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An experimental study on the relationship between localised zones and borehole instability in poorly cemented sands

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ABSTRACT

Poorly cemented sands are mainly located in areas where layers of unconsolidated formations exist. Drilling a borehole in the ground causes stress perturbation and induces tangential stresses on the borehole wall. If the cohesion between sand particles generated by existing cementation is not high enough, the tensile stress concentration may cause grain debonding and, consequently, borehole breakout. In this study a series of solid and thick-walled hollow cylinder (TWHC) laboratory tests was performed on synthetic poorly cemented sand specimens. The applied stresses were high enough to generate breakout on the borehole wall. Simultaneous real-time monitoring and deformation measurement identified the development of localised breakout zones and compaction bands at the borehole wall during the tests. The results from the video recording of the tests showed that a narrow localised zone develops in the direction of the horizontal stress, where stress concentration causes the full breakout in specimens. Dilation occurred at lower confining pressures in TWHC specimens and contracting behaviour was observed during the onset of shear bands at higher pressures. Scanning electron microscopy (SEM) studies showed that sand particles stayed intact under the applied stresses and micro- and macrocracks develops along their boundaries. The SEM imaging was also used to investigate and characterize pre-existing microcracks on the borehole wall developed due to the specimen preparation. It showed that boring the solid specimen in order to produce a TWHC specimen could generate microcracks on the borehole wall prior to testing which affects the process of borehole failure development during the test.

1. Introduction

Drilling a borehole in the ground is a common method for measuring the spatial position of underground formations, characteristics of faults and fractures, extracting oil and gas and also for monitoring the petrographic assessment of borehole walls. Several borehole instability problems during and after borehole completion have been reported by drilling companies in Australia. When a borehole is drilled through such a weak formation, instability or grain bonding breakage at the borehole wall may occur due to the relaxation of the pre-existing in situ stresses underground. Tangential stresses develop around the borehole and the radial stress tends to become zero on the borehole wall in case no supporting system is available (Hagin and Zoback 2004, a,b). If the strength of the borehole wall is not high enough, the borehole may collapse. This is due to the spontaneous re-establishment of the equilibrium in the ground after the borehole excavation. A large number of mines, as well as unconventional oil and gas reservoirs are located in formations containing geologically young and unconsolidated sands or sandstones where the particles are either weakly bonded, or even un-cemented all around the world (Musaed et al., 1999). Mavko and Jizba (1991) showed that the presence of poorly cemented sandstone increases the potential of borehole instability.

A well designed experimental study can be a valuable approach for acquiring in-depth knowledge on the failure behaviour of granular materials. These localised zones develop due to grain dislocation and crushing which may leads to formation of compaction bands and porosity reduction or dilatant zones. Haimson and Herrick (1986) and Maloney and Kaiser (1989) presented a clear correlation between the borehole breakout dimensions and the in situ stress levels. Haimson and Kovacich (2003) and Lee (2005) studied borehole instability in high-porosity Berea, Tablerock and Mansfield sandstones. They found that a narrow zone ahead of a fracture-like breakout tip underwent apparent localised grain debonding and compaction. Nouri et al. (2006) suggested

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Nomenclature

TWHC	thick-walled hollow cylinder
w_c	weight ratio of cement to sand grains
δ	weight ratio of coarse to fine sand
w_w	weight ratio of water to sand grains
τ	shear stress (MPa)
UCS	Uniaxial compressive strength
D_{50}	mean grain diameter (mm)
C_u	coefficient of uniformity
q	deviator stress (MPa)
σ_{conf}	confining stress (MPa)
ϕ	angle of internal friction (deg)
ν	Poisson's ratio

