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GeoMechanical Innovations in Mitigating Geohazard Risks and Submarine Landslides in Nigerian Deepwater Oilfields

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Abstract

Offshore oil operations of Nigeria especially in the technically complex Niger Delta play host to a variety of geohazard risks that has the potential to compromise the security, productivity and sustainability of oil production operations. These risks are mainly controlled by geo mechanical conditions such as rates of sedimentation, gas hydrate dissociation, tectonic activity and accumulation of pore pressure. These hazards promote the danger of submarine landslides resulting from sediment destabilisation and over pressurisation factors. Such an eventuality can lead to considerable destruction of subsea pipelines, wellbores, and oil platforms causing adverse effects on the environment, huge losses, and costly time overruns. This review discusses the geo mechanical factors that lead to slope instability in the Niger Delta region and stresses the need for sustainable risk management programs. Real-time monitoring devices like the ADCPs and inclinometer arrays can be used to produce early signals for slope failure thus the operators can intervene before the complete failure of the slope. Flexible pipeline and floating production system seaborne assets are useful in improving the existence of offshore facilities. Consequently, there are underlying concerns highlighted in the findings regarding the progressive need for effective geotechnical assessment, forecasting, risk management and management solutions for the Nigerian offshore oil environment in an attempt to promote operational safety and longevity. Future research should continue to improve the procedures for threat assessment and evolution of seismic risk maps, increase the application of real-time monitoring techniques, and improve the integration of engineering disciplines in better controlling the hazards in this region.

Keywords: Geohazard risks; Submarine landslides; Niger Delta Oilfields; Realtime Monitoring; Gas hydrate dissociation

Abbreviations: ADCPs: Acoustic Doppler Current Profilers; FPS: floating Production Systems; DP: Dynamic positioning; SCE: safety-critical equipment; ERT: Electrical Resistivity Tomography; FFP: Free-fall penetrometer; SBP: shear band propagation; CFD: Computational Fluid Dynamics; IoT: Internet of Things

Introduction

Crude oil exploration in Nigeria's offshore territory (Figure 1) has become a strategic component of the Nigerian economy because oil contributes greatly to its national revenue and export income. Nigeria being the largest oil-producing country in Africa, has always relied on crude oil export and offshore projects especially the deep and ultra-deep offshore environment that has assumed a central role in the country's economy. As it has been observed, offshore fields especially the Niger Delta basin are a key factor in sustaining Nigeria's oil production rates. These fields are responsible for producing more than half of the nation's crude oil while the traditional onshore fields have depleted and produce less oil because of the years of exploitation [1]. The area of the Niger Delta contains the largest number of shallow and deep water oil fields, making it one of the richest regions in terms of hydrocarbon resources [2]. Nigeria's offshore activities include exploration, production and development activities. Such activities have become more involving, especially with firms moving to newer and murkier waters as observed by [3]. The discovery of oil in deeper offshore regions has forced international oil companies to incorporate new technologies and associate with the Nigerian NNPC. All these are important in the bid to replace depleting onshore reserves and to ensure Nigeria continue to play a strategic role in the global energy market [4]. Deepwater projects in Bonga, Agbami, and Egina fields have also transformed the nation's oil industry by globally positioning the industry [5].

In addition, Nigeria offshore is marked by the application of rather complex subsea technologies, which help the firms get access to previously untapped ultra-deep fields with water depths exceeding 3,000 meters [1]. This shift is driven by two key factors: the growth of energy consumption around the world and the need to search for new sources of hydrocarbon production as the deposits in known fields decline [1]. Nevertheless, as the operations in the offshore environment advance, so does the problem list connected to it. The offshore part of the Niger Delta province is geologically more complex due to submarine canyons, faults, fault blocks and variations in sedimentation rates (Figure 3). These factors present crucial threats to the operations in the business of exploring and producing oil [6]. Additionally, as oil companies exploit oil resources in water depths, they are faced with increased uncertainties which include unstable pressure regimes, unstable sea floors, and deep sea risks, which are devastating to structures and operations [7]. Thus, despite the aforementioned risks, offshore oil continues to be Nigeria's economic pillar forming a basis for employment promotion, and infrastructure development as well as generating income for the government [8]. Therefore, due to the large prominence of offshore oil fields, the Nigerian economy depends on the stability and management of geohazard risks for its offshore oil fields [9] (Figure 1).

