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Effect of Particle Size Distribution on Formation Failure During Drilling Operations: Niger Delta Field as a Case Study

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Abstract:

This study explores the interrelationship between particle size distribution (PSD) and stress-strain characteristics of subsurface formations to understand the potential for brittle failure during drilling operations in "Field XY" of the Niger-Delta. We conducted comprehensive sieve analysis to determine PSD and performed uniaxial compressive strength tests to elucidate the stress-strain behavior of rock samples collected at varying depths. The PSD results indicated a higher proportion of fine particles in shallower depths, while deeper samples presented a coarser grain structure. Correspondingly, stress-strain tests revealed a transition from ductile to brittle failure mechanisms with increased depth. A thorough examination of moisture content influence indicated that variations in mechanical properties were not solely attributed to moisture variations but also to intrinsic geomechanical characteristics influenced by PSD. The findings from this study contribute to the growing body of knowledge on drilling-induced formation damage and offer insights for optimizing drilling parameters to mitigate the risks of subsurface failure.

Keywords **—**Formation failure, Drilling operation, Particle size distribution, Subsurface, Stress-Strain

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I. INTRODUCTION

Drilling operations are a fundamental aspect of petroleum exploration and production. The process involves penetrating the earth's subsurface to access hydrocarbon reservoirs. One critical challenge in drilling is maintaining the stability of the wellbore to prevent formation failure [1]. Formation failure can manifest as borehole collapse, sand production, or loss of circulation, leading to operational delays, economic losses, potential safety concerns and wellbore instability.Ensuring wellbore stability is a paramount concern in the oil and gas industry, not only for the safety of drilling operations but also for the economic efficiency and success of hydrocarbon production [2]. The literature on wellbore stability is extensive and provides a wealth of evidence to support this statement.For example, Aadnoy and Belayneh[3] state that wellbore instability can account for 10-15% of the total drilling cost, a significant figure that emphasizes the economic impact of wellbore stability issues. These authors also note that instability-related problems are a leading cause of non-productive time during drilling operations.

Moreover, the work of Fjaer et al. [4] on petroleum-related rock mechanics points out that wellbore stability depends on the balance between the insitu stresses and the strength of the formation being drilled. If the stresses induced by drilling exceed the rock's strength, failure may occur, leading to borehole collapse, stuck pipe incidents, or lost circulation. These events pose direct risks to the safety of drilling personnel and equipment and can lead to environmental hazards such as uncontrolled releases of oil and gas.Zoback et al. [5] in their comprehensive study on wellbore stability demonstrate that understanding the state of stress in the Earth's crust is crucial for predicting wellbore stability. Their research underlines that wellbore instabilities are often the result of a complex interaction between rock properties, in situ stress, drilling trajectory, and the drilling fluids used.

Al-Ajmi and Zimmerman [6] further emphasize that the mechanical properties of the rock, such as its elastic moduli and strength, which are influenced by the rock’s particle size distribution and fabric, play a critical role in maintaining wellbore integrity. When rocks are subjected to stress changes due to drilling, their response can vary dramatically based on these properties, directly affecting wellbore stability.The significance of wellbore stability is also highlighted in the work of Bailey et al. [7], who examined the role of mud weight in maintaining wellbore stability. These studies and many others in the field illustrate the complexities of wellbore stability and the multifaceted approach required to manage it effectively. They provide empirical evidence and theoretical frameworks that underscore the importance of maintaining wellbore stability for the safety and economic viability of oil exploration and production.

The influence of particle size distribution (PSD) on the mechanical behavior of geological materials is well documented in geotechnical and petroleum engineering literature [8]. The PSD is a fundamental characteristic that affects several key properties of soil and rock formations, which in turn dictate their response to mechanical stresses during drilling and production activities.In the context of soil mechanics, Mitchell and Soga [9] detail how the PSD affects the engineering properties of soils. Fine-grained soils, such as clays, which have a larger surface area due to smaller particle sizes, can exhibit plastic behavior and are more susceptible to consolidation and shearing issues due to their ability to hold water. In contrast, coarse-grained soils, like sands and gravels, have larger particles that interlock and provide higher shear strength and lower compressibility, influencing the stability of the wellbore.Skempton[10] describes how the PSD impacts the pore structure and permeability of geological formations. Finer materials tend to have smaller pore throats, leading to lower permeability, which can affect the efficiency of fluid flow within a reservoir and complicate the extraction process. Conversely, coarser materials often present higher permeability, allowing for easier fluid transport.

