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Effect of different stress path regimes on borehole instability in poorly cemented granular formations

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ABSTRACT

Boreholes are drilled for different purposes such as discovering potential new deposits of underground minerals, extraction of petroleum, underground strata investigation, etc. Although no specific significant problems have been reported on drilling through hard rocks and strong formations, considerable problems have been observed in areas consisting of a sandy formation where particles are not strongly cemented by natural cement agents such as clay, iron oxide or calcite. In this study, a series of the thick-walled hollow cylinder (TWHC) laboratory tests was conducted on synthetic poorly cemented sand specimens in which the applied stresses were at levels of generating breakout on the borehole wall. Five different stress paths were designed and applied to the specimens to investigate the effect of stress paths on the borehole failure. Two borehole diameter sizes (10 mm and 20 mm) and three different cement contents (6%, 7% and 8%) were considered to evaluate the effect of the borehole size and grain bonding strength on the borehole failure in poorly cemented sandy formations. The results showed that in these weak formations the confining pressure has a more significant effect on the instability of the borehole than the cement agent content. It was found that for any stress path the effect of the supporting stress on ε_1 was more significant for 10 mm borehole sizes. In addition, based on the applied stress paths a new failure quadrilateral was determined for poorly cemented sands. Results showed that with increasing the cement content, similar quadrilaterals with almost parallel sides will be established. These outcomes can contribute to improving the design of the supporting systems and can be utilised to predict the borehole instability prior to drilling.

1. Introduction

Drilling a borehole into the earth crust and removing the underground geomaterials cause stress concentration around the borehole. After the borehole is drilled, tangential stress will be induced on the borehole wall based on the magnitude of the in situ stresses, while the radial stress will tend to zero if there is no supporting pressure acting inside the borehole. The magnitude of stresses depends on the borehole trajectory, value and orientation of in situ stresses and mud pressure inside the borehole (Bradley, 1979). In a poorly cemented sand formation, since there are no adequate cement agents on the interface of sand grains, the induced extensile stress leads to the breakage of bonding between the particles and creating an inelastic damaged zone around the borehole (Ewy and Cook, 1990a, 1990b). The progressive growth of this damaged zone may lead to the borehole failure and render the borehole useless for any other purposes. Failure of the borehole can cause problems such as stuck pipes, lost circulation, etc. Usually, depending on the ground conditions and method of drilling (e.g. air pressure or filled with a drilling mud) the excavated area is supported by a specific supporting system exerting a pressure, P_w on the borehole wall (Zoback et al., 2003).

Aadnoy and Belayneh (2008) introduced an analytical solution for modelling the load history and evaluating the fracturing pressure at the borehole wall considering the effects of temperature changes and Poisson's ratio. They showed that excluding the Poisson's ratio from the calculations results in the significant underestimation of the fracturing pressure.

It has been estimated that about 70% of the world's oil and gas reserves are found within this category of weakly-consolidated or non-consolidated strata (Bellarby, 2009). Sand production occurs in oil wellbores due to the combination of extensile stress concentration and fluid flow pressure at the wellbore wall (Ranjith et al., 2013). In fact, sand production control is one of the most effective ways of increasing well production in oil and gas

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Nomenclature

TWHC	thick-walled hollow cylinder.
w_c	cement to sand grains weight ratio.
σ_Θ	tangential stress (MPa).
σ_z	vertical stress (MPa).
D_{50}	mean grain diameter (mm).
UCS	uniaxial compressive strength (MPa).
σ_{conf}	confining stress (MPa).
ϕ	angle of internal friction (degrees).
σ_n	normal stress (MPa).
σ_2	intermediate principal stress (MPa).
D_i	diameter of TWHC specimen (mm).
P	perimeter of TWHC specimen (mm).

reservoirs. Hashemi et al. (2014a) introduced a numerical model of the borehole failure in granular materials and showed that the main reason for the borehole failure in such formations is the dislocation of particles due to fluid pressure and in situ stresses.

