Novel true triaxial apparatus applied to the study of sand mass production under anisotropic stress conditions

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ABSTRACT: Using a novel true triaxial setup, sand production tests on hollow quasi-cylinder Castlegate sandstone specimens have been performed on irreducible water saturated specimens with oil flow under varying levels of axial and lateral stress anisotropy, obtaining sand onset and rate. The experimental results have been compared with analytical models for sand onset and sand rate predictions. Also, a new model that includes the effect of axial and lateral stress anisotropy has been developed and calibrated on the test results.

1 INTRODUCTION

Increasing the profitability of sand producing fields requires sand management and accurate predictions of sand onset and sand mass such that the well completion method and the drawdown and depletion during the life of the well is optimized. Research in sand production has addressed various issues and has advanced the state of the art by, for example, studying sand onset and sand production rate, by classifying sandstones according to their sand production potential, by looking at multiphase flow conditions and the effect of water breakthrough and gas flow in gas reservoirs (Hettema 2006, Papamichos et al 2008).

Despite the progress made, sand production models have not been proven under fully anisotropic stress conditions (true triaxial stress states) which are most commonly encountered in the field. In fact, most of sand production models in the literature have been experimentally validated under isotropic stress conditions and subsequently applied to anisotropic states as well. However, this extrapolation may not be directly valid. Moreover, sand rate models are inherently difficult to field validate due to for example unknown conditions downhole at the sand producing intervals, lack of or unreliable sand measurement instrumentation, measurements at interconnected wells etc.

So far most of the available experimental setups for anisotropic studies have been using cubical samples, often without any pore pressure control and the possibility of fluid flow, giving unrealistic stress conditions (Papamichos 2010). To be able to study sand mass production, borehole stability and hydraulic fracturing under realistic anisotropic conditions, SINTEF and MTS Systems Corporation have recently together developed a novel true triaxial cell with the capability of studying semi-cylindrical rock specimens under fully anisotropic stress conditions, with radial fluid flow (MTS 2018).

In this paper we present the exciting new experimental setup, together with preliminary experimental results from an ongoing investigation of sand production on hollow quasi-cylinder Castlegate sandstone specimens, comparing the results with a newly developed model that includes the effect of axial and lateral stress anisotropy.

2 EXPERIMENTAL SETUP

2.1 *The true triaxial apparatus*

SINTEF has been running research projects on borehole stability and sand production for more than two decades. Most of this research has been based on experiments under isotropic stress conditions (Papamichos et al 2001, Papamichos et al 2019). After noticing an increased demand from industry on recreating more realistic stress conditions, SINTEF started a process to design and acquire a new true triaxial setup around 5 years ago. The goal was to design a machine that would give us true triaxial stresses (that is, the possibility to independently control stresses in three directions) on a quasi-cylindrical specimen geometry, with the possibility of pore pressure control and radial fluid flow. Also, the mounting of specimens and the operation of the machine had to be relatively fast to be able to provide services for the industry at a reasonable and competitive cost.

The stresses are provided by confining pressure outside a rubber sleeve around the sample, in addition to an axial actuator and two lateral actuators. The main difficulty with using a cylindrical geometry, is how to transfer the lateral forces onto your specimen without creating unrealistic stress concentrations and causing leaks. In the design phase, SINTEF therefore ended up with a semi-cylindrical sample geometry where opposite sides of the cylinder are slabbed (shown in Fig. 1). The lateral forces are applied from the two horizontal actuators by metal pistons contacting the rubber sleeve (having the same curvature as the sample diameter), transferred through the sleeve, onto metal inserts which, together with the rock specimen, forms a complete cylinder, before reaching the slabbed parts of the specimen. Simulations have been performed to evaluate the stress conditions, showing that the design gives very little stress concentration and recreates realistic true triaxial stresses in an extended region around the borehole.

