Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 519–531

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

A borehole stability study by newly designed laboratory tests on thick-walled hollow cylinders

S.S. Hashemi*, N. Melkoumian, A. Taheri

Deep Exploration Technologies Cooperative Research Centre, School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, Australia

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
4 June 2015
Accepted 9 June 2015
Available online 30 July 2015

Keywords:
Real-time monitoring
Experimental investigation
Thick-walled hollow cylinder (TWHC)
Poorly cemented sand formations

ABSTRACT

At several mineral exploration drilling sites in Australia, weakly consolidated formations mainly consist of sand particles that are poorly bonded by cementing agents such as clay, iron oxide cement or calcite. These formations are being encountered when drilling boreholes to the depth of up to 200 m. To study the behaviour of these materials, thick-walled hollow cylinder (TWHC) and solid cylindrical synthetic specimens were designed and prepared by adding Portland cement and water to sand grains. The effects of different parameters such as water and cement contents, grain size distribution and mixture curing time on the characteristics of the samples were studied to identify the mixture closely resembling the formation at the drilling site. The Hoek triaxial cell was modified to allow the visual monitoring of grain debonding and borehole breakout processes during the laboratory tests. The results showed the significance of real-time visual monitoring in determining the initiation of the borehole breakout. The size-scale effect study on TWHC specimens revealed that with the increasing borehole size, the ductility of the specimen decreases, however, the axial and lateral stiffnesses of the TWHC specimen remain unchanged. Under different confining pressures the lateral strain at the initiation point of borehole breakout is considerably lower in a larger size borehole (20 mm) compared to that in a smaller one (10 mm). Also, it was observed that the level of peak strength increment in TWHC specimens decreases with the increasing confining pressure.

1. Introduction

Borehole stability analysis is an important issue for researchers in the field of geotechnical, mining and petroleum engineering. Several borehole instability problems during or after the completion of drilling have been reported by a number of exploration companies in Australia. Many of these problems were reported in drilling projects in poorly cemented sand formations at the depth of up to 200 m beneath the ground. The sand production problem, as it is known, has also been observed in weakly bonded sandstones where the debonding of sand grains can be triggered by fluid pressure and induced stresses leading to the failure of sandstone at the borehole wall (Geertsma, 1985; Perkins and Weingarten, 1988). The strength of a granular material formation is generated mainly by a natural cementing agent that bonds sand grains together (Al-Awad et al., 1999).

In recent decades, a number of numerical and experimental studies have been conducted on borehole stability in different rock formations. Gough and Bell (1982) showed that, in a large number of vertical oil wells, the orientation of consistent breakouts coincides with the direction of the regional minimum horizontal principal stress. Numerical studies on poorly cemented sand formation by Hashemi et al. (2014a, b) revealed that breakage of weak bonding between sand particles causes instability and sand grains remain intact in the case of a borehole failure. In laboratory conditions it was shown that borehole breakouts grow mainly through radial penetration into the rock mass without any circumferential extension (Lee and Haimson, 1993). Haimson and Song (1993) conducted laboratory tests on two varieties of Berea sandstones with 17% and 22% porosity, respectively, and revealed two distinct breakout patterns directly related to the microstructures of these rocks and their different modes of failure. Microscopic observation by Hagin and Zoback (2004) revealed that the fundamental mechanism behind sand production is the growth of small, opening-mode and splitting cracks oriented parallel to the tangential stress, starting very close to the borehole wall and propagating deeper into the matrix with increasing stress. Similar

* Corresponding author. Tel.: +61 426111280; fax: +61 883134359.
E-mail address: shashemi@civeng.adelaide.edu.au (S.S. Hashemi).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2015.06.005

borehole instabilities have also been documented by many other authors (Fischer et al., 1978; Ewy and Cook, 1990a, b; Chang et al., 1997; Al-Ajmi and Zimmerman, 2006).

Unconfined compressive strength triaxial and thick-walled hollow cylinder (TWHC) tests are two of the most useful laboratory experiments (King, 1912; Robertson, 1955; Hoskins, 1969; Adeyanju and Olafuyi, 2011). The geometry of the TWHC allows the application of various load path combinations to simulate stress conditions around boreholes. The classical hollow cylinder approach is not well suited to investigating the stability of poorly cemented formations because, during or subsequent to these tests, the instability of the weak sandstone arch and the grain debonding process in sandy formations cannot be captured. The hollow cylinder tests on an intact rock sample focus mainly on rupture phenomena such as shear and tensile failure (Hall and Harrisberger, 1970; Tippieand and Kohlhaas, 1973; Cleary et al., 1979).

In this study, a series of newly designed laboratory tests involving real-time monitoring of the development of breakout in an unsupported borehole was conducted. The paper aims to provide a more accurate representation of the actual behaviour of poorly cemented sands, which will be invaluable in designing appropriate borehole support systems. The tests were conducted on specimens of poorly cemented sands prepared in laboratory and the effects of different mixture characteristics (i.e. proportion of sand, cement and water) on their mechanical behaviours were studied by conducting compression tests on solid and hollow cylindrical specimens.

