Abaqus/Standard Coupled Simulation of Thermally Assisted Gravity Drainage of an Oil Sand Formation

Abaqus Technology Brief

Summary

Oil sands are becoming an increasingly important source of petroleum. The form of oil in these deposits is highly viscous, making conventional drilling practices unfeasible. Extraction with wells is facilitated by increasing the temperature of the oil-bearing layer, thereby reducing the viscosity of the oil and enabling it to flow under gravity [1,2]. An example of this approach is steam-assisted gravity drainage.

Abaqus/Standard provides an analysis capability that allows for coupling between heat transfer, pore fluid flow, and displacement. In this Technology Brief, we demonstrate how this capability can be used to simulate the thermally assisted gravity drainage of an oil sand formation.

Background

The oil in a conventional reservoir can be extracted by drilling a well. This approach is possible because of the oil's ability to flow and the natural pressure in the reservoir. The oil in a sand formation differs in that it is typically in a highly viscous, semi-solid state, thus requiring unconventional extraction techniques.

Different methods are available to extract the petroleum that resides in an oil sand deposit. In the thermally assisted gravity drainage method, horizontal well bores are created in the oil-bearing layer. Pairs of parallel bores are drilled to form a grid, with each bore vertically separated as shown in Figure 1. Steam is forced into the oil-bearing layer through the upper well bore. The steam heats the surrounding material and lowers the viscosity of the oil, enabling it to flow into the lower well bore; it is then pumped to the surface. The effectiveness of this method depends on the coupled mechanical deformation, permeability, and heat transfer properties of the oil-bearing layer.

Oil sands are primarily composed of sand, clay, water, and viscous oil, and can have varying levels of compaction and porosity. The flow into the lower bore is affected by the pore pressure gradients as well as pore fluid viscosity, the latter being strongly dependent on temperature. The steam also condenses during the extraction process, giving rise to latent heat effects and the associated pore pressure modifications. Numerical simulation of these complex phenomena can help in the design and optimization of the thermally assisted process.

Finite Element Model

The simulation can be approached in a step-by-step fashion by first solving a simplified problem. We adopt this
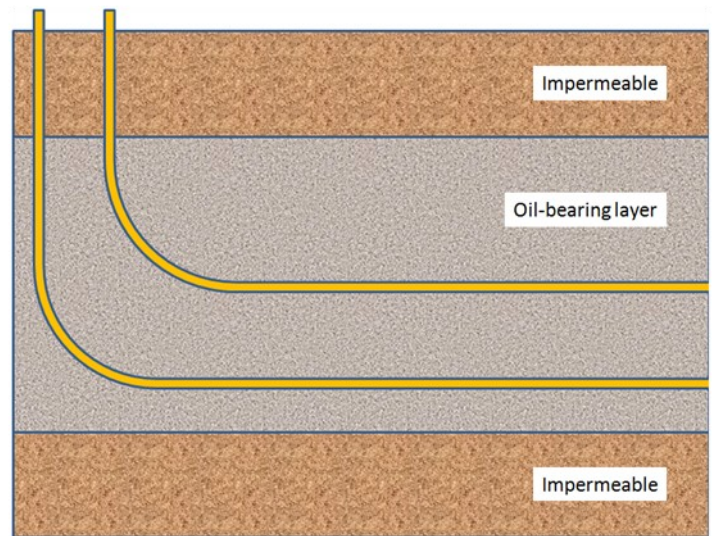

Figure 1: Schematic diagram of the upper and lower well bore in the thermally assisted gravity drainage and extraction process

Key Abaqus/Standard Features and Benefits

- Fully coupled temperature-displacement-pore fluid flow solution method in Abaqus/Standard for modeling temperature dependent flow in porous media
- Temperature-dependent pore fluid permeability

approach in this Technology Brief. Specifically, the gaseous phase (steam) of hot fluid is not modeled separately, and we assume that only heated water is pumped through the upper well bore. This allows us to model the process as a single phase fluid flow through the medium and enables heat transfer due to convective effects only. The oil-bearing layer is considered to be elasto-plastic, and full coupling between the mechanical, pore fluid flow, and thermal phenomena is modeled.

