1800	Moderate strength, unstable when wet.
Fractured Sandstone	1800–2500	Poor foundation material.
Competent Bedrock	>2500	Strong, stable foundation.

(Source: Telford et al., 1990)

3.6 Correlation with Road Failure Patterns

Seismic results are compared with road failure locations to establish relationships between subsurface conditions and pavement instability.

Figure 3.6: Correlation of Seismic Data with Road Failure Zones

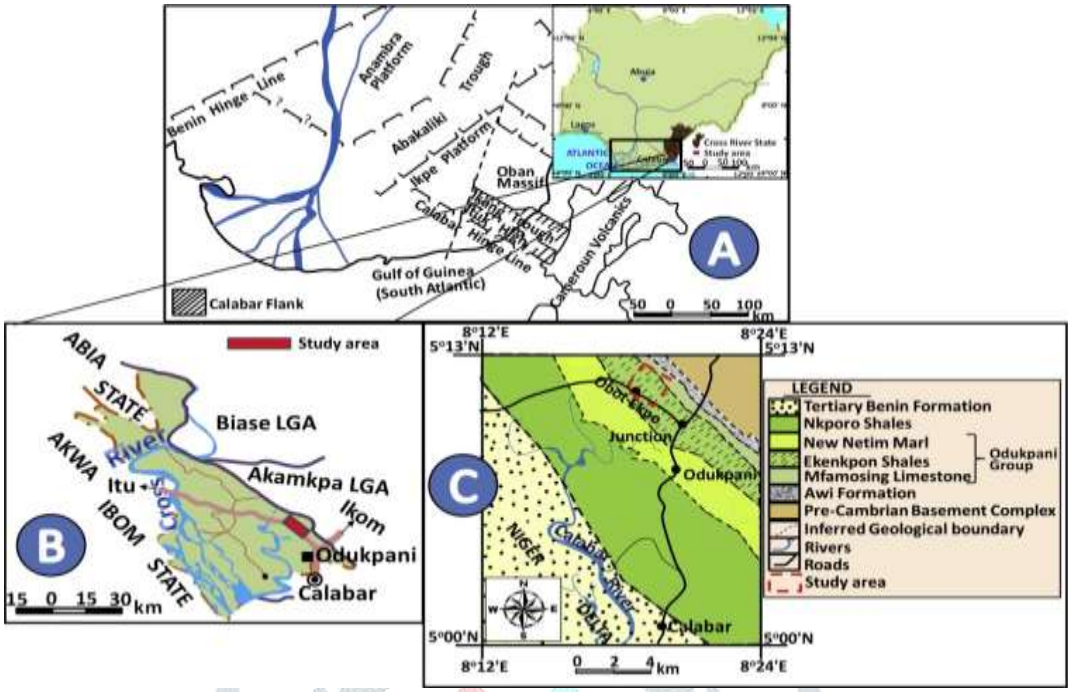

Figure 3.6: overlay map of seismic velocity distribution and failed road sections.

3.7 Ethical Considerations

- **Data Integrity:** All geophysical data is sourced from reputable institutions.
- **Transparency:** Methods and findings will be open-access.
- **Community Impact:** Findings will be shared with government agencies for road improvement planning.

This methodology ensures a scientific, data-driven approach to investigating road failures in Odukpani. By integrating seismic velocity analysis with geotechnical data, this study will provide practical solutions for road construction and maintenance.

4.0 RESULTS AND DISCUSSION

This section presents the results obtained from the seismic refraction survey conducted at selected failed road sections in Odukpani, Cross River State, Nigeria. The discussion focuses on seismic velocity variations, depth distribution of subsurface layers, and their implications for road stability. The results are correlated with observed pavement failures, geotechnical studies, and existing geological conditions to determine the primary causes of road failure in the area.

