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RESERVOIR GEOMECHANICS

How reservoir geomechanics is being addressed by SIMULIA

INTRODUCTION

Energy consumption in the world is increasing. The growth in consumption is expected to be strongly driven by China, India and other non-OECD countries. Most of this consumption will be related to oil and gas, mainly for transportation and electricity. Oil and gas also are primary raw materials for a wide range of products including plastics and chemicals, and their usage is also increasing fast. This increase in the demand for oil and gas needs to be satisfied reliably and sustainably. How can we ensure that this happens?

Extraction of oil and gas is a capital intensive activity; wells need to be drilled, offshore structures need to be erected, both well in advance of the actual oil and gas extraction. The oil and gas producer needs to plan out the expenditure and revenue well in advance to ensure profitability. Without a good profit, the producers will not produce, which would result in insufficient supply to meet the demand.

ROLE OF GEOMECHANICS

Oil and gas extraction leads to modifications in the existing stresses in the ground. These modifications may result in undesirable safety implications such as induced earthquakes, cap rock failure, etc. Additionally, these modifications affect the oil and gas production, and hence need to be understood and taken into account for obtaining reliable estimates of oil and gas supply. There are also other criteria involving health, safety, and environment issues that the producers and society need to think about. Safety, reliability, and profitability, thus, form the three important facets of the oil and gas industry, and geomechanics, which is the science that helps in estimating the modifications of stresses in the ground, hence becomes critically important as it has a bearing on all of these facets.

The following are some of the operations and applications in the oil and gas industry wherein geomechanics plays an important role:

- Fault stability analyses to understand and avoid any triggered seismicity
- Caprock integrity or equipment integrity analyses to avoid related environmental issues
- Lost returns and wellbore stability analyses to ensure reliable and efficient drilling processes
- Water injection and stimulation analyses for ensuring optimal oil and gas production
- Water disposal and drill cuttings re-injection analyses for efficient waste management

Figure 1 shows an illustration of the layers in the ground with a petroleum-bearing reservoir region colored as red.

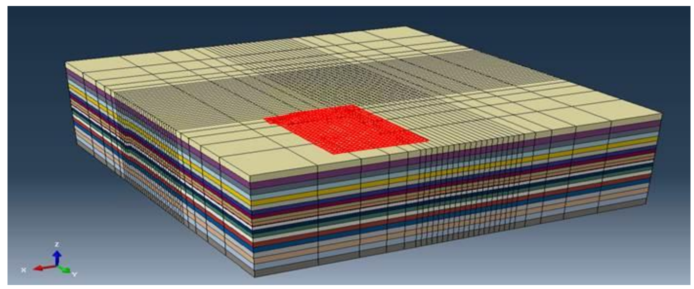

Figure 1: Layers of the ground with the reservoir region shown in red.

Reservoir geomechanics is not new for SIMULIA. The initial development of Abaqus was driven in part by the requirements from the oil and gas industry. Our efforts started in the 1980's, with an initial relationship with Exxon. Subsequently, our capabilities and features have been enhanced by the input from different partnerships and projects undertaken in the subsequent years. These include collaborations with Eni, Baker Hughes and now again with ExxonMobil. The collaborations with Eni and ExxonMobil are described in the recent SIMULIA Community News magazines, and the cover pages of these are shown in Figure 2.

Figure 2: SIMULIA Community News articles describing the collaborations with [Eni, SpA](), and [ExxonMobil]().

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As geomechanics plays a very important role in ensuring the safety, reliability, and profitability of oil and gas extraction, let us look into how we can help understand and include the finer aspects of geomechanics into the decision-making processes in the oil and gas extraction industry.

GEOMORPHOLOGY

For including geomechanics, we first need to describe the structure and morphology of the ground, including the geometry of the layers in the ground and their material characteristics.

For describing the geometry of the layers in the ground, one needs to gather information from seismic measurements and drill logs. This information is spatial, in 3D. By itself, this information is difficult to use for simulation purposes. Therefore, this information is first examined by expert geologists, who interpret this information and decide, based on this information, where they think the different layers of the ground are spatially located, including the locations and extents of the faults. This interpreted data can then be used as the basis to describe the geo-structure.