Nguyen et al.[11] focus on the strength characteristics of rocks and soils, highlighting that the presence of fines can fill voids between larger particles, which can either increase the overall strength by improving particle interlock or decrease it by creating planes of weakness. The compaction behavior and the susceptibility to undergo stress-induced grain crushing also relate directly to the PSD, as shown by Wang et al. [12], with finer grains often leading to higher compaction potential and a higher likelihood of mechanical alteration under load.Additionally, Ghassemi et al.[13] provide insights into failure mechanisms associated with different PSDs. For instance, liquefaction potential, which is a concern during seismic events and drilling, is significantly influenced by the PSD. Fine sands are particularly susceptible to this phenomenon, whereas clays and coarse sands are generally more resistant.

In petroleum engineering, the work of Aadnoy [14] on the rock physics handbook illustrates how PSD affects the mechanical properties that are crucial for predicting and preventing formation failure. Rock stiffness, compressibility, and failure envelopes can all vary with changes in the PSD.Lastly, understanding the effects of PSD is also crucial for the design and optimization of drilling fluids, as pointed out by Caenn et al. (2011) [15]. The correct fluid must be selected to maintain wellbore stability depending on whether the formation is fine or coarse-grained.Overall, the literature firmly establishes that PSD is a key determinant in the mechanical behavior of subsurface formations, affecting pore structure, permeability, and strength. This knowledge is integral for developing strategies to predict and mitigate formation failure, ensuring the safety and efficiency of drilling operations.The objective of this Study is to examine the effects of PSD on the mechanical stability of subsurface formations during drilling operations. A variety of studies have highlighted the importance of PSD in the context of geotechnical engineering and wellbore stability. For example, Santarelli et al.[16] demonstrated the impact of grain size on sediment compressibility and shear strength. However, a gap remains in the direct application of these principles to real-time drilling operations, particularly in the challenging environments of the Niger-Delta.

II. METHODOLOGY

Geological Sample Preparation

In the context of subsurface formations, particle size distribution (PSD) is a fundamental attribute that significantly impacts the mechanical behavior and stability of rock during drilling operations.

The Niger-Delta is characterized by complex geological formations with a high degree of heterogeneity due to its sedimentary nature, history of hydrocarbon generation, and accumulation processes. The variability in rock types and properties within this region can pose significant challenges during drilling, such as differential sticking, wellbore collapse, and lost circulation. Studies on the Niger-Delta have shown a comprehensive stratigraphic and sedimentological descriptions, highlight the need for careful sample preparation and testing to understand the behavior of these formations under stress.

Rock samples were prepared according to ASTM D4543-08, "Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances." The core samples were collected from the "Field XY" in the Niger-Delta, a formation known for its heterogeneity and drilling challenges.The preparation of rock core samples as cylindrical test specimens involves precise cutting and grinding to achieve smooth ends and uniform dimensions. This process is vital to ensure that the subsequent testing and analysis are not compromised by surface irregularities or shape inconsistencies, which can lead to stress concentrations and misleading test results. The ASTM standard ensures that samples prepared for testing are representative of the in-situ conditions.

The particle size distribution was determined using sieving methods as per ASTM D422-63, "Standard Test Method for Particle-Size Analysis of Soils.Sieving methods for determining PSD involve passing soil or crushed rock samples through a series of sieves with progressively smaller openings. The quantity of material retained on each sieve is weighed to determine the PSD. This method provides a granulometric distribution of the particles, which is a critical factor in the mechanical behavior of the rock. According to Mitchell et al. [9], PSD influences the shear strength, compressibility, and hydraulic conductivity of geologic materials. Understanding these influences is essential for predicting potential issues like sand production and formation damage during drilling.