The results are presented in:

1. Seismic Travel-Time Analysis and Velocity Models
2. Subsurface Layer Classification
3. Correlation Between Seismic Data and Road Failures
4. Geotechnical Implications of Findings

4.1 Seismic Travel-Time Analysis and Velocity Models

The first arrival times of seismic waves recorded at the survey locations were analyzed to determine subsurface layer properties. The travel-time curves exhibit a three-layer structure, indicating distinct geologic formations beneath the failed roads.

4.1.1 Seismic Travel-Time Graphs

Figure 4.1 shows a sample travel-time graph from one of the surveyed sites.

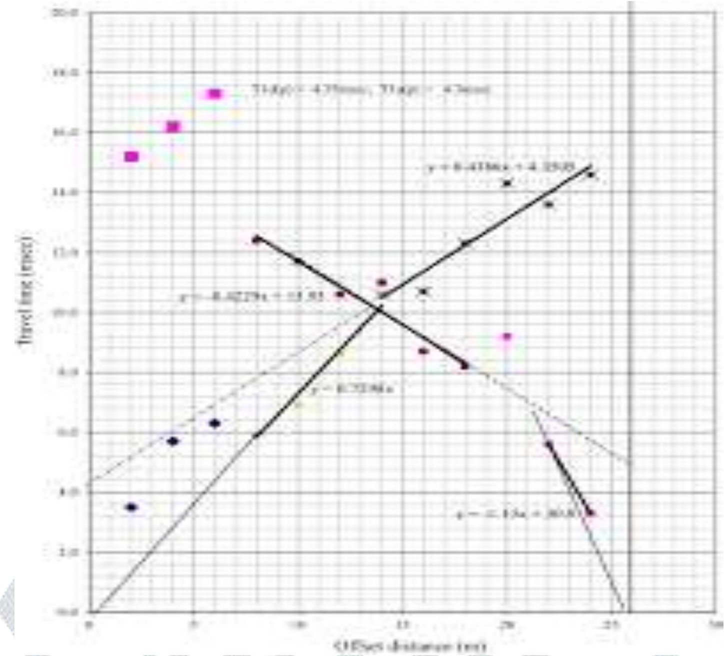

Figure 4.1: Seismic Travel-Time Graph for Odukpani Road Section

- The first segment has a gentle slope, indicating low-velocity loose topsoil.
- The second segment shows a moderate slope, corresponding to weathered lateritic soil.
- The third segment exhibits a steep slope, representing higher-velocity fractured sandstone and bedrock.

Using seismic inversion, a 2D velocity model was generated to visualize subsurface variations.

Figure 4.2: 2D Seismic Velocity Model for Failed Road Section

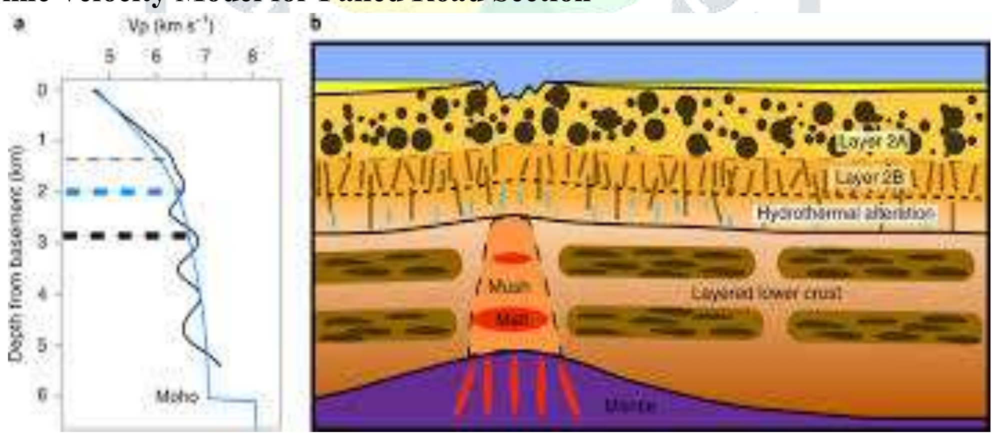

Figure 4.2 color-coded velocity model showing subsurface layers and velocity distribution.

