Physical Modeling for SAGD Caprock Integrity with the Centrifuge Facility

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Summary

Caprock integrity is of great importance for recovering oil and gas efficiently and safely. To some extent, however, it can be heavily affected by human activities. Identifying its deformational behavior and failure mechanisms has become one of the main issues for resources exploitation. The objective of this paper is to demonstrate a new research method, centrifuge modelling test, and its reliability for researching deformational behavior and failure mechanisms of caprock. Based on database about Alberta Cretaceous shale physical and mechanical properties, a suite of conventional experiments will be conducted to find an analog material of caprock for physical modelling tests, and a constitutive model of the Cretaceous shale will be established for numerical experiments. The analog material will be used for identifying effect of discontinuities, pressure and temperature on caprock deformational behavior and failure process at high gravitational field. By comparing results of numerical simulation method with that of physical modelling tests, validity of numerical simulation method on identifying caprock failure mechanism can be obtained.

Introduction

In order to satisfy the growing needs of energy, a few methods such as cyclic steam stimulation (CSS), steam flooding and steam assisted gravity drainage (SAGD) (Butler, R. M., 1994b, 1998, 2004a) have been developed. Most of these methods have been used to recover resources in practice (Gronseth, J. M. 1989; Alvarez, J., 2013; Das, B. K., 2005a).

As to oil sands reservoirs in Alberta (Figure 1), very few of them are shallow enough for replacement of non-bituminous overburden. Most of the resources are very thin or burial depth is so high that it is uneconomical to remove the overburden. Under this circumstances, the CSS or SAGD method are considered as suitable method to recover the energy. Because of the lower pressure required by SAGD (Collins, P. M., 2013), it is widely applied in practice in Alberta in recent years. However, this method still involves injection of steam into the formation. This leads to the potential of affecting caprock integrity, such as the incident of Total E&P Canada Ltd. (Total) Joslyn Creek SAGD project occurred in May 18, 2006 (ERCB, 2010).

Caprock, especially those in North Alberta, is mainly shale and mudstone (Uwiera, M., 2011). These cretaceous clay shales are highly over-consolidated and form the overburden of oil sands reservoirs. Its low permeability effectively traps resources within reservoirs during the geological history. In recent years, however, human activity have greatly affected the caprock integrity. The hydraulic integrity of caprock can prevent reservoir fluid from migrating into the shallow groundwater system while the mechanical integrity of caprock can prevent the surface heave and protect the facility on the ground surface. Tensile fracturing, fault activation, and bedding plane slip are considered as three possible mechanisms that compromise the geomechanical integrity of the caprock (Bruno, M. S., et al). The conventional methods, such as triaxial tests, unconfined compressive tests and many other tests, can only get basic physical and mechanical properties of caprock using relatively small samples. In spite of this, these methods are very difficult to model the in situ condition. However, the physical modelling tests using centrifuge facility can easily solve problems encountered in conventional tests. The centrifuge modelling tests, which was first proposed by Phillips in 1896, was considered as one of the most important developments in geotechnics over the previous 50 years (Ng, C. W., 2014). The objective of this paper is to elucidate the reliability of the new development to research the failure mechanism of caprock under the impact of discontinuities, temperature and pressure (Figure 2).

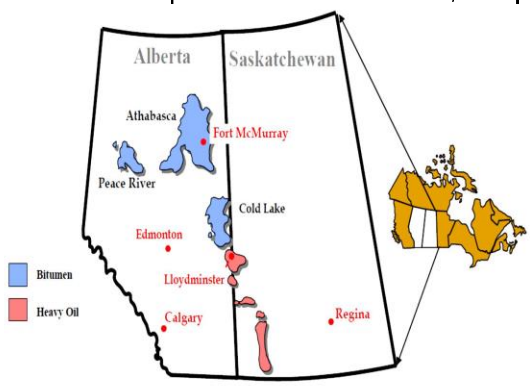


Figure 1 Oil sand deposits of Canada (Nasr T. N. et al, 2005)


Figure 2 The50g-tonne beam centrifuge facility

Theory and/or Method

The centrifuge modelling test is one of the most important developments in geotechnics over the past 50 years (Ng, C. W., 2014). It has been successfully applied in practice to research failure mechanism of tunnel, landslides etc. (Nomoto, T., 1999). In order to fully understand the deformational behavior of caprock at high gravitational field, the 50g-ton beam centrifuge facility which has a 2m rotation radius from the rotation axis to the swing basket platform is used. The beam centrifuge has a nominal capacity of 50g-ton which means a maximum payload of 500kg can be spun at 100g. Based on the scaling law, a 20cm thick centrifuge model can simulate the deformational behavior of a 20m thick caprock formation.

The principle of centrifuge modelling test is that the models placed at the end of a centrifuge arm can subject to high acceleration when centrifuge is spun at high speed. Because of the centripetal acceleration ($r\omega^2 = ng$, where r and ω represents the radius and angular velocity respectively), the “gravitational” field in the $1/n$ scale model can increase n times. So it can recreate the stress conditions existed in the prototype.

