The Investigation of Fluid Flow in the Fissured Clearwater Shale Using 3D Numerical Approach – Case Study of Joslyn Creek SAGD Project

Alireza Khani, Alireza, Rangriz-Shokri, Rick Chalaturnyk

University of Alberta

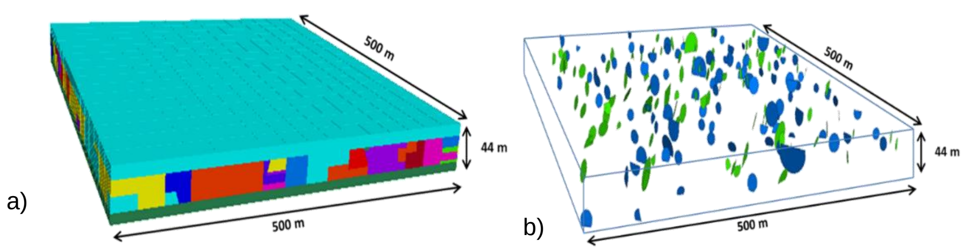
Summary

The objective of this paper is to explore the effects of fluid flow in the fractured caprock, and the various loading conditions applying at the base of caprock due to steam injection, on the surface heave, caprock deformation, and joint normal and shear displacements. The impact of different fracture intensities on surface and caprock displacements, joint shear and normal displacements is also investigated. In addition, different modes of failure under various conditions of pore pressure are also inspected for fissured caprock to capture the collaboration of hydraulic and mechanical phenomena in the fractures assuming the caprock is being hit by the pressure front. It was observed that considering fluid flow in the fractures results in effective stress reduction on the joint planes consequences in touching shear failure envelope sooner and having more sheared planes compared to the no flow analysis which has been done by the authors in SPE-189751-MS.

Methodology

3DEC, the Itasca code using for discontinuous media, was employed to investigate the impact of fluid flow in the fractures on different mechanisms of caprock failure in SAGD operation. A variety of Maximum Operating Pressure (MOP) as an uplift pressure at the base of caprock for different fracture intensities was also applied to explore surface heave, caprock deformation and joint normal and shear displacements in the fractures. Consequently, the demonstrated results were compared with the results of the previous study performed by the authors with the assumption of no flow in the fissured caprock.

As shown in Figure1, the size of 500m × 500m × 44m for the full hydro-mechanical models was kept the same as the realizations size utilizing in geomechanical analysis performed in [2]. The extent of the inner domain was extended to achieve negligible boundary effects. As Figure 1.b demonstrates two sets of joints with different orientations were included in fractured caprock. The uplift pressure resulting from pressure front in SAGD operation was applied to a center region of 90m x 90m at the base of Wabiskaw layer (Figure 1.c). Table 1 summarizes the input data of intact rock and joint properties for the base model [2].



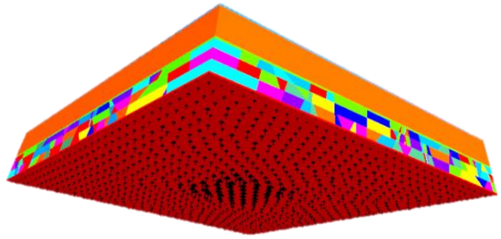
c) 

Figure 1. (a) 3DEC realization including fractured the Caprock, (b) sets of fractures in one of many realizations of discrete fracture network to represent pre-existing joints in caprock, (c) central load to mimic SAGD steam chamber exerted at the base of the model [2].

