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Research Article

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Investigating the Potential for Brittle Failure of Subsurface Formation for "Field XY" in Niger-Delta during Drilling Operation

Nubel Bariza[1], Okoro Emeka Emmanuel[1,2], Oscar I. O. Ogali[1], Ogbonna F. Joel[1,3]

[1]Department of Petroleum and Gas Engineering, University of Port Harcourt, Nigeria
[2]Centre for Petroleum Research and Training, University of Port Harcourt, Nigeria
[3]Africa Centre of Excellence in Oilfield Chemicals Research, University of Port Harcourt, Nigeria

Abstract Ensuring the structural stability of subsurface formations is of utmost importance during drilling activities, especially in geologically intricate areas like as the Niger Delta. This study assesses the vulnerability of formations in "Field XY," a prominent hydrocarbon-rich location in the Niger Delta, to brittle failure. We conducted a series of controlled laboratory stress-strain experiments to examine the mechanical properties of core samples taken from different stratigraphic periods. The reactions of the samples under axial loading yielded valuable information regarding their elastic and plastic characteristics, which is crucial for comprehending the zone of transition between brittleness and ductility. The analysis primarily examined the link between corrected deviatoric stress and axial strain. It specifically identified the stress points at which the maximum sustainable load could no longer be sustained, leading to collapse. The brittleness of the formation was assessed using liquidity and plasticity indices, which were generated from Atterberg limits experiments. The results showed a pattern in which samples with negative liquidity indices had a larger peak stress, supporting a greater likelihood of brittle failure. Furthermore, the presence of a post-peak stress reduction in specific samples indicates the existence of a crucial threshold at which sudden failure modes may be triggered. This study is important because it contributes to the assessment of drilling risk in "Field XY" by providing a predictive understanding of how formations behave under stress. The observed mechanical qualities are crucial for optimizing drilling tactics, reducing the hazards of wellbore instability, and improving operational safety. Furthermore, the research enhances our understanding of the geological characteristics of the Niger Delta, enabling us to make educated decisions while extracting its petroleum resources and effectively mitigating geohazards.

Keywords Brittle failure; Mechanical properties; Elastic and plastic characteristics; Collapse; Wellbore

1. Introduction

The term "brittle failure of subsurface formation" describes the abrupt and disastrous fracturing or rupture of rock or formation layers beneath the Earth's surface caused by the application of stress or pressure. This failure occurs when the underlying material achieves its maximum strength without undergoing considerable plastic deformation and cracks quickly [1]. Comprehending the possibility of brittle collapse in subsurface formations is essential in geology, geotechnical and drilling engineering to evaluate the stability of subsurface constructions, wellbores/ boreholes, mines, and natural geological formations [2]. The probability of brittle failure in subsurface formations can be influenced by factors such as the geological composition, stress distribution, pore pressure, and structural discontinuities. It is crucial to monitor and anticipate the likelihood of brittle failure in underground formations to guarantee the safety and soundness of infrastructure constructed on or in close proximity to these formations. Engineers and geologists employ a range of methods, including geophysical surveys, borehole logging, and laboratory testing, to analyze the mechanical characteristics of materials beneath the surface and determine the likelihood of brittle fracture [3]. Professionals can create resilient structures by comprehending and reducing the hazards linked to brittle failure and subsurface geological problems.

Rock failure criteria play a vital role in engineering applications, especially in the fields of geotechnical and rock mechanics. Comprehending and examining the in-situ strength and geomechanical properties of rocks are crucial for the discovery of hydrocarbons and minerals [4]. Due to the rising expenses associated with laboratory measurements, the utilization of machine learning in log-based prediction has become more prominent in the estimation of in situ rock properties. If it is not possible to obtain samples from deep hydrocarbon mining sites, logging data can be used to forecast rock physical and mechanical properties, as shown by Odunlami et al. [5]. These correlations are valuable assets for experts, scholars, and rock engineers engaged in many fields, such as rock failure analysis, geomechanics, drilling optimization, and formation evaluation. By utilizing these criteria, engineers can acquire knowledge about the behavior of rocks under various loading conditions, allowing them to create structures that are both secure and stable while making informed choices [6]. Rock failure criteria offer insights on the durability and steadfastness of rocks. Engineers can utilize these criteria to evaluate the likelihood of failure or deformation in rock slopes, tunnels, foundations, and other structures [7]. It aids in the development of more efficient support systems and guarantees the long-term durability of structures and wellbore stability. Through the comparison of stress conditions and failure criteria, engineers can assess whether stress levels surpass the rock's strength, so highlighting potential hazards of instability or failure and enabling the execution of essential safety measures.

