The Roles of Material Dilatancy in Post Failure Borehole Stability Analysis for Underbalanced Drilling Wells in Shale - A Sensitivity Analysis

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Abstract

It is well known that the shale exhibits anisotropic behaviour due to sedimentation processes. The anisotropy is apparent both with respect to deformation and strength and such anisotropy can be evaluated by performing a triaxial testing. The research-in-progress presented here concerns an investigation of laboratory and Finite Element Method (FEM) approach for the behaviour of material dilation & yielding in highly anisotropic materials such as shale. Both drained and undrained post failure stress path, hardening and softening behaviour has to be clarified. In reality the effective stress path for an undrained triaxial test will never be vertical and there will always be some change in the mean effective stress together with observed a change of volume due to shearing. The observed behaviour is what we called dilatancy and it has a number of impacts in post failure borehole instability. Therefore, the main aim in this work is to explain the confinement and deformation dependent material dilation roles in transient pore pressure & material yielding together with their impact on borehole displacement to cause instability. In the same way to explain about their influences on time delayed Mud Weight (MW) design particularly for underbalanced drilling (UBD) wells located in shale. A standard keyword version of the input material model is developed using the FEM for UBD wells in Pieere-1 Shale, which is simulated through the ABAQUS/CAE. Laboratory investigation is taken for provided model input parameters.

The simulation results indicated that the material dilation, directional properties, and transient pore pressure impacts in mud design program of shale is significant and should not be avoided their effects on borehole failure assessment. The outcome of this study will help us to understand the physics of material dilation & yielding on time delayed borehole instability.

Introduction

The mechanical behaviour of rocks and rock masses has been extensively investigated in the fields of civil & mining engineering and adaptation of rock failure mechanism from these fields in use in the petroleum industries in the area of borehole stability analysis. It is found that the most challenging part in borehole stability modelling is to organize the consistent input parameters, while material dilation is one of the crucial one which might be considered in borehole stability assessment. Because it is influenced pre-peak non linear rock deformation when material is reached at yielding. Cook [3] proved that dilation during compression to failure was a pervasive volumetric property of rocks and not a superficial phenomenon. Dilation represents the true volumetric behaviour of rocks, and it is closely related to the process of rocks failure. Experimental and field observations of rock failure show that the failure process is closely associated with rock dilation, which is a phenomenon associated with micro-crack initiation and propagation, and increase in void space together with decrease in transient pore pressure when the rock is loaded beyond a certain threshold. Since, transient pore pressure together with peak rock strength & stiffness has direct influenced on time delayed borehole failure; a sensitivity analysis is essential to evaluate material dilation impacts on material yielding along with transient pore pressure trend.

It is important to understand nonlinear characteristics of rocks before and after the peak stress and subsequently test the behaviour under various loading conditions in numerical modelling with a constitutive model for a better understanding of rock failure process. However, it is a very challenging and difficult task to develop a constitutive model which represents the complete stress-strain behaviour of rocks adequately, especially for the nonlinear response such as dilation. Therefore, in most popular failure criteria, such as linear Mohr-Coulomb failure criterion and non-linear Hoek-Brown failure criterion, the rock dilation is assumed to remain as a constant when the rock mass is deformed. Moreover, in many numerical analysis tools [Itasca, Ansys, ABAQUS], the default value for dilation angle is often zero for all the nonlinear constitutive models. In fact, a constant dilation angle is an approximation that is clearly not physically correct. This assumption of constant dilation is made largely because little is known about how the dilation of a rock changes past peak load. Some researchers [Alejano et al 2995, Detournay et al 1986, Cai, M., et al 2010] illustrates that it may be unrealistic and misleading to use a constant dilation angle. They also point out that dilation angle should be a function of plastic parameters and confining stress.

