# Limitations with Currently Used Geomechanical Models for Determining a Maximum Operating Pressure for Steam-Assisted Gravity Drainage Schemes in the Shallow Thermal Area

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# 1 Introduction

Steam injection pressure is one of the most important operating parameters that determine the success of shallow steam-assisted gravity drainage (SAGD) schemes. The Alberta Energy Regulator (AER) uses a formula to calculate the maximum operating pressure (MOP) for SAGD schemes. The MOP formula was developed to ensure that the bottomhole injection pressure would be below the caprock tensile failure pressure throughout the life of the project.

The MOP formula is:

$$MOP_{(bottomhole)} = \text{Safety factor of } 0.8 \times \text{Caprock fracture closure gradient} \times \text{Depth at shallowest base of caprock}$$

For some shallow SAGD schemes, the MOP may be too low to make the project economic because higher temperatures are needed to lower the bitumen viscosity. As a result, some companies are relying on geomechanical modelling to support higher MOPs. While geomechanical modelling is useful for rock mechanics and rock engineering (e.g., parametric analysis and sensitivity analysis), it has limitations when used to determine an MOP for shallow SAGD schemes. Because of the risks associated with a caprock breach at shallow depths, the MOP must be as reliable as possible.

This report presents the limitations of geomechanical modelling in determining an MOP for shallow SAGD schemes. This report also discusses the nature of rock masses, as well as uncertainties associated with measured geotechnical properties.

One limitation not discussed in this report is the difficulty of accurately simulating nonuniform steam chamber growth in the reservoir due to potential pathways. Consequently, for coupled geomechanical and reservoir simulation models of the SAGD process, the biggest source of uncertainty may come from the reservoir simulation model.

It should be noted that the MOP formula only addresses tensile failure of the caprock. The potential for caprock shear failure is more difficult to analyze, and geomechanical modelling is the only tool available to assess the complex factors contributing to potential caprock shear failure.

# 2 Nature of Rock Masses

A rock mass is to some degree anisotropic and heterogeneous; it has faults and fractures, and it exhibits inelastic behaviour during loading and unloading. It is under compressive gravitational stress in the ground and may also be loaded laterally by tectonic stresses in the upper crust of the earth. A rock mass is also a porous medium with fluids such as water, oil, methane, and air in either liquid or gas phases under a complex set of in situ stress, temperature, and fluid-pressure conditions (Jing, 2003). Given also that the faulted, fractured, and bedded rock mass is a discrete system and that the geometry of loading is not uniform, closed-form stress-strain solutions do not exist. Numerical methods must therefore be used to solve practical engineering problems. However, all these stated qualities make a rock mass difficult to accurately represent mathematically by geomechanical modelling.

## 3 Geomechanical Modelling

To develop a mathematical representation of a rock mass, a geomechanical simulator must

a) identify the physical processes and mathematical expressions;

b) delineate the mechanical and constitutive laws, as well as their associated variables and parameters;

c) specify the pre-existing state of rock stress;

d) specify the pre-existing temperature and pressure of the rock mass;

e) include the presence of systematic or large-scale natural fractures and faults; and

f) include the variations in rock properties at different locations, directions, and scales (Jing, 2003).

The extent to which these features can be incorporated into a geomechanical simulator will depend on the complexity of the physical processes involved and the purpose of the modelling. Development of a fully coupled geomechanical and reservoir model that includes all the physical processes involved in a SAGD scheme is extremely difficult because it requires detailed knowledge of the physical properties and geometrical parameters of the fractured rock masses and how they may change over time. A geomechanical simulator does not have to be complete and perfect; it only has to be adequate for the purpose (Jing, 2003).

As can be expected based on the above, geomechanical modelling is both a science and an art. It rests on a scientific foundation but requires empirical judgement supported by accumulated experience through long-term engineering practice (Jing, 2003). This will remain the case because there likely will never be comprehensive, good-quality supporting data for geomechanical modelling. Because of the lack of data, full verification of computer models by field experiments in rock mechanics is not possible. Working with uncertainty and variability in processes, properties, loading conditions and load history, initial and boundary conditions, etc., is unavoidable in rock engineering. Therefore, the reliability and credibility of a geomechanical model are always relative, subjective, and case-dependent (Jing, 2003).

The following are challenges relating to rock mass characterization:

a) The in situ stresses are not easy to characterize over the region to be modelled.

b) Rock properties measured in the laboratory may not be representative of larger-scale values.

c) Rock properties cannot be measured directly on a larger scale.

d) Rock properties will change with temperature, stress, and strain.

e) Rock properties may have to be estimated from empirical characterization techniques, and the reliability of these methods remains uncertain.

f) The uncertainties in rock property estimation are not easy to quantify because there is no method to determine the absolute correct values of any given property.

g) The stress-strain behaviour of a rock material under complex loading conditions, temperature variations, and stress-temperature histories (e.g., how shear dilation is affected by confining stress and temperature) is inherently difficult to accurately describe.

