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Technical Note

The failure behaviour of poorly cemented sands at a borehole wall using laboratory tests

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1. Introduction

Borehole stability analysis is an important challenge 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 are reported in drilling projects in poorly cemented sand formations at depths 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 the sandstone at the borehole wall [1,2]. The strength of a granular material formation is generated mainly by a natural cementing agent that bonds sand grains together [3].

Numerical studies on poorly cemented sand formation by Hashemi et al. [4] 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 [5].

Unconfined compressive strength (UCS) triaxial and thick-walled hollow cylinder (TWHC) tests are among the most useful laboratory experiments [6–10]. 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.

In this study a series of newly designed laboratory tests involving real-time monitoring of the development of borehole breakout was conducted. The paper aims to provide a more accurate representation of the actual behavior 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 the laboratory and the effects of different mixture characteristics (i.e. proportion of sand, cement and water) on their mechanical behavior 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

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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. Quartz grains are mostly fine and sub-angular with random orientations.

When the drilling string reaches the porous poorly cemented sand layer, the borehole may collapse, should the bonding between sand particles may not be strong enough to provide stability. In addition, occasionally the actuator is unable to restart and rotate the rod if the gap between the drilling rod and the borehole wall is completely filled with sand grains and thus the drilling rods jam in the borehole. According to reports from the 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. However, there are other factors that account for borehole instability in exploration boreholes such as erosion and poor drilling practice, and these are not considered in the current study.

3. Experimental study

3.1. Laboratory test facilities and arrangements

Specimens that were both of a reasonable diameter and of a borehole wall thickness that satisfies the TWHC theory condition (i.e. $R_i < 10t$) were used. Hence, a HQ Hoek triaxial cell of 63.5 mm diameter and 127 mm in height was utilised.

A servo-controlled axial loading system of 100 kN loading capacity with 0.1 N accuracy was used for applying vertical stress to the specimen. Although the Hoek cell was originally designed to apply high confining pressures to hard rock specimens, the hydraulic pressure gauge was modified to allow measuring the confining pressure at very low amounts.

The TWHC specimens, consisting of poorly cemented sands, cannot be retrieved from the cell after the destructive tests due to the development of a large number of macro- and micro-cracks and the debonding of sand particles. To address this issue, the triaxial cell was modified to allow simultaneous capturing of the borehole failure mechanism and the process of sand grain debonding at each time step and at different stress paths. A micro camera with a 225 pixel per inch (ppi) resolution was installed inside the hollow platen to record the process of sand debonding and borehole breakout. The micro camera was connected to a personal computer to record the borehole conditions throughout the test.

The steel moulds were designed and manufactured for the tests (Fig. 1(a)). The dimensions of the moulds were 127 mm in length and 62.5 mm in diameter. Two removable steel dowels with the diameters of 25 mm and 10 mm were used together with the moulds. These dowels were embedded in the mould to create the borehole in the specimens.

A tool was designed and manufactured to uniformly compact the mixture, as shown in Fig. 1(b). Each specimen was compacted in three separate layers of equal thickness (42 mm). The compaction energy for each impact was maintained constant and equal to 0.35 Nm/cm^3, which was calculated based on the applied force of the manufactured compactor. To minimise the bedding error effect for the very top layer a collar was used allowing this layer to achieve conditions similar to those of the lower layers (see Fig. 1a).

Two sets of cylindrical platens were manufactured from hardened steel and were hardened prior to grinding and lapping. The platens were designed using the commercial finite element analysis software ABAQUS 6.11 and loading steps similar to those applied during test conditions were applied to the model (Fig. 2). According to the results of simulated platens, the strain of the platens was less than 0.01% with the application of the maximum load of 100 kN. This is far greater than the predicted strength of the specimens.

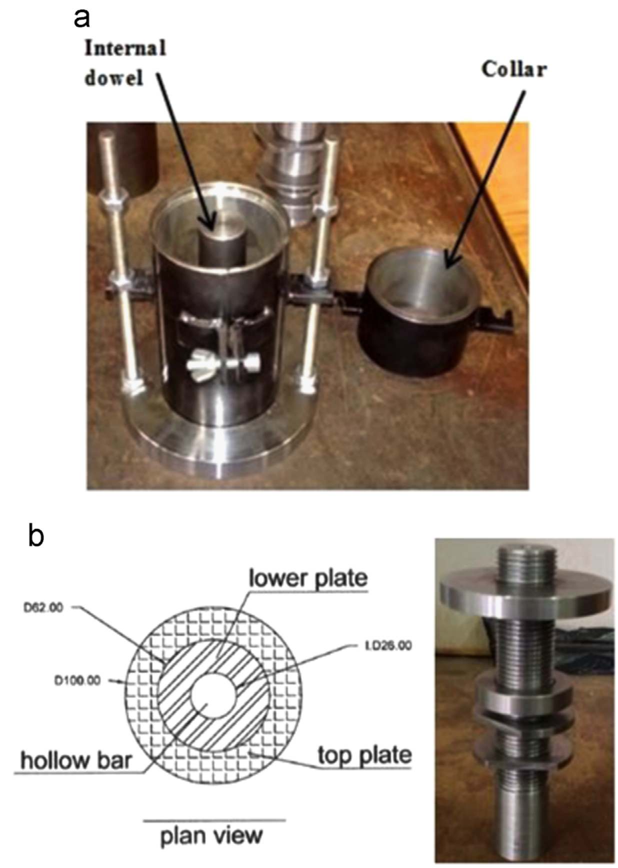

Fig. 1. Apparatus developed to prepare the specimens. (a) Special moulds for preparing TWHC specimens and (b) special device for compacting the mixture in the mould uniformly.

To avoid applying the weight of the triaxial cell to the specimen during the test, a wooden base was manufactured to support the weight of the triaxial cell. Thus, there was no need to apply an external pressure on the specimens to hold the triaxial set before transferring it to the loading machine.

3.1.1. Test procedure and setup

Pairs of axial and lateral strain gauges were used to measure local deformations on the specimen. Two linear-variable differential transformers (LVDTs) were installed between the top and bottom rams of the loading machine to measure axial displacement externally. The captured image of the micro camera was checked to ensure that the focal length of the lens was on the middle of the specimen hole and the position of the LEDs was controlled to ensure the borehole illumination was suitable for recording. In the first stage of loading the vertical and confining stresses were increased simultaneously up to a certain stress level, which simulates the hydrostatic condition. Then, in the second stage, the sample was subjected to vertical compression at a constant displacement rate of 0.07 mm/min.

The video capture software was synchronised with the data acquisition system to facilitate the observation of the sand particle