In practice, these standardized methodologies allow for the systematic investigation of how variations in PSD could lead to different mechanical responses within the subsurface formations, potentially leading to brittle failure when subjected to the stresses of drilling operations. The literature suggests that fine-grained distributions may be more prone to plastic deformation and ductile flow, while coarser distributions may exhibit brittle fracture patterns under stress. For example, studies by Santarelli et al. [16] have shown that the size and distribution of particles within a rock matrix can influence the pore structure and fracturing behavior under load.

Mechanical Testing

Mechanical testing of rock samples is fundamental to understanding their behavior under stress conditions similar to those encountered during drilling operations. Suite of tests that are designed to measure different strength parameters of the rock, which are critical for predicting and mitigating drilling-related formation failures are:

Uniaxial Compressive Strength (UCS): The UCS test is a basic measure of the mechanical strength of rock. It involves applying axial load to a cylindrical rock specimen until failure occurs. The UCS is a key parameter in rock engineering as it provides an estimate of the load a rock can withstand before failing. According to Bieniawski[17], UCS is directly related to various other mechanical properties of rocks and is often used in the design and analysis of geotechnical engineering projects. The ISRM (International Society for Rock Mechanics) suggests methods for UCS testing, which ensure standardization and repeatability across different studies.

Triaxial Shear Tests: These tests measure the strength and deformability of rock under controlled confining pressures, simulating the conditions deep within the Earth's crust where in-situ stresses are significant. The rock sample is placed in a pressure chamber where it is subjected to axial stress while being confined laterally. The results of triaxial tests, which include parameters such as the cohesion and internal friction angle of the rock, are vital for evaluating the stability of rock masses under load.

Haimson and Cornet [18] demonstrated the importance of triaxial tests in understanding the in-situ stress field of rock formations, which is critical for drilling and production from oil and gas reservoirs.

The specimens were extruded from the upper part of samples. The tested specimens had a diameter of 50 mm and a height of 100 mm. Initial cell pressure was 200 kPa. Consolidation tests were performed in ten stages. The specimens had a diameter of 50 mm and initial height of 20 mm. As Fairhurst and Hudson [19] advocate, the standardization of these tests is imperative for the comparison of rock mechanical properties and the assessment of rock behavior in response to drilling activities. These mechanical tests provide valuable insights into the rock's behavior under various loading conditions and are essential for drilling operations. They help in designing appropriate drilling strategies, selecting suitable drilling equipment, and predicting possible challenges such as wellbore stability issues, which can be corroborated with findings from the literature and empirical correlations from drilling history.

III. RESULTS AND DISCUSSION

All paragraphs must be indented. All paragraphs mTable 1 show the results of a sieve analysis, which is a test to determine the particle-size distribution (PSD) of formation rock samples for different depths in Field XY. The PSD result is for the depth range of 180.40 – 405.90 m (Depth Sample 1).

Table 1. Particle-Size Distribution for Formation Depth Sample 1

Weight of Sample	(g)	500	
Sieve Size (mm)	Retained on Sieve		Percent Passing Sieve (%)
	Weight (g)	Percent (g)	
19.000			
9.500			100.0
4.750	1.0	0.2	99.8
2.360	11.3	2.3	97.7
1.180	50.7	10.1	89.9
0.600	150.3	30.1	69.9
0.425	247.8	49.6	50.4
0.300	352.4	70.5	29.5
0.150	486.0	97.2	2.8
0.075	494.2	98.8	1.2
<0.075	5.8		

The total weight of the sample subjected to sieving, in this case, 500 grams.Sieve Size is the mesh size of the sieves used to sort the particles by size. The Retained-on Sieve Weight is the weight of the sample retained by each sieve.Percent Retained on Sieve is the percentage of the total sample weight that was retained on each sieve.Percent Passing Sieve is the cumulative percentage of the sample that has passed through each sieve (or is finer than the sieve size). Table 1 shows that most of the material is finer than 0.6 mm, as indicated by the 69.9% passing at this sieve size.The material is very fine overall, with a significant portion (over 98%) finer than 0.075 mm.

