# EXPERIMENTAL SANDING ANALYSIS: THICK WALLED CYLINDER VERSUS TRUE TRIAXIAL TESTS

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**Abstract**

Using a true triaxial stress cell (TTSC) the authors performed several sanding tests on cubes of synthetically made samples. The samples prepared based on an established procedure developed in the laboratory. Samples, with a dimension of 100×100×100 $mm^3$, were subjected to far-field stresses while increasing the pore pressure inside the cell. Sands were produced from a borehole in the sample centre. An experiment was conducted with anisotropic lateral stress to investigate the effect of stress anisotropy on sand production. By applying uniform lateral stresses, an experiment analogy to TWC was performed for comparison purposes. Comparison of the results of these two experiments demonstrated the importance of considering the intermediate stress component in sanding analysis. The results of these experiments are presented in this paper.

## 1. Introduction

Sand production laboratory experiments have been conducted since 1930’s (Terzaghi, 1936). The majority of the earlier tests were carried out on loose sands to study the effect of arching around a cavity (Hall and Harrisburger, 1970, Tippie and Kohlhaas, 1973, Bratli and Risnes, 1981). Later on, it was observed that even consolidated reservoirs may experience problems due to sand production. Since then, efforts have been made to simulate and study this phenomenon in laboratories (Vriezen et al., 1975, Antheunis et al., 1976, Perkins and Weingarten, 1988, Tronvoll et al., 1993, Papamichos et al., 2001, Wu and Tan, 2002, Nouri et al., 2004).

Most commonly, sanding experiments are performed on cylindrical shaped samples. The cylindrical sample, with a predrilled hole at its centre, is subjected to axial and lateral (i.e. radial) mechanical loads. A draw-down pressure is simulated by applying fluid pressure at the outer boundary of sample and producing from the borehole at the centre. This type of test commonly referred as thick walled cylinder (TWC) test, is the conventional test used to study sand production initiation in laboratories. However, one of the major limitations of such tests is that a uniform confining pressure is applied on the sample outer boundary, an unrealistic representation of the in-situ stress states surrounding a borehole or perforation in fields.

It is well known that depending on the relative magnitudes of three far-field principal stress components, different types of shear failures may occur around an opening (Jaeger et al., 2007). Hence an appropriate laboratory sanding simulation should be the one which includes the effect of three independent stress components. In practice, this is only possible if the experiment is conducted on cubic samples. In this approach, the stresses represent three principal far-field stresses and the induced stresses around the borehole are not symmetric. This is a more realistic way to simulate sanding as happens in real situations. Only few attempts have been made so far to conduct sanding experiments on cube samples (Kooijman et al., 1992, Kooijman et al., 1996).
This study was motivated as a result of the above discussion. In the following sections the specifications of a true-triaxial stress cell (TTSC) which was used for sanding simulations will be briefly reviewed and the modification applied for this purpose will be explained. The results of sanding test under lateral stress anisotropy is reported and compared with a test corresponding to TWC.

## 2. Experiment setup

The true triaxial stress cell (TTSC) consists of a pressure cell surrounded by a vertical and four horizontal hydraulic cylinders (Figure 1). Independent vertical and two horizontal stresses ($\sigma_v \neq \sigma_H \neq \sigma_h \neq 0$) can be simulated during an experiment. The maximum operating loads are 450 kN and 250 kN for vertical and horizontal hydraulic cylinders, respectively. The cell can be pressurized up to 21 MPa to simulate pore pressure by injecting fluid. The cell can accommodate a cubic sample of up to 300×300×300 $mm^3$ for conducting various advanced laboratory experiments under a true 3D stress condition. An outlet hole is designed at the bottom of the cell to access the sample during the test for injection purposes or disposal of the produced sand grains.
The design of the hydraulic cylinders allows their independent control using manual or automatic hydraulic pumps. The fluid flow, which simulates the hydrocarbon production, was pumped with a reciprocating pump with a maximum flow rate of 130 lit/hr and a maximum pressure of 36 MPa. The fluid is injected via an inlet located on the body of the pressure cell. Figure 2 shows a schematic of the experiment configuration.

