Wellbore instability mechanisms in very hard clay
Les mécanismes de l’instabilité de forage très dur d’argile

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ABSTRACT
This paper summarizes the results of an integrated program of laboratory measurements and numerical analyses that have been performed to understand the mechanisms of instability associated with drilling of high angle wells through un lithified mudstones/very hard clays. The laboratory tests use Resedimented Boston Blue Clay (RBBC) consolidated to confining pressures up to 10 MPa as an analog test material. Cavity deformations are measured in a novel Thick-Walled Cylinder (TWC) apparatus with independent control of the vertical stress and radial pressures acting on the inner and outer walls of the specimen. Numerical simulations of these experiments are obtained using finite element analyses incorporating the MIT-E3 effective stress soil model, with parameters directly calibrated from high-pressure element tests. Comparisons with the deformations measured in undrained TWC tests provide an initial validation of predictive capabilities for vertical wellbores.

RÉSUMÉ
Ce document résume les résultats d’un programme intégré de mesures en laboratoire et d’analyse numérique qui ont été effectués pour comprendre les mécanismes de l’instabilité associée à l’angle de forage de puits par l’intermédiaire de pétrifications/très dur d’argiles. Les tests de laboratoire utilisent Resedimented Boston Blue Clay (RBBC) consolidée à des pressions jusqu’à 10MPa comme un matériel analogique pour tests. Les déformations de cavité sont mesurées dans un Thick-Walled-Cylinder (TWC), un nouvel appareil, où les contrôles des pressions verticale et radiale agissants sur les murs intérieurs et extérieurs de l’échantillon sont indépendants. Des simulations numériques de ces expériences sont obtenus en utilisant l’analyse par éléments finis intégrant le modèle MIT-E3 de stress effectif du sol, avec des paramètres directement calibrés à l’aide d’essais à haute pression sur l’élément. Les comparaisons avec les déformations mesurées dans les essais pas drainés TWC valident la capacité de prédiction pour les forage verticaux.

Keywords : Clay, laboratory test, thick-walled cylinder, borehole closure, constitutive model, finite element analyses

1 INTRODUCTION
Shallow oil reservoirs at depths less than 1000 m are situated within formations that are poorly lithified, e.g. very hard clays and lightly-cemented granular materials. The wells are bored within reservoir and overburden rocks that are much weaker and more deformable than those encountered at more typical deep reservoirs and are therefore expected to undergo large plastic deformation, creating a more extensive zone of disturbance around the borehole. In contrast to typical deep reservoirs, where wellbores pass vertically through the upper weak sediments, shallow field development rely on a small number of surface drilling locations, with high-angle wells and complex directional trajectories. In these situations control of the drilling operations is closely linked to an understanding of wellbore instability mechanisms.

There have been surprisingly very few experimental studies to evaluate systematically the strength and deformation properties of soils in the relevant range of consolidation pressures, 2-10 MPa (exceptions include work on sands by Coop & Willson 2003; and on clay by Bishop et al. 1965; Petley 1994; Gutiérrez et al. 2008). On the other hand, wellbore stability in lithified rock has been investigated through numerical techniques (e.g. Crook et al. 2003) and model experiments (e.g. Haimson & Song 1998) and comparison with actual field drilling results (e.g. Edwards et al. 2004). These materials fail in a quasi-brittle manner (e.g. Santerelli & Brown 1989) creating classic borehole breakout failure patterns in the rock. There are no comparable prediction methods for evaluating the stability of shallow boreholes drilled in very hard soils and poorly lithified rock formations.

The current study was conducted with the aim of investigating the mechanisms of instability through an integrated program of laboratory tests on Resedimented Boston Blue Clay (RBBC), numerical model calibration and validation. Thick-Walled Cylinder (TWC) tests have been used to study stability of a vertical wellbore at reduced-scale by decreasing internal pressures in the model borehole over relatively short time periods with no external drainage of pore fluid. Numerical simulations of these experiments are obtained using finite element analyses incorporating the MIT-E3 effective stress soil model, with parameters directly calibrated from high-pressure element tests. This paper presents the equipment, testing procedures, experimental test results, and calibration of model along with comparison of model results with measured data at different consolidation pressures.

