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

N.O. Abdulhadi, S.A. Akl, J.T. Germaine & A.J. Whittle
Massachusetts Institute of Technology, USA

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 unlithified 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 independents. 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; Gutierrez 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

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specimens of clay, Figure 1. 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.

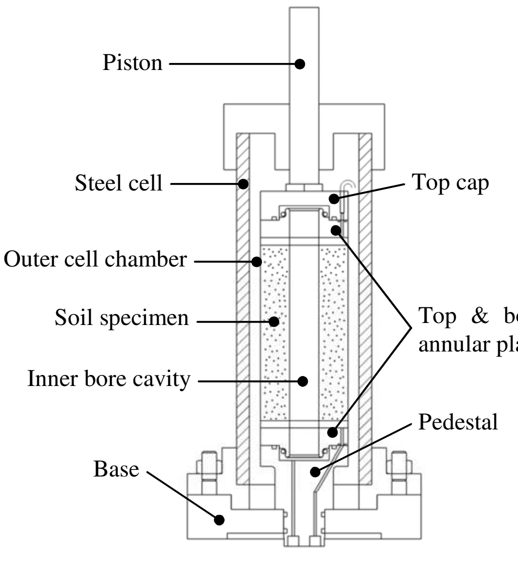


Figure 1. Schematic of new TWC apparatus

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 then unloaded to overconsolidation ratio, OCR = 4. 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 of 23 %.

Specimen Preparation – The central core of the soil specimen, which is fixed in the mold, was formed by drilling using a drill press. Succession of four metal drill bit sizes (12.7, 19.05, 23.8 & 25.4 mm) was used to create the cavity. The difference between the last two drill diameters was selected to be small in order to minimize disturbance of the inner surface of the annular soil specimen. Note that the soil specimen has outside diameter equal to the diameter of the consolidometer and therefore does not require trimming.

Setup 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, $\sigma'_v = 0.15$–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 %.

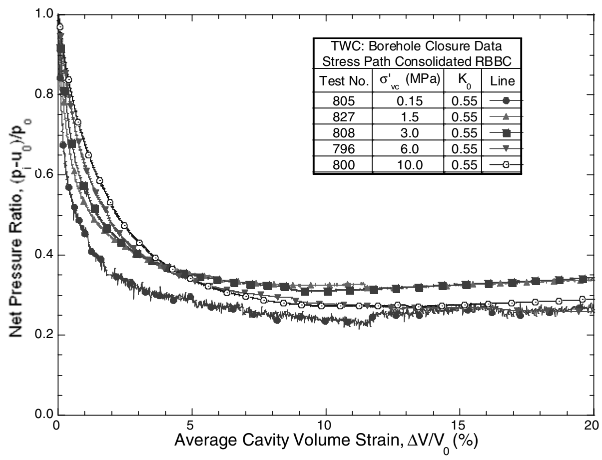


Figure 2. Effect of consolidation stress level on net cavity pressure ratio for RBBC specimens

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:

Table 1. Effect of consolidation stress on engineering properties of K_0-normally consolidated RBBC

	Consolidation Stress, σ'_{vc} (MPa)	
Parameter	0.15	10.0
s_{uTC}/σ'_{vc}	0.33	0.28
ε_{ap} (%)	0.2	1.4
E_u/σ'_{vc}*	450	150
ϕ'_{TC} (°)	38.0	29.0
K_{0NC}	0.52	0.56

* Defined at $\varepsilon_a = 0.01\%$

The results show remarkable reductions in the undrained strength ratio (s_{uTC}/σ'_{vc}) with consolidation stress level, significant reduction in the stiffness ratio, increase in the strain to mobilize the peak shear (ε_{ap}), and most surprisingly a decrease in the large-strain 'critical state' friction angle, ϕ'_{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).

Figures 3a and 3b compare the effective stress paths for elemental CK_0UC tests computed by the MIT-E3 model, based on the re-calibration at high consolidation pressures, versus measurements reported by Abdulhadi et al. (2009). The figures also include prior model results for low pressure behavior (Whittle et al. 1994), and simulations of undrained traixial extension tests (for which no data are currently available at high pressure). These results show that the recalibrated version of the model is capable of capturing the rise in ductility and diminution of post-peak strain softening. A value of φ_{TE}=34.5° is chosen according to Sheahan and Germaine (1992).

5 COMPARISON BETWEEN SIMULATIONS AND MEASURED BEHAVIOR

A 2-D axisymmetric finite element model is created using ABAQUS™ program as shown in Figure 4. The elements used are 6- noded triangular elements with quadratic interpolation of deformations and pore pressures.

The TWC test is assumed to be pressure controlled such that the soil specimen is assumed to respond only to the change of pressure inside the cavity. The pressure-time frame is structured in the model to mimic the key results of the TWC tests stated in section 3. The top caps are assumed to be infinetly rigid to provide non-uniform distribution of axial pressure exerted by the top cap. The tests were simulated using the actual time frame of pressure reduction and hydraulic conductivity of the soil. The pore water is allowed to migrate within the specimen, meanwhile global drainage is not allowed, and all boundaries of the FE model are considered impervious.