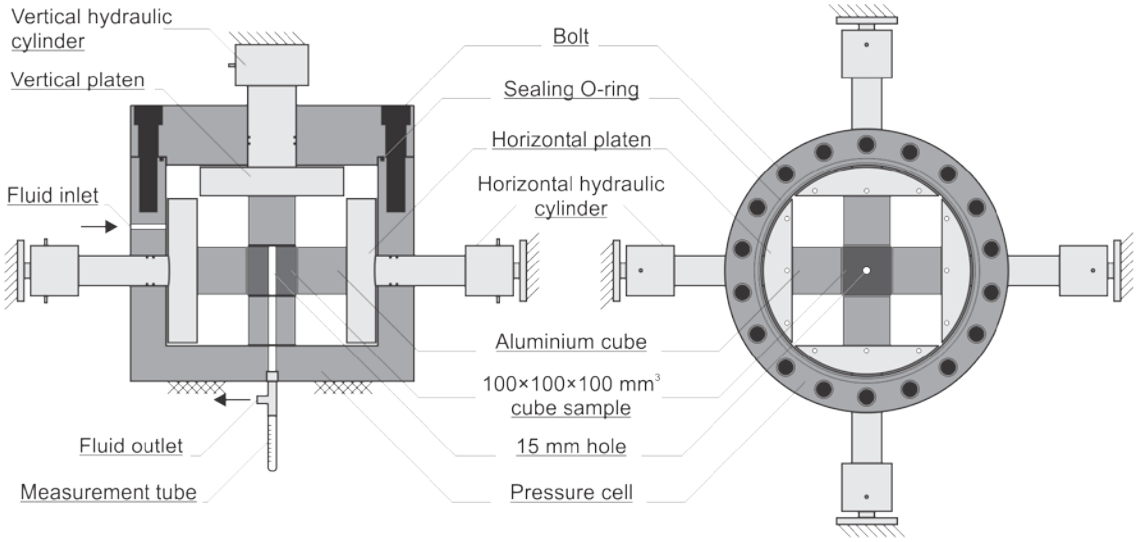



**Figure 1. The side view (left) and top view (right) of the TTSC.**

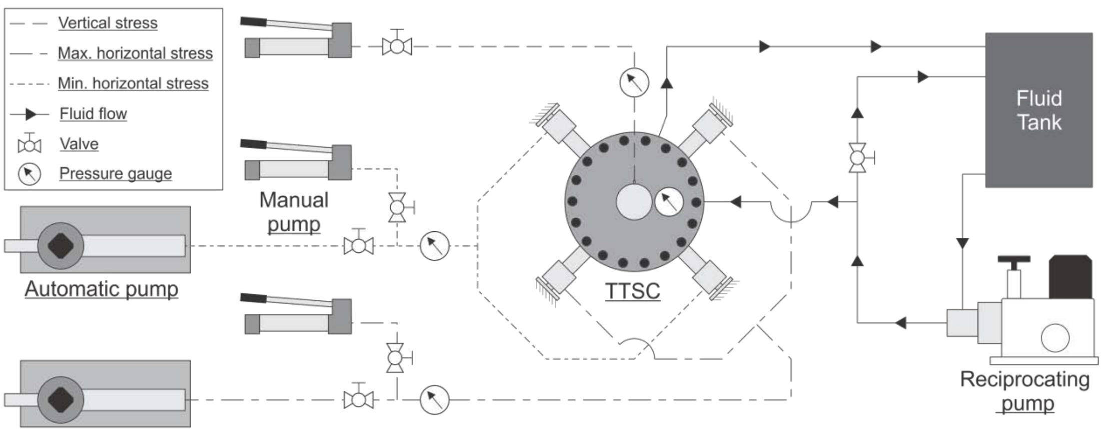



**Figure 2. Laboratory sand production experiment configuration.**

In this study, the experiments were conducted on 100×100×100 mm$^3$ cubic samples. Six aluminium block of size 97×97×100 mm$^3$ were placed around the sample to transmit the loads from the rams to the sample surfaces. A gap was formed between the neighbouring spacers as a result of the spacer size being smaller than the sample size. These gaps serve two purposes. Firstly, it accommodates the sample deformation due to loading, and secondly, it allows testing fluid to enter the sample. The stress concentration, introduced by the difference between the areas of the sample and spacers, at the corner of the sample is negligible (Younessi et al., 2012,a). The upper and lower faces of the sample were sealed using a 1 mm thick rubber sheet glued to their surfaces. The lower sheet has a 15 mm diameter hole in its centre to connect the hole to the outlet of the pressure cell. The lower Aluminium spacer has the same diameter hole. To make sure that the fluid pressure is uniform at the boundary of the sample four woven stainless steel wire meshes were placed between the sample and the spacer. Fluid is flowed through the sample to its borehole and then to the outlet of the cell. Figure 3 shows a schematic of the setup of the sample and the Aluminium spacers in TTSC.

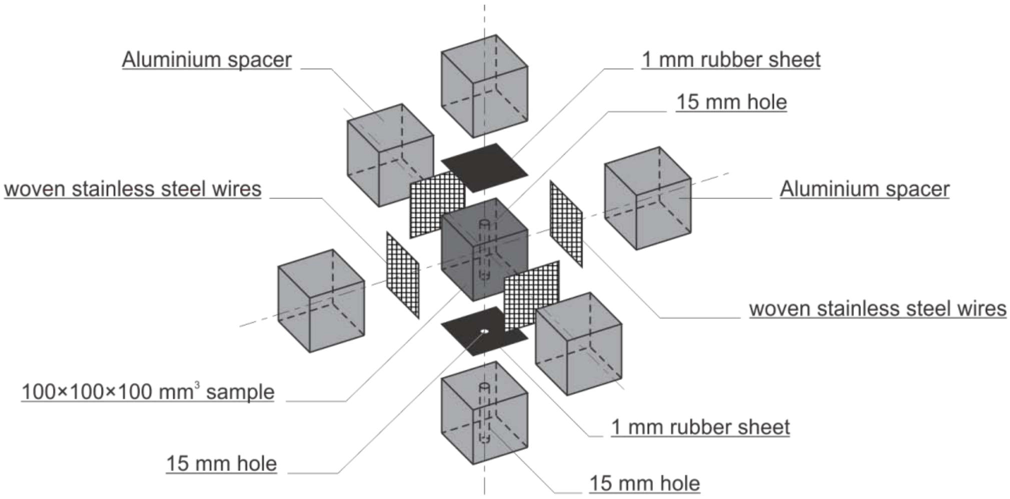