Table 1. Mechanical properties of intact rock and joints in caprock and overburden [1,2]

Intact rock properties	Clearwater caprock	Quaternary deposits
Young's modulus (MPa)	500	200
Poisson's ratio	0.4	0.3
Friction angle (°)	30	35
Cohesion (kPa)	100	100
Tensile strength (kPa)	0	50
Dilation angle (°)	20	15
Rock density (kg/m3)	2140	2140
Joint properties		
Normal stiffness (kPa/m)	4.50E+05	
Shear stiffness (kPa/m)	0.1*joint normal stiffness	
Friction angle (°)	20	
Cohesion (kPa)	100	
Tensile strength (kPa)	100	

Results

For a mature steam chamber in which the injection pressure is applying at the base of caprock, it was observed that considering fluid flow in the fractures results in effective stress reduction on the joint planes consequences in touching shear failure envelope sooner and having more sheared planes compared to the no flow analyses. The results also illustrate that displacement at the base of caprock and joint normal displacement are increased by 30%, 58% respectively once fluid flow is considered in discontinuities under 1800 kPa as uplift pressure at the base of caprock. These variations in behavior are significant and illustrate that the assumption of no fluid flow in the fractured caprock may lead to conservative estimates of steam containment and ultimately, underestimation of the risk for caprock failure.

For the lower bound of MOP, 740 kPa, based on the current AER formulation, maximum vertical displacement would be 33.5 cm at the base of caprock with associated heave of 28 cm at ground surface. If MOP is increased to 1200 kPa, the vertical displacements at the base of caprock and surface would increase to 61.8 and 50 cm, respectively. For the upper bound of MOP, 1800 kPa, practiced by the operator in Joslyn SAGD well pair prior to failure, the associated vertical displacement at the base of caprock and surface heave would increase to 98.5 and 84 cm, respectively. It should also be noted that the number of slipped joints due to failure increases by applying a higher load at the base of caprock, i.e. higher MOPs lead to more failure along fracture planes. Looking at vertical displacements, it seems that higher load from SAGD steam chamber increases the difference between subsurface and surface displacements by increasing the vertical displacement of caprock and surface heave (Figure 2a). This is because a portion of the applied load would be spent on changing shear and normal displacements of the joints within the caprock, and it consequently would lead to less deformation at the ground surface.

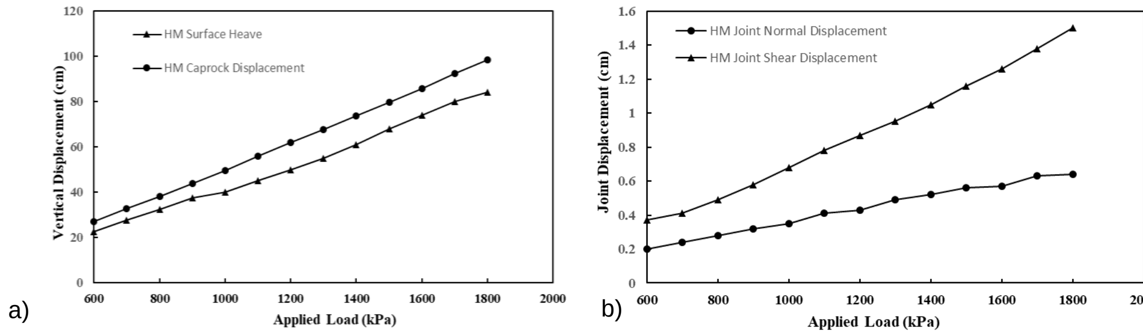


Figure 2. a)Impact of applied load on vertical displacement at the base of caprock and surface heave for HM analysis, b) Impact of applied load on joint normal and shear displacements for HM analysis

Figure 2b displays that increasing the applied load at the base of caprock results in higher joint normal and shear displacements in the case of considering fluid flow in the presented fractures of the Clearwater formation.

- **Impact of Fracture intensity**

In the geomechanical study, it was found that using higher fracture intensity lead to less vertical displacement at the base of caprock and surface heave, highlighting the fact that fracture intensity significantly affected deformability and strength of the rock mass. In this paper, two sets of fracture were selected. The regular fracture intensity is 0.0025 with about 200 fractures in the base model and higher fracture intensity is 0.006 with more than 500 fractures. These two sets were investigated under different uplift pressure at the base of Caprock and as Figure 3a, b show, both caprock displacement and surface heave are less once the number of fractures increase in the caprock. This observation indicates that the number of fractures in the caprock should be estimated as accurate as possible with the lowest amount of uncertainty. Because less fractures lead to underestimation of the risk for caprock failure and raises the question that the integrity of caprock could not be properly addressed if monitoring of surface heave is the only measure to be taken by operators and regulatory bodies. The results also show that larger joint displacements were experienced when fracture intensity was increased.