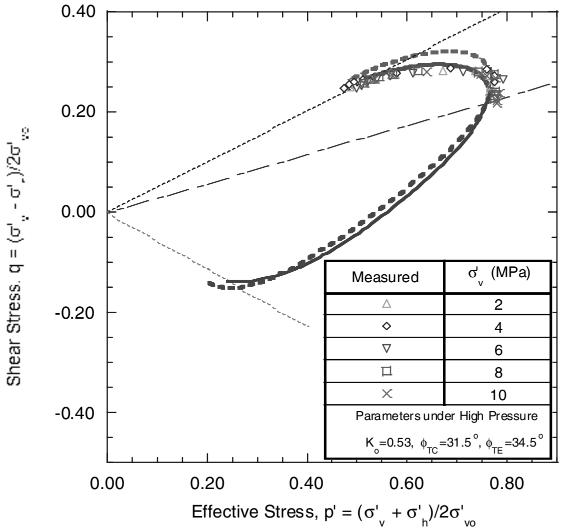
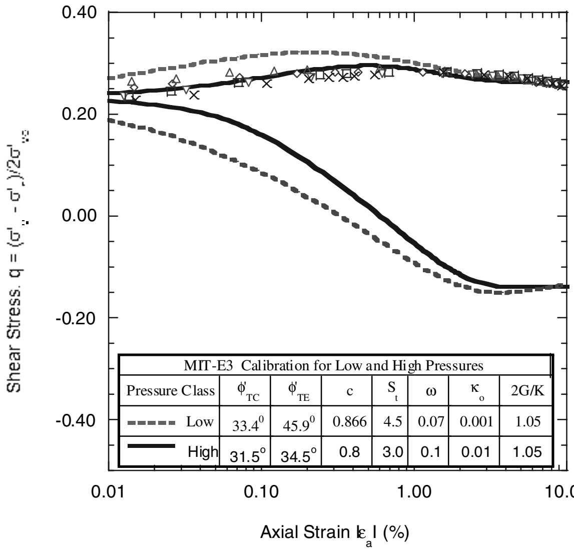


Figure 3a. Effective stress path from MIT-E3 simulations under low and high pressures; compared with triaxial compression results from high pressure tests



Pressure Class	ϕ'_{TC}	ϕ'_{TE}	c	S_t	ω	κ_o	2G/K
Low	33.4°	45.9°	0.866	4.5	0.07	0.001	1.05
High	31.5°	34.5°	0.8	3.0	0.1	0.01	1.05

Figure 3b. Stress-strain behavior MIT-E3 simulations under low and high pressures; compared with triaxial compression results from high pressure tests

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.

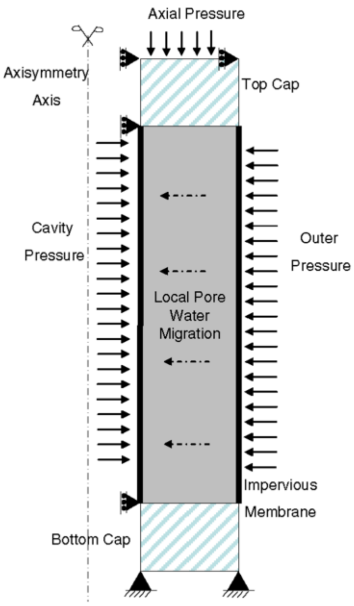


Figure 4. A schematic diagram showing the numerical model used in TWC simulations

The numerical simulations capture very well the initial slope of the change in net pressure ratio with respect to cavity volume strain. However, with high strains in cavity volume the numerical simulations tend to over estimate the change in net pressure ratio. This may be attributed to the effect of the finite rate of drawing the cavity fluid in the apparatus. The numerical simulation induces failure in the FE model instantaneously; however the response of the specimen in the TWC device is inevitably affected by the rate of fluid withdrawal from the cavity.

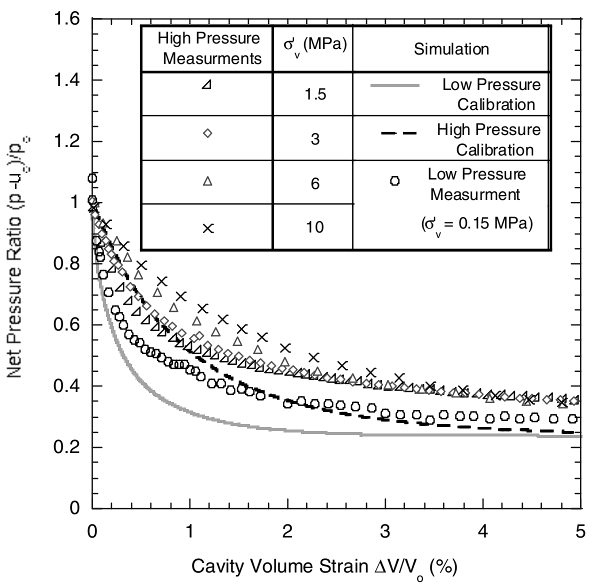


Figure 5. FE simulations compared to TWC lab results.

6 CONCLUSIONS

The folowing 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 σ'_v = 0.15–10.0 MPa. The data show borehole closures occurring at net pressures in the range, $(p_i - u_0)/p_o$ = 0.25-0.35 and volume strains, $\Delta V/V_0$ = 8-12%. 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, σ'_v = 2-10 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 presure.

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