**Figure 3. Setup of the sample and spacers inside the TTSC.**

## 3. Sample material properties

The laboratory experiments were conducted on synthetic sandstones. The synthetic samples were produced following a procedure proposed by Younessi et al. (2012,b) to make samples with similar characteristics to a weak-consolidated sandstone. The properties of the sample and the fluid used for laboratory experiments were estimated by conducting a series of standard laboratory tests. Physical and mechanical properties of the synthetic sandstone and the fluid (which was a hydraulic oil) obtained in this study are tabulated in Table 1.

**Table 1. Physical and mechanical properties of the synthetic sandstone and the fluid used for sanding studies.**

| Synthetic Sandstone | | | | | Hydraulic Oil | |
|---|---|---|---|---|---|---|
| Bulk density | Porosity | Permeability | Young's modulus | Poisson's ratio | Dynamic viscosity | Density |
| 1815 kg/m$^3$ | 0.274 | 1.6E-13 m$^2$ | 7.65 GPa | 0.184 | 0.024 Pa.s | 803 kg/m$^3$ |

The material was assumed to have an elastic-perfectly plastic behaviour based on the observation from its stress-strain curve obtained in the triaxial tests. The rock was assumed to have a linear-elastic behaviour before its ultimate strength, hence the hardening phase was not considered. The mechanical parameters of two different strength models, Mohr-Coulomb and modified Drucker-Prager, were derived from triaxial tests. These properties and parameters are tabulated in Table 2.