The interpreted data, although simpler than the seismic data, is often in a form that cannot be directly used for simulation purposes. In order to be used for simulation, we need to describe the layers in the form of CAD data or similar kinds of data that are appropriate for numerical simulation models. Also, the geometrical information may be too dense for contemporary simulation technologies. Approximations may therefore be done to coarsen the data to make it suitable for simulations. This coarsening process is called upscaling.

For simulation, we also need to have data on the material properties. The different layers of the ground can have different material properties. These properties, such as those pertaining to fluid flow and elasto-plasticity, need to be interpreted based on core samples, drill cuttings, and acoustic measurements. These material properties need to be described in detail with good fidelity over the full range of stress and fluid pressure values that can be expected in the ground during oil and gas extraction and related operations.

After the material characterization is done, one can perform a flow simulation analysis, which is used for computing how oil and gas flow due to modifications in fluid pressure and temperature, and, subsequently, also a geomechanical analysis, wherein the effects of the modifications in fluid pressure and temperature on rock deformation are obtained. Ideally, one needs to perform both these simulations simultaneously using a coupled analysis scheme.

MULTI-STAGE WORKFLOW

The workflow starting from seismic measurements together with drill logs, and ending at flow and geomechanical simulations, is a multi-stage process. Some of these stages are well established in the industry, and some can benefit from further refinement. In particular, we are trying to provide capabilities to make this workflow as smooth as possible by filling in a few gaps that have been identified:

- The model creation stage, currently, is more suited towards flow simulation; however, it can be improved for performing geomechanical simulations. The CAD models suitable for geomechanical simulations need to follow strict requirements to allow them to be used as bases for finite element mesh generation. We have developed different schemes for creating geometrical CAD models suitable for meshing purposes, as described in the next section.
- The next gap involves incomplete description of the geo-structure, and/or extreme topological complexities that make creating CAD geometries and subsequent meshing tasks a bit difficult. Obtaining precise information on the geo-structure as well as incorporating enhancements to the geometry creation tools can help alleviate these issues.

Additionally, to help in providing smooth end-to-end workflows, we are also connecting all our technologies, including reservoir geomechanics and downstream workflows, with other solution providers in the industry, so as to provide users an open framework for exchanging data. The end goal is to provide a digital continuity for reservoir geomechanics simulations. These connections will allow users to:

- Prepare and identify drilling sequences, and plan for the completion of wells
- Improve production performance
- Improve waste management

EARTH MODELING

Earth modeling is mainly the creation of meshing-ready CAD models from interpreted geological models. The interpreted geological models essentially describe the geo-structure using the following: (1) the geological layers, (2) horizons or surfaces between the layers, and (3) faults.

The layers are the regions between the horizons and the horizons are described by surfaces. The topography of the faults is also described by surfaces. The interpreted geological models are thus often just surfaces, and these then need to be used for coming up with 3D geometrical data to describe the stratigraphy of the ground. An illustration of the horizon surfaces and faults is shown in Figure 3.