The presence of these problems does not mean that one cannot supply rock characterization parameters, but it does mean that the limitations of numerical modelling must be carefully considered (Jing, 2013).

# 4 Geomechanical Modelling Practices and Limitations

## 4.1 Geomechanical Simulators Used by Industry

The majority of geomechanical modelling studies submitted to the AER to address caprock integrity issues have used either GEOSIM or ABAQUS.

GEOSIM is a proprietary coupled geomechanical and reservoir simulator that combines a three-dimensional (3-D), three-phase thermal reservoir simulator with a general 3-D, finite-element, stress-strain geomechanical simulator. GEOSIM is widely used for full-field compaction studies, waterflood and waste injection studies, and geomechanical modelling of conventional and thermal recovery processes.

ABAQUS is a general purpose simulator used for standard structural analysis that has constitutive models for rock materials. ABAQUS's parallel solution technique makes it possible to run large-scale coupled models, such as for a full SAGD pad, within a reasonable timeframe (e.g., a few days or weeks).

Both GEOSIM and ABAQUS have limitations when applied to practical rock mechanics and rock engineering problems. For instance, their designs are based on the principles of continuum mechanics; hence, their ability to simulate the response of a discrete, naturally fractured system is limited. ABAQUS cannot directly model thermal multiphase flow problems, such as the SAGD process. To run a geomechanical analysis with ABAQUS, pressures and temperatures must be initially set, and they are normally derived from a separate reservoir simulation model (e.g., ECLIPSE or CMG STARS). Because ABAQUS uses a one-way coupling process, the impact of the geomechanical responses on the reservoir properties (e.g., porosity, permeability, etc.) is not taken into account. To accurately determine an MOP for shallow SAGD schemes, a complete two-way coupling method is important. GEOSIM has an embedded reservoir simulator that can be run in either a one-way or a two-way coupling mode. However, its ability to run large-scale coupled models within a reasonable timeframe is limited.

### 4.2 Configuration of Geomechanical Models and Boundary Conditions

Most geomechanical modelling studies submitted to the AER are two-dimensional (2-D), plane-strain models that represent a typical cross-section perpendicular to SAGD well pairs. A few are 3-D models, but the grid blocks and their associated properties along the direction of the SAGD well pairs are sparse and geological features are not well captured. In addition, the models usually simulate a single SAGD well pair with roller boundary conditions applied at the bottom and the lateral boundaries. Such a model is intended to represent an infinite number of repeated identical SAGD well pairs, which is acceptable when used to investigate the potential tensile failure of a caprock. However, the capability of such a model is limited when used to assess caprock shear failure for an entire SAGD well pattern because this type of model does not include actual edges, where shear failures are most likely to occur.

Figure 1 illustrates the basic configuration of a geomechanical model with appropriate boundary conditions. Considering the lengthy computational time required to run a coupled geomechanical model, a half-symmetry model with appropriate boundary conditions is generally used. A far-field in situ stress condition should be imposed on the far-field boundary together with a reasonably designed mesh or block size. In such a model, the requirement for stress equilibrium (i.e., force balance) is satisfied across all vertical cross-sections. Furthermore, the stress boundary condition should be applied at a distance far enough away from the zone of stress and temperature change so that the assumption of a constant boundary loading condition is correct.

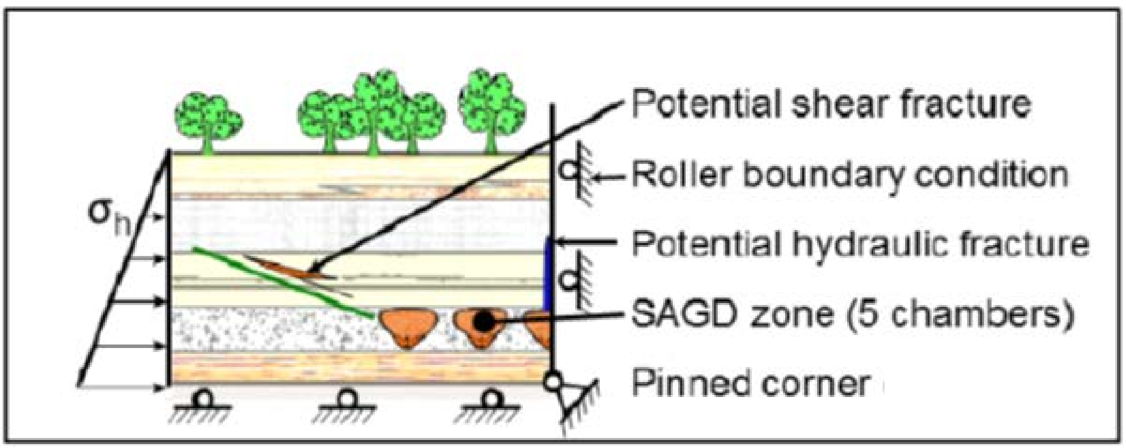


**Figure 1. Configuration of a typical geomechanical model with appropriate boundary conditions**

The following explains why the model configuration and boundary conditions described on the previous page are necessary:

a) To simulate the shear effects indicated in figure 1, the model must contain more than one steam chamber. The shearing is likely to be the greatest at later times because the greater the reservoir volume that is heated, the greater the total displacement that occurs at the edges of the SAGD zone.