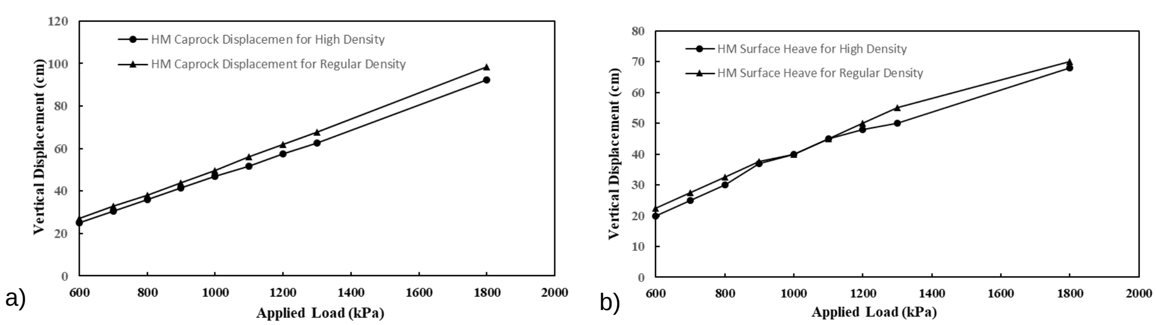


Figure 3. a) Caprock displacements for regular and high densities in HM analysis, b) Surface heave for regular and high densities in HM analysis

- **Geomechanical vs. Hydro-mechanical simulation**

A geomechanical analysis regarding the influence of discontinuities on displacements and failure modes of the fissured caprock without fluid flow was conducted in SPE-189751-MS by the authors [Khani et al, 2018]. The Figure 4a shows that for lower bound of MOP, 740 kPa, the surface heave with existence of fluid flow in the model is about 18% higher than the same situation when no fluid flow is considered. For 1200 kPa the difference is about 26% and for upper bound of the injection pressure at 1800 kPa, the surface heave is about 37% higher. The results show a non-linear relationship between the surface heave increments for different amounts of uplift pressure at the base of caprock.

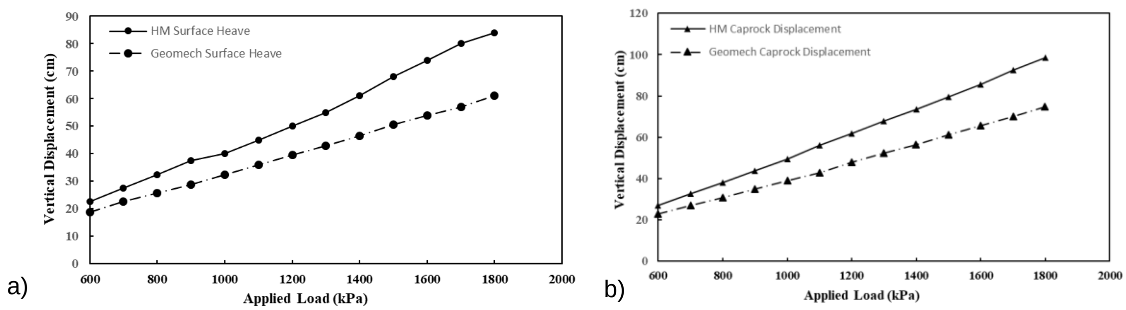


Figure 4. a) Influence of fluid flow in fractures on surface heave, b) Influence of fluid flow in fractures on caprock displacement

The displacement for the base of caprock is also increasing with consideration of fluid flow in the simulation. Figure 4b shows that the increase is about 18%, 29% and 31% for applied loads of 740, 1200 and 1800 kPa, respectively.

The simulation results demonstrate that the existence of fluid flow in the fractures in the hydro-mechanical analysis causes reduction of effective normal stress on the joints planes. Consequently, joint normal and shear displacements increase significantly in comparison with the case with no fluid flow in the model as shown in Figure 5 a, b respectively.