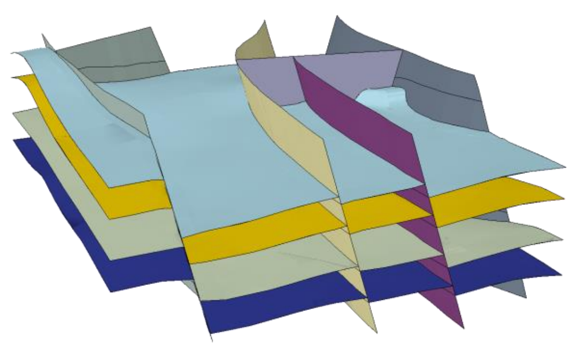

Figure 3: Interpreted horizon surfaces and faults in a geological model

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The horizon and fault surfaces in the interpreted geological models are derived from point cloud data values that are directly obtained from seismic and bore-log observations. In the interpreted model data, these surfaces are then described by triangulated surfaces, such as in the SAT format. Adjacent triangulated surfaces can be spaced vertically away from each other, or these can sometimes merge or vanish according to the erosion history undergone by the geological strata. The continuity of the surfaces can also get terminated at the faults. Also, when point cloud data is interpolated by best fit polynomial or other entities, extraneous outliers may get introduced in the interpolated surface profiles. Due to these kinds of complexities that may exist in the interpreted geological models, it may often become difficult to directly use these interpreted geological models for generating CAD models suitable for meshing with finite elements. Specific extra editing tasks are hence then required, which can involve modifying the coordinates of some outlier points, merging or projecting nodes in the triangulated surface data, or deleting or creating new triangular elements, in order to obtain watertight definitions of the surfaces or cells.

We have now outlined some methods for creating meshable CAD models for some of the complex topographical descriptions observed in interpreted geological models. These methods can help users in building up finite element models for geomechanical analyses.

CAD MODELS SUITABLE FOR MESHING

There are several ways to create meshable CAD models from orphan-meshed or triangulated surfaces that represent horizons and faults:

The first one is by using only Abaqus/CAE technologies. This workflow consists of 5 mains steps:

- Import of the orphan meshed surfaces
- A new interpretation phase to fix specific surface definitions, using mesh editing tools
- A mesh simplification phase for reducing the complexity and the number of elements along those surfaces, if needed, using mesh editing tools
- The creation of geometrical faces from the triangular elements of the orphan meshes using a dedicated Abaqus/CAE plug-in, and ignoring geometry edges for the subsequent meshing step by using virtual topology tools
- Surface mesh and mesh extrusion using the bottom-up meshing technique in Abaqus/CAE

The second workflow starts with the same steps, but uses Abaqus/CAE as well as CATIA. The following are the steps for this workflow:

- Orphan meshed surface import
- Interpretation, mesh simplification, and geometrical face creation in Abaqus/CAE
- Importation of these geometrical faces into CATIA Apps of the 3DEXPERIENCE platform to close the volumes and create individual cells
- Importation of these cells back into Abaqus/CAE in an assembly context to be meshed with the regular top-down approach, or with the bottom-up technique.

Figure 4 shows a model containing horizons and faults created using the second workflow.

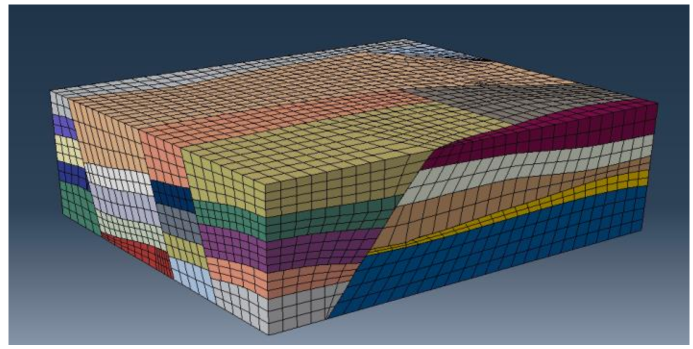

Figure 4: A model containing horizons and faults created using the second workflow. Both, Abaqus/CAE as well as CATIA, are used for creating this model.

In the third workflow, instead of starting from horizons and fault surfaces, one can start from a reservoir flow model, for example, Eclipse from Schlumberger, and create the over-, under- and side-burden mesh with the bottom-up technique. This complete workflow has been well captured with several examples (Refs. 1-3). We also have the Reservoir Modeler Abaqus/CAE plug-in that enables one to manage and drive this workflow. This plug-in and the translator for creating Abaqus meshes from Eclipse data can be made available to users. This workflow has been in use for several years by our customers and improvements are being made to the plug-in to simplify and automate the tasks involved.