We model a pair of well bores that are part of a grid. The grid consists of parallel horizontal well bore pairs spaced 24 m horizontally, center-to-center. The oil-bearing layer is 12 m thick and is sandwiched between two impermeable layers. The depth of the top of the oil-bearing layer is 100 m from the ground surface. The lower well bore is placed 2 m above lower boundary of the oil-bearing layer

and the upper well bore is placed 5 m above the lower well bore. Exploiting symmetry in this configuration, only a section of this space is meshed (Figure 2). The impermeable layers are represented by appropriate loading and boundary conditions. The well bores are long compared to the other dimensions of the model and hence a plane strain condition is assumed, which is represented in the three-dimensional setting by applying appropriate boundary conditions. The model thickness along the length of the well bores (Y direction) is taken to be 0.01 m. The diameters of the upper and lower well bores are identical and taken to be 0.2 m.

In practice, steam is injected into the oil-bearing layer through the top region of the upper well bore. The steam condenses and heats the surrounding material. In this analysis we do not model the phase change associated with the condensation of steam. Instead, the fluid pumped through the upper well bore is assumed to be water at a temperature of 100° C. The region of the upper well bore through which this hot water is forced into the oil-bearing layer is highlighted in Figure 3.

Figure 3: Highlighted region showing the upper well bore surface through which hot fluid is forced
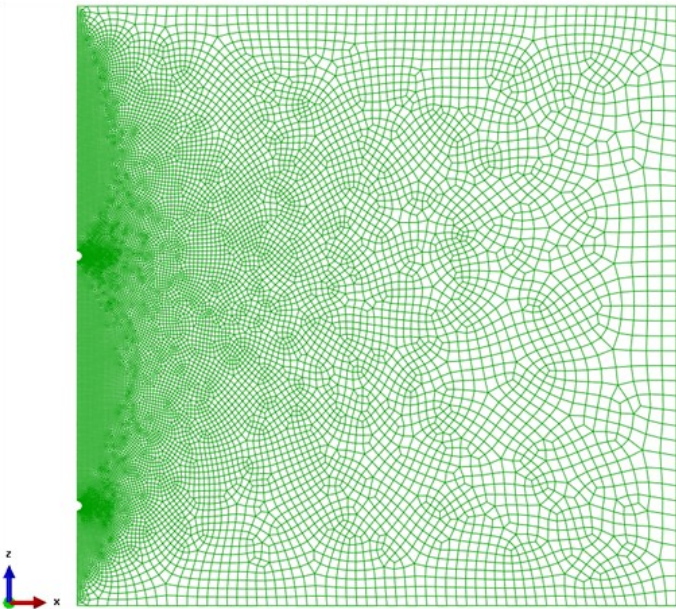

Figure 2: Symmetric mesh of the oil-bearing region

Heat transfer takes place in the medium due to conduction in the soil skeleton, and conduction and convection of the pore fluid. Injection of the heated water also results in an increase in the pore fluid pressure in the neighborhood of the upper well bore. As only a single fluid phase is modeled, the properties of the water that is forced into the layer, and those of the oil contained in the layer, are assumed to be identical. The fluid properties include temperature-dependent permeability. The oil-bearing layer is modeled as an elasto-plastic material using the Drucker-Prager plasticity model.

Mechanical loading and boundary conditions

The pressure load from the upper overburden layer onto the oil-bearing layer is taken to be 2.5×10^6 Pa and is assumed to be spatially and temporally uniform. Displacement in the vertical direction is restrained along the lower boundary of the model. Displacement is also restrai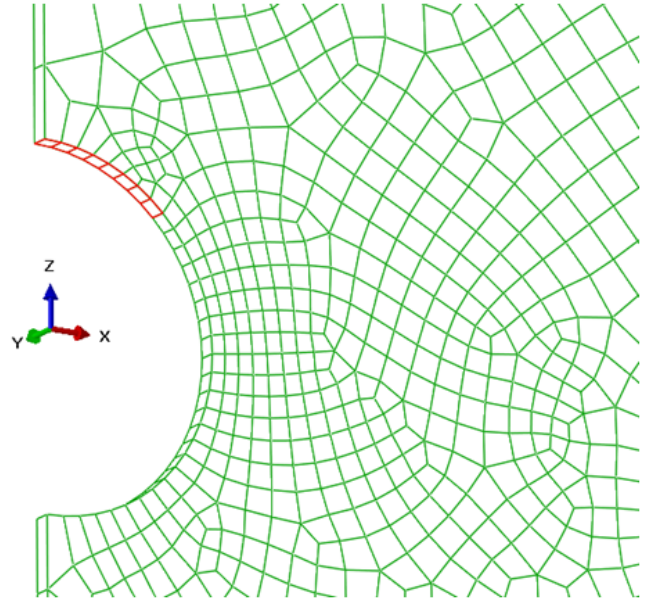ned along the vertical sides of the model to represent symmetry boundary conditions. Distributed pressure loading is applied on the inner periphery of the well bores as appropriate for the initial stress and pore pressure conditions.