**Table 2. Mechanical strength parameters of the synthetic sandstone used for sanding studies.**

| Uniaxial compressive strength | Tensile strength | Mohr-Coulomb | | Modified Drucker-Prager | | |
|---|---|---|---|---|---|---|
| | | Cohesion | Friction angle | Shear yield stress | Friction angle | Flow stress ratio |
| 5.4 MPa | 0.7 MPa | 1.5 MPa | 32.6 deg | 3.0 MPa | 52.8 deg | 0.8 |

## 4. Test procedure

Due to the nonlinear behaviour of the testing material in the plastic zone, the propagation of the plastic zone depends on the stress path. Therefore, to achieve the desirable far-field stresses, the stresses must be applied to the sample following a consistent procedure as explained in four stages below and illustrated in Figure 4:

Stage 1. Sample sealing: After a test sample is set up in the cell, a small vertical stress (1.4 MPa) is applied to the sample to make sure that a good seal between the sample surfaces and the vertical aluminium blocks is achieved.

Stage 2. Sample saturation: Small horizontal stresses and pore fluid pressure are applied on the sample outer boundary hold constant for at least 10 minutes to make sure that the sample is fully saturated with fluid.

Stage 3. Sand production: The stresses are increased step by step following the stress ratio defined for the test program (here in this study minimum to maximum lateral stress ratios were 0.4 and 1). In each step the vertical stress is increased prior to increasing the two horizontal stresses, and the pore pressure was increased after all the three stresses were applied. The sand produced in each step was monitored and measured using a measurement tube located at the outlet of the vessel. Each step lasts for at least 5 minutes.

Stage 4. Unloading: The unloading phase is quite similar to the loading stage but in reverse order, where pore pressure, horizontal and vertical stresses are reduced, respectively. This is done to ensure that the unloading stress path does not induce further extension of the failure zone around the borehole.

Figure 4 shows an example of loading-unloading path for a test (the stages has been marked on the chart).