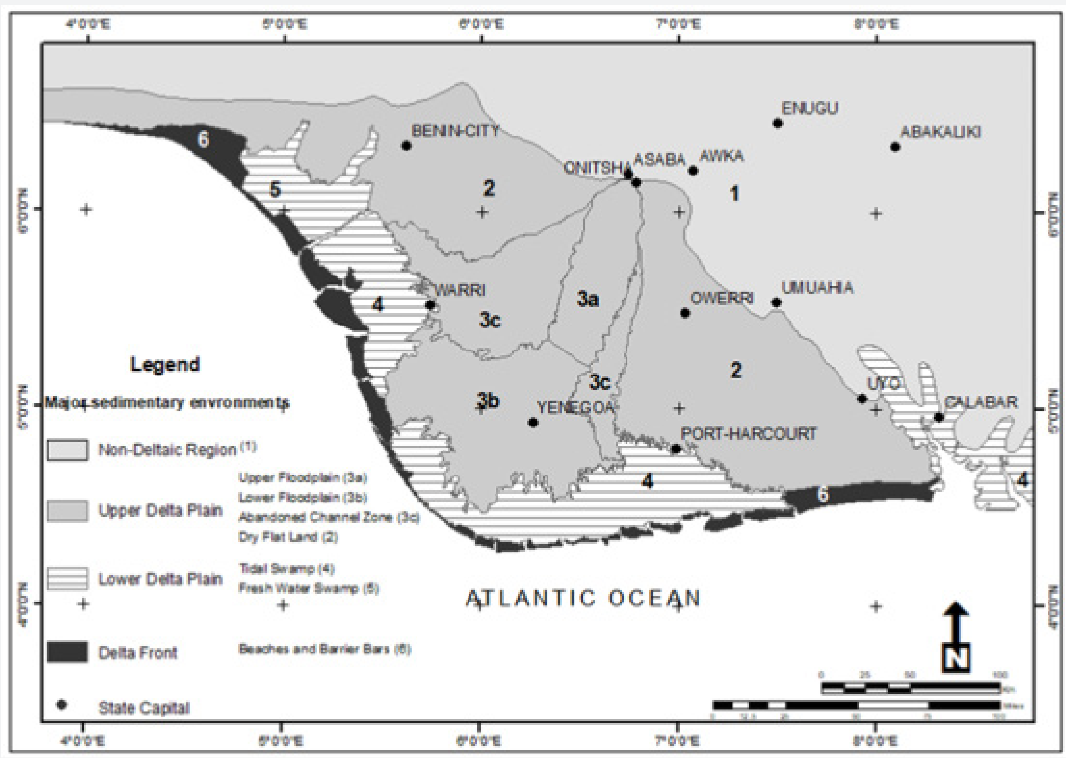

Figure 1: Map of the Niger Delta showing the deltaic system from [22].

Geohazard Risks in Offshore Environments

Offshore environments encompass a range of geohazard risks, which endanger human lives, cause environmental instability, and disrupt the sustainability of operations. They include several geologic risks such as mud diapirs, fault ruptures and shallow gas. In addition, the differences in structures of the seabed, challenges in mapping the fault lines, and the mobility of fluids within various rock formations also help in understanding how the advanced 3D seismic data have to be applied to enhance the

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efficiency of drilling and reduce the risks involved [10]. Regarding the offshore oil operations in Nigeria, the expansion of operations calls for exposure to several geohazard risks, particularly in the potentially active Niger Delta region. Offshore geohazards refer to factors of a geological structure that pose the likelihood or possibility of risk or instability of, for example, an offshore platform or oil & gas infrastructure that may disrupt operations [5]. Slope failures are also another identified geohazard common in the Niger Delta region whereby the term is used to refer to the collapse of the seabed. Such situations happen often as a result of over pressurization of sediments when a layer of sediment accumulates on the seabed quickly while there is inadequate time for fluid evacuation [11]. The triggering factors include increased sedimentation rates, tectonics, gas hydrate degradation and fluid migration [12].

High sedimentation rates in the Niger Delta have compounded the problem of high pore pressure build up within the seabed materials, leading to relatively reduced seabed stability and a higher tendency for slope failures as identified by [2]. Slope failures can cause massive movements of sediment loads, affecting subsea pipelines and oil platforms, thereby triggering expensive stoppages in oil production, and potential hazards to the environment [3]. Another threat to offshore oil operations is the production of gas hydrates – crystalline structures that incorporate water and natural gas, especially methane. These hydrates are generally regarded to be stable under deep water conditions (Figure 2).

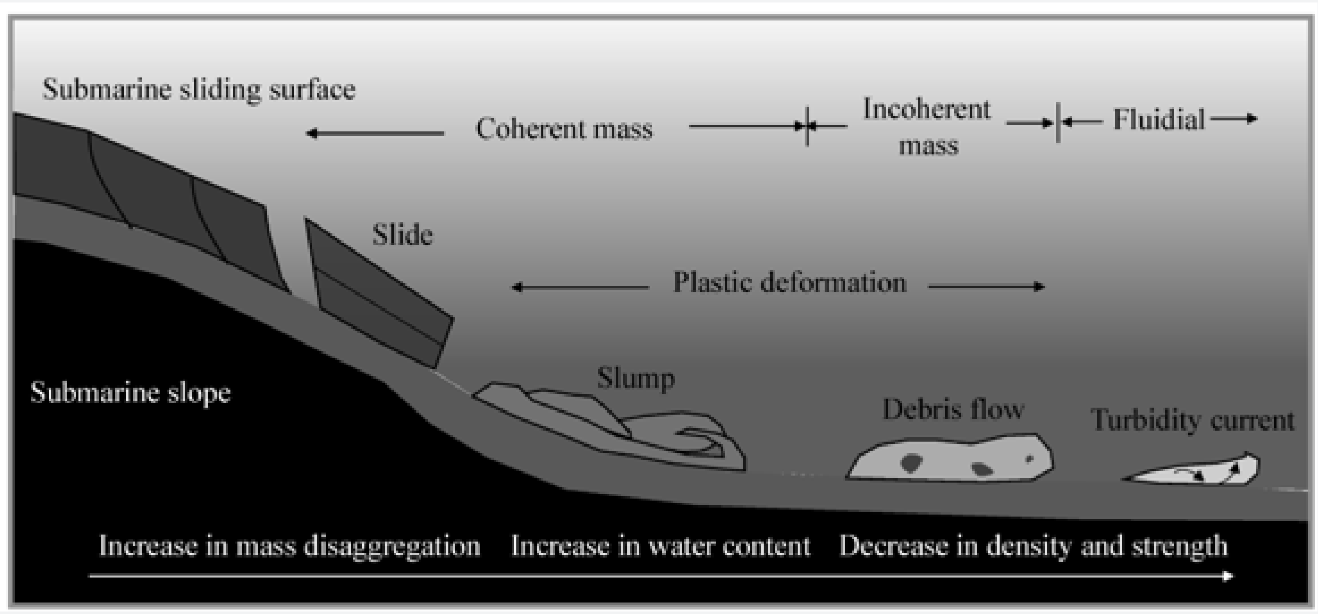

Figure 2: Overview of the stages in the evolution of a submarine landslide from [45].