Ensuring the stability of the wellbore is of utmost importance in the process of drilling and producing hydrocarbons [8]. The process entails manipulating the geometry of the hole, averting collapse, and overseeing many aspects like rock strength, earth tensions, fluid pressure, pore pressure, and mud structure. Wellbore instabilities can result in the reduction of hole size, growth of the hole, loss of drilling fluid, collapse of the hole, influx of solid particles, and failures of equipment [9]. These problems can be resolved by diverting or discontinuing the use of wells. In the elastic analysis, a criterion based on peak strength is utilized, whereas in the elastoplastic analysis, a yield criterion that corresponds to the peak strength is employed. Wellbore instability can result in a range of failures, each having distinct characteristics and consequences. The failures can be categorized into many forms, such as wide breakout (shear failure), high angle echelon (shear failure), shallow breakout (shear failure), and fracture (tension failure) [10-11].

2. Materials and Methods

The coring operation were performed in Field XY by the OML operators and the samples were delivered to the laboratory for testing. The methodological approach is specifically designed to get a thorough comprehension of the mechanical behavior beneath the surface, enabling efficient planning and reduction of risks in drilling operations inside the intricate geological structure of the Niger Delta within the scope of these study.

The testing was conducted in accordance with established test protocols, specifically:

i. ASTM stands for the American Society for Testing and Materials, specifically referring to the 2005 Edition.
ii. BS 1377 refers to the British Standard from 1990.

ASTM refers to the American Society for Testing and Materials, specifically the 2005 Edition. It is used in the context of the Unconsolidated Undrained Triaxial Test. ASTM is responsible for creating and releasing optional agreement-based technical standards for various materials, goods, systems, and services. These standards have a global application in various industries to guarantee uniformity, safety, and excellence. ASTM standards are commonly used in various applications. Experimental evaluation of construction materials such as concrete, steel, formation core samples and asphalt.

BS 1377, also known as the British Standard, is a set of guidelines specifically designed for testing soils in the field of civil engineering. This standard is commonly employed in the United Kingdom and other nations that adhere to British standards. The tests outlined in BS 1377 are employed to ascertain a range of soil characteristics, including:

i. Moisture content

ii. Particle size distribution
iii. Plasticity
iv. Compaction characteristics
v. Shear strength
vi. Consolidation properties

Shear strength refers to the ability of a material to resist forces that cause it to slide or deform along a plane parallel to its surface. The design and construction of structures, wellbores/ boreholes, and other geotechnical engineering projects rely on these crucial soil qualities.Geotechnical and drilling engineers, soil testing facilities, and construction businesses rely on BS 1377 to provide uniform and precise soil testing.

2.1 Geology of the Study Area

The geology of Rivers state is situated in the Nigerian tertiary-recent coastal plain of the Eastern Niger Delta formation. The surface geology of the area consists of recent fluvial-deltaic sediments that have been mostly transported by distributaries of the Niger River, as well as other rivers like Andoni, Bonny, Imo, and New Calabar. The overburden materials, known as regolith, consist of clays, peats, silts, sands, and gravel stones. These materials can have a thickness ranging from the existing ground surface to 30.0m, and in certain cases, they can extend to hundreds of meters. The depositional sequence exhibits a substantial accumulation of continental sandstones that are situated above a succession of sandstone and clay layers with a marginal marine origin. Eventually, these layers transition into thick marine clays. In this region, sand is the most abundant type of rock, making up the majority of the soil. Mud is present in the brackish waters of the river areas. Peat is found in bogs and shallow pits and contains various vegetation and animal fossils. The subsurface rock consists of gravels and pebble stones, which are located at the bottom of the river channels. The topography of the area can be classified into three primary categories: freshwater areas, mangrove swamps, and coastal sand ridges zones. Figure 1 is the Geological sketch map of Nigeria, illustrating the primary geological components. The basement, younger granites, and sedimentary basins are shown with a red dot to indicate the location of soil research [12].

