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Review Article

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Micromechanical Analysis of Compaction and Drilling of Granular Media-A Review

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Abstract

Granular matter is ubiquitous in our daily life yet far from completely understood. These granular materials have constituted a class of complex systems which exhibit global behaviors been reminiscent of solids, liquids, gases, or otherwise uniquely their own. The key to achieve good properties lies in the material structure from the molecules, via structures on nano and micro levels to the macroscopic material. This paper also reviewed selected approaches and models that have been developed for granular media prediction. However, development of new approaches at the micro and nano scales to sense the stress distribution characteristics of complex rock media, especially the grounds bearing petroleum resources of Nigeria has been of vital concern/importance to the area of petroleum drilling and exploration. By conducting such fundamental level research, development of highly efficient drilling processes with potentially much less energy inputs and minimizing the carbon blue prints is the best approach.

Keywords: Micromechanical; Compaction; Granular media; Numerical modeling methods; Drilling

Introduction

Interesting phenomena, not yet well understood take place with granular media. Examples include: avalanches, segregation (which grains of different type separate under vibration), crystallization (when grains arrange into ordered configurations), pattern formation (when grains arrange into patterns, such as dunes or ripples) or jamming (when the flow of grains stops abruptly) [1]. Micromechanical analysis of compaction and particulate/granular materials has been of significance to academics and industrial communities, from beach sandcastles to chemical, pharmaceutical, food, mechanical, civil, mining and petroleum engineering as well as underground reservoir industry, and materials processing sectors [2-15]. Granular media are thermal, quite normal after all, usually with different particle-scale properties and inter-particle interactions, which are responsible for their complex behaviors at the low gravitational environment and macroscopic scale and difficult to assess experimentally [6,11,12,16-22]. Several researchers have proposed calibration procedures relating the micro parameters to macro properties of the granular material [23-25]. These granular size and compaction affects the force penetration behaviour of drilling equipment's. The higher the granular size, the more the fluctuation in the fine aggregate grains, but increase the magnitude of the force fluctuation grains [18]. Under different external loading environments, granular media exhibit a variety of unusual characteristics at both microscopic and macroscopic scales which make them different from conventional solids, liquid and gaseous matter. The macromechanical response of a particulate assembly to external shear forces compaction forces, mixing forces or discharge processes has been reported to be closely related to the micro-mechanical properties of the granular system, which are determined by the interactions between the particles in the system [26-28].

Advanced particulate numerical modeling methods, such as discrete element modeling (DEM) and molecular dynamics, have helped in understanding the microscopic origin of shear strength in particulate assemblies [4,11,14,15,20,29,30-44]. Although DEM is very closely related to molecular dynamics; hence this method has generally been distinguished by its inclusion of rotational degree-of-freedom as well as stateful contact and often complicated geometries. Due to a complex particle shape and a complex interaction between particles, DEM simulations of clayey soils are difficult and thus, rare [40]. DEM has been proven to be more suitable tool than Finite Element Method (FEM) and Finite Volume Method (FVM) to simulate compaction [45,46]. Some researchers have also used the hybrid approaches- a combination of Finite-Discrete Element Methods-FDEM to analyze geomechanical problems [25,47-53]. FDEM and Y-Geo software, despite their limitations (mesh sensitivity, lack of hydro-mechanical coupling and fluid propagation in the cracks, long computational times), has effectively simulated complex rock slope instability problems from triggering, initiation, evolution, run out and deposition processes [47,54]. Engineering understanding on the mechanical strength characteristics of rock masses and other natural composites due to the formation of cracks and openings, and how they get influenced due to nano-particle fillings (such as Nigeria natural clay) are of high importance in petroleum drilling operations. To the best of our knowledge, there is no existing continuum constitutive model that reproduces all of these behaviors. However, since the DEM involves many individual particles and interactions between them, it is computationally expensive and therefore it is not applicable to large-scale problems [25]. Disadvantage of the DEM model is the lack of a systematic method for an objective determination of micro material parameters. As opposed to the continuum-based models for which the strength and elastic properties can be determined directly from laboratory testing, the micro properties cannot be determined by direct measurements of the macro responses on the laboratory specimens.

Many reservoir engineers and tectonic encounter this complex problem to predict both the occurrence and extent of inelastic deformation and failure hinges upon a fundamental understanding of