that in soft rocks a pure shear failure or a combined shear-spalling process seems to occur, while in hard rock formations a combination of shear and extension fractures was observed. In the case of weak rocks, material was totally plastified, while in some cases when the rock material was stronger the zone remained relatively intact. Haimson and Klaetsch (2007) showed that in natural high porosity sandstones grains are bonded along narrow contact areas while in low porosity sandstones particles' bonds are all around them. Therefore, in high porosity rocks grains will be dislodged when the in situ stresses reach the strength of the narrow cementation zone (e.g. Navajo and Aztec sandstones). A number of researchers have performed laboratory tests aimed to produce compaction bands by applying high triaxial compressive stresses (Haimson, 2007; Olsson et al., 2002; Vajdova and Wong, 2003; and Olsson, 1999). Haimson (2007) and Vajdova and Wong (2003) reported the formation of compaction bands in laboratory tests on hard rocks. Vajdova and Wong (2003) performed triaxial tests on slotted cylindrical sandstones and found a high stress concentration at the notch edge, which resulted in compaction bands. Katsman and Aharonov (2006) simulated the compaction bands with a network of springs and stated that compaction bands can be generated around the borehole. It is worth noting that the localised compaction bands are important factors in actual field conditions, as they can induce local permeability reduction in underground layers. Also, Desrues et al. (1996) suggested that the localisation phenomenon causes failure in porous soft rocks especially at low stresses and temperatures.

The thick-walled hollow cylinder (TWHC) test is a common method for simulating stress and strain states adjacent to underground excavations in order to study the failure behaviour of geomaterials under different stress paths. The specific shape and loading paths that can be applied to these specimens make them more popular for simulating in situ stress conditions around underground openings such as boreholes, wellbores and tunnels and for reproducing various combinations of stress paths (Daemen and Fairhurst, 1971). Hoskins (1969) investigated the strengths of five different rocks in the form of TWHCs. Alsayed (2002, 1996) utilised TWHC specimens to study the effect of different loading conditions on the behaviour of hard rocks. Santarelli and Brown (1989) and Perie and Goodman (1988) investigated the macroscopic failure mechanisms of synthetic rocks made of gypsum cement by conducting TWHC tests.

In this paper a series of TWHC laboratory tests was designed and conducted under fully controlled conditions. Real-time monitoring of sand debonding was carried out during the test in order to study the failure mechanism of poorly cemented sands around the borehole. Micromechanical behaviour of the specimens when inducing a localised zone on the borehole wall under different stress conditions was investigated using scanning electron microscopy (SEM). This study aims to provide a more realistic and comprehensive view on the behaviour of poorly cemented sands and can be helpful when designing an adequate supporting system to keep the borehole open during the service period.

2. Exploration drillings

Exploration boreholes are being drilled throughout Australia to discover new mineral reserves leading to potential mining activates. One of these drilling sites is located in Burra, South Australia where exploration boreholes are being drilled through a poorly cemented sandy formation. The majority of these boreholes are 25–30 cm in diameter with lengths varying from 80 m–250 m depending on the mine exploration plan. The subsurface investigations of sediments and borehole surveys show that the sediment above the bedrock is heterogeneous and irregular, and shallower layers of the sediment are composed of silt and fine sand. This layer is underlain by dark grey plastic clay, and then by a

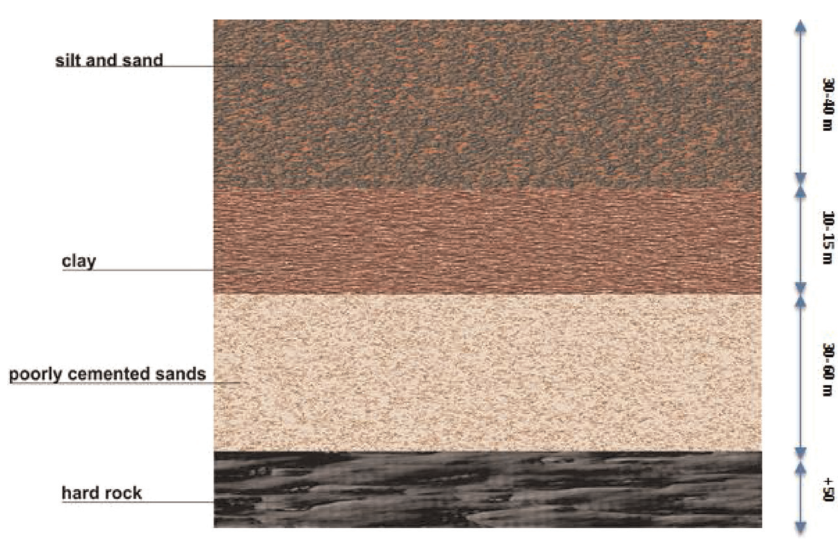

Fig. 1. Geological cross section near Burra, South Australia (Hashemi et al., 2014).