MATERIAL PROPERTY ASSIGNMENT

Reservoir geomechanics analyses not only need a good topographical model, but also realistic definitions and assignment of material properties. Many times the material assignment processes can be complicated due to the large number of material regions involved, and also due to the dependence of the material properties on the prevailing stress values in situ. The first and second workflows described previously allow the user to create just the finite element mesh. The third workflow includes finite element mesh creation as well as material assignment; both of these are enabled through the Reservoir Modeler plug-in. Material assignment can be done for the first and second workflows using mapping, and appropriate scripts can be written for this purpose.

MESHING AND PROPERTIES USING JEWELSUITE

The process of mesh creation and material assignment can also be done by leveraging 3rd party solutions provided by our partners. One such partner is Baker Hughes.

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We have partnered with Baker Hughes to incorporate Abaqus in their JewelSuite product. Jewelsuite helps the user to build up meshes based directly on the interpreted geological data, which is the same data that is used for performing flow analyses. Furthermore, the Jewelsuite product also helps the user assign material properties using mapping, apply boundary conditions, loading conditions, and build up run-ready Abaqus models. The models are then analyzed using Abaqus, and post processed using Jewelsuite. This procedure is similar to the third workflow described previously; however, the procedure using Jewelsuite is much smoother and user-friendly. One thing to note here is that in the third workflow, the finite element mesh is based on the flow simulation grid in Eclipse, which contains hexahedral cells; the topography of which is directly used for constructing the finite elements. In the Jewelsuite procedure, however, the finite element mesh is independent of the flow simulation grid, although the positions and topography of the horizons and faults are preserved between these. The 3D layer regions between the horizons are meshed using tetrahedral elements in the Jewelsuite procedure.

MESHING USING SKUA-GOCAD

We have recently partnered with Paradigm to provide users an alternative approach to create reservoir meshes suitable for geomechanics analysis. Using SKUA-GOCAD, users can create finite element mesh data that can be directly used for constructing Abaqus reservoir geomechanics models. SKUA-GOCAD also interfaces with flow simulation codes. This workflow is similar to the one using Jewelsuite, and reservoirs containing faults can be meshed accurately using this approach. It is then possible for the users to perform subsidence, fault stability, and fault reactivation studies.

COUPLED DEFORMATIONS AND FLUID FLOW

In a reservoir, the mechanical deformations and fluid flow are coupled to each other. This coupling can be significant in reservoirs that contain compressible rock. The goal of performing coupled reservoir geomechanics analyses is to find out the mechanical deformations due to oil and gas extraction, and also simultaneously include the changes in fluid flow resulting from mechanical deformations in the reservoir rock. The modeling of fluid flow involves sophisticated analyses that need to include multiple fluids and fluid components differentiated according to the molecular weight of the constituent hydrocarbon fluids. The fluids can undergo dissolution and chemical changes depending on the prevailing pressure and temperature. The pressure of the fluid leads to modifications in the stress regime in the rock, which in turn can give rise to rock deformations and strains. A fully coupled analysis that includes such complex fluid flows along with mechanical deformations would be the ideal solution for realistic reservoir geomechanics simulations. However, in the absence of such complex techniques, the next best solution is to perform a co-simulation analysis between the fluid flow and mechanical deformations, wherein data transfer between the codes takes place at every time increment. Alternatively, a staggered exchange of data can be done, wherein the data is transferred at pre-defined regular intervals. A further simplified approach is through a one-way data transfer to compute the effect of fluid pressure changes on the mechanical deformations. In all these cases, one needs to transfer data between the flow simulation codes and Abaqus. Techniques for such a data transfer have been developed by SIMULIA for Eclipse™ (from Schlumberger), and for other flow simulation codes through collaborative solutions provided by our partners. These are for one-way transfer of data from flow simulation codes to Abaqus. Users have also developed in-house routines to enable such data transfers (Ref. 4).

Extraction of oil and gas from the reservoir leads to a redistribution of pore fluid pressure. This causes redistribution of stress in the rock. Temperature field is likely to change also, especially in cases of enhanced oil recovery (EOR) techniques, such as steam injection. Cold water may sometimes be injected, which can lead to thermal shock and fracturing of the reservoir rock. Heat transfer can occur, both due to conduction in the rock as well as convection due to the movement of the fluids. All these aspects, including the multiple fluids, phase changes due to steam condensation, etc. need to be taken into account in realistic simulations.