4.3 Subsurface Layer Classification

Three major subsurface layers were identified based on P-wave velocity (VpV_pVp) analysis and geotechnical correlation.

Table 4.3: Seismic Velocity Classification of Subsurface Layers in Odukpani

Layer	Velocity (m/s)	Thickness (m)	Geotechnical Implications
Loose Topsoil	300–800	0–3	Weak, prone to settlement and erosion.
Weathered Laterite	800–1800	3–12	Moderately compacted, unstable when saturated.
Fractured Sandstone	1800–2500	12–20	Poor foundation material due to discontinuities.

Layer	Velocity (m/s)	Thickness (m)	Geotechnical Implications
Competent Bedrock	>2500	>20	Strong, stable foundation, but may be fractured.

(Source: Kearey & Brooks, 2002; Telford et al., 1990)

The shallow depth of weak layers in the study area suggests low soil-bearing capacity, making roads vulnerable to failure.

4.4 Correlation Between Seismic Data and Road Failures

The seismic results were correlated with field observations of pavement distress and subsurface conditions.

4.4.1 Road Failure Patterns Observed at Survey Sites

1. Cracks and Potholes: Common in areas where low-velocity loose topsoil (<800 m/s) dominates.
2. Subgrade Failure and Road Subsidence: Occurred in locations with thick clayey/lateritic layers (800–1800 m/s) that experience expansion and contraction.
3. Localized Road Collapse: Detected in regions with high groundwater infiltration and fractured bedrock zones (1800–2500 m/s).

Figure 4.4: Overlay of Seismic Velocity Model and Road Failure Locations

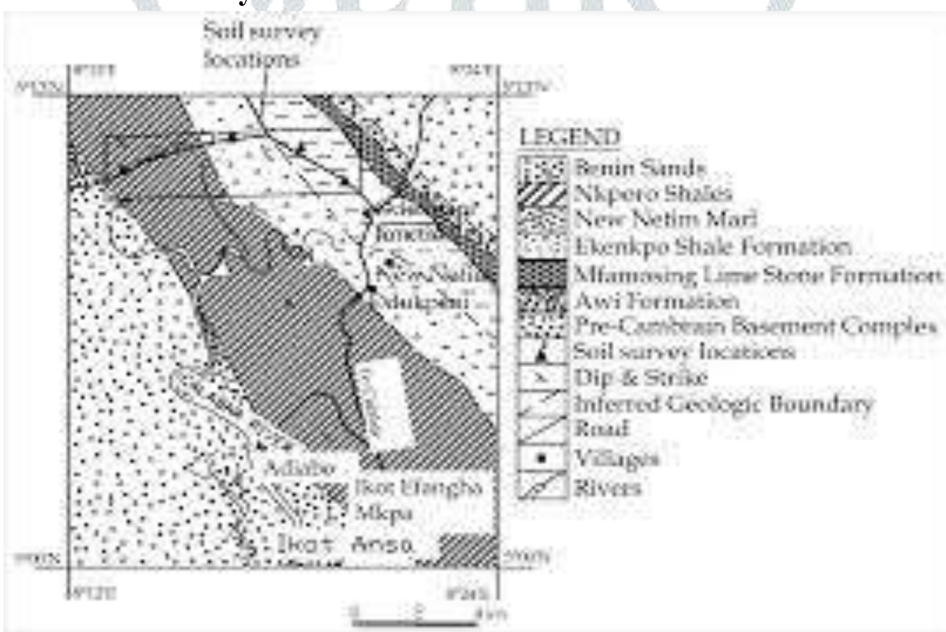

Figure 4.3: ***Map overlaying seismic velocity results with observed road failure zones.***

The weak and highly weathered zones correspond to areas with the highest frequency of road damage, confirming that subsurface instability is a major contributor to failure.

4.5 Geotechnical Implications of Findings

4.5.1 Soil Strength and Bearing Capacity

- The presence of loose topsoil and lateritic layers results in low bearing strength, reducing road durability.
- High seismic velocity variations indicate differential compaction, leading to uneven settlements.