However, they can be dissociated by changes in temperature or pressure for instance by drilling, although this will in turn trigger the release of large quantities of gas [13]. They may lead to the mobilisation of the seabed, causing submarine slides (Figure 2) or the emergence of large oval pockmarks, described as depressions where dissolved gases escape from the seabed. According to [11], mass-wasting events related to the disintegration of gas hydrates possess a likelihood of changing the base of the gas hydrate stability zone and can result in structural deformation, and in some instances, the possibility of subsea failure. [14] note that the leakage of the fluid from fault zones and the movement of slopes triggered by tectonic forces are key risks affecting offshore operators. Given the complexity of these geohazards, efficient risk management measures have to be taken to ensure the safety and functionality of the offshore oil business in Nigeria. This requires carrying out detailed geo mechanical investigations of the seafloor to determine regions that may be susceptible to failure, as well as installation of sophisticated monitoring networks designed to capture the slightest signs of slope failure or gas hydrate disintegration [15] Thus, by understanding the geohazards that exist in offshore environments and using technologies to reduce these risks, the oil companies will be able to carry on the exploration of Nigeria's huge offshore oil resources on its coast safely [16].

Objective of the Review

The purpose of the research is to determine the geo mechanical factors leading to slope failure in the Niger Delta's

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offshore fields with emphasis on the following issues; Rapid sedimentation and gas hydrate dissociation. The study also evaluates the harm that certain geohazards pose to offshore structures -specifically, submarine landslides - and relates these hazards to potential production delays and environmental risks. Moreover, the study proposes strategies to manage risks such as state-of-the-art seismic surveys installation of flexible pipelines, and real-time monitoring technologies for increasing operational safety. In addition, it fosters partnerships between geotechnics and petroleum engineers, to enhance the overall accommodation of geohazard throughout the lifespan of offshore projects.

Methodology

Literature Review

Previous and recent works undertaken on the geohazard risks linked to offshore oil drilling within the Niger Delta area were reviewed. This includes investigations on the shallow gas, slope failure, submarine slide and the instability of the sea floor. Geo mechanical factors that were discussed with regards to their relevancy in the cause of geohazards in the offshore environment included, pore pressure fluctuations, gas hydrate dissociation, tectonics and fluid movement.

Case Study Analysis

Several offshore case histories from the Nigerian oilfields were examined for correlation between documented geohazards to actual instances of infrastructure damages such as wellbore failures, pipeline bursts and production losses. The case studies were particularly useful in assessing the effectiveness of the current hazard assessment and Management plans with special emphasis on the deep water Niger Delta context.

Innovative Solutions

These comprised emerging geo mechanical and engineering advancements, including; real-time monitoring devices; ADCPs and inclinometer arrays. The purpose of these technologies as applied to identifying early signs of slope instability and managing risks was also considered. In addition, the review also involved the consideration of new geophysical techniques; pipelines and floating production structures that were an effort to develop sound solutions for infrastructure in perilous offshore conditions.

Geo mechanical Causes of Slope Instability in Offshore Environments

Seabed Instability and Sediment Loading

Some of the factors which lead to seabed instability in offshore settings include the nature of the seabed which is constituted by soft sediments, high sedimentation rates, and overloading of the seabed on steep slopes. Soft sediments, especially those in which intra sedimentary gas hydrates are present have of course also been postulated as triggers to slope instability. Gas hydrates entail that when dissociated, they lead to an increase in the pore pressure which reduces the effective stress causing the failure of the slope. This has been identified in areas like the Northern Cascadia Margin where warming or depressurisation of gas hydrates leads to substantial slope deformations [17,18]. Also, the increased rate of sedimentation is a great influence towards the formation of several weak layers within structures of sedimentary types. Weak layer formations in sediment structures tend to raise the pore pressure and subsequently lower effective stress, leading to instabilities as illustrated by the situations at the St. Pierre Slope [19]. When the loads of sediment are very high the slopes that are steep may develop such a type of slope failure known as static liquefaction mainly affecting loose layers of sand. Wave action and marine currents also increase the shear stress, which leads to slope failure [8]. Natural catastrophes like earthquakes can produce conditions that exacerbate these effects, and make slopes more vulnerable to catastrophic failures. For this reason, the assessment of such geo mechanical processes is deemed critical to determine the stability of offshore oil operations, where natural factors pose a risk to installation and activity.

Submarine Landslides

Offshore submarine landslides are a powerful geohazard, the development of which is influenced by many geo mechanical conditions in combination with gas hydrate dissociation, seismicity and pore pressure fluctuations. These mechanisms play a major role in altering the stability of the slopes and, in turn, present a very high risk to the development of oil and gas enterprises in the offshore zone. For example, the dissociation of gas hydrates might cause the destabilisation of slopes mainly due to the rise in the pore water pressure and consequent reduction of the strength of the sediment. Even a relatively minor dissociation of about 1% can lead to an overpressure of about 1 MPa, under which conditions, progressive landslides occur [17]. Likewise, earthquakes apply dynamic loads that quickly fluctuate pore pressures, and this may cause large-scale mass movements [18] Changes in pore pressures are also other considerable sources of slope instability." In soils with high trapped gas content, the actual pressure exerted by the gas bubbles formed in the confined pore space reduces the effective stress in the sedimentary fill. This can lead to liquefaction under conditions of high gas pressure that in turn increases the likelihood of slope failure [6]