Literature serves [Cook et al 1970, Brace et al 1966, Bieniawski et al 1967, Lajtai et al 1974, Martin et al, 1994, Cai M et al 2004], implied that the failure process of brittle rocks can be divided into the following stages. 1) crack closure; 2) linear elastic deformation; 3) crack initiation; 4) stable crack growth; 5) crack coalescence and damage; 6) unstable crack growth; 7) failure; 8) post peak behaviour. A detailed illustration of the dilation process of rocks can be found in [Zhao et al 2010]. On the other sides, fields observation indicate that rock failure, deformation, and associated radial dilation near the borehole boundary are highly dependent on confinement. Under low confinement condition, spalling is the dominant failure mode around underground excavations in brittle hard rocks subjected to high stresses. Once the crack damage stress level is exceeded, volumetric deformation of the rock increases drastically [Cai, M et al 2004]. As noted by Kaiser et al., the volume increase of stress-fractured rocks near an excavation results from three sources; 1) dilation due to new fractures growth, 2) shear along existing fractures or joints, and 3) dilation due to geometric incompatibilities when blocks of broken rocks move relative to each other as they are forced into the excavation. It should therefore be anticipated that the strength and dilation behavior of rocks near excavation boundary should differ from those encountered at some distances away from the excavation boundary. Recently Cai. M., et al 2010 shown that the generation of borehole displacement decreases rapidly as confinement increases. This means, on the boundary of an unsupported borehole ($\sigma_3 = 0$) and the highest tangential stresses ((σ_1 = maximum), maximum rock dilation may take place if the rock fails. With the increase of σ_3 away from the excavation boundary, the dilation of surrounding rocks will decrease significantly and excavation to deeper grounds, dilation decreases gradually and finally vanishes at high confining stresses. It is one of the reasons to assume dilation angle zero in borehole stability analysis model located at overburden zone.

As already mentioned that this paper work is provided a sensitivity analysis to understand the significance of material dilation effects on material failure state under pre-peak and post peak conditions. To accomplish this study goal following activities were focused:

- Evaluates material dilatancy of Pieere-1 shale through a volumetric –axial strain relationship by using triaxial testing with various bedding planes orientation.
- Using a mobilized dilation angle model [1] by accounting influence of confining stress and plastic shear strain on excavation-induced displacement distribution around borehole.

- Using a develop More-Coulomb elasto- plastic material model [2] to quantify the impact of material dilation on material yielding, distribution of transient pore pressure, component of stress matrix and their combined effect on a mater of appropriate mud design to prevent borehole collapse for UBD wells. In this respect the lessons learned during development of the virtual hollow cylinder material models are calibrated against laboratory investigation. The feasibility of such approach of evaluating mechanical strength & stiffness subject to intact rock simulations is currently being explored by Islam et al 2010.

Model

The Mohr- coulomb elasto- plastic and a confinement and deformation dependent dilation angle model were used in this study work. These models were developed by Islam et al 2010 [2] and Cai, M., et al 2010 [1]. The way of model constructions, limitations and others relevant necessary information are explicitly discussed through these published work.

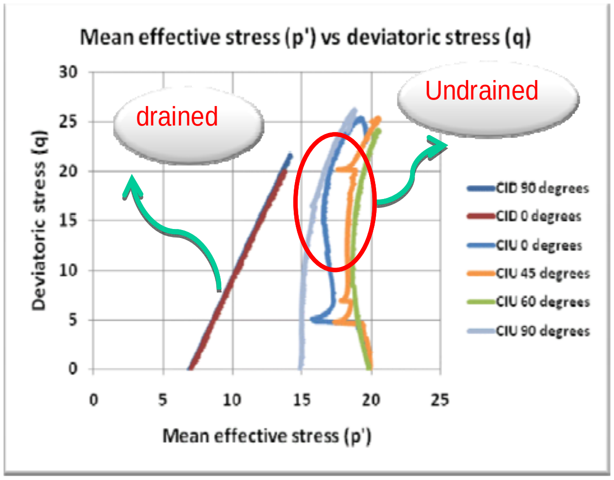
Work flow

The main workflow of this paper work is:

- Analyse & evaluate of material dilation trend from triaxial test of Pieere-1 shale subjected to different beddings plane orientations (0^0, 45^0, 60^0, & 90^0).
- Applying the developed mobilized dilation angle model to quantify the excavation induced displacement around borehole located in shale.
- Applying the developed M-C elasto plastic material model to quantify the excavation induced transient pore pressure, yielding and displacement around borehole.
- Proposed MW to prevent borehole collapse.