Pore fluid loading and boundary conditions

The layers over- and underlying the oil-bearing layer are considered to be impermeable and are represented with a boundary condition of zero pore fluid flow at the layer interfaces. Pore fluid flow also does not occur across the vertical boundaries of the model due to symmetry, which arises from the periodicity in the grid configuration.

Initial pore pressure values are specified with an approximate hydrostatic distribution. During the analysis, pore pressure in the lower well bore is modified to simulate the pumping of oil from the oil-bearing layer. Additionally, prescribed pore fluid flow is defined over the top region of the upper well bore to represent the injection of water.

Thermal loading and boundary conditions

The model is assumed to have an initial temperature of 20° C. It is also assumed that the upper and lower impermeable layers are able to conduct heat away from the oil-bearing layer. This heat loss is modeled with a thermal film condition that relates the heat flux to the temperature at the boundary nodes.

The temperature at the nodes on the top surface of the upper bore (Figure 3), are then increased to 100° C to represent the temperature of the injected fluid.

Analysis Procedure

The analysis is performed in two steps. In the first step we perform a geostatic analysis to ascertain that the initial conditions are in equilibrium with the applied loading and boundary conditions.

The second step is a fully coupled consolidation step. The pore pressure along the periphery of the lower well bore is reduced to zero to represent the extraction of the oil. Simultaneously, a prescribed distributed pore fluid flow

of 1x10^{-6} m/s is applied on the top surface of the upper well-bore (Figure 3) along with a temperature of 100° C at the corresponding nodes to represent the injection of heated fluid. The coupled analysis simulates a time period of 1000 days.

Results and Discussion

In the consolidation step, the forced fluid flow increases the pore pressure in the neighborhood of the upper well-bore. Regions of the oil-bearing layer that get subjected to higher amounts of pore pressure expand volumetrically. Conduction and convection of the heated pore fluid gives rise to volumetric thermal expansion as well. Both effects result in an uplift of the top boundary of the oil-bearing layer as seen in Figure 4. This figure is a snapshot of the deformed shape of the oil-bearing layer at 1 year. Figure 5 shows the pore pressure distribution at 1 year. Figure 6 shows contours of maximum principal plastic strain in the neighborhood of the upper well bore. High plastic strain values are caused by the forced entry of the pore fluid through the top region of the upper well bore.

By the end of the analysis the values of vertical displacement and pore pressure reduce, as shown in Figures 7 and 8. Temperature distribution after 1000 days is shown in Figure 9.

As all nodes along the periphery of the lower well bore are taking part in extracting oil, the sum total of the nodal fluid volume provides a measure of the total fluid that has been extracted from the oil-bearing layer. Figure 10 shows a plot of the summed nodal flow versus time. The rate of change increases in magnitude as the oil-bearing layer heats with time. Accounting for symmetry, the total volume of fluid extracted after 1000 days is 11.36 m^3 per meter of the lower well bore.

As a comparison, in the absence of any thermal assistance, the rate of fluid flow is only 1.6 m^3 per meter of the lower well bore.