Case Studies from Nigerian Offshore Oilfields

The analyses of slope failures and geohazards in the Nigerian offshore oilfields made in the context of the provided literature (Table 1) show that the problems related to offshore drilling are complex and dangerous. These risks which are mainly slope stability, abnormal pore pressure and mass movement are implicit threats to oil installations such as rigs, pipelines and subsea equipment. An assessment of each of the studies presented in the table promotes a deeper understanding of the causes, outcomes,

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and unique effects on drilling operations. Drawing from their research in the shallow offshore Niger Delta, [5] provided a critical analysis of the abnormal pore pressures. The use of 3D seismic inversion afforded the identification of areas which had been characterized by enhanced pore-pressure levels due to intensified rates of sediment deposition. These abnormal pressures lead to slope instabilities; hence, higher chances of failure during actual drilling. In practical application, these cases have led to wellbore failures that lead to time loss in the production process and the need to stabilise both the wellbore and other supportive structures at extra cost. The application of seismic inversion methodology in the exploration of subsurface features has a way of helping to predict such risks before they become operation risks. However, the key complication arising from the analysis of pore pressure is that it is normally random and characterised by sudden short bursts, which poses a high risk (Figure 3).

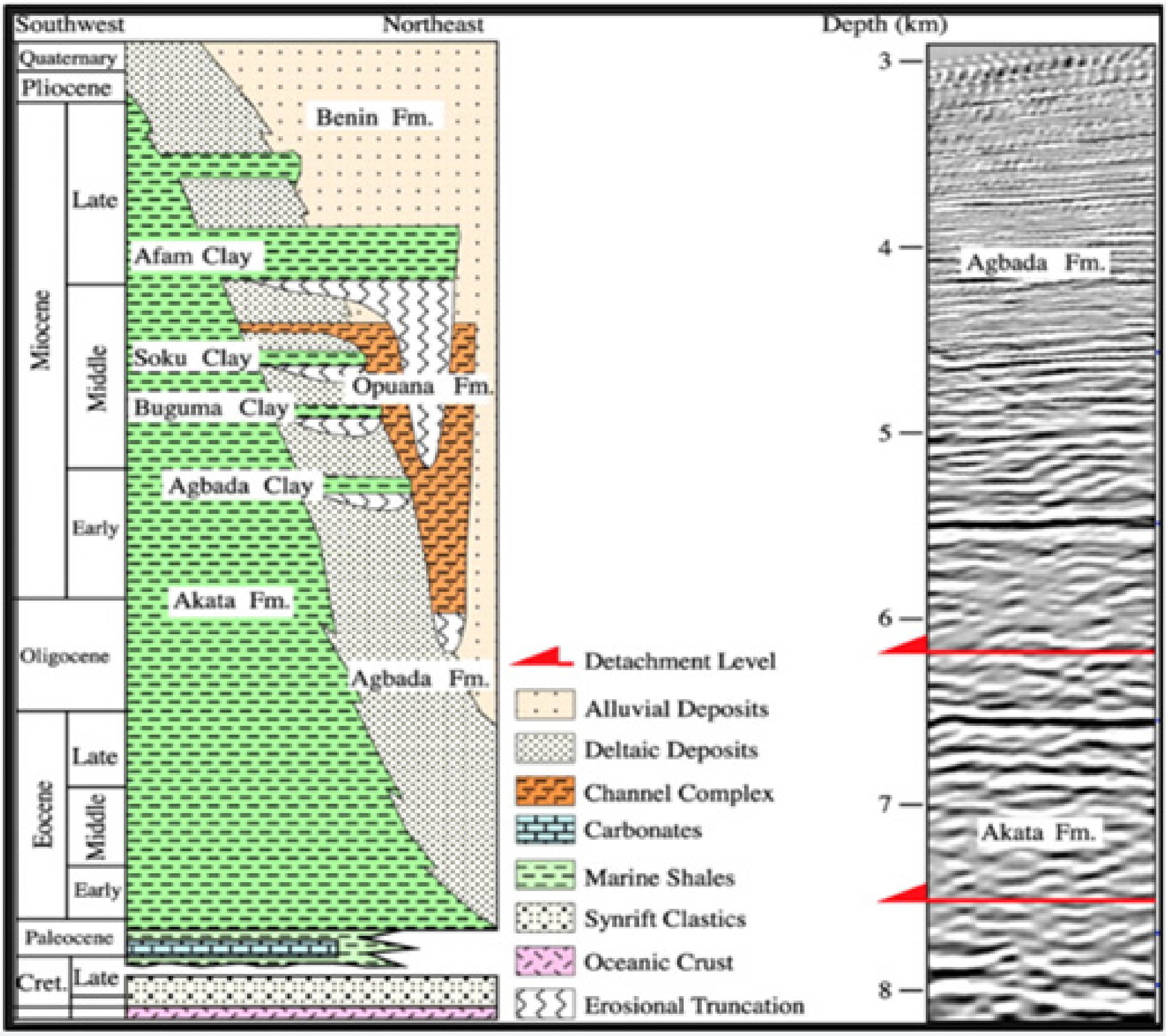

Figure 3: Schematic diagram of the regional stratigraphy of the Niger Delta and variable density seismic display of the main stratigraphic units [13].