Result & Discussion

The laboratory tests showed that **(Fig. 1)** during assumed undrained conditions the effective mean stress was changing also in the elastic domain. This could be an indication of dilatancy, i.e. a pore pressure development due to undrained shear loading. The test results also implied that the effective mean stress change during undrained shear loading depends on the relative Poisson's ratios and Young's modulus. As the peak strength is stress path dependent (Fig 2), this implies that the dilatancy will have an important role for fully undrained numerical capacity analyses using peak strength. If the soil is stiffer vertically (E_t > Ep) we obtain D > 0, while for a larger horizontal stiffness (E_t < Ep) the stress path is D <0. (Et = tranverse young modulus, Ep = Young modulus parallel to beddings, D = dilatancy parameter).For a traditional layered shale the latter is often the case (E_t < Ep), meaning that we numerically will have a contractant behavior in the elastic domain for a fully undrained behavior. This could underestimate the strength significantly. And care should be taken when choosing the appropriate stiffness values.

a) 

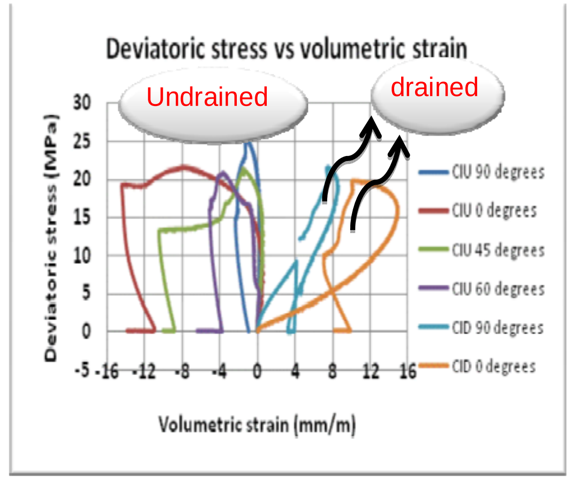
b) 

Fig. 1 Experimental investigation both drained & undrained mechanisms to show stress path (left side) & material dilation behavior (right side).

Simulated results show that the M-C, elasto-plastic numerical model is acceptably predicting mechanical failure stress state. The model enables to quantify material dilation and yielding effects at the near borehole wall region. A quite large plastic area was obtained because the M-C elasto- plastic model is normally designed for large deformation and low mud weight (MW). The simulated results also indicated that undrained material model is sensitive for material dilation because transient pore pressure distribution is strongly influenced by material dilation. Thus, it is essential to investigate the effect of material dilation on material yielding and pore pressure distribution around the borehole wall.

a) b)

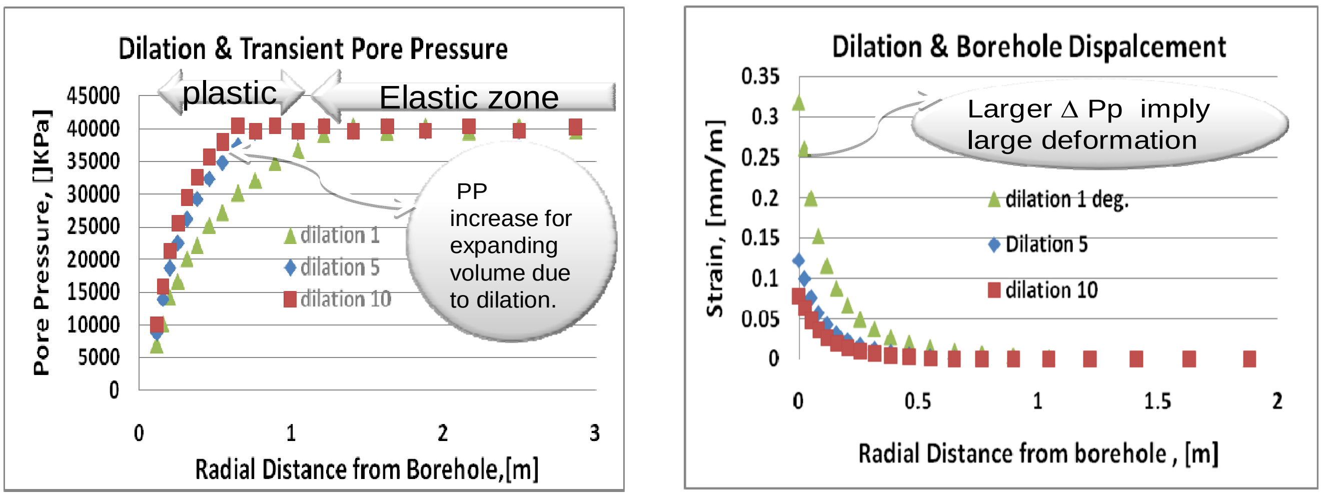


Fig.2 The effect of material dilatancy on the transient pore pressure (left site) and borehole displacement (right site) at constant in-situ stress regimes.

References

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