In literature concerning subsurface formation failure during drilling operations, PSD is a crucial factor [20]. A finer-grained distribution can indicate a higher potential for issues like drilling fluid invasion, which can cause borehole instability and can lead to issues such as pipe sticking, tight hole conditions, or even borehole collapse. This is because fine particles, such as clays, can swell or disperse when in contact with drilling fluids, especially if the fluid is not properly conditioned to the formation's properties.Comparatively, a coarse-grained PSD can suggest better borehole stability but might also be more abrasive to the drilling equipment. It's also likely to be more permeable, which can be beneficial for fluid flow but might require more robust filtration systems to prevent the loss of drilling mud into the formation [21].

From Table 1, the high percentage of fine particles suggests that the formation might be prone to problems associated with fines, such as swelling or dispersion, which could contribute to borehole instability during drilling operations. These findings would likely suggest the need for a well-designed mud system with appropriate additives to stabilize the fine particles and prevent their interaction with the drilling fluid, thus mitigating the risk of formation failure.In terms of literature comparison, this PSD would be consistent with many fine-grained formations such as shales or clay-rich sandstones, which are often discussed in drilling literature as challenging environments due to the reasons mentioned above. The specific challenges and mitigation strategies related to such fine-grained distributions are well-documented, particularly in the context of the Niger Delta where certain formations are known for their reactive clays. It would be useful to compare this PSD to those found in literature from similar geological settings to better understand the potential challenges and design appropriate drilling and completion programs.

Table 2 show the PSD results is for the depth range of 405.90 – 676.5 m (Depth Sample 2). Table 2 shows the percentage by weight of particles that fall within various size ranges.

Table 2. Particle-Size Distribution for Formation Depth Sample 2

Weight of Sample	**(g)**	**500**	
Sieve Size (mm)	**Retained on Sieve**		**Percent Passing Sieve (%)**
	Weight (g)	**Percent (g)**	
19.000			
9.500			
4.750			100.0
2.360	0.8	0.2	99.8
1.180	18.0	3.6	96.4
0.600	115.9	23.2	76.8
0.425	181.7	36.3	63.7
0.300	242.1	48.4	51.6
0.150	324.5	64.9	35.1
0.075	338.5	67.7	32.3
<0.075	161.5		

The results show that a significant amount of the material (23.2%) is retained by the 0.6 mm sieve (Table 2).The majority of the sample is finer than 0.6 mm, given that 76.8% passes through this sieve.A substantial amount of very fine material is present, as evidenced by the 67.7% passing the 0.075 mm sieve.In the context of subsurface formation failure during drilling operations, Coarser materials tend to have better stability, higher permeability, and are less prone to issues like swelling, dispersion, or fines migration. However, the presence of fine particles can be problematic, as they can clog pores, reduce permeability, and react with drilling fluids, potentially leading to wellbore instability.

The literature often points out that formations with a high percentage of fine particles are susceptible to mechanical instability when drilled, especially if reactive clays are present.The literature also indicates that such formations may require specialized mud systems with appropriate filtration control to maintain borehole stability and prevent formation damage [22].The interaction between drilling fluids and fine-grained formations is a well-documented problem. Drilling fluids can induce swelling in clays or transport fine particles that may lead to pore-throat plugging.Overall, this PSD suggests a need for careful drilling fluid design and potential formation stabilization measures to manage the fine particles present. The formation may exhibit thixotropic behavior, where it becomes more fluid when agitated (during drilling) and then solidifies, potentially trapping drilling tools or causing differential sticking.

Table 3 show the PSD results is for the depth range of 676.5 – 1488.3 m (Depth Sample 3), and the percentage by weight of particles that fall within various size ranges.