Conclusion

In this Technology Brief we have demonstrated the modeling of the thermally assisted gravity drainage process in the presence of some simplifying assumptions. While the actual process is substantially more complex, involving the condensation of steam and also natural convection of fluids within the oil-bearing layer, the three-way coupled thermal pore fluid flow displacement capability in Abaqus/Standard provides a means for computing fluid extraction estimates and the elasto-plastic deformations of the oil sand. Extensions to the approach include modification of the flow regime through the use of void-ratio dependent permeability.
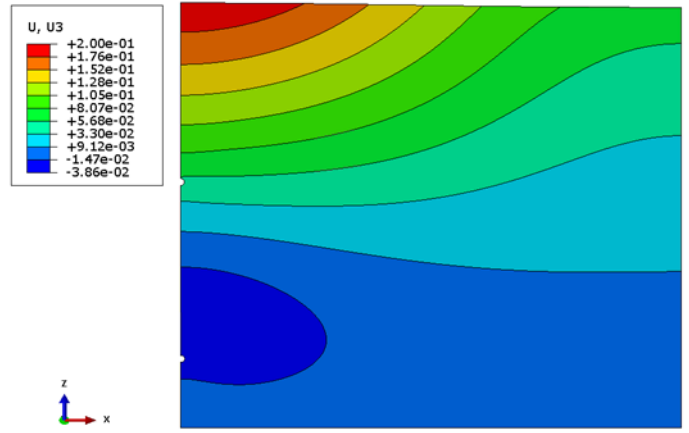

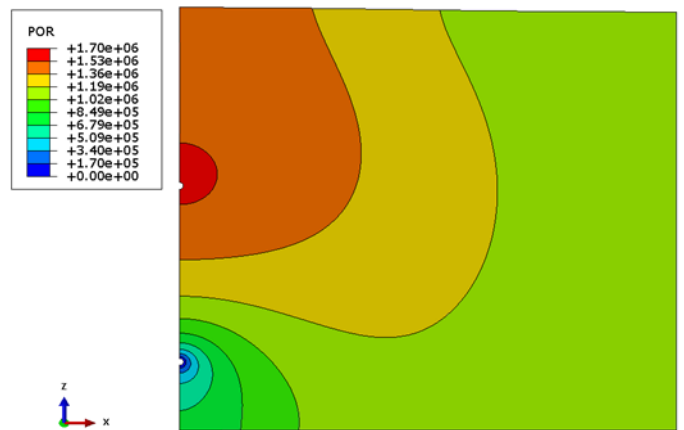Figure 4: Displacement (m) in the vertical direction at 1 year

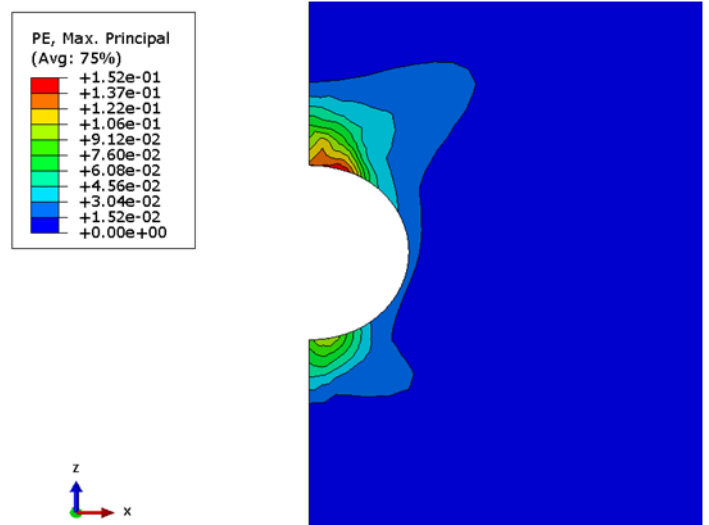Figure 5: Contours of pore pressure (Pa) at 1 year