Techniques such as steam assisted gravity drainage (SAGD) are used to extract oil from bituminous sands. Significant mechanical deformations can occur during these procedures. Reservoirs containing compressible rocks can also undergo significant deformations due to oil and gas extraction, necessitating the use of coupled techniques for realistic simulations.

As discussed before, a fully coupled technique would be the ideal choice; however, due to the complexities involved, one can consider using simplifications such as co-simulation analysis, two-way staggered coupled analysis, or one-way coupled analysis.

The above schemes can be used for simulating scenarios such as subsidence, cap rock integrity, fault reactivation, well path optimization, etc. These models can then be employed as global models that can then be used to drive submodels for studying in detail scenarios like casing failure, well-bore stability, mud-window analysis, etc.

Some results from a subsidence analysis performed by Eni, SpA, are shown in Figure 5. The analysis is done as a one-way coupled analysis using Eclipse as the flow simulation code. The Abaqus mesh is created directly from the flow simulation grid by using a translator developed for this purpose. The available Reservoir Modeler plug-in can be used to automate this mesh creation process.

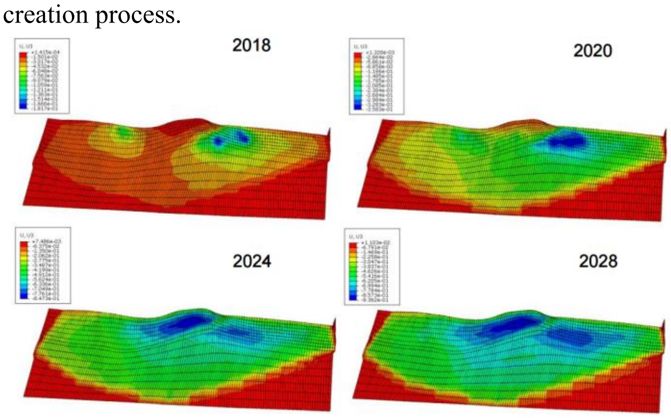

Figure 5: Four increments in an Abaqus FEA simulation of subsidence in a hypothetical oilfield, displayed over ten years (Ref. 2). Blue areas denote greatest downward displacement of

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the surface. This particular example from Eni contains just 300,000 degrees of freedom; enhancements in model setup and automation now allow the running of huge full-scale models with millions of DOF in just a few hours.

CO-SIMULATION

As shown previously, co-simulation between Abaqus for geomechanics and a reservoir flow simulator can dramatically improve the accuracy of oil and gas production estimates. The Co-Simulation Engine (CSE) should allow one to connect these codes, each running on its own machine or on the same machine.

Accurate estimates of upstream oil and gas production are essential to allow one to manage the supply of petroleum products downstream. Performing co-simulation analyses will enable one to reduce the uncertainties involved in oil and gas extraction. Prediction of hydrocarbon extraction associated with enhanced oil recovery techniques, and also the design and optimization of these techniques can be improved by performing co-simulation analyses. Co-simulation can be very helpful for improving the accuracy of steam assisted gravity drainage operations, in-situ operations performed for oil shale, and similar applications including those for reservoir rocks exhibiting significant compressibility.

Import of pore pressures for co-simulation in 3D had already been supported, and now export of void ratios has also been made available. The pore pressures can be used by Abaqus to compute the mechanical deformations and modified values of void ratio in the reservoir rock. These void ratios can now be exported out through the co-simulation engine and can then be used by the flow simulation codes to compute modified permeabilities for flow simulation. This process can be repeated at frequent intervals.

MULTI-SCALE APPROACH FOR GEOMECHANICS

Reservoir geomechanics applications can be addressed using a multi-scale approach as well. Figure 6 shows an illustration of the different levels of scale that can be found in reservoir geomechanics.