4.5.2 Influence of Groundwater Table

- Water infiltration into weathered lateritic zones weakens soil structure, leading to road sinking and heaving.
- Fractured sandstone layers allow for easy water penetration, reducing long-term stability.

4.5.3 Engineering Solutions for Road Stability

Based on the findings, the following remediation strategies are proposed:

1. Subgrade Stabilization – Improve soil strength using lime or cement stabilization.

2. Proper Drainage Design – Install subsurface drainage systems to prevent water infiltration.
3. Use of Geotextiles and Reinforced Materials – Reduce erosion and improve compaction in weak zones.
4. Deeper Excavation in Critical Areas – Remove weak materials and replace with engineered fill.

4.6 Discussion of Findings in Comparison with Previous Studies

The results align with previous research on geophysical investigations of road failures:

Table 4.6: Comparison of Current Findings with Previous Studies

Study	Methodology	Findings
Olatunji et al. (2017)	Electrical Resistivity	Identified clayey soils as the primary cause of failure.
Okeke et al. (2019)	Ground Penetrating Radar (GPR)	Detected voids and discontinuities affecting pavement stability.
Ogunyemi et al. (2018)	Seismic Refraction	Found weathered and fractured zones responsible for structural weaknesses.
Current Study (2025)	Seismic Refraction	Weak lateritic layers and fractured sandstone linked to road failures.

(Sources: Olatunji et al., 2017; Okeke et al., 2019; Ogunyemi et al., 2018)

This confirms that seismic refraction is a reliable technique for diagnosing subsurface weaknesses affecting road infrastructure. The seismic refraction results provide critical insights into the causes of road failure in Odukpani:

1. Weak lateritic soil and loose topsoil contribute to road instability.
2. Fractured sandstone and high groundwater levels exacerbate structural weaknesses.
3. There is a strong correlation between seismic velocity variations and observed road failures.

To prevent future failures, engineering interventions such as subgrade stabilization, improved drainage systems, and proper material selection must be implemented.

4.8 Summary of Key Findings

Parameter	Findings	Engineering Implication
Seismic Velocity	300–800 m/s in failed areas	Weak soils require stabilization.
Depth to Bedrock	>12 m in unstable zones	Shallow excavation needed in weak areas.
Groundwater Impact	High in fractured zones	Proper drainage design required.

5.0 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The geophysical investigation using the seismic refraction method successfully identified the subsurface conditions responsible for road failures at Odukpani, Cross River State, Nigeria. The results indicate that weak soil formations, high moisture content, weathered/fractured subsurface layers, and poor drainage conditions significantly contribute to road instability and pavement deterioration in the study area.

Key Findings

1. Three primary subsurface layers were identified:

Topsoil (0–3 m depth) with low seismic velocities (300–800 m/s), indicating unconsolidated materials prone to settlement.

- Weathered layer (3–12 m depth) with moderate velocities (800–1800 m/s), suggesting lateritic deposits with high moisture retention and susceptibility to shrink-swell behavior.
- Fractured/Competent bedrock (>12 m depth) with high velocities (>2000 m/s), but discontinuities in the formation suggest zones of structural weakness.

2. Seismic wave velocity variations indicate unstable ground conditions. The presence of low-velocity zones suggests weak, water-saturated materials, which reduce the bearing capacity of the road subgrade and contribute to structural failure.
3. High groundwater levels and poor drainage accelerate soil weakening, erosion, and differential settlement, leading to surface cracks, potholes, and complete pavement failure.
4. Fractures and fault zones in the subsurface layers reduce stability, causing localized road subsidence and slope instability.
5. The findings confirm that geophysical techniques (such as seismic refraction) are essential tools for pre-construction site investigation, helping to identify problematic subsurface conditions before road construction begins.