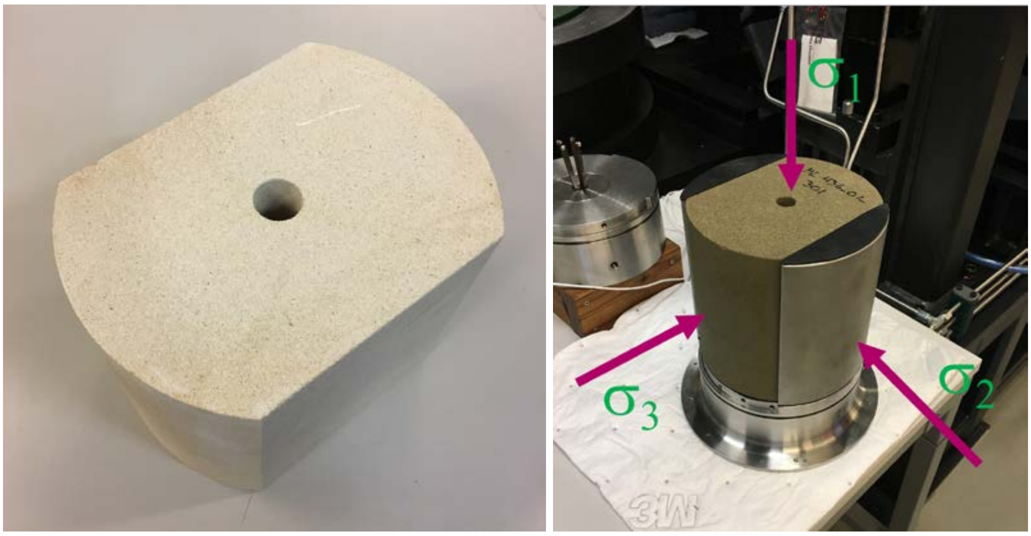

Figure 1. (Left) Hollow cylinder rock specimen with slabbed sides, which is the standard geometry used in the true triaxial apparatus. (Right) Part of the sample stack showing the rock specimen and the metal inserts that make up a complete cylinder. The three main stress directions are also indicated.

After the completion of the specimen design, the task of designing and building the apparatus was handed over to MTS Systems Corporation, which has extended experience in building custom-made large-scale material testing solutions. They final design, as shown in Figure 2, consists of a pressure vessel providing up to 100 MPa confining stress, in addition to a 2.6 MN axial actuator and two 2.1 MN lateral actuators, all hydraulically controlled. The upper dome of the cell can be lifted hydraulically to reveal the sample stack, which then can be moved horizontally to a parking position with easy access for mounting and instrumenting the specimen.

Instead of using a conventional flange design with a large number of bolts for sealing the cell, this apparatus uses an innovative locking mechanism with two large metal clamps (as can been seen in Fig. 2) held together by four threaded rods. To achieve the necessary closing force on the rods, hydraulic nuts are used. This means that the cell can be closed and locked within minutes, without the need to manually tighten any bolts.

Figure 2. Overview of the true triaxial apparatus, with the dome in the lifted position. The two metal clamps with the threaded rods, for locking and sealing the cell, can also be seen.

The sample stack uses a very flexible modular design which can take truncated specimens with a diameter ranging from 50 mm to 200 mm, with a typical length to diameter ratio of 1:1. When run in a biaxial-mode (without the use of the lateral actuators), the setup can even accommodate samples up to 400 mm in diameter.

The base plate of the sample stack has a wide range of available fluid ports and instrumentation feedthroughs for connecting fluid lines and any needed in-vessel transducers (typically pressure sensors, and LVDT's and clip gauges for sample deformation measurements), as shown in Figure 3. In addition, there are 26 coaxial feedthroughs for ultrasonic transducers, meant for any future acoustic system upgrade.

The whole setup is controlled by a versatile and upgradable MTS FlexTest 200 controller, providing high-speed closed-loop control, transducer conditioning and data acquisition.

2.2 *Sand production experiments*

Experiments to study sand production were carried out on slabbed, hollow cylinder specimens of Castlegate sandstone, a yellow outcrop sandstone from Western Colorado that has been used as an analogue of weak to medium strength reservoir sandstones, with a diameter of 20 cm, height of 20 cm and 2 cm inner hole. It has porosity of 26-28%, brittle quartz cementation, and permeability of ca. 500-600 mD. Castlegate has a uniaxial compressive strength (UCS) of 14-18 MPa at oil saturated conditions and 7-9 MPa at irreducible water saturation conditions, i.e. a water saturation of S_{wi} = 30-35% in these experiments. In S_{wi} saturation the remaining pore volume is saturated with kerosene oil. The tangent Young’s modulus at 50% the peak stress at uniaxial tests was calculated as E_{50} = 7-9 GPa for oil saturated rock and as E_{50} = 1.6-2.4 GPa for S_{wi} rock.

In these sand studies, fluid flow is quasi-radial towards the hole. A sand trap, as shown in Figure 4, is also placed underneath the specimen for real-time monitoring of any produced solids to calculate sand rate and cumulative sand as a function of time. The borehole is usually kept at ambient pressure during these experiments.

Figure 3. Two different views of the complete sample stack. The rock specimen is located inside the black rubber sleeve, with the axial load cell on top of the stack. The various fluid ports and instrument feed-throughs can be seen on the base flange.