Sample used for centrifuge modelling tests can affect availability of the result. A suite of experiments will be conducted to find an analog material of caprock. The analog material will be used to explore the impact of discontinuities on caprock failure process, and to conduct centrifuge tests by injecting an inert gas to dislocate/as-uplift mechanics in the caprock failure process. Finally, a constitutive model of Alberta Cretaceous shale will be established. By comparing the numerical simulation test results that of physical modelling tests, the validity and improvement of the numerical simulation method and centrifuge modelling tests can be obtained.

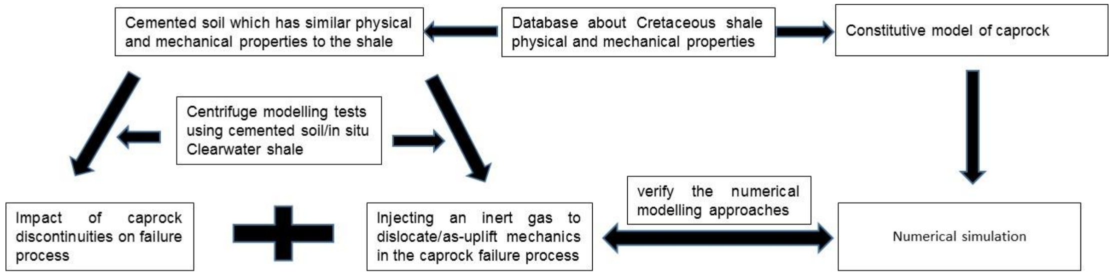


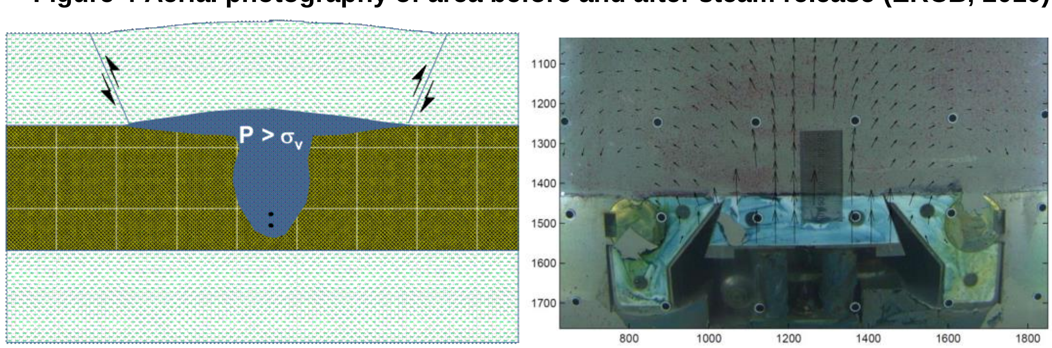
Figure 3 The research methodology for physical modelling tests of caprock integrity

Despite abovementioned research, in situ caprock will also be sampled and tested to evaluate the stress-displacement relationship in centrifugal environments. The validity of using centrifuge modelling tests and numerical modelling approaches to model SAGD caprock failure process will be verified. The research methodology has been shown in Figure 3.

Examples

One of the most notable example about importance of caprock integrity was Total E&P Canada Ltd. (Total) Joslyn Creek steam-assisted gravity drainage (SAGD) operation on May 18, 2006 (ERCB, 2010). Steam released from the reservoir caused a surface disturbance approximately 125 m by 75 m (Figure 4). According to the survey, the most possible reason for the incident is the shear failure of caprock induced by high pressure steam. Because of the incident, the ERCB recognized the importance of better understanding of caprock integrity affected by external forces.

Figure 4 Aerial photography of area before and after steam release (ERCB, 2010)



(a) (b)

Figure 5 Alalysis of shale barrier failure mechanism, (a) Failure of a shale barrier by shear on the shoulders of a zone with a pressure greater than the vertical stress (ERCB, 2010); (b) Zoomed view of the displacement vectors at the GeoCDM area when the GeoCDM moves up by 5.5mm (unit in pixel) (Wu J., 2015).

The custom-designed GeoCDM (Geomechanical Caprock Deflection Mechanism) is used to research the failure process of caprock (Figure 5-b). By comparing Figure 5-(a) with Figure 5-(b), it can be found that results of centrifuge modelling tests can be used to analyze the failure mechanism of caprock. Based on the centrifuge facility and the custom-designed device, the next step for this research will focus on failure mechanism of caprock under impact of discontinuities, high pressure and high temperature.

Conclusions

From the above analysis, the following conclusions can be obtained:

(1) The GeoREF 50g-tonne beam centrifuge can be used to model the caprock failure process at a high gravitational field.

(2) By using this device, the failure mechanism of caprock under the impact of discontinuities, high pressure and high temperature can be obtained.

(3) Finally, by comparing the physical modelling results with that of numerical simulation tests, the validity of numerical simulation test can be obtained.

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