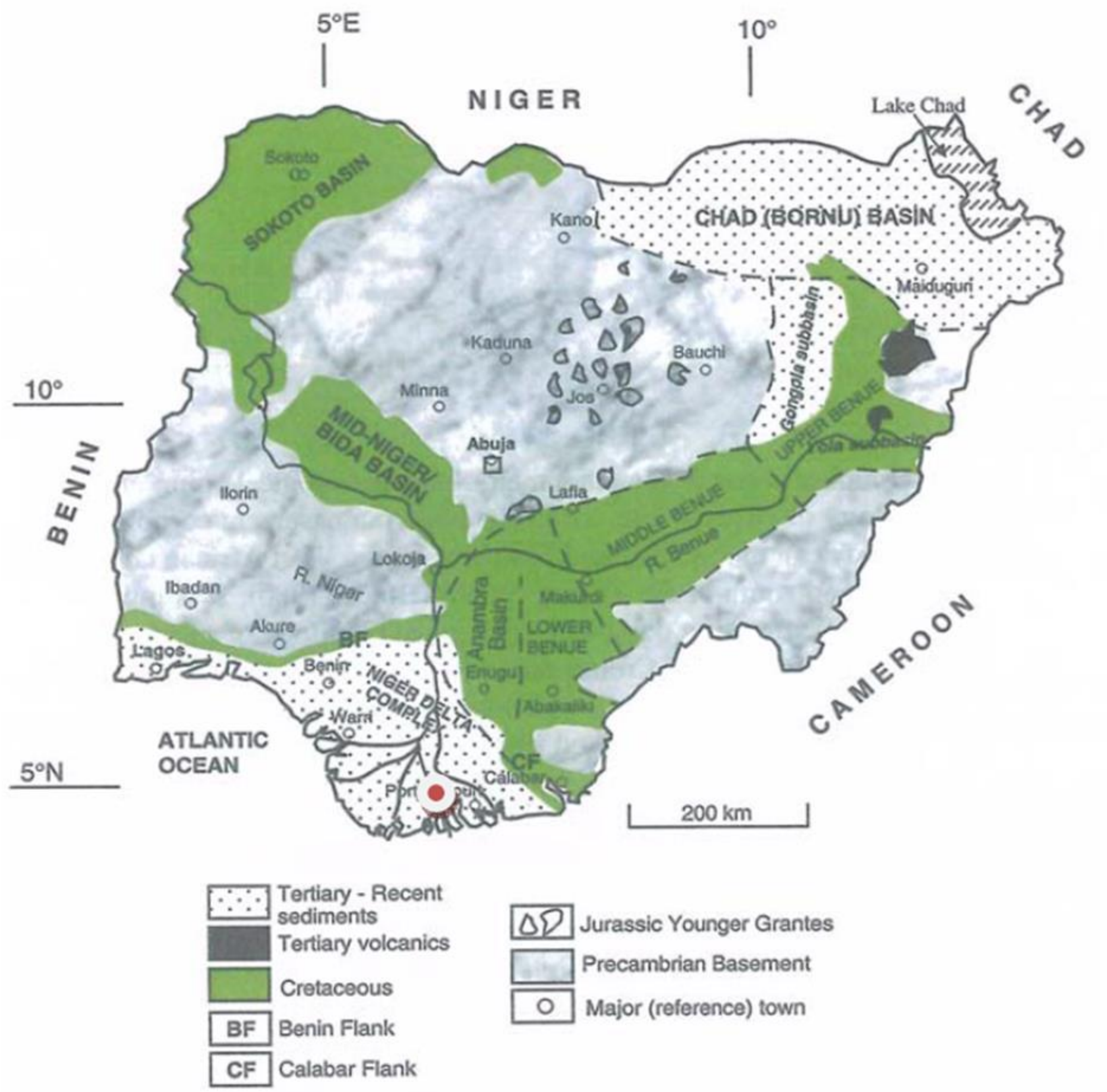

Figure 1: Geological Sketch Map showing Major Geological Components in Nigeria [12].

2.2 Materials

The scope of this study comprises of two (2) wells and their Test depth ranges from core penetration operations.

Core Samples: Extracted from various stratigraphic layers within "Field XY" at predetermined depths, ranging from shallow sediments to deeper, more consolidated formations.

High-precision Drilling Equipment: To obtain undisturbed core samples with minimal alteration of the in-situ stress states.

Triaxial Testing Apparatus: Equipped with sensors to measure axial and radial stresses, axial strains, pore pressures, and temperature during testing.

Atterberg Limits Testing Set: Including tools for liquid limit, plastic limit, and shrinkage limit determinations.