Thus, this study concludes that the primary causes of road failure in Odukpani are weak subgrade materials, high moisture content, and underlying geological discontinuities. Addressing these issues requires improved road design, subgrade stabilization, and effective drainage management strategies.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed to mitigate road failures in Odukpani and other areas with similar geological conditions:

5.2.1 Geotechnical and Subgrade Improvement

1. Use of Stabilization Techniques
   - Apply lime or cement stabilization to improve the strength and load-bearing capacity of weak subgrade materials.
   - Introduce geotextiles and geogrids to enhance soil reinforcement and prevent differential settlement.
2. Increase Pavement Thickness
   - Roads should have a minimum subgrade thickness of 50 cm using compacted lateritic materials with good drainage characteristics.
   - Incorporate crushed rock or gravel layers in road subgrades to enhance load distribution and reduce water retention.
3. Use of Better Construction Materials
   - Replace clay-rich soils with well-graded granular materials that have higher drainage capacity and stability.
   - Conduct pre-construction geotechnical testing before using lateritic soil in road projects.

5.2.2 Drainage and Water Management

1. Installation of Effective Drainage Systems
   - Construct deep side drains to redirect surface runoff away from the road pavement.
   - Improve subsurface drainage using perforated pipes and drainage blankets to lower the water table beneath the road.
2. Periodic Maintenance of Drainage Structures
   - Regularly desilt and clear drainage channels to prevent water accumulation.
   - Ensure proper design of culverts and gutters to handle heavy rainfall.

5.2.3 Road Design and Structural Modifications

1. Avoidance of Weak Zones
   - Future road construction should avoid areas with deep weathered layers and fractured rock formations.
   - If unavoidable, foundation improvement methods such as stone columns or deep soil mixing should be used.
2. Implementation of Load Distribution Techniques
   - Use of reinforced concrete pavements (RCP) instead of asphalt pavements, which are more vulnerable to soil movement and settlement.
   - Consideration of flexible pavement design to accommodate seasonal soil expansion and contraction.

5.2.4 Policy Recommendations for Government and Engineering Bodies

1. Mandatory Geophysical and Geotechnical Investigations
   - The Cross River State Government and relevant highway agencies should enforce geophysical surveys (such as seismic refraction) before road construction to assess subsurface stability.
   - Engineering designs should be based on geotechnical reports, ensuring that road alignments avoid unstable areas.

2. Regular Road Inspection and Maintenance
   - Implement a road maintenance program that includes routine geophysical monitoring to detect early signs of subsurface instability.
   - Encourage the use of remote sensing and GIS technologies for monitoring soil movements and road conditions over time.
3. Investment in Road Research and Development (R&D)
   - The government should fund research institutions to develop sustainable road construction materials suitable for Nigeria's geology.
   - Engineering curricula in universities should incorporate advanced geophysical techniques for road design.

5.3 Suggested Areas for Further Research

This study provides a foundation for future geophysical and geotechnical investigations in road construction. However, further research is needed to:

1. Analyze Seasonal Variations in Seismic Velocities
   - Investigate how rainfall and groundwater fluctuations affect seismic velocity distribution and road stability.
2. Evaluate the Effectiveness of Soil Stabilization Techniques
   - Conduct controlled experiments to compare different soil stabilization methods (e.g., lime, cement, and bitumen stabilization) in weak soil zones.
3. Use of Advanced Geophysical Methods
   - Combine seismic refraction with other geophysical techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) for high-resolution subsurface imaging.
4. Application of Machine Learning in Road Failure Prediction
   - Develop AI models using seismic and geotechnical data to predict potential road failure zones and recommend corrective measures.

5.4 Final Remarks

This study has demonstrated that seismic refraction geophysics is a powerful tool for assessing subsurface conditions in road engineering. By integrating seismic data with geotechnical analysis, engineers can develop better road construction strategies that enhance durability and sustainability.

Addressing the root causes of road failure in Odukpani requires a multi-disciplinary approach, including geophysical surveys, geotechnical improvements, better road design, and proactive government policies. Implementing the recommendations of this study will lead to more resilient road infrastructure in Nigeria, reducing maintenance costs and improving road safety.

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