In their work, [12] focused primarily on the area of the Gabo Field in the Niger Delta, analyzing the interaction between pore pressure management and wellbore stability. The researchers' conclusions pointed out that pore pressure that is poorly controlled will lead to wellbore collapse and reservoir instability that poses a direct threat to oil pipelines and installations nearby. Such failures can cause immediate loss of infrastructure, which requires a halt of production operations while the damages are being rectified. The financial consequences include the cost of repair and that costs in terms of revenue due to the production line being halted. The analysis also stresses the importance of continuous pressure measurement and the flexibility of management interventions to minimize the possibility of wellbore issues. [11] analyzed the possible hazards associated with mass-wasting occurrences and the consequent influence on the stability of the gas hydrate in the deep water of the Niger Delta offshore.

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This study revealed that submarine landslides pose a risk towards the destabilisation of gas hydrates that in turn cause the emission of methane and subsequent instances of secondary landslides as seen in the present study. The implications for subsea installations are significant given that the moving seabed has a direct impact on pipeline pressure and associated structures such as drilling equipment. Additionally, mass wasting has arguably possible environmental effects and hence is also an operational risk. [11] has further pointed out that even though these occurrences can be partially predicted through seismic surveys and geotechnical monitoring, the consequences of hydrate destabilisation introduce a new layer of challenge to geohazard management in the region.

[2] offered an understanding of how appraisal of potential risks is conducted before the rig mobilisation with specific reference to the TM Field. Their findings pointed out the need to undertake detailed evaluations before the arrival of a rig on site since assessment shortcomings have been recognized as the cause of infrastructure damage. They showed that issues such as the stability of the seafloor and its slopes can lead to the undermining of rig foundations thus making major repairs and long downtime inevitable. This reemphasises the fundamental fact that in hazard identification and risk management, one needs to conduct an in-depth study at each phase of drilling, as well as before rig movement to ensure proper footing. Here, lack of adequate preparation meant that the production process was slowed down, and averting the losses that come with these experiences would have been possible if extra and more intensive pre-deployment checklists had been conducted. [3] later analysed seafloor and buried mounds on the western slope of the Niger Delta, to determine the depth, type and distribution of formations that have a bearing on slope stability. These buried mounds which are commonly generated by sedimentation and tectonic forces, have the possibility of creating weak areas on the seabed, which may further develop to geohazard risks like slope failures that may have the capability to impair pipelines. These factors explain why the need for extensive mapping cannot be overemphasised. Following infrastructure failures due to features which are often ignored such as buried mounds because of the geomorphological characteristics of the area under study.

Structural deformation as a factor of slope channel morphology was also captured by [13] while analyzing a Pleistocene feeder channel system. The results of this work are of great importance to analyze the shaping of the channels and the impact on them and on the infrastructure of the oil industry, such as pipelines, which are often laid along the channel of steeper slopes resulting from tectonic processes. Slope instabilities can cause trench or channel orientations to change throughout the operation, which affects the pipeline route, and may lead to pipeline deformation and cracking thus posing operational and environmental hazards. [20] also considered the structural deformation related to the submarine channel system and, in general, the larger Niger Delta continental slope. The researchers established ways in which movements of submarine channels concerning slope deformation affected features such as pipelines and other structures. The study outlined how these deformations could be predicted, thus allowing operators to place pipelines in less hazardous zones or strengthen susceptible regions to prevent major damage to structures.

[1] focused on the geo mechanical aspects of the Miocene Niger Delta reservoirs and once again emphasized that pore pressure fluctuation leads to reservoir and infrastructure failure. Based on pore pressure mismanagement as a cause of equipment failure, [1] stress that reservoir stability is critical to avoid losses arising from production delay. [21] another study focused on the occurrence of mud diapirs in the deep water Niger Delta and established that they were a major cause of slope failure. Such a diapir can tilt and cause damage to subsea equipment, something, which often entails shutdowns due to damage to the subsea structures that require repair or replacement. Mud diapirism, driven by diapir-controlled basin structures, presents a distinctive challenge, as it can develop gradually over time. Hence, monitoring in real-time should be a vital consideration to ensure little impact on the pipelines as well as other subsea structures [4], used 3D seismic analysis to study mass-transport deposits (MTDs) along Nigeria's Transform Margin, which exposed the effects of recurrent slope failures on oil structures. The creation of multiple MTDs is now a danger to subsea pipelines because the continual development and trailing of the sediments can cause seabed erosion or shifting which in turn cause pipeline failure and subsea apparatus failure. Moreover, to predict the likelihood of formation of these deposits, the study calls for real-time seismic surveillance.

Another related study carried out in this field of research was conducted by [22] and further by [23] in which gas hydrates and seafloor depressions in deep water Nigeria were considered as possible factors contributing to slope failures. The outcomes of both studies reveal that the dissociation of gas hydrates and the generation of seafloor depressions are a threat to subsea pipelines. Depression shifts or hydrate release may lead to a decrease in structural support and equipment failure with the added hazards of methane production and infrastructure collapse. Similarly, [9] associated the occurrence of gravitational collapse in deep water Niger Delta systems with pipeline shifts or wellbore damage and stressed that the instability of the shale structure could provoke long-term production losses. Thus, it can be concluded that the studies shown in the table, taken together, form an overall understanding and describe how geohazards such as abnormal pore pressure, mass-wasting and overall structural deformation have profound implications for the oil structures in the Niger Delta area. Finally, the impact of slope failures is catastrophic and enormous and the theme of financial loss and loss of production time is apparent throughout the case studies. Such consequences can include wellbore failures, and pipeline ruptures and can even extend to the destabilization of the rig (Table 1).