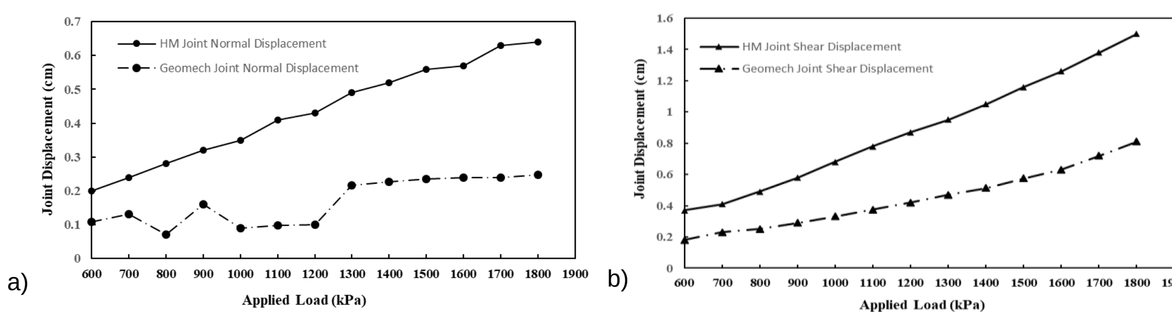
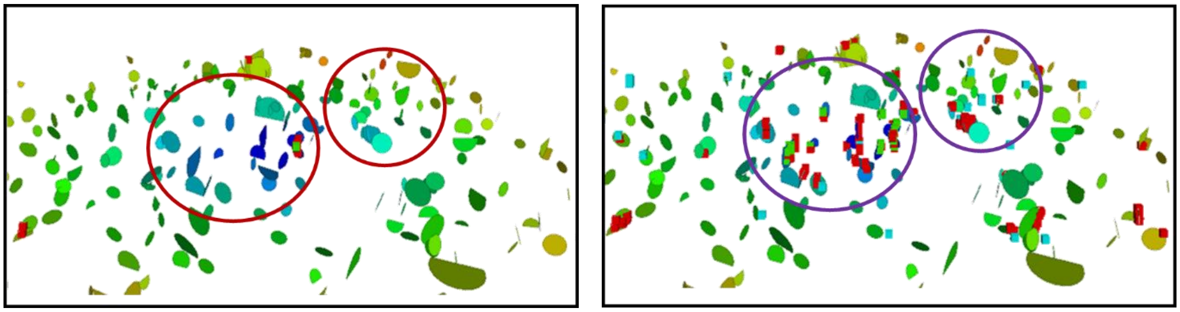


Figure 5 a) Influence of fluid flow in fractures on joint normal displacement, b) Influence of fluid flow in fractures on joint shear displacement

As Figure 6 illustrates fluid flow in the discontinuities causes a decrease in effective stresses and results in shear failure in the model sooner in comparison to no flow analysis in the fractures.



a) b)

Figure 6 Slip modes (a) considering no fluid flow (b) considering fluid flow in discontinuities

Novelty

About 5 months after starting circulation in well pair 1 on the Joslyn Steam Assisted Gravity Drainage (SAGD) project, the steam released to the surface in 2006. Despite broad investigations, there is no definitive resolution regarding the failure mechanisms yet so that, this unfortunate event still has a significant influence on the approval process for SAGD projects. Understanding the hydro-mechanical behavior of fractures regarding pore pressure increase and failure modes is undeniably necessary in caprock integrity world. The inclusion of a fractured medium considering fluid flow in the discontinuities for the assessment of caprock integrity has not been studied in literature.

Acknowledgements

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[1] Total E&P Canada Ltd., (2007) Summary of Investigations into the Joslyn May 18 2006, Steam Release; TEPC/GSR/2007.006.

[2] Khani, A., Rangriz-Shokri, A., & Chalaturnyk, R. J. (2018, March 13). The Influence of Discontinuities on Geomechanical Analysis of the Joslyn SAGD Steam Release Incident. Society of Petroleum Engineers. doi:10.2118/189751-MS