Physical Modelling in Geotechnics

Physical modelling of synthetic over-consolidated shale deflection

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ABSTRACT: Numerous recorded geotechnical incidents indicate that over-consolidated shale (i.e. caprock) has posed a serious challenge to hydrocarbon extraction, coal mining, slope stability, tunnel settlement, and other engineering activities. During the geological history of caprock, the low permeability of caprock has effectively trapped resources within reservoirs. However, human activities, such as the in-situ recovery process, may compromise both hydraulic and mechanical caprock integrity. The hydraulic integrity of the caprock prevents reservoir fluid from entering the shallow groundwater, while mechanical integrity guarantees that caprock deformation is within tolerable values and the stress state in the caprock is below the failure envelope. Unlike other studies using reservoir simulation, this study employs the geotechnical centrifuge to reveal the caprock deformation mechanism. Although caprock deformation, which involves the uplift/deflection behaviour of the shale barrier, has never been studied through geotechnical centrifuge modelling, similar studies pertaining to the uplift resistance of soils are extensive, such as horizontal plate anchor, trap-door tests. One of the biggest challenges for geotechnical centrifuge modelling in these tests is obtaining samples. Geotechnical centrifuge modelling prioritizes using field samples for testing, but because of the extremely friable nature of shale, the material easily disintegrates to a slurry after being exposed to water, thus making it impossible to obtain samples using conventional methods. To overcome the shortage of Clearwater shale samples, for this study a suitable synthetic formula is developed for over-consolidated shale with physical and mechanical properties that are very close to the prototype material.

Keywords: Over-consolidated shale, caprock integrity, uplift behavior, geomechanics.

1 INTRODUCTION

Due to the fragile nature of Clearwater shales, it becomes difficult to get large-scale samples from field for physical modelling tests. To overcome the barrier of the shortage of the Clearwater shale samples, this study develops a synthetic material to replicate the behaviour of Clearwater Formation shale for the physical modelling tests. Reconstituted Speswhite kaolinite clay, which was used for initial caprock integrity centrifuge modelling tests, is far too weak to represent the behaviour of Clearwater shale (Wu, 2015). Therefore, it is essential to develop a suitable synthetic soil that can appropriately capture the behaviour of Clearwater shale for the physical modelling test.

Numerous recorded geotechnical incidents indicate that over-consolidated shale (i.e. caprock) has posed a serious challenge to hydrocarbon extraction, coal mining, slope stability, tunnel settlement, and other engineering activities. During the geological history of caprock, the low permeability of caprock has effectively trapped resources within reservoirs. However, human activities, such as the in-situ recovery process, may compromise both hydraulic and mechanical caprock integrity. The hydraulic integrity of the caprock prevents reservoir fluid from entering the shallow groundwater, while mechanical integrity guarantees that caprock deformation is within tolerable values and the stress state in the caprock is below the failure envelope.

Unlike other studies using reservoir simulation, this study employs the geotechnical centrifuge to reveal the caprock deformation mechanism. Although caprock deformation, which involves the uplift behaviour of the shale barrier, has never been studied through geotechnical centrifuge modelling, similar studies pertaining to the uplift resistance of soils are extensive, such as horizontal plate anchor, trap-door tests(Sakai & Tanaka, 2007; Sutherland, 1988; Terzaghi, 1943).

A summary of previous studies provides valuable guidance for the development of model material (Stimpson, 1970). Johnston and Choi (1986) developed a synthetic soft rock to predict the behaviour of the Melbourne mudstone under external forces or displacement. The principal component of the synthetic soft rock is reconstituted mudstone, while ordinary Portland cement is chosen as the cementing agent. Tavenas, Roy, and Rochelle (1973) developed a synthetic material to model mechanical properties of the Champlain clay. This synthetic soil is a mixture of kaolinite, bentonite, Portland cement and water. These studies not only contribute to the design of a test plan for making synthetic soil but also provide detailed information about the procedure of making the synthetic soil.

The concept of mixing cement with soft clay to improve soil strength has been widely recognized by researchers around the world (Cuccovillo & Coop, 1997; Haralambos, 2009; Horpibulsk et al., 2011; Horpibulsuk et al., 2003; Rotta et al., 2003). Miura N. et al. (2001) proposed a clay-water/cement ratio defined as the ratio of the total soil-water content to the cement content to reflect the effect of the water content and the cement content on cemented soil strength. The higher the clay-water/cement ratio is, the lower the soil strength is (Miura et al., 2001).