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Author & Year	Objective of Study	Methodology	Geohazard	Locations	Causes	Consequences on Oil Infrastructure	Impact on Drilling Operations and Infrastructure	Limitations of the study
[5]	3D modeling of abnormal pore pressure in shallow offshore Niger Delta using seismic inversion	Seismic inversion techniques	Abnormal pore pressure	Shallow offshore Niger Delta	Rapid sediment deposition	Risk of drilling failures due to sudden pore pressure spikes, leading to rig collapse and wellbore instability	Increased drilling costs and delays due to wellbore failures	Limited seismic data coverage, leading to less accurate 3D modeling of pore pressure variations
[12]	Assessment of pore pressure and wellbore failure in the Gabo field	Reservoir stability modeling and geo mechanical analysis	Pore pressure-induced wellbore failure	Gabo Field, Niger Delta	Improper pore pressure management	Risk of wellbore collapse and reservoir instability, potentially damaging pipelines	Production delays due to wellbore collapses, leading to financial losses	Assumptions in pore pressure models may not account for all geological variables affecting wellbore stability
[11]	Study of mass-wasting-induced shifts in the gas hydrate stability zone	Seismic and geotechnical surveys	Mass-wasting and gas hydrate dissociation	Offshore Niger Delta Basin	Submarine landslides and gas hydrate destabilization	Pipeline and subsea installations damage due to landslides and hydrate shifts	Environmental hazards from methane release and potential structural damage to subsea installations	Focuses primarily on seismic data; limited integration with continuous geotechnical monitoring data
[2]	Pre-rig mobilization hazard evaluation in offshore drilling in TM Field	Geohazard assessments and risk analysis	Seafloor instability and slope failures	TM Field, offshore Niger Delta	Steep slope gradients, high sedimentation rates	Rig destabilization, infrastructure collapse if mobilization hazards aren't addressed	Production delays and rig damage due to lack of proper hazard evaluations	Pre-mobilization assessments could benefit from longer-term historical data on sedimentation patterns
[3]	Analysis of seafloor and buried mounds on the western slope of the Niger Delta	Geophysical surveys and 3D seismic analysis	Seafloor mound instability	Western slope of Niger Delta	Sediment deposition and tectonic shifts	Risk of slope failure impacting nearby pipelines and subsea equipment	Potential for production halts due to infrastructure threats from buried mounds	Limited to surface-level data; lacks integration with deeper geological structures and continuous monitoring
[13]	Impact of structuration on slope channel geomorphology and architecture	Geomorphological and sedimentological analysis	Slope channel instability	Pleistocene feeder channel, Niger Delta	Structural deformation due to tectonics	Channel shifting leading to potential pipeline deformation	Financial losses due to shifting channel sediments affecting drilling and pipeline operations	Limited temporal data; does not account for rapid changes in tectonic activity and channel sedimentation
[20]	Quantifying the relationship between structural deformation and submarine channels	Structural and morphological mapping	Structural deformation and submarine landslides	Niger Delta continental slope	Submarine channel deformation	Deformation of pipelines due to channel movements	Damage to oil infrastructure, leading to costly repairs and production delays	Insufficient data on long-term structural deformation patterns; limited understanding of deeper subsurface geological processes

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[1]	Study of pore pressure and geo mechanical properties of reservoirs	Geo mechanical and reservoir analysis	Pore pressure instability	Miocene Niger Delta region	Reservoir pressure mismanagement	Risk of equipment failure due to pressure build-up	Financial losses due to delayed production and necessary infrastructure repairs	Simplified geo mechanical model may not account for all pressure variations across different reservoir layers
[21]	Depositional model for mud diapir-controlled intra-slope basins	Geological and geophysical surveys	Mud diapirism and slope failures	Deepwater Niger Delta	Diapirism and slope instability	Damage to subsea installations from mud-driven slope collapses	Equipment damage, leading to costly shutdowns and operational delays	Limited scope to mud diapir-driven failures; lacks consideration of other slope instability factors
[3]	3D seismic analysis of Cenozoic slope deposits and fluid-flow phenomena	Seismic and geophysical data	Mass-transport deposits (MTDs)	Nigerian Transform Margin	Sediment overloading and fault activity	Repeated MTDs damaging subsea pipelines and structures	Subsea equipment failures and pipeline ruptures, leading to production halts	Limited long-term data on the recurrence and frequency of MTDs
[38]	Prediction of fracture pressure in the Niger Delta Basin	Fracture pressure modeling	Seafloor fractures	Niger Delta Basin	Fracture pressure mismanagement	Wellbore and pipeline damage due to unexpected fractures	Financial losses from equipment failure and operational delays	Models lack high-resolution temporal data on fracture pressure changes, leading to potential inaccuracies
[39]	Geo mechanical analysis of gas-hydrate pockmarks in deep water Nigeria	Geo mechanical modeling and analysis	Gas hydrate dissociation and pockmarks	Deepwater Nigeria	Gas hydrate destabilization	Pipeline damage due to seafloor pockmarks and hydrate release	Infrastructure damage, methane release, and financial losses from halted production	Lacks real-time data on pockmark evolutio; potential gaps in hydrate dissociation risk monitoring
[40]	Study of seafloor depressions and hydrate distribution on Nigerian margin	Seismic and sub-seabed hydrate surveys	Seafloor depressions	Nigerian margin	Hydrate dissociation and seafloor depression	Pipeline and subsea equipment damage from depression shifts	Subsea installation damage and production delays	Limited integration of data from multiple surveys; temporal variation in seafloor depression activity not well-understood
[9]	Role of shale deformation in the development of deep water gravitational systems	Structural and tectonic modelling	Shale deformation	Deepwater Niger Delta	Gravitational collapse and shale deformation	Pipeline shifts and wellbore damage due to structural instability	Infrastructure deformation, production delays, and financial losses	Lacks continuous monitoring of gravitational systems; assumptions in the tectonic models may oversimplify shale deformation