2.3 Methods

Core Sample Collection: Using the high-precision drilling equipment, collect core samples ensuring minimal disturbance. Catalog and store the samples under controlled conditions to preserve their native state.

Petrographic Analysis: Perform a detailed mineralogical and textural study of the core samples to identify the composition and fabric that may influence the mechanical behavior of the formations.

Atterberg Limits Tests: Determine the liquid, plastic, and shrinkage limits to establish the plasticity index and liquidity index for each sample, which are indicative of the material's ductility and potential for brittle behavior.
Triaxial Compression Tests: Subject the core samples to controlled triaxial compression tests, simulating in-situ pressures and temperatures. Measure and record the deviatoric stress, axial strain, and any pore pressure changes throughout the test to capture the material's response up to the point of failure.
Validation: Cross-validate laboratory findings with field data on drilling performance and wellbore stability incidents, to ensure the reliability of the predictive models for brittle failure.
Laboratory tests performed on Sample ID 01 till 15:

- Determine the Moisture Content MC in [%],
- Determine the Moisture Density ρw in [g/cm³],
- Determine the Specific Gravity ρg in [g/cm³],
- Determine the Atterberg Limits – Liquid Limit WL in [%], Plastic Limit WP in [%], Plasticity
- Stress-Strain relationship

3. Results and Discussion

In this section, the experimental results and other parameters deduced are presented as Figure and Table.

3.1 Stress-Strain Relationship

A comprehensive comprehension of the stress-strain correlation of formations is crucial for ensuring secure and effective engineering designs. This understanding enables the anticipation of formation behavior in diverse operating scenarios during drilling operations. Figure 2 shows the stress-strain correlation of Field XY for two difference sampling depth ranges (795.0 – 874.5 m and 2098.8 – 2178.3 m).

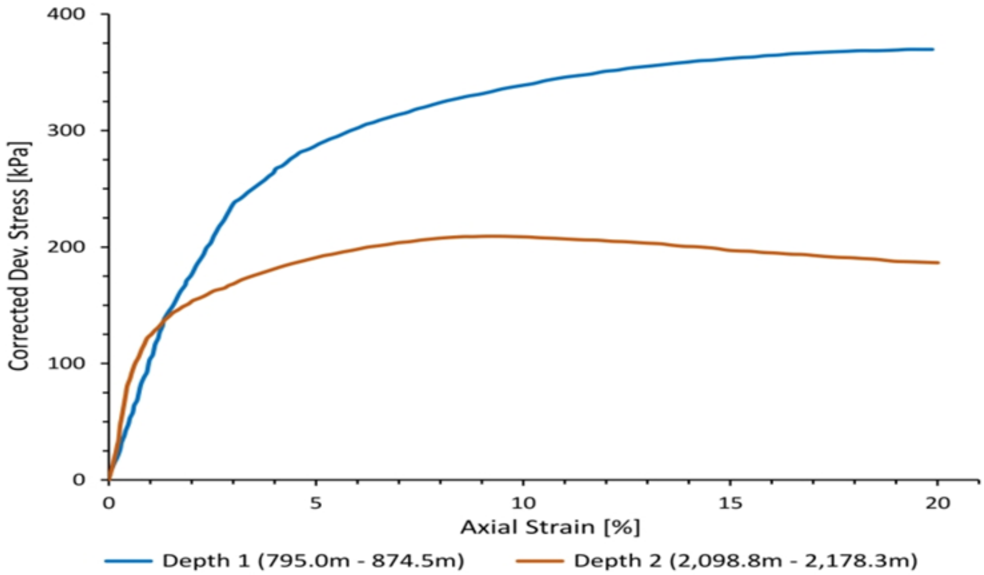

Figure 2: Plots of Stress versus Strain for two depths in a well in Field XY.

Figure 2 shows that the first depth sample (Depth Sample 1) exhibits a steep, linear section, which suggests that the material behaves elastically, deforming in accordance to the applied stress. The value is steadily increasing, but the rate of increase is slowing down, indicating a progressive shift from elastic to plastic deformation. The absence of a peak or decreasing stress in the curve suggests that the sample has not yet achieved its maximum strength or failure point, even at axial strains of up to 20%. The observed behavior indicates that the sample is ductile, meaning it can undergo significant deformations without breaking.
The initial slope of Depth Sample 2 is less steep than that of Depth Sample 1, suggesting a lower modulus of elasticity or initial stiffness. Depth Sample 2 exhibits a wide peak, indicating that the material has reached its highest level of stress and may be beginning to undergo strain softening or failure beyond this threshold. The stress does not exhibit a significant decrease immediately after reaching its highest point, indicating that the sample may retain some remaining strength even after surrendering.