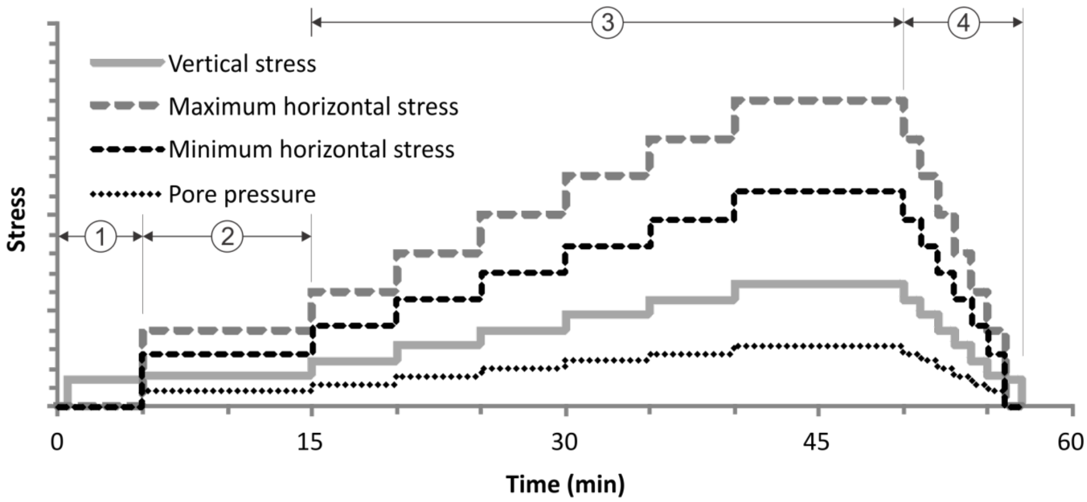


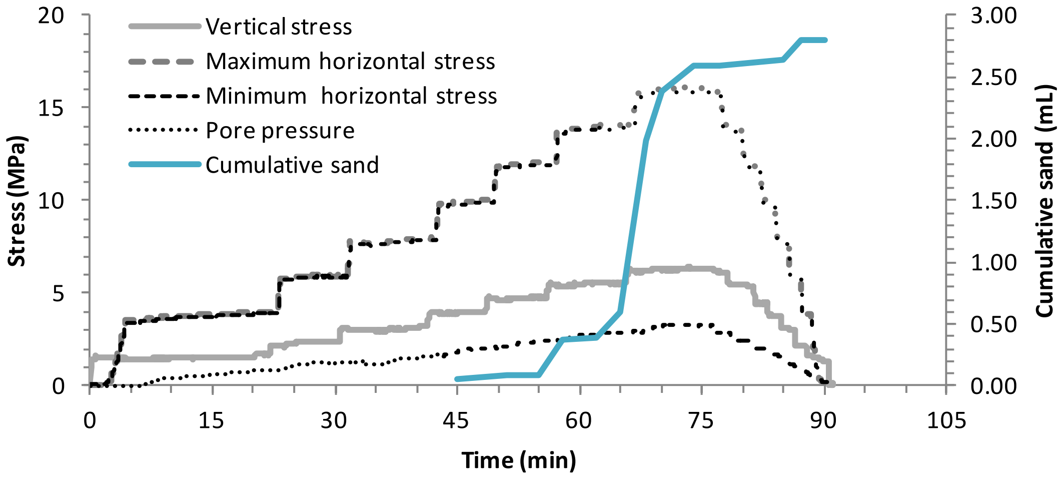

**Figure 4. Loading and unloading stages applied in sanding experiments.**

## 5. Results and discussions

Two tests were conducted on two identical samples. The tests were designed to compare the results of borehole failure under both isotropic and anisotropic lateral stress conditions. In both experiments the test procedure presented in the preceding section was followed.

Figure 5 shows the loading path and the amount of sand produced in each experiment. Theoretically the sand around the borehole reaches its yield stress at the very beginning stage of loading (at the beginning of stage 2). However, the fluid flow seems to be inadequate to detach failed sand grains from borehole wall. For both experiments the initiation of sanding was mainly governed by the rate of fluid flow. Sand production was initiated once the boundary pore pressure increased to 2 MP when small amount of sand grains were observed at the measurement tube. A noticeable amount of sand was produced at pore pressure of 2.8 MPa. Finally a relatively large amount of sand grains were produced when pore pressure reached 3.2 MPa, i.e. at the last step of loading stage.

The rate of sand production may also have a correlation with the size of the failure zone. To investigate the dimension of the failure zone, the stresses were unloaded (as explained in the preceding section) and the sample was taken out from the TTSC. Large amount of failed sands were still attached to the borehole wall when the samples were taken out of the TTSC. These have been removed by blowing pressurized air into the borehole.



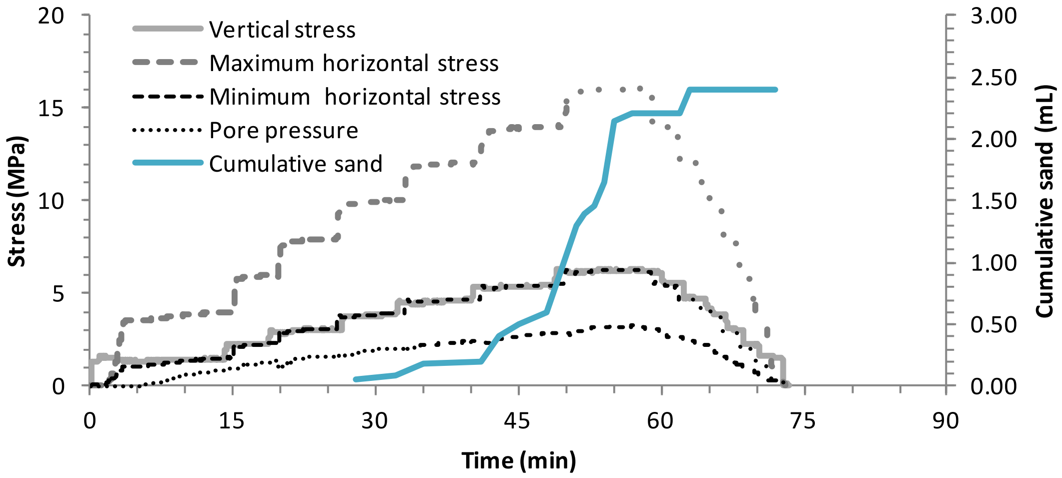




**Figure 5. Loading path and the amount of sand produced in experiments with isotropic (top) and anisotropic (bottom) lateral stresses.**

The shape of the failure zone was then captured precisely using a borescope. Figure 6 shows the failure zones developed around the borehole for the two experiments. This figure shows that the average depth of the failure zones is reasonably equal in the two tests while it is the width of the failure zone which shows an increase in the case of isotropic test.