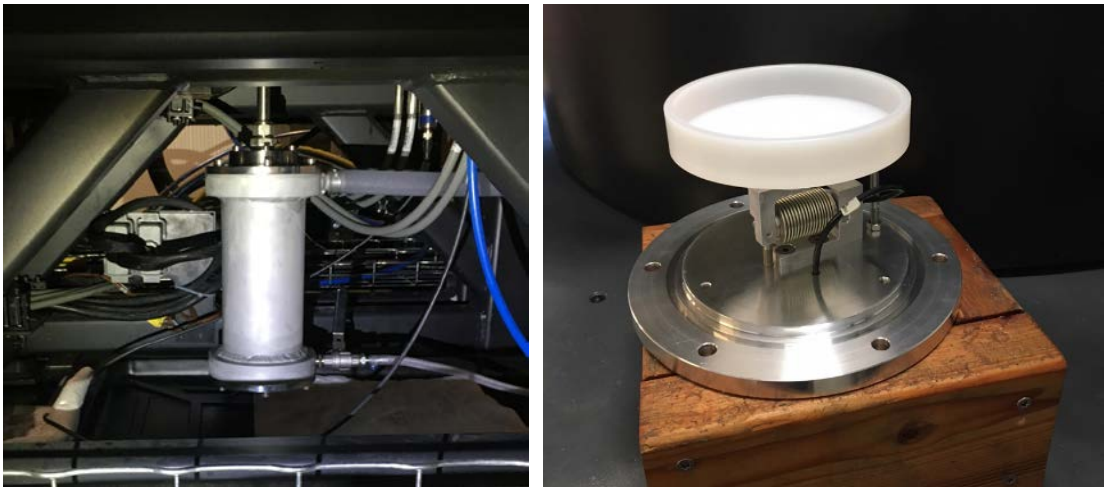

Figure 4. Sand trap at the bottom of the cell for real-time monitoring of any produced sand. The outer cell (left) houses a bowl sitting on top of a load cell (right).

3 RESULTS AND DISCUSSION

Typical test results are shown in 5, where the minor lateral stress is plotted as a function of the tangential strains at the inner hole at the two principal stress directions, together with a plot of the sand mass production as a function of the minor lateral stress.

In Table 1 the stress anisotropy conditions that have been studied so far in the true triaxial test setup are listed. Similar stress anisotropy ratios for the effective stresses can be encountered in depleting fields. The values reported for the various stress anisotropy ratios correspond to the measured major lateral stress at sand onset.

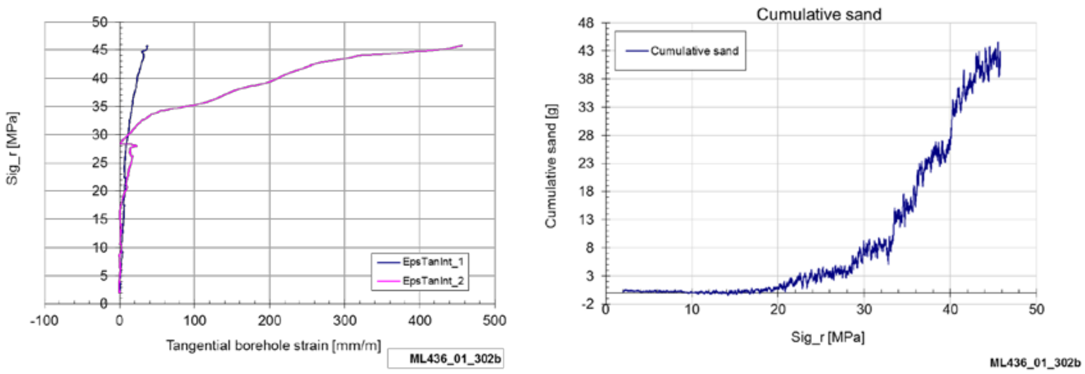

Figure 5. (Left) Minor lateral stress vs the tangential borehole strains along the two principal stress directions, and (right) cumulative sand as a function of minor lateral stress for $K_z = 1$, $K_r = 2/3$.

Table 1. Stress anisotropy test conditions investigated, where σ_R, σ_r and σ_z denote the major lateral, minor lateral and axial stress, respectively. The reported value for each stress anisotropy ratio corresponds to the critical sand onset stress σ_R observed in the experiments.

Stress anisotropy	**$K_z = \sigma_z/\sigma_R$**		
$K_r = \sigma_r/\sigma_R$	**2/3**	**1**	**2**
1		33.0	
2/3	28.4	26.5	25.4
1/3		23.7	

A photograph of the bottom of the sample after testing, together with CT scans normal to the borehole axis, can be found in 6. An extensive damage zone, with breakouts developing, is observed along the direction of the minor lateral stress.