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Innovations in Mitigating Geohazard Risks and Submarine Landslides in Deepwater Oil Fields

It is crucial therefore to anchor seabed to prevent failure in areas that are sensitive to slope failure with view of providing adequate support and safety especially in offshore oil exploration activities like the Nigerian example. Subsea retaining structures that should be designed to follow regional geological features are crucial in preventing forces like ocean currents and seismic activities [16]. When combined with slope monitoring and warning systems, such designs are inevitable for successful risk management in geohazard-prone areas. Acoustic Doppler Current Profilers (ADCPs) significantly improve the accuracy of slope stability studies by investigating sediment movement and water flows in weight loss and currents, which are critical in understanding their functions in erosion and slope failure [24]. The combination of ADCPs and inclinometers constitutes a surveillance system that supports the predictive models and enhances the reduction of risks at complex offshore structures [25,26]. However, the problem of achieving stable long-term operation and accurate data transmission in inherently unstable environments remains a concern [27].

Proactive engineering changes like flexible pipelines and floating Production Systems (FPS) are crucial in the execution of offshore oil activities in Nigeria. While rigid pipelines are more susceptible to rupture during slope instability due to ground movement and pressure differential resulting in a high likelihood of failure if constructed of conventional material such as steel or concrete, flexible pipelines used in these pipelines are made of high-strength composites and can easily change shapes to accommodate the movement of the ground [28,29]. The aforementioned pipelines, therefore, demonstrate enhanced resistance to corrosion, thus ensuring the elongation of their functional years particularly in the context of a fluctuating seabed environment [28]. Dynamic positioning (DP) systems ensure that FPS platforms can change position in real time following changes in the seabed; the platforms are therefore less susceptible to structural damage as a result of slope failures. Additionally, safety-critical equipment (SCE), which is fabricated to perform optimally in unfriendly environments, contributes to the stability of these floating systems [30]. These physical interventions are supported by innovations in the development of predictive modelling that has enhanced geohazard prevention. It is therefore crucial to invest in high-resolution bathymetric and geophysical surveys to detect submarine landslides, slope failures and turbidity flows. Fundamental tools like multibeam echosounders and repeated bathymetry surveys give out useful information on the bottom slope and investigation of sediment displacement over some time. This is of particular importance in high-risk zones such as the Niger Delta and others as stated by [31]. Geophysical surveys complement these assessments by revealing subsurface structures which signify geological vulnerabilities and thereby improve the prognosis of subsequent ground instability [32].

Electrical Resistivity Tomography (ERT), systems and other real-time subsea monitoring tools have inevitably become very useful in identifying potential geohazards through seismic profiling. Seismic profiling uses the response of materials to the seismic waves to determine the conditions of the subsurface and provides a detailed kinematic study of slope stabilities [9]. Similarly, real-time monitoring tools are used to measure the conditions on the seabed in real-time to allow for the identification of early signs of slope failure and for remedial action to be taken as soon as possible [33]. These technologies are complemented by recent developments in acoustic and seismic monitoring that give real-time information on sediment motion and slope deformation [34]. Moreover, geotechnical sampling and testing are of significant significance in the evaluation of slope stability, especially in area like the Niger Delta. Free-fall penetrometer (FFP) enables the faster collection of some information concerning the state of the seabed's surface layer, the importance of which is evidenced by the need to avoid adverse situations during oilfield development [31]. Advanced laboratory tests are then used in the laboratory to further enhance the existing slope stability models after samples have been collected in the field. This is accomplished by assessing the nature of the sediment, regarding its shear strength and consolidation characteristics. The use of numerical simulations, for instance, coupled thermo-hydro-mechanical modelling helps in achieving a deeper understanding of specific geohazard risks such as those posed by natural gas hydrates, which might lead to the creation of slope failures [35]. Recent developments in the finite element methods have provided additional tools to the assessment of slope stability where techniques such as shear band propagation (SBP) modelling provide important clues as to how the submarine slide might develop in the future [36,37] also established that Computational Fluid Dynamics (CFD) modelling has also been used in the assessment of the possible effects of landslides on nearshore pipelines and offshore structures in general to enhance their design. Offshore geohazard mitigation strategies aimed at managing the natural risks on oilfields depend, therefore, on the synergistic application of geomorphological mapping, seismic profiling, real-time monitoring, and computational models. The deployment of Internet of Things (IoT) devices and associated subsea sensors guarantees the expedient identification of any potential hazards, thereby enabling prompt intervention before they cause damage to devices and subsea installations [38]. The utilization of all of these technologies presents a more adaptive and proactively minded approach to managing geohazard risks, especially within the Niger Delta which is characterized by frequent and diverse geological risks [39-56].

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Conclusion

The geo mechanical causes of slope failure in the offshore areas in Nigeria especially in the Niger Delta area are hard to explain as this involves several contributing factors. These factors are high rate of sedimentation, high pore pressures, tectonic activity, dissociation of gas hydrates and fluid migration which contribute to the occurrence of submarine landslides and seabed collapses. Soft sediment, steep seabed slopes combined with the influences of over pressured sediment are a potential danger to offshore oil installations in the area. The geohazards listed above can threaten or damage pipelines and wellbores along with platforms, which in turn, may lead to operational disruptions, environmental risks, and infrastructure breakdowns. Slope instability and other associated geo mechanical hazards that lead to submarine landslides pose a major threat to the sustainability of oil operations. It is thus important to understand these processes and to develop efficient and innovative engineering and monitoring approaches to counter the associated risks. To sustain the offshore pipeline infrastructure in Nigeria, there must be the use of appropriate slope stability analysis, proper reinforcement of seabed and reliable real-time monitoring. The use of risk models, early warning systems as well as advanced considerations about geotechnical conditions is crucial for recognizing high-risk territories and launching preventive activities. Further, the adoption of a flexible pipeline design, floating production system and dynamic monitoring system solution may greatly enhance the overall reliability of the subsea solution. These measures alongside strict safety measures and implementation of these new technologies will go a long way in providing operational stability and environmental issues in offshore oil fields in Nigeria.