2 THE TWC: EQUIPMENT AND PROCEDURES

2.1 Apparatus overview

The TWC was modified from an existing high pressure triaxial apparatus where major modifications were made at both the top cap and pedestal to accommodate thick-walled cylindrical
specimens of clay. The resulting automated high pressure apparatus allows for independent control of the vertical stress and radial pressures acting on the inner and outer walls of the cylinder. The apparatus consists essentially of a steel cell which mates to the base and encloses a pedestal, floating top cap, top and bottom annular platens, annular porous stones, and a hollow cylinder specimen sealed with internal and external custom-made latex membranes. The specimen has outside diameter of 76 mm, inner diameter of 25 mm, and length of 152 mm. These dimensions provide aspect ratios that are consistent with recommendations from prior experience using TWC tests on lithified rock (e.g. Santarelli & Brown 1989) to eliminate boundary end effects and provide a reasonable representation of the stress field around a borehole.

The entire system is axially loaded through the use of a 2 Ton capacity bench-top screw driven loading frame. Custom-designed pressure-volume controllers (Sheahan & Germaine 1992) are used to precisely regulate the pressure and measure the volume change in the external cell, internal cavity and pore water in the specimen. The cell, cavity, and pore pressures are measured by pressure transducers. The system also measures the axial load and displacement using an external load cell and displacement transducer. A closed-loop automated control is carried out using a PC and a control program which is able to perform all phases of the TWC test.

Figure 1. Schematic of new TWC apparatus

![Figure 1](image)

**2.2 Test procedures**

Resedimentation – The natural Boston Blue Clay (BBC) powder was mixed with 100 % water content to produce soil slurry before it was vacuumed and placed in the consolidometer. The slurry is loaded incrementally to a prescribed maximum vertical stress and radial pressures acting on the inner and outer walls of the cylinder. The consolidation time in the consolidometer, which has double drainage, lasts from 4 to 6 weeks depending on stress level. The average specific gravity of the RBBC was found to be 2.81. The liquid limit was found to be 46 % with a plasticity index and therefore does not require trimming.

Settling and Saturation – A dry setup was adopted to prevent the specimen from swelling. This requires semi-dry porous stones, dry filter paper, and no water left on the top cap and bottom pedestal in the TWC cell. After completing the apparatus setting-up, the water lines were vacuumed to remove the air and flushed with water. The specimen was then back pressure saturated to 400 kPa by ramps of internal and external soil specimen pressures, and back pressure to make sure that the specimen and pore lines are fully saturated. The Coefficient B was measured by ramps of internal and external pressures while measuring the back pressure and was generally above 95 %.

Consolidation – The soil specimen was anisotropically consolidated under stress control to a pre-defined target value, $K_0 = 0.55$ to the required vertical effective stress and is then left for a further 24 hours at constant effective stress to allow for secondary compression. Since the reconsolidation in the apparatus was under a higher stress than the initial maximum consolidation pressure in the consolidometer (i.e. normally consolidated, with OCR = 1), the experiment simulates a high-quality test with minimal disturbance to the soil around the cavity and unloading starts from the at-rest stage.

Undrained Borehole Closure – mechanisms of instability were introduced by reducing the internal cavity pressure within the model bore while keeping the external cell pressure and axial stress constant. Borehole closure was performed by drawing out cavity fluid using the pressure-volume controller at an average cavity volumetric strain rate of 10 %/hour. The tests were terminated at 20 % cavity volumetric strain. The drainage valves were closed to maintain overall global undrained conditions during cavity contraction while reading the pore pressures inside the specimen.

3 EXPERIMENTAL RESULTS

Figure 2 shows the net internal cavity pressure inside the borehole normalized with respect to external cell cavity pressure ($p_i - u_0/p_o$) versus cavity volumetric strain ($\Delta V/V_0$) for RBBC tests consolidated to vertical effective stress, $\sigma'_{vc} = 0.15$–10.0 MPa. All the tests are performed on normally consolidated specimens, i.e. OCR = 1. The results show the non-linear relation between the volume strain and the pressure ratio. Also, the bulk of the pressure drop occurs within the first 4-6 % volume strain and the borehole becomes unstable (deforms without further reduction in cavity pressure) when net pressure ratio, ($p_i - u_0/p_o = 0.25$-0.35 at volume strain in the range $\Delta V/V_0 = 8-12$ %.