Table 3. Particle-Size Distribution for Formation Depth Sample 3

Weight of Sample	(g)	500	
Sieve Size (mm)	Retained on Sieve		Percent Passing Sieve (%)
	Weight (g)	Percent (g)	
19.000			
9.500			
4.750			100.0
2.360	0.6	0.1	99.9
1.180	4.3	0.9	99.1
0.600	46.0	9.2	90.8
0.425	85.2	17.0	83.0
0.300	130.8	26.2	73.8
0.150	243.9	48.8	51.2
0.075	284.1	56.8	43.2
<0.075	215.9		

Table 3 shows that A larger proportion of the sample has particles finer than 0.425 mm, as 83% of the sample has passed through this sieve.There is a significant amount of very fine material; 56.8% of the sample passes the 0.075 mm sieve, indicating that more than half of the material consists of silt and clay-sized particles.In literature related to subsurface formation failure mechanisms during drilling operations, PSD is known to significantly influence the mechanical strength and behavior of geological formations [23]. In the case of Mechanical Stability,formations with a higher content of coarse particles are generally more mechanically stable and less prone to compaction or collapse. In contrast, fine-grained distributions, especially with high silt and clay content as seen in your data, tend to be more compressible and may present challenges for wellbore stability.

The presence of fine particles in significant quantities suggests a potential for reactive behavior with drilling fluids, particularly if clay minerals that swell or disperse upon contact with water-based fluids are present.Fine particles can also lead to formation damage by migrating and plugging the pore spaces, especially during drilling operations, reducing permeability and impairing production.

Literature indicates that formations with finer particles can be more susceptible to hydraulic fracturing due to lower permeability and higher pore pressure during drilling, which may also lead to differential sticking of the drill pipe.The high percentage of fines in the sample suggests that the formation may be prone to problems such as borehole instability, including sloughing and caving, especially if the fines are reactive clays [24].

Table 4 show the PSD results is for the depth range of 1488.3 – 2886.4 m (Depth Sample 4), and the percentage by weight of particles that fall within various size ranges.

Table 4. Particle-Size Distribution for Formation Depth Sample 4

Weight of Sample	(g)	500	
Sieve Size (mm)	Retained on Sieve		Percent Passing Sieve (%)
	Weight (g)	Percent (g)	
19.000			
9.500			
4.750			100.0
2.360	0.4	0.1	99.9
1.180	13.9	2.8	97.2
0.600	58.5	11.7	88.3
0.425	92.4	18.5	81.5
0.300	227.4	45.5	54.5
0.150	266.7	53.3	46.7
0.075	267.0	53.4	46.6
<0.075	233.0		

The results show that most of the sample has particle sizes smaller than 0.3 mm, as 54.5% of the material passes this sieve size (Table 4).A significant fine fraction is evident, as 53.4% of the material is finer than 0.075 mm, indicating a high content of silt and clay-sized particles.Formations with a high percentage of fine particles generally exhibit low permeability, which may influence fluid flow during drilling operations and lead to differential sticking or increased fluid pressures.

Finer materials often exhibit higher compaction potential, affecting the mechanical strength and deformation characteristics of the formation.Fine particles, especially clays, can react with drilling fluids, potentially leading to wellbore instability and formation damage.Literature suggests formations with high fines content are susceptible to wellbore collapse, especially in the presence of water-based drilling fluids, due to clay swelling or dispersion. High fines content can lead to formation damage during drilling due to particle migration and pore throat plugging, as indicated by Hale et al. [25].

Relationship between Particle-Size Distribution and Formation Failure

The relationship between Particle-Size Distribution (PSD) and stress-strain behavior of subsurface formations has significant implications for formation failure during drilling operations. The PSD affects the physical and mechanical properties of geological materials, which in turn influence their response to stress and the likelihood of failure under strain [26].

The PSD determines the pore size distribution and connectivity within a formation. Coarser grains typically result in larger and more interconnected pore spaces, leading to higher permeability. Conversely, fine-grained materials, like clays and silts, have smaller pore spaces and lower permeability, which can affect fluid flow and pressure buildup during drilling.The mechanical strength and stiffness of a formation are influenced by PSD. A well-graded mixture of particles can lead to a denser packing structure, which enhances the formation's ability to withstand higher stress. Uniformly graded or poorly graded sediments may not compact as well, resulting in weaker and less stiff formations.The PSD also impacts the compaction and consolidation behavior of a formation. Sediments with a range of particle sizes can achieve a more compact state with reduced compressibility, which is favorable for maintaining wellbore stability under applied stress [27].