Recommendations for Future Research and Practice

Enhanced Seismic and Geophysical Studies: Therefore, it is suggested that further studies should be devoted to the development of seismic and geophysical methods, with the aim at increasing the reliability of the slope failure estimation in the Nigerian offshore fields (Figure 4). Since the geohazard risks in these areas are rooted in geo mechanical characteristics such as tectonic activity, dissociation of gas hydrates and sediment loading, therefore it is clear that the basic requirements are sophisticated geophysical methods required to identify areas of potential subsurface failure. The application of high-resolution 3D seismic surveys and geophysical risk assessment helps determine areas of poor rock quality, faults and other sites with potential for instability. This allows the operators to make an informed decision as to where these infrastructures should be and where and how the various hazard mitigation measures should be put in place. However, these technologies can also be used to periodically evaluate changes in subsurface conditions hence aiding in timely intervention before a steep slope fails catastrophically. Accordingly, it becomes necessary to develop tailored geophysical models as a supplement to site-specific evaluations influenced by the region's peculiar geological characteristics (Figure 4).

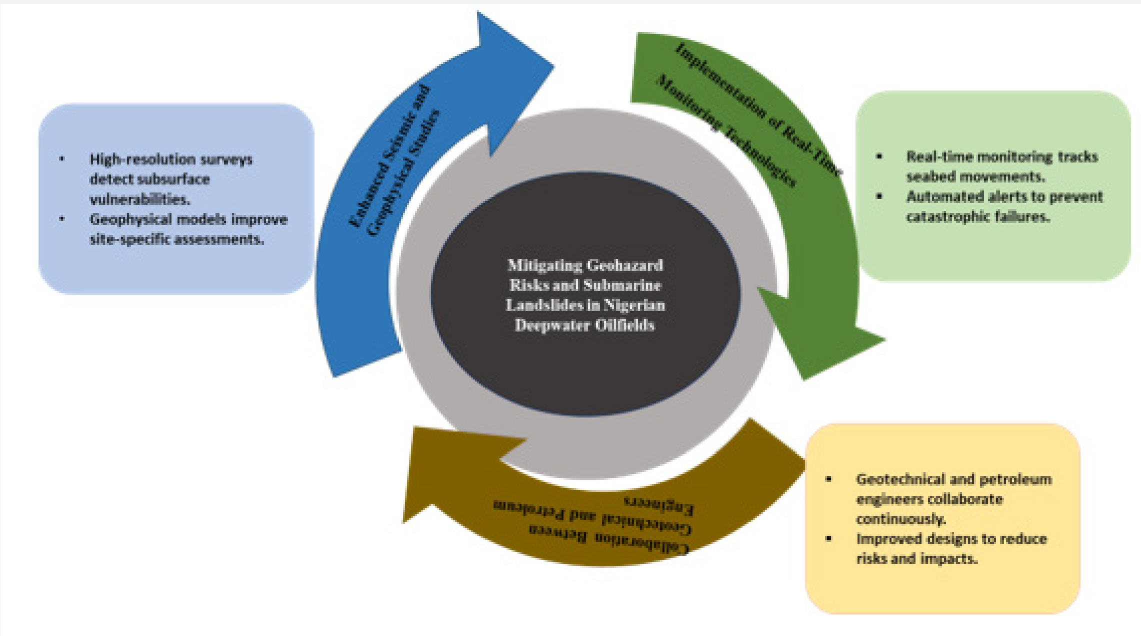

Figure 4: Future Research Directions for Mitigating Geohazards and Submarine Landslides in Nigerian Deepwater Oilfields.

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Implementation of Real-Time Monitoring Technologies: The use of real-time monitoring systems remains critical for tracking the seabed's active motions and generating early warning indicators of emergent geohazards. Such systems, for instance, systems that use Acoustic Doppler Current Profilers (ADCPs) and inclinometer arrays can detect these conditions thereby allowing an instant response to the possibility of a slope failure. The ability to monitor geo mechanical processes such as sediment compaction, pore pressure and fluid movement in real terms and apply these results in designing improved risk management will lower the general incidences of failures in infrastructures. Further, the aforementioned technologies should be equipped with an automatic alarm system that sounds to alert the operators whenever seabed movement crosses beyond the safety limits and allow for corrective action in due course.

Collaboration Between Geotechnical and Petroleum Engineers: Appropriate control and management of geohazards call for increased synergies between geotechnical and petroleum engineers to ensure that slope stability issues are captured from the pre-drilling consideration, through the drilling, and production phases of the offshore oil exploration and production projects. Ideally, such interaction should transpire right from the choice of the site up to the point of drilling construction and the conclusion of the production phase. When geotechnical specialization is integrated with petroleum engineering approaches, engineers can create infrastructure designs that are less susceptible to slope instability dangers. This kind of integrated methodology will not only improve the safety of offshore activities but will also increase operational efficiency in the extraction of natural resources and minimize negative effects on the environment.

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