![Figure 2](image)
The effect of stress level is also illustrated in Figure 2. The figure shows that at the same net pressure ratio, there are much larger volume strains for tests at higher consolidation pressures. The initial stiffness also decreases as stress level increase.

4 CALIBRATION OF MIT-E3 USING HIGH PRESSURE BEHAVIOR

Previous studies of RBBC have assumed normalized engineering properties of the soil (following the SHANSEP framework; Ladd & Foot 1974) such that the undrained shear strength and stiffness of $K_0$-normally consolidated clay is proportional to the vertical effective stress at the end of consolidation. However, Abdulhadi et al. (2009) have found significant differences in the stress-strain-strength properties measured in undrained triaxial compression shear tests at high pressures. The main changes can be summarized as follows:

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<th>Parameter</th>
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<th>10.0</th>
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<tr>
<td>$\sigma_{\text{v}}$ (MPa)</td>
<td>0.33</td>
<td>0.28</td>
</tr>
<tr>
<td>$E_u$ (%)</td>
<td>0.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$\phi_{\text{v}}$</td>
<td>450</td>
<td>150</td>
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<tr>
<td>$\phi_{\text{v}}$ (°)</td>
<td>38.0</td>
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</tr>
<tr>
<td>$K_{0\text{NC}}$</td>
<td>0.52</td>
<td>0.56</td>
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* Defined at $\varepsilon_a = 0.01\%$

The results show remarkable reductions in the undrained strength ratio ($\sigma_{\text{RTC}}/\sigma_{\text{v}}$) with consolidation stress level, significant reduction in the stiffness ratio, increase in the strain to mobilize the peak shear ($\varepsilon_{up}$), and most surprisingly a decrease in the large-strain 'critical state' friction angle, $\phi_{\text{TC}}$.

These results cannot be simulated directly by constitutive models that are based on assumptions of normalized clay behavior, including advanced elasto-plastic models such as MIT-E3 (Whittle & Kavvadas, 1994). Prior studies have focused on the behavior of RBBC at effective consolidation stresses in the range 0.1 – 0.4 MPa. In order to simulate the TWC tests presented in Figure 2, it is first necessary to re-calibrate model input parameters at the high consolidation stress levels (up to 10 MPa).

Two simulations are performed to represent the two considered classes of consolidation pressure as shown in Figure 5. The low consolidation pressure class (<1 MPa) uses the common calibration parameters of the MIT-E3 model. The high consolidation pressure class (1–10 MPa) uses the new calibration parameters discussed in the previous section. The numerical simulations acquired the same trend observed in the measured behavior. The initial stiffness tend to decrease with increasing the consolidation pressure. Also, the degradation of stiffness is faster and the behavior is more ductile.

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6 CONCLUSIONS

The following conclusions may be drawn on the basis of the content of the present paper:

- A new automated, high pressure, thick-walled hollow cylinder apparatus (TWC) was developed to perform borehole closure tests on clay.

- A program of TWC borehole closure tests have been performed on specimens of an analog clay (Resedimented Boston Blue Clay, RBBC) at vertical effective stresses ranging from $\sigma_v' = 0.15\text{–}10.0$ MPa. The data show borehole closures occurring at net pressures in the range, $(p_\text{n} - u_0)/p_\text{n} = 0.25\text{–}0.35$ and volume strains, $\Delta V/V_0 = 8\text{–}12\%$. There are significant reductions in the normalized stiffness with increased consolidation stress level.

- Laboratory element tests also show significant changes in the deformation and shear strength properties of the analog clay, RBBC, when consolidated at high pressures. The anisotropic effective stress soil model, MIT-E3, has been re-calibrated to simulate the measured stress–strain–strength behavior for consolidation stresses in the range, $\sigma_v' = 2\text{–}10$ MPa.

- Numerical finite element simulations (using MIT-E3) capture quite well the effects of initial confining pressure on the relationship between net pressure and cavity volume in the laboratory TWC tests. Further work is needed to understand the material properties controlling the minimum internal pressure.

ACKNOWLEDGMENTS

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REFERENCES