Figure 6: Contours of maximum principal plastic strain in the neighborhood of the upper well-bore at 1 year. High plastic strain values are seen due to the forced entry of the pore fluid into the oil-bearing layer.
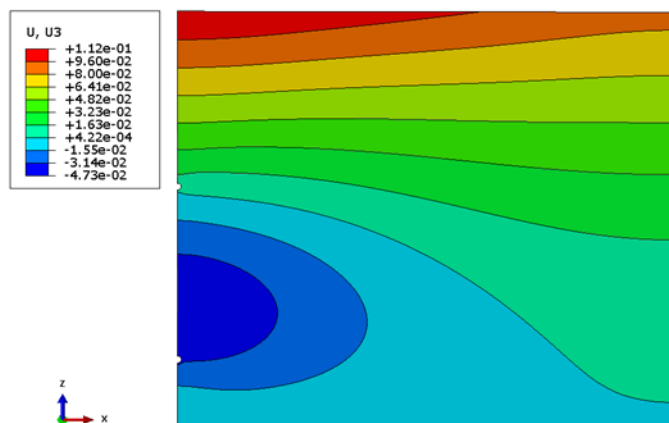
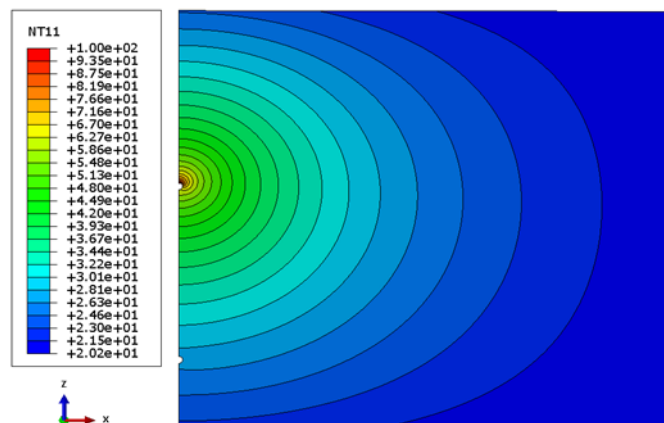Figure 7: Vertical displacement (m) after 1000 days
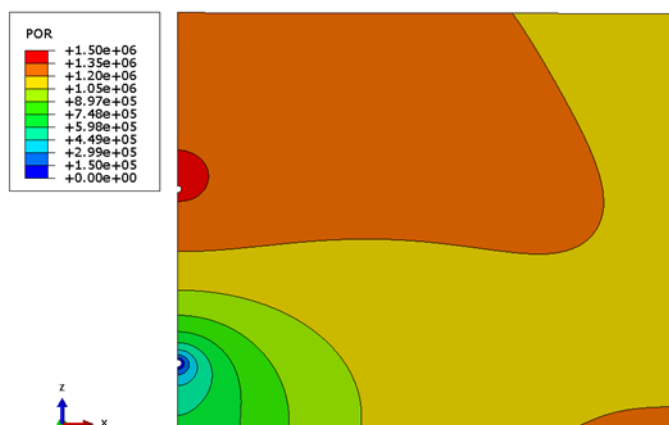

Figure 9: Temperature (^{o}C) after 1000 days
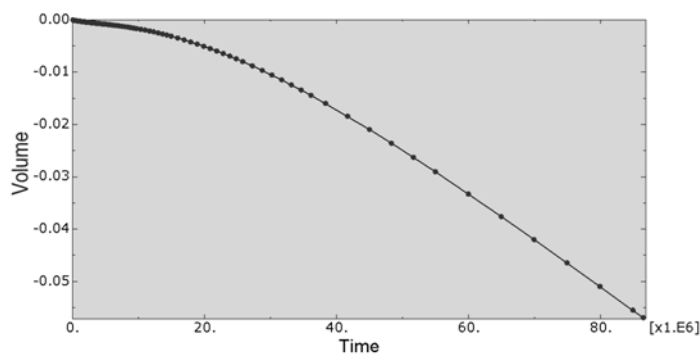

Figure 8: Pore pressure (Pa) after 1000 days

Figure 10: Total volume of fluid (m^3) extracted from the oil bearing layer v. time (s)

References

1. Geomechanical Coupling Simulation in SAGD Process; a Linear Geometry Model, by Azad, A. and Chalaturnyk, R.J.; Proceedings of the 3rd CANUS Rock Mechanics Symposium, Toronto, May 2009.

2. Operational and Reservoir Parameters Influencing the Efficiency of Steam-Assisted Gravity Drainage (SAGD) Process in Fractured Reservoirs, by Fatemi, S. M. and Kharrat, R.; Brazilian Journal of Petroleum and Gas, v. 3 n. 4 pp 125-137, 2009.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, please see the following Abaqus Version 6.12 documentation references:

- Analysis User's Manual
    - 'Coupled pore fluid diffusion and stress analysis,' Section 6.8.1

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