Depth Sample 1 is stiffer initially and can sustain higher stress levels before yielding, showing ductile behavior with a high degree of plastic deformation possible without failure. Depth Sample 2 is less stiff and reaches its peak stress at a lower strain level, suggesting it may not be as strong or ductile as Depth 1. The data suggests variability in the mechanical properties of the samples, which could be due to differences in the soil composition, structure, moisture content, or other factors at the collection depths.

The stress-strain relationship of a formation characterizes how the formation material deforms under applied stress. The observed differences in the stress-strain relationships of Depth Sample 1 and Depth Sample 2 indicate distinct mechanical behaviors that are pivotal for understanding subsurface formations' response to external loads. Depth Sample 1's higher stiffness and ductility, as indicated by its ability to sustain higher stress levels before yielding, align with characteristics often attributed to formations with lower porosity, higher compaction, or a more cemented structure. This behavior is akin to findings by Santamarina et al. [13], who noted that the mechanical properties of geological materials are significantly influenced by their microstructure and composition, which directly affect their stiffness and strength.

Depth Sample 2, exhibiting peak stress at a lower strain level, suggests a less compact structure, possibly with higher porosity or a higher degree of unconsolidated materials, which typically show lower strength and stiffness. This is supported by the work of Viggiani and Atkinson [14], who found that softer soils with higher moisture content tend to exhibit lower stiffness and strength, impacting their ability to undergo plastic deformation without failing.The variability in mechanical properties between the two depth samples underscores the heterogeneity of subsurface formations. Such variability could indeed be attributed to differences in soil composition, as well as the degree of saturation, as suggested by Oh and Vanapalli [15]. The presence of water within the pore spaces of soil can reduce effective stress, thereby altering the soil's stiffness and strength characteristics.

Moreover, Terzaghi's effective stress principle elucidates how variations in moisture content can influence a soil's mechanical response. Effective stress, the difference between total stress and pore water pressure, is a critical factor in determining soil behavior under load. According to Suprunenko and Ghayoomi [16], changes in moisture content can significantly affect the effective stress, thereby influencing both the stiffness and peak stress of the soil. The findings from the simulated study contribute to a broader understanding of geomechanical behavior, offering insights into how different subsurface conditions affect the structural integrity of geological formations. This knowledge is essential for designing and drilling hydrocarbon wellbore.

3.2 Moisture Content and Atterberg Limits of the Samples

The Atterberg Limits are a basic measure of the critical water contents of a soil or formation: its shrinkage limit, plastic limit, and liquid limit. The limits in this study are a collection of several parameters, including Liquid Limit (wL) in [%]; Plastic Limit (wP) in [%]; Plasticity Index (IP) in [%]; Consistency Index (IC) in [-]; Liquid Index (IL) in [-]. These parameters are used to determine the classification of the formation. Table 1 presents geotechnical properties for two different depth ranges in Field XY, reflecting soil behavior which is vital for subsurface characterization and drilling operations. Depth 1 (795.0m – 874.5m) vs Depth 2 (2,098.8m – 2,178.3m):

Moisture Content:

Depth 1 has a slightly lower moisture content than Depth 2. This could imply that Depth 2's formation might be more susceptible to hydro-mechanical changes, the moisture content can significantly impact soil behavior [17]. The sample with a higher moisture content (Depth 2) is less stiff initially, indicated by the less steep initial slope. Both samples exhibit ductility, as shown by their capacity to undergo significant plastic deformation. The absence of a failure point in both samples within the tested strain range suggests that they can endure substantial deformation without failing.

Table 1: Characteristics of two intermediate casing depths for a well in Field XY.

	Depth 1 (795.0m – 874.5m)	**Depth 2 (2,098.8m – 2,178.3m)**
Moisture Content [%]	17.6	19.0
Moisture Density [g/cm^3]	1.86	1.89
Specific Gravity [-]	2.653	2.662
Liquid Limit [%]	47.3	46.0

Plastic Limit [%]	34.0	31.0
Plasticity Index [%]	13.3	15.0
Consistency Index [-]	2.2	1.8
Liquid Index [-]	-1.2	-0.8

Moisture Density:
The moisture density is slightly higher in Depth 2, which suggests that the material could be more compact or contain heavier particles. Bishop and Henkel [17] explained that higher moisture density can enhance the load-bearing capacity of soils. The sample with a slightly higher moisture density (Depth Sample 2) shows a less stiff behavior but similar ductility compared to the one with a lower moisture density (Depth Sample 1).