2. Drilling field investigation

Exploration boreholes are usually drilled to uncover potential future mine sites. In many cases, drilling is undertaken through poorly cemented sand formations. Generally, the boreholes are 250–300 mm in diameter and 50–200 m in length, depending on the underground conditions in Australia. This study focuses on solid and TWHC laboratory test specimens based on disturbed samples collected from a problematic drilling site at Burra, South Australia. At this site the sediment above bedrock is heterogeneous, with the shallower layers composed of silt and fine sand and the deeper layers transition to dark grey plastic clay. The problematic, poorly cemented sandstone underlies this clayey layer and consists of sand particles with a weak cementation due to the presence of iron dioxide, clay and calcite (Fig. 1). Quartz grains are mostly fine and sub-angular with random orientations. The yellowish-grey specimens were prepared in laboratory so that their fabric closely resembles that of the poorly cemented sands at the drilling site.

To drill a borehole at this site, different drilling methods have been tried to minimise the risk of borehole failure. In some cases, drilling mud has been used to maintain an open borehole during drilling. However, to conduct further investigation, some boreholes need to remain open for several months after drilling. The air core drilling and reverse circulation drilling methods were used in these cases. These are dry drilling methods and have been conventionally applied to drilling through soft ground in Australia. The cuttings are conveyed to the surface and pass through the sample collection system from where they are collected. Drilling continues with the addition of rods to the top of the drill string. When the drilling string reaches the poorly cemented sand layer, the borehole may collapse if the bonding between sand particles is not strong enough to provide stability. According to the reports from drilling company, the main factors affecting borehole instability include the low strength of poorly cemented sands which cannot sustain the existing in-situ stress after drilling, and, in few cases, fluid flow due to a confined aquifer near the borehole collapse zone.

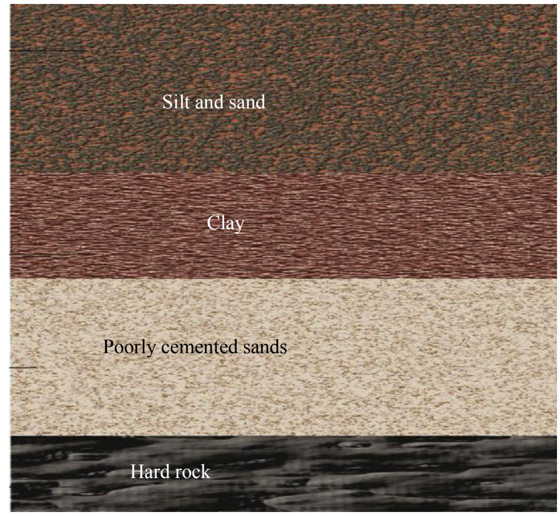

Fig. 1. Vertical geological cross-section near Burra, South Australia (Hashemi et al., 2014a, b).

3. Thick-walled hollow cylinders (TWHCs)

Hollow cylinder specimens were first used in the early 20th century when the importance of adopting a realistic model was identified for an underground opening. The opening was located at a depth of 9.5 km and susceptible to collapse due to high in-situ stresses (Hoskins, 1969). Since then, a wide range of experimental investigations involving hollow cylindrical specimens has been conducted. Robertson (1955) studied the effect of the inner-to-outer diameter ratio on the strength of various rocks. King (1912) analysed the system of fractures that might develop during compressive tests on hollow cylinder specimens under different stress states. Bridgman (1952) performed hollow cylinder tests under different loadings. Pomeroy and Hobbs (1962) examined the strength of hollow cylinder coal specimens. Mazanti and Sowers (1966) studied the behaviour of hollow cylinder granite specimens and the effect of the intermediate principal stress (σ_2) on their strength. Ewy et al. (1988) studied the deformation and fracture development in a hard rock around a borehole using TWHC tests. These and other work involving TWHC tests show that the TWHC configuration tests are well suited for identifying and investigating both the macro- and micro-properties of different rock types.

Depending on the thickness of a hollow cylinder specimen, stresses that develop in its wall due to the application of uniform stresses can be analysed by two different methods. In a TWHC specimen, the wall thickness, t, which is much smaller in comparison to its inner diameter, D_i (i.e. $D_i > 20t$), the stresses that distribute across the specimen walls can be considered almost homogeneous and uniform. This assumption is not fully acceptable in the case of a thick-walled hollow specimen, the wall thickness of which is larger in comparison to its inner diameter. In the latter case, stress distribution is not homogenous in the specimen wall. In many textbooks (e.g. Obert and Duvall, 1967; Jaeger et al., 2007) closed form solutions based on the linear theory of elasticity for calculating stresses and strains in both thin- and thick-walled hollow cylinder specimens were presented. For a TWHC with an inner diameter of D_i, outer diameter of D_o and length of L, subjected to axial force (F), uniform internal stress s_i and external stress s_o, the principal stresses at any point at a radial distance r from the centre of the specimen can be presented in cylindrical coordinates as follows (Jaeger et al., 2007):