2 EXPERIMENTAL SET UP

2.1 Uplifting device

The Geomechanical Caprock Deflection Mechanism (GeoCDM) is a custom-designed device to mimic the expansion of the steam chamber beneath the shale barrier. It comprises the driving system and transmission system. The driving system, which comprises a Parker BE233D servo motor controlled by a Parker AR-08CE controller and a Parker RX23-100-S2 gearhead with a reduction ratio of 100:1, provides power to the transmission system. The transmission system comprises a rotation shaft, two sets of worm gears, the center-lifting table, the left flank, the right flank and two fixed side blocks (See Fig. 1).

The width of the uplifting table is 10 cm, while that of each flank is 5 cm. The motion of the uplifting table is controlled by the Parker Servo Motor, while the motion of the two flanks is controlled by the uplifting table. When the uplifting table moves upward, it exerts an uplifting force on each flank. The joint between the flank and the uplifting table is sealed with O-rings to prevent water and soil slurry flowing down to the inner space of the GeoCDM device.

2.2 Material used and characterization

Geotechnical experience has indicated that shale poses a serious challenge to coal mining, slope stability, tunnel settlement and other engineering activities (Skempton & Brown, 1961; Tiwari & Ajmera, 2011). These incidents cannot be solely attributed to the lack of good knowledge of the physical and mechanical properties of the shales. It is also essential to realize that the shale mechanical properties can drop to the same level as those of the reconstituted shale after being exposed to water for a few hours. This is mainly because the shale can transition to slurry type conditions very quickly after being exposed to water (i.e., slaking), resulting in serious practical problems.

In practice, the definition of a shale is not straightforward, and many terminologies have been used to describe the material, such as mudrock, argillaceous material, weak rock and shale. However, it is worth noting that these terminologies represent the shale at different conditions. For example, mudrock is used by geologists to represent the shale that has been extremely weathered and has no cementation. Engineers in different fields may work at different depths and thus prefer to use different names to describe the shale. For this study it is referred as a weak rock with relative strong cementation.

The particle size distribution of the Clearwater shale is shown in Fig. 2. The content of materials passing through the No. 200 sieve (75 μm) ranges from 45% to 95%. The clay content ranges from 5% to 55%. The Clearwater shale is therefore categorized as silty clay material.

Initial experimental results with consolidated Speswhite kaolin clay show that the material is too ductile to represent the Clearwater shales. Subsequently, a mixture of Speswhite kaolin clay, silt (Sil325 38-75μm), cement and water is assessed but again, unconfined compressive strength of the mixture material indicates that this mixture material is relatively soft when compared with the Clearwater shale. This leads to undertaking an extensive program to understand the components of synthetic Clearwater shale more efficiently, which involves collecting and analyzing previous studies pertaining to synthetic soils/rocks. An experimental program, which includes 160 separate formulations and considers the effect of water content, cement content, Atterberg limits and soil particle size distribution, is developed for the establishment of the database for the synthetic Clearwater shales.

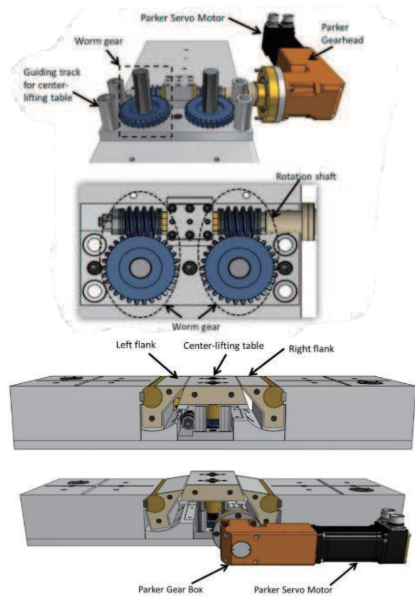


Fig. 1 GeoCDM devise - Left: driving and transmission system; Right: front view a zero−deflection position and back view at 20 mm deflection peak position

Group No.	Spk-to-S325 proportions (%)
G1	100 : 0
G2	90 : 10
G3	80 : 20
G4	70 : 30
G5	60 : 40
G6	50 : 50
G7	40 : 60
G8	30 : 70
G9	20 : 80
G10	10 : 90