Specific Gravity:
Depth 2 has a slightly higher specific gravity, indicating denser mineral composition. As per McCarthy et al. [18], specific gravity reflects the mineralogical composition of the soil which can influence the overall stiffness and strength. The sample with a slightly higher specific gravity (Depth Sample 2) shows a less stiff response than the one with a lower specific gravity (Depth Sample 1).

Liquid Limit and Plastic Limit:
The liquid limit is higher in Depth 1, but Depth 2 has a higher plastic limit, resulting in a greater plasticity index. This implies that Depth 2 may undergo more significant plastic deformation before becoming a liquid, which is essential for understanding the behavior of the soil under varying stress conditions [19].

Plasticity Index:
Depth 2 has a higher plasticity index, indicating a greater range between the liquid and plastic limits, which could result in a more plastic and potentially more compressible soil layer. Holtz and Kovacs [20] noted that a higher plasticity index typically correlates with increased soil compressibility and potential for shrink-swell behavior.

Consistency Index:
A higher consistency index at Depth 1 indicates a firmer soil consistency than Depth 2. As Terzaghi and Peck [21] highlighted, the consistency index can be used to predict the soil's behavior under loading, with higher values suggesting less likely deformation.

Liquid Index:
The negative liquid index values imply that both depths are in a semi-solid state, but Depth 1 is further from the liquid state compared to Depth 2. Casagrande [22] established the importance of the liquid index in assessing the soil's current state in relation to its liquid and plastic limits.

When comparing these results with the existing literature, it is evident that the mechanical behavior and stability of subsurface formations are highly contingent on their geotechnical properties. The variations between the depths suggest different handling and management strategies during drilling operations. For instance, the higher plasticity at Depth 2 might necessitate different mud formulations to prevent issues like differential sticking, a challenge in drilling operations as discussed by Lyons and Plisga [23]. Additionally, the soil's behavior under the imposed stresses from drilling activities will be different between these layers, potentially influencing the wellbore stability analyses. It is critical to integrate these geotechnical characteristics into models predicting subsurface behavior to mitigate risks associated with drilling in such formations.

4. Conclusion

In concluding the investigation into the potential for brittle failure of subsurface formations in "Field XY" in the Niger-Delta region during drilling operations, the study has meticulously evaluated various geomechanical and geotechnical parameters that influence the failure mechanisms. Depth-specific data have highlighted that moisture content, specific gravity, plasticity, and consistency indices significantly vary with depth, indicating heterogeneity in mechanical behavior across the studied strata.

The analysis reveals that formations at shallower depths (Depth 1) exhibit higher consistency indices, suggesting a more brittle nature with a propensity for sudden failure under stress, whereas deeper formations (Depth 2) show higher plasticity indices, indicating a more ductile response to deformation. The liquid and plastic limits corroborate these findings, indicating a critical moisture threshold where soil behavior transitions from plastic to liquid states, influencing drilling fluid interactions and wellbore stability.

The stress-strain relationships derived from the data portray a clear picture of the varying stiffness and strength at different depths, with shallower formations potentially offering more resistance to initial stress but posing a risk for brittle fracture if the yield point is surpassed. On the other hand, the deeper formations, while less stiff, may tolerate larger strains before failing, allowing for a more predictable and manageable response to drilling stresses.

The application of advanced simulation tools, incorporating the detailed soil mechanics profiles acquired, has provided valuable insights into the effective management of drilling parameters to mitigate the risk of brittle failure. Optimization of mud weight, careful monitoring of wellbore pressures, and strategic casing placement have been recommended based on the analyses to ensure the mechanical integrity of the wellbore throughout the drilling operation.

Overall, the study emphasizes the need for a comprehensive understanding of subsurface mechanical properties, which are paramount in designing a robust drilling strategy that can prevent catastrophic brittle failure. The findings of this investigation not only contribute to the safe and efficient exploitation of hydrocarbon resources in the Niger-Delta but also serve as a reference for similar geological settings where drilling-induced brittle failure presents a significant operational risk.

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