The values obtained from the experiments (see Table 1) are compared in Figure 7 with theoretical models that take into account effect of stress anisotropy (Papamichos and Furui 2019). In the left side plot of Figure 7 results for the effect of lateral stress anisotropy are shown. The comparison with the model predictions are here satisfactory. The major lateral stress for sand onset is normalized here with the lateral stress for onset under isotropic condition. Similarly, the right side of Figure 7 plots the results for the effect of axial stress anisotropy. The comparison with the model predictions deviate for the low stress anisotropy ratio. Further tests will demonstrate whether this is an actual trend or possible experimental variability.

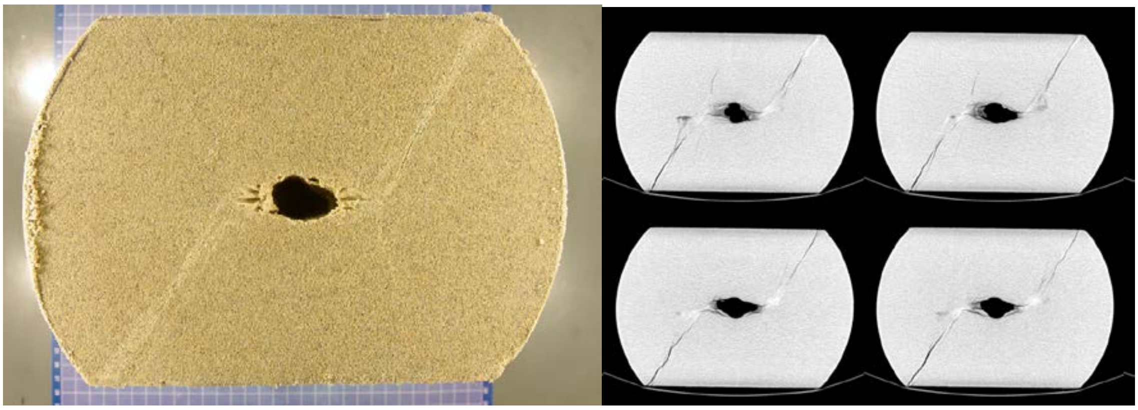

Figure 6. Post-test (left) photograph and (right) CT scans normal to the borehole axis for a specimen tested under $K_z = 1$, $K_r = 2/3$ stress anisotropy ratios.

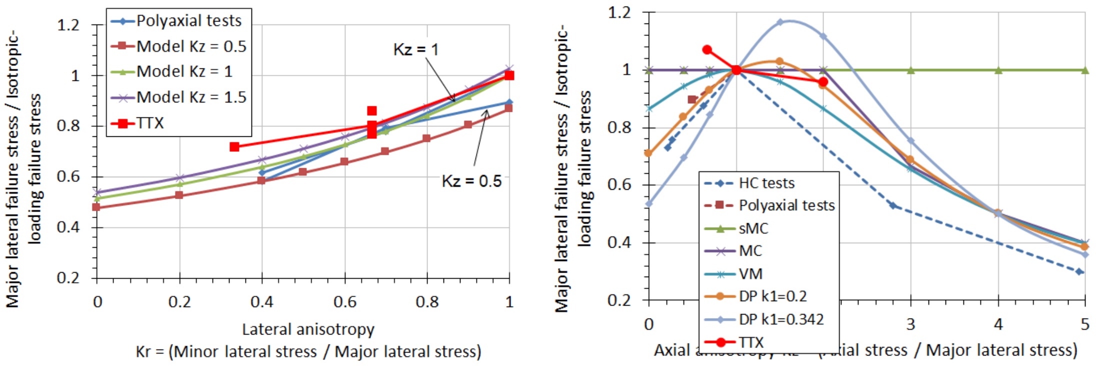

Figure 7. Comparison of experimental predictions with theoretical results on the effect of (left) lateral anisotropy, and (right) axial anisotropy on sand onset major lateral stress.

4 CONCLUSIONS

Sand production experiments have been performed in a novel true triaxial test system on Castlegate sandstone specimens to investigate the effect of anisotropy on sand onset and sand rate. The preliminary results of the tests that have been performed so far suggest that the models can adequately capture the effect of the lateral stress anisotropy. The differences with respect to the axial stress anisotropy seen in the tests are not significant and may lie within the experimental variability. This anisotropy effect will be further analyzed after widening the studied anisotropy range.

ACKNOWLEDGMENTS

This publication has been produced with support from the KPN project "Increasing profitability from sand producing fields". The authors acknowledge the following partners for their contributions: Aker BP, DEA, Hess, Anadarko and the Research Council of Norway (268159/E30).

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