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the phenomenology and micromechanics of compaction in reservoir rock [53,55]. The consequences of such inelastic compaction can be economically severe and include surface subsidence and various production problems [56]. Significant reduction of permeability may also accompany the compaction [57]. Well instability is caused by narrow fractures in sandstone from 1/16 to 1/12 inches wide while drilling through the granular media (Figure 1). If the mud weight is larger than anticipated, the mud will invade into the formation, causing tensile failure of the formation. On the other hand, a lower mud weight can result in shear failures of rock, which is known as borehole breakouts. To predict the potential for failures around the wellbore during drilling, one should use a failure criterion to compare the rock strength against induced tangential stresses around the wellbore at a given mud pressure. The Mohr-Coulomb failure criterion is one of the commonly accepted criteria for estimation of rock strength at a given state of stress [58,59]. Basically modified the M-C criterion by absorbing the critical state defined, and then quantifying the necessary deviation from the linear form, using a large body of experimental test data [60,61]. A similar criterion for the shear strength of rock masses, with σ_c for the rock mass potentially based on the simple formula $5\gamma Q_c^{1/3}$ (where $Q_c = Q\sigma_c/100$ (MPa)) [62]. They reported that based on six parameters involving relative block size, inter-block friction coefficient and active stress, the rock density is γ, and Q is the rock mass quality [63]. It is observed that the rock properties which govern drilling rate are not completely understood. Furthermore, correlation is lacking between strength and elastic properties as measured at laboratory conditions and those which exists at the depths of interest to the oil industry. Usually mechanical activities such as sandstone drilling induce additional stresses within sandstone beds. When stresses acting on the sandstone exceed their critical strength, it fractures. Considering that World's Petroleum drilling operations, most especially that of Nigeria often encounter layers of granular media, excessive fracture of them is thought to result into significant levels of financial losses for Petroleum industry due to wellbore instability caused by high level of stress concentration at the crack location- this is one of the major problem to overcome in the Nigerian oil` industry as of now. Despite extensive studies reported in this field, new understandings on the crack initiation and propagation characteristics of rock masses under mechanical loading is lacking and it has been the most challenging tasks in designing engineering structures from moderately to heavily jointed rock [64]. One of the methods presently explored in many parts of the world is to use particulate materials, either manufactured artificially or in natural form as a healing agent of cracks in rock masses. However, it is not yet well known on how natural particulates such as these naturally available Nigerian bentonite clay particles could retard the propagation of cracks in rock media. It is important to recognize that Nigeria has natural bentonite available in abundance. Hence the above said problem in Nigerian petroleum drilling rock masses can be effectively solved by utilizing the natural minerals available in Nigeria or using other nano-particles if we develop comprehensive level understandings of the strength characteristics of rock mass using advanced sensing techniques. At first, this requires establishing a suitable methodology by which stress concentration factors on real rock sample material under different loading pressures can be quantified and bench marked to evaluate their efficiency under real processing/operating conditions. The current state of measuring stresses on rock masses due to external loading is using conventional strain gauges at selected number of points, and then converting these discrete measures to component of stress acting along the direction of the strain gauge mounting, which is a cumbersome procedure with limited applicability. Qiujiao has applied the use of a sensor to monitor stress-strain signals in a granular medium and detection of seismic precursory information [65]. When compared with the widely used sensors of borehole stress in the rock, the sensor has more convenient operation, higher output sensitivity, compactness and farther propagation effect. However, development of a bench mark system by which whole field stress measurements on rock masses can be made is very necessary and methods to be implored/adopted in order to get the desired results is by using nascent computational methods and photonic stress (sensor) analysis with the aid of advanced software packages [66-69].

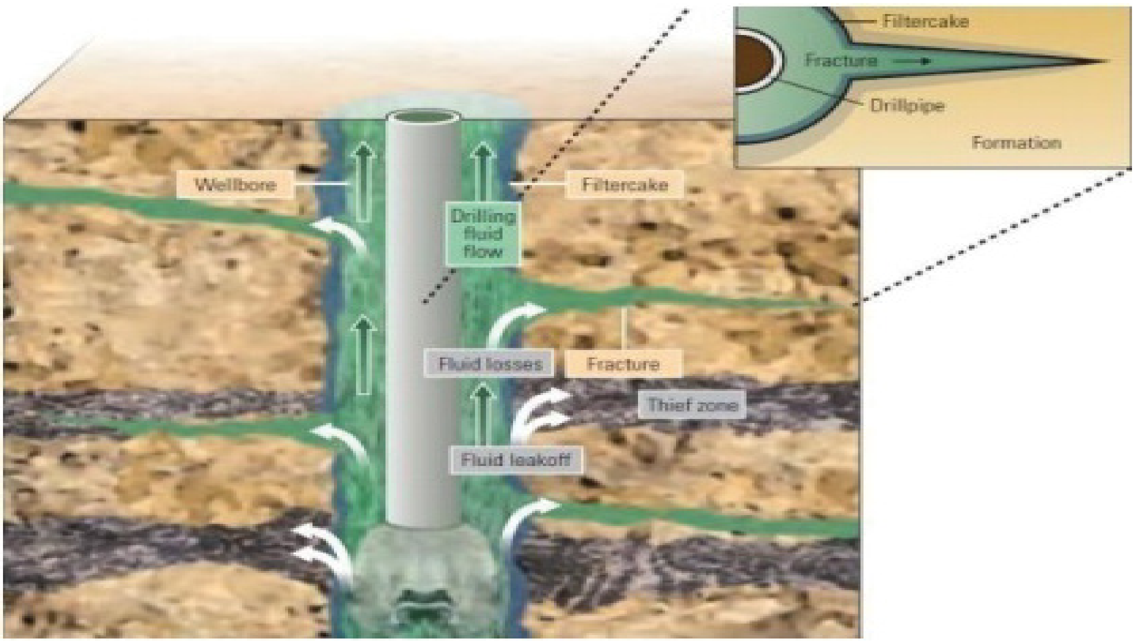

Figure 1: Schematic illustration of formation of cracks during petroleum drilling operations.

Conclusion

A fundamental understanding of micro-macromechanical compaction and drilling of granular media has been of centrality to a number of issues in reservoir and geotechnical engineering for which deformation and fluid transport are intimately related. It has been observed that estimation of granular media such as rock mass behaviour is still a challenging one. However, the consequences of such inelastic compaction could be economically severe, include surface subsidence and various production problems and therefore, extensive researches in this areas of compaction and drilling of granular media shouldn't be overlooked in that it is the central point for engineering profession.

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