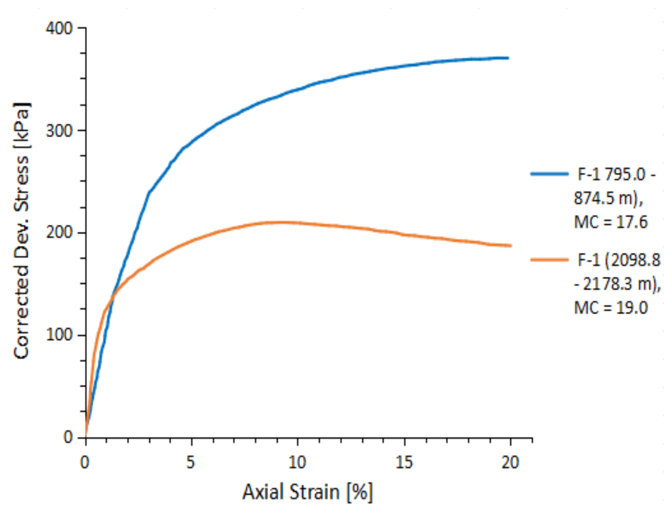

Fig. 1. Stress-Strain Relationship for different Moisture Contents

The sample from the shallower depth shows a more gradual increase in stress with strain and does not reach a clear peak within the range of strain shown in Figure 1. This suggests a more ductile material behavior, which could accommodate larger strains without failing.The sample from the greater depth exhibits a steeper initial slope (higher initial stiffness), reaches a peak stress value at a lower strain value, and then seems to begin to soften or yield, which is characteristic of more brittle behavior compared to the shallower sample. This trend was similar for other depths under consideration.

Literature suggests that fine-grained materials with a higher proportion of clay and silt can exhibit more ductile behavior due to their ability to realign and slide over each other under stress. In contrast, coarse-grained materials with larger sand and gravel particles are more prone to brittle failure, where cracks can propagate more easily through the larger grain contacts. The moisture content can also influence the behavior of the materials ([28],[29]). Higher moisture content can lead to lower friction angles and, therefore, lower shear strength. The sample from the greater depth has a higher moisture content and might be expected to be less brittle, yet its stress-strain behavior suggests otherwise. This could indicate a difference in PSD or mineralogical composition that counteracts the effect of moisture.

Comparing these results to the literature, Dusseault and Morgenstern [30] discuss how PSD impacts the deformation behavior of geologic materials under load. In their work, they show that materials with a broader range of particle sizes exhibit increased peak and residual strength. The more ductile response of the shallower sample could be due to a more uniform PSD or the presence of more clay-sized particles, as seen in studies by Louafi and Bahar [31].The stress-strain behavior observed in Figure 1 could be indicative of a transition from a more ductile to a more brittle failure mechanism with depth, which might be correlated with changes in PSD. The trends can be explained within the context of established geotechnical principles regarding the role of PSD in defining the mechanical behavior of soils and rocks.

IV. CONCLUSIONS

The analysis of subsurface formation samples from "Field XY" in the Niger-Delta provided significant insights into the mechanical behavior influenced by PSD and its implications on drilling operations. Shallower formations with finer particle distributions demonstrated higher ductility, accommodating greater deformation before failure. In contrast, formations at greater depths with a coarser PSD exhibited a more pronounced brittle behavior, with a lower threshold for deformation before reaching failure. These results align with established geotechnical principles and highlight the critical influence of PSD on the mechanical integrity of subsurface formations.

Therefore, understanding the PSD within a specific geological context is essential for anticipating and managing the risk of formation failure during drilling. The study underscores the importance of integrating granulometric data into geomechanical models to enhance the predictability of formation response to drilling stress and optimize drilling strategies for safe and efficient hydrocarbon extraction.

PSD fundamentally influences the mechanical properties and stress-strain behavior of subsurface formations, which are crucial to predicting and mitigating formation failure during drilling operations. Accurate assessment of PSD and integration into geomechanical models, as well as drilling fluid design, are essential practices to ensure successful and safe drilling operations, as extensively discussed in petroleum engineering literature.

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