The results showed that in an anisotropic stress test the development of the failure is in the direction of minimum horizontal stress. However, there is no preferred failure direction when the two horizontal stresses are isotropic. The main axis of wellbore ovalisation in the test with isotropic stresses was not oriented to the minimum stress direction. The authors believe this is due to heterogeneity of the sample.

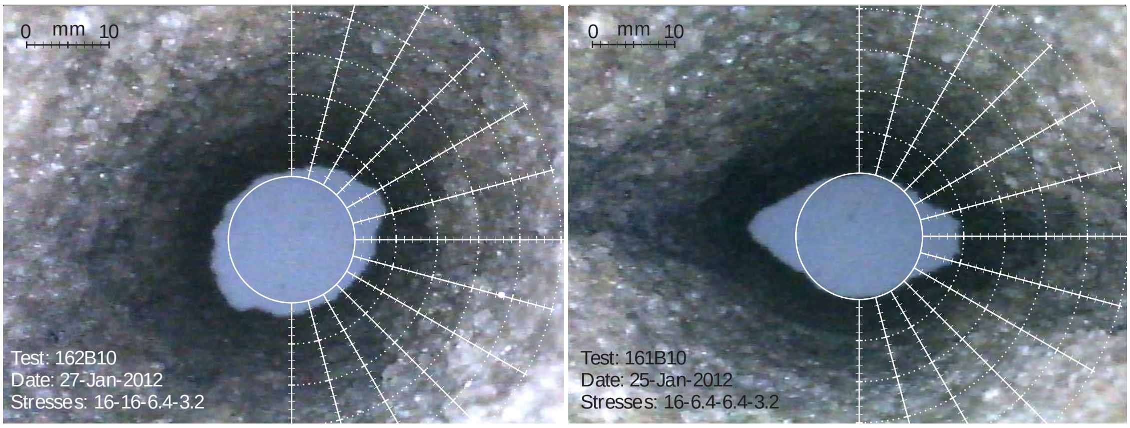



**Figure 6. Experimental results: sanding under isotropic (left) and anisotropic (right) state of stresses.**

## 6. Conclusions

Two experiments were conducted to study the difference between the conventional sanding test results (i.e. TWC) and test under true triaxial stress conditions. The tests were conducted on 100×100×100 mm$^3$ synthetic sandstone. The test setup and procedure for a cube sample subjected to true triaxial stresses and fluid flow was discussed in detail. The followings can be concluded from this investigation:

- The sand production initiation point does not necessarily coincide failure point. The observations indicated that a minimum fluid flow rate is needed to detach the failed sands around the borehole.
- A critical fluid flow rate can be defined as when a significant sand production rate is observed.
- The amount of sands produced at the critical flow rate depends on the geometry of the failed zone, which is a function of the sample mechanical properties and far-field stresses.
- The results showed how the direction of the failure zone in a TWC test has an arbitrary direction which is mainly governed by sample heterogeneity. Oriented breakouts in the direction of minimum stress can only be simulated on a cube shaped sample which was studied here.

Following recommendations are presented for the future work in this research area:

- In all experiments conducted in this study the borehole pressure was atmospheric. Applying a back pressure at the outlet line would allow tests to be conducted under a more realistic downhole condition.
- The tests may be performed on different samples with different mechanical properties to investigate how rock properties (e.g. mechanical strength) may impact sanding.
- The tests may be performed on samples with different sizes and to investigate the effect of the sample size on sanding. The effect of the borehole size is another parameter which could be studied.

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