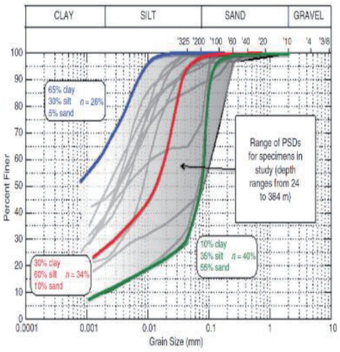


Fig. 2 Left: Experimental program of synthetic Clearwater shale; Right: Grain size distribution of the Clearwater shales (Shafie Zadeh & Chalaturnyk, 2015)

In general, an experimental plan should consider two different types of variables: 1) the independent variables, which are silt content, cement content and the total soil-water content in this study, and 2) the dependent variables, which are the after-curing moisture content, the unconfined compressive strength, the after-curing void ratio and the degree of saturation of the cement-treated synthetic soils. To study the impact of these independent variables on the dependent variables, the concept of a controlled experiment is adopted in this study, indicating that only one variable changes at a specific time while the other keeps constant. There are 10 groups of synthetic soils to investigate the role of the major factors. Each group has 16 recipes, each of which has different normalized water content and cement content. Table 1 summarizes the experimental program. The silt content increases from 0% in G1 to 90% in G10. The total soil-water content (C_w) values use in the material matrix are 1.1, 1.5, 2.0 and 2.5 times the liquid limit. The total soil-water to cement ratio (C_w/A_w) values of the mixture matrix are 3, 5, 7 and 8, resulting in a total of 160 possible formulas. Three samples were prepared for each formulation and cured for 28 days before completing the UCS test.

The results of this program provide the most suitable formulation (Speswhite kaolin clay and silt ratio: Sil325= 40:60, C_w= 2.5 times the liquid limit, C_w/A_w = 3), which is used for the geotechnical centrifuge modelling tests. The mechanical properties of the synthetic Clearwater shale, are quite close to those of the Clearwater shales (see Fig. 3).

2.3 Experimental procedure

A synthetic soil with the following components is used to make samples for the centrifuge modelling tests: formula G7 with total soil-water content value of 2.5 times the liquid limit and total soil-water to cement ratio values of 3. The following describes the model preparation and boundary conditions of the centrifuge tests conducted in this study.

Curing period:

The distilled water is added into the mixing pot of the GS1500 vacuum mixer, followed by the Speswhite kaolin and silt (SIL325) powder. Immediately after the vacuum pressure of the GS1500 vacuum mixer is up to -60 kPa, the mixing procedure starts. The mixing process lasts for 2 hours. After the soil slurry is thoroughly mixed, the well mixed cement slurry is then added to the vacuum mixer and mixed with the soil slurry for 30 minutes. After being well mixed, the soil-water-cement slurry is then transferred to the plane strain box (PSB) in five separate layers. After filling each layer, the trapped air bubbles are then removed by tapping the PSB with a rubber hammer. The Plane Strain Box is then sealed with plastic film. After 28 days, the sample is then used for the physical modelling tests.

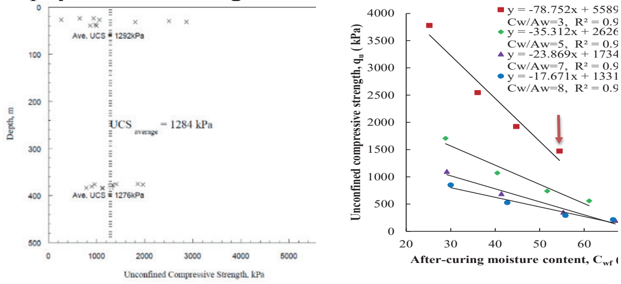


Fig. 3. Top: Unconfined compressive strength of natural Clearwater shale; and Bottom: synthetic shale (arrow points formula used in this study)

Pre-Centrifuge test installation:

To create sufficient texture for the model for PIV analysis, a thin layer of uniform fine red sand is sprinkled on the front surface of the specimen. After installing the Plexyglass window of the PSB, three layers of filter paper should be placed on top of the sample to prevent the materials adhered to the lead bars used as overburden material in the model. The weight of lead bars depends on the requirement of the experiment. The Mariotte bottle which is used to control water level in the PSB is installed, followed by the Parker Servo Motor which is used to control the movement of the uplifting table of the GeoCDM.