b) In a half-symmetry model, the midpoint symmetry line must be constrained as a roller boundary to allow free vertical movement.

c) The bottom boundary is a roller boundary, but there must be some reasonable thickness of the underlying strata in order to make sure that the boundary proximity is not affecting the results. The thickness of the underburden should be 4–5 times the thickness of the SAGD zone.

d) To maintain the far-field stress equilibrium condition, the far-field boundary should be constrained with the in situ stress condition. Any model that uses zero displacement boundary conditions on both vertical sides may not satisfy the stress equilibrium.

Very few of the geomechanical models submitted to the AER satisfy all of these conditions. They usually have a far-field boundary constrained by rollers rather than in situ stresses to represent a half-SAGD well pad. Applying a roller boundary condition to the far-field boundary rather than a stress condition is acceptable as long as the boundary is set far enough away from the edge of the last steam chamber to ensure that the stress state at the boundary will not be affected by significant stress changes introduced by SAGD schemes.

A limitation with half-symmetry or quarter-symmetry models is the implicit assumption that deformations will be identical on both sides of the symmetry boundary, which is never true in the field. The heterogeneity of the deformations resulting from the development of the steam chambers in the vertical cross-section is shown in figure 2. The blue curve is the computed heave profile, while the black curve is the real heave profile in the field. Nonuniform steam chamber growth may increase the risk of generating stress conditions conducive to tensile failure. As such, the current half-symmetry or quarter-symmetry models, especially the 2-D models, may underestimate the potential for tensile failure.

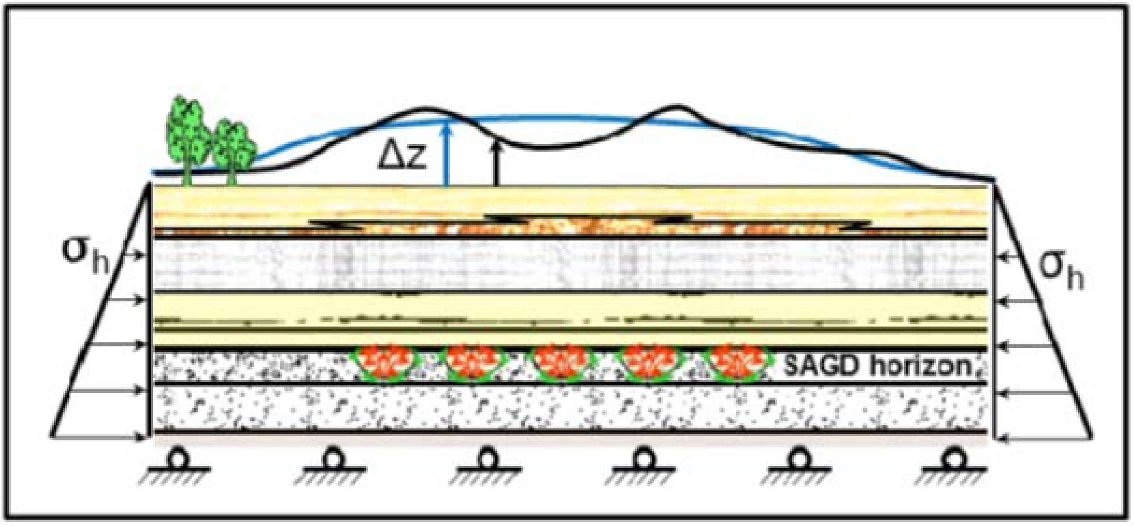


**Figure 2. Heterogeneity of deformations at a SAGD well pad in the field**

## 4.3 Constitutive Models for Caprock and Oil Sands

The nonlinear, stress-strain behaviour of oil sands must be considered in geomechanical models. Oil sands dilate under low confining stress because the sands largely consist of strong quartz grains that do not crush. Instead, the grains roll on top of each other, leading to a volumetric increase (dilation) during shear. Under laboratory conditions, shear dilation is evidenced by a total increase in volume of about 1 per cent. In the field, however, horizontal movement of the formation is constrained; dilation is mostly vertical and large surface heave is observed. For shallow SAGD schemes, the shear dilation may account for a large portion of the total surface heave. Yet neither ABAQUS nor GEOSIM has rock constitutive laws that are capable of accurately modelling oil sands dilation for shallow SAGD schemes.