Laboratory tests are one of the best approaches for studying the borehole stability in both hard and weak rocks. The thick-walled hollow cylinder (TWHC) test is a common approach for simulating stress and strain states around a borehole in order to investigate the failure mechanism of an underground formation under different stress paths through independent internal and external pressures, and transference of the external boundary to an infinite distance. Pomeroy and Hobbs (1962) examined the strength of coal hollow cylinder specimens. Mazanti and Sowers (1966) studied the behaviour of granite hollow cylinder specimens and the effect of the intermediate principal stress (σ_2) on their strength. Perie and Goodman (1989) investigated the macroscopic failure mechanism of synthetic rocks made of gypsum cement by conducting TWHC test. Ewy and Cook (1990a, 1990b) carried out valuable experimental studies on the behaviour of Indiana limestone and consolidated Berea sandstone by conducting tests on TWHC. Papamichos and van Den Hoek (1995) estimated the scale effect by a two-dimensional Cosserat-Mohr-Coulomb flow theory of elastoplasticity model with friction hardening/cohesion softening, and the results were compared with experimental data. They showed that for TWHC with hole diameter larger than 70 mm for Berea sandstone and 160 mm for Castlegate sandstone, no significant scale effect was observed. However, in the case of poorly cemented sands ($UCS < 2$ MPa), Hashemi et al. (2015a) and Hashemi et al. (2015b) showed that the scale effect is considerable even for inner-hole diameter 25 mm. Alsayed (1996) conducted a series of TWHC tests on rock samples to study the effect of anisotropic stress conditions on the behaviour of hard rocks. Alsayed (2002) stated that different stress paths can be applied to TWHC specimens to simulate the underground in situ stresses. Papanastasiou and Thiercelin (2010) suggested a borehole failure model based on fracture mechanics and layer buckling theories. They found a strong correlation between the TWHC strength normalized by the rock strength and the borehole size normalized by the square of the ratio of fracture toughness over tensile strength for both the model predictions and experimental results. Papamichos et al. (2010) experimentally investigated the borehole stability of Red Wildmoor sandstone, which is a weak and porous outcrop. They used acoustic emission source location to monitor the progression of internal damage and borehole failure localization and showed that stress anisotropy has an impact on hole deformation, failure stress and failure mode.

The main purpose of this study is to investigate the effect of different stress regimes on the failure of boreholes in poorly cemented sandy formations. In the current research, a number of TWHC laboratory tests were designed and performed under controlled laboratory conditions. Various stress paths were designed based on both far-field and an element on the borehole wall, and the results were compared for different stress paths. The borehole behaviour was monitored by a real-time video camera recording in order to determine the borehole failure along with measuring the stresses and strains for poorly cemented sand specimens. The outcome of this paper presents a more realistic understanding of the actual failure behaviour of poorly cemented sandy formations under different stress paths.

2. Exploration borehole drilling site observations

Borehole instability and consequent stuck-pipe issues were reported at a drilling site located near Burra, South Australia. At this site boreholes were drilled with a purpose to discover mineral deposits for potential new mines. According to the in situ geological tests, borehole failures took place in a poorly cemented sandy layer. Conventional dry drilling methods, including air core and reverse circulation (RC) drilling, were used to drill the boreholes. Subsurface investigations of sediments showed that the layers above the bedrock are not homogeneous, the shallower layers of the sediment are composed of silt and fine sand, the deeper layers of the sediments change to dark grey plastic clay, and the problematic poorly cemented sandstone comes after this clayey layer. The drilled boreholes were generally 25–30 cm in diameter with 50–200 m in length depending on the underground conditions. During the drilling process, when the drilling rod encounters the poorly cemented sandy layer, there is a considerable potential for the borehole instability. Although in previous studies (Durrett et al., 1977; Nouri et al., 2006) the fluid velocity has been identified as an important factor in wellbore instability, site investigations show that in shallow depth boreholes where no fluid velocity exists and low pore pressure has a trivial effect on the instability of drilled boreholes the effect of induced stresses on the borehole wall instability dominates.

Samples were collected from each metre of the unconsolidated sandy layer and subsequently solid and TWHC specimens were prepared for laboratory tests based on the size and geometry of sand particles collected from the site. Geochemistry tests showed that the formation consists of quartz sand grains with a weak cementation interface of iron dioxide, clay and calcite as cementing agents. The yellowish-grey grains were mostly fine and subangular with random orientations.

3. Principal stresses at the borehole wall

In the cylindrical coordinate system, the stress states at a borehole wall comprise tangential, radial and vertical stresses. These stresses are induced due to the presence of in situ stresses and can be calculated using different equations such as Kirsch equations based on the theory of elasticity (Jaeger et al., 2009; Obert and Duvall, 1967). According to the Kirsch equations, tangential and radial stresses will change across the cylinder wall with the radial distance, r. Fairhurst (2003) indicated that the maximum principal vertical stress is calculated as the weight of the overlying layers at a certain depth. The minimum horizontal stress can be measured by hydraulic fracturing and leak off test (Amadei and Stephansson, 1997). It should be noted that