Centrifuge tests:

The average time required to spin up the centrifuge to the 100 g is about 10 minutes. After reaching the desired acceleration field, the centrifuge acceleration keeps constant to consolidate the sample for at least 8 hours. Water level in the PSB is maintained through the Mariotte bottle. After the consolidation is approximately completed, the uplifting table of the GeoCDM is simulated. The onboard camera (IDS, 2448x2048 pixel, gigabit ethernet uEye RE model, CINEGON 1·8/4·8 CMPCT RUGGEDZD lenses mod-el) is used to take images of soil deformation before and during the upward movement of the GeoCDM. After reaching the desired vertical displacement, the GeoCDM is stopped. Samples are then removed out of the centrifuge pit for postexperiment observations.

Post-Centrifuge tests:

Those images captured during the centrifuge modelling tests are then analyzed using GeoPIV to detect model deformation behavior under uplift forces.

2.4 Tests performed

This study focuses on the impact of the uplifting velocities, as shown in Table 2 on the caprock deformation behaviour, which serves as a proxy for the rate at which the steam chamber develops below a caprock interval. To ensure the consistency of the material properties, the centrifuge model utilized in the three tests is prepared using the same preparation procedure.

Table 2 Experimental program of the geotechnical centrifuge modelling test

Test	Overburden, kPa	Uplifting velocity, m/s	Thickness, m†	Time, yr†
1	527	2.14×10^{-6}	20	3
2	509	6.43×10^{-7}	20	10
3	510	4.29×10^{-7}	20	15

† scaled to prototype

3 RESULTS OF UPLIFTING TESTS

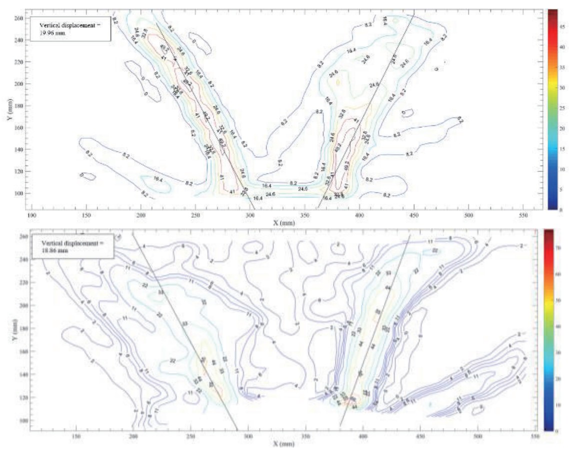
3.1 Uplifting tests

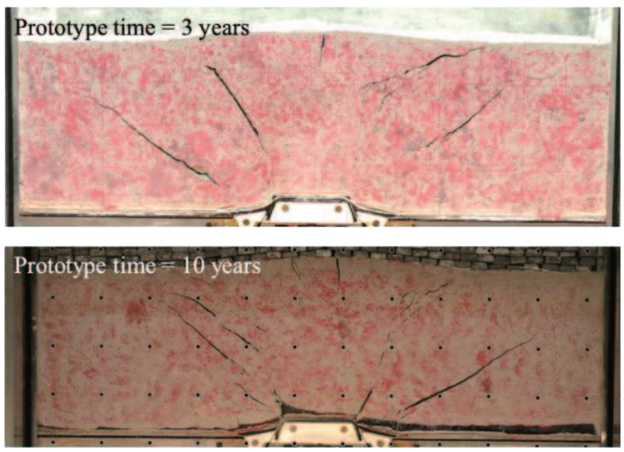
This study adopts maximum total shear strain as the criteria for determining the position of the failure surface since it has been used successfully by other researchers (Liu et al., 2012; Yamamoto & Kusuda, 2001). The Fig. 4. shows the characteristics of the failure planes of the three tests with different uplifting velocity and similar overburden boundary conditions (see Table 2). When analyzing this results a few interesting points can be obtained:

1. When the prototype time is 3 years, the corresponding failure plane is a curvature. At the bottom of the model, the failure plane is almost perpendicular to the uplifting table.With the decrease of the model depth, the failure plane turns into a straight plane and eventually extends to the model surface.
2. When the prototype is 10 years and 15 years, the failure plane is a straight plane at the bottom of the model, and then gradually turns into a curvature as the model depth decreases.