Another issue is the unloading Young's modulus of the caprock material, particularly when a major loss of horizontal stress (i.e., stress reduction) is occurring in the overburden formations as a result of the thermal expansion of steam chambers during the early stage of a SAGD process. Materials such as Cretaceous shales and siltstones have a high unloading modulus that is normally substantially higher than the loading modulus of an intact (undisturbed) rock. All the geomechanical models submitted to the AER to date did not take this factor into account, which could underestimate the potential for tensile failure.

## 4.4 Model Coupling Methods

The SAGD process involves multiphase fluid flow, heat transfer, and rock deformation processes. Ideally, a fully coupled mathematical model that simultaneously solves for all of the equations would be the most robust and accurate approach to determining the MOP for a shallow SAGD project. However, such a model does not exist, and industry practice is to use one-way explicitly coupled or two-way iteratively coupled models, such as ABAQUS and GEOSIM.

In a one-way, explicitly coupled model, computations for multiphase flow and heat transfer at each time step are performed by a reservoir simulation model, while geomechanical calculations for rock deformations are done at selected time steps by the stress-strain model. The frequency of geomechanical updates is determined by the changes in the pore volume during the time steps (Dean et al., 2003). One of the benefits of using this technique is that it is straightforward to couple an existing reservoir simulator with an existing geomechanical model. All ABAQUS models submitted to the AER have been one-way coupled models. However, the one-way coupling neglects the geomechanical effects on the rock porosity and permeability, which may be important when attempting to accurately model SAGD steam chamber growth and determine an MOP.

In a two-way, iteratively coupled model, the thermal multiphase flow and solid deformations are iteratively coupled at each time step. Pressure and temperature changes are calculated by the reservoir simulator and then transferred to the geomechanical model. Updated strains and stresses are calculated by the geomechanical model and then transferred to the reservoir simulator to update the porosity and the permeability (Dean et al., 2003). The main advantage of the two-way, iteratively coupled model is its flexibility and modularity. Theoretically, if converged, this model should give the same results as those from a fully coupled model. However, conventional reservoir simulators are usually developed using the finite difference method, whereas geomechanical simulators are usually developed using the finite element method. In practice, the coupling terms cannot be easily treated in a system with two discretization methods. GEOSIM is a two-way coupled geomechanical and reservoir simulator, but it can also perform one-way coupling.

# 5 Uncertainties Associated with Measured Geotechnical Properties

It is common practice to obtain rock properties from small-scale laboratory tests. However, these properties cannot be directly used to establish the characteristics of a large-scale rock mass. For example, due to sample disturbance and the expansion of small amounts of interstitial gas, laboratory tests give substantially lower values of stiffness than actually exist in situ. As a result, the use of rock properties derived from small-scale laboratory tests tends to underestimate tensile failure.

For large-scale models, rock masses are often assumed to be continuous rather than discrete bodies, and therefore the equivalent properties need to be evaluated mathematically; this is referred to as up-scaling and homogenization of the rock mass properties. Rarely are in situ experiments conducted to obtain rock mass properties. In situ experiments are difficult to control in terms of loading and boundary conditions. As a result, rock mass properties remain an area of particular uncertainty (Jing, 2003).

## 6 Conclusions

The characteristics of a rock mass differ from other engineering materials in that the rock mass is always, to some degree, fractured and heterogeneous, and also generally anisotropic. In shallow SAGD schemes, multiple physical processes coexist and interact, and the parametric values of the main features of the system remain largely unknown. The lack of information about the rock mass and fracture geometries and properties means that working with uncertainty and variability is unavoidable for numerical modelling in rock mechanics and rock engineering. Because of these difficulties, a geomechanical model does not have to be complete and perfect; it only has to be adequate for the purpose (Jing, 2003).

Although current numerical modelling can to some extent handle very large scale and complex systems of equations, there are limitations to the ability of modelling to provide a quantitative representation of the physics of fractured-rock-mass response to combined thermal and hydraulic loading. In the case of tensile failure, the MOP formula provides an alternative to modelling. The MOP formula eliminates the uncertainty in trying to determine where the steam chamber is in all parts of the reservoir at all times and reducing the pressure as the steam chamber rises.

The MOP formula only addresses tensile failure. A caprock can also fail in shear mode due to steam injection, which may lead to a loss of reservoir containment. The potential for shear failure is more difficult to analyze than tensile failure. Although there are limitations to geomechanical modelling, it is the only tool available that can be used to assess the complex factors contributing to potential caprock shear failure. As such, the AER proposes that applicants for shallow SAGD schemes be required to conduct geomechanical modelling to assess shear failure of the caprock and provide the data used for the modelling, the source of the data, and a discussion of the results.

## 7 References

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