When analyzing the characteristics of these failure planes, a few interesting points can be obtained:

1. Surface heave is observed in the three geotechnical centrifuge modelling tests.
2. Vertical fractures accompanying surface heave initiate at the top surface of the model and propagate towards mid-height of the model whatever the uplifting velocity is. Based on the analysis of the horizontal displacement contours, the vertical fractures at the top of the model is the combined result of uplift movement of the model and the low tensile strength of the model material. However, vertical fractures of the three tests only propagate towards the mid-height of the model for a few centimeters and then stops propagating as the uplifting table still moves up. Moreover, with the increase of model depth, the width of these vertical fractures decreases, indicating that high horizontal stress can effectively prohibit the development of tensile fractures.
3. The second observation is that the inclined fractures extend to the ground surface when the prototype time is 3 years while those fractures for prototype time of 15 years seem to propagate horizontally when reaching a certain level.





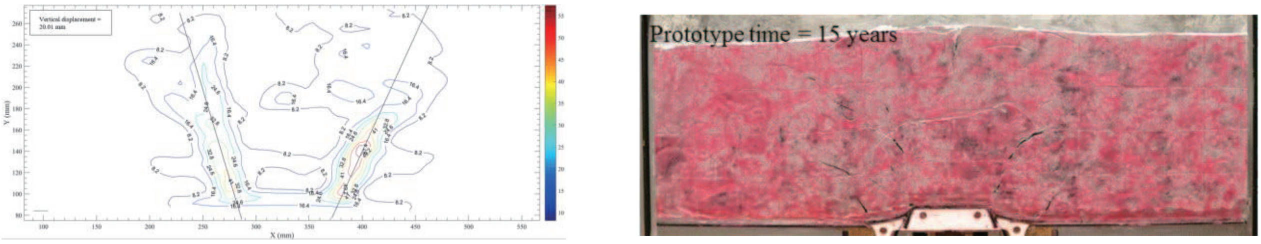


Fig. 4. Evolution of maximum shear strain –top: 3 year; middle: 10 years; and bottom: 15 years (time scaled to prototype).

4. Uplifting table and the two flanks are the origin of these inclined fractures. Therefore, when designing a SAGD project, the engineer should not only consider material properties but also the combined effect of material properties, radius of pressurized zone and expansion rate of steam chamber.

3.2 Numerical analysis

By using the physical and mechanical properties of the synthetic Clearwater shale as the input parameters, a series of numerical simulations of the centrifuge tests are compared with the experimental results from the geotechnical centrifuge modelling tests to assess the ability of numerical models to capture the deformation and failure modes seen in the centrifuge tests. There is no perfect approach to assessing a geotechnical problem from the perspective of quality and reliability of the results, cost and efficiency but comparisons of centrifuge modeling and numerical simulation can provide substantial verification that key mechanisms are being captured for relevant failure mechanisms. As shown in Fig. 5, caprock deformation behaviour from the numerical simulation coincides well with that from the centrifuge modelling tests.

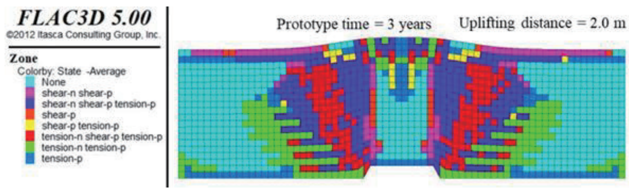


Fig. 5. Zone state of caprock with 3 years prototype time when the uplift displacement is 2 m

4 CONCLUSIONS AND PERSPECTIVES

Centrifuge facility has been widely used in geotechnical engineering to solve complex geotechnical problems. One of the biggest advantages of the technique is that it uses small-scale samples to mimic the behaviour of large-size prototype samples. Compared with field test, the geotechnical centrifuge modelling technique is more efficient. Compared with the numerical simulation approach, the geotechnical centrifuge modelling technique can accurately reflect the actual condition.

ACKNOWLEDGEMENTS

This work was financially supported by the NSERC Energi Simulation Industrial Research Chair and Consortia in Reservoir Geomechanics and the Reservoir Geomechanics Research Group [RG]^2 at the University of Alberta for their invaluable technical support.

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