Starting from the rock microstructure, the macro-properties of the rock can be obtained by suitable homogenization techniques. We are collaborating with Simpleware for improving macro-property characterization based on the micro-structure of rock and similar materials. This scale can range from fractions of a millimeter to about a centimeter.

The macro-properties of the rock can then be used on wellbore-scale models for performing bore-hole stability type of analyses. New material models have now been introduced in the code to enable one to include rock anisotropy and the development of shear bands. The clay plasticity material model in Abaqus has now been enhanced and made applicable for representing anisotropic material behavior. A special softening regularization scheme has also been included in this model to allow for shear band formation and to obtain grain-size-sensitive response. This scale can range from a few centimeters to about a meter.

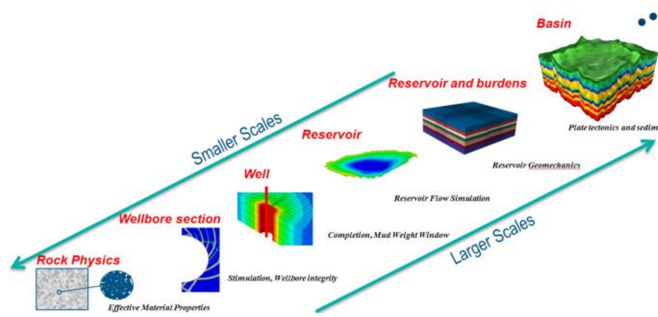

Figure 6: Different levels of scale that can be found in reservoir geomechanics.

For scales larger than the well bore, we can include some rock region in its neighborhood. For this scale, which can range from about a meter to hundreds of meters, we have developed techniques for simulating the formation of hydraulically driven fractures. To allow for the simulation of the formation and propagation of these fractures, we have developed new techniques such as improved pore pressure cohesive elements and extended finite element techniques that include pore fluid flow in the rock and the fracture. To enable the accurate application of mechanical load from the well-bore to the rock, a new loading condition has been implemented, which takes into account the prevailing value of the pore pressure at the well and applies it as distributed load onto the interior surface of the well-bore. As this pore pressure value is solution-dependent, an automatic way of applying the distributed load was hence necessary.

At the reservoir scale, techniques for performing co-simulation analyses are being made available. One-way coupled schemes are available both using Abaqus as well as through our partners. Meshing schemes are being improved to enable one to create and edit mesh grids constructed from flow simulation codes and interpreted geological data. This scale ranges from a hundreds of meters to thousands of meters.

A still larger scale encompasses the reservoir as well as the over-, under-, and side-burden regions. On this scale and also in the previous one, one can encounter geological faults that can slip due to stress modifications in the rock. Techniques for predicting the likelihood of fault slippage are being made available through improved contact modeling capabilities and also through improved pore pressure cohesive elements that can take into account the movement of fluid along the fault surface. This scale ranges from a kilometer to several kilometers.

On a still larger scale over hundreds of kilometers, the basin consisting of tectonic plates can be modeled along with faults, subduction, mountain-building processes, etc. Analyses on this scale can be used to predict the likely configuration of the geological structure millions of years in the past. Such analyses help geologists predict the likelihood of success in obtaining hydrocarbon resources in the ground by looking at the current and past configurations of the geological layers. Contact and creep modeling capabilities in Abaqus can help in these types of analyses.

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NEW FEATURES AND TECHNOLOGIES

New features have recently been implemented in Abaqus for addressing the needs of users for realistically simulating reservoir geomechanics. These include the following:

- Crack propagation with cohesive and XFEM methods
- Submodeling at multi-scale levels
- Fluid pipe elements and connectors for modeling 1D well bores in reservoirs and automatic application of distributed loads from pore fluid using a special loading condition.
- New element formulations, for example, new coupled pore-pressure-displacement tetrahedral elements and pore pressure cohesive elements with a smooth transition between Darcy flow and Poiseuille flow.
- New material models for geological materials, for example, orthotropic clay plasticity model, and soft-rock plasticity model.

The following are some of the workflows that can be addressed by these new features and technologies:

- Stimulation or creating hydraulic fractures for increased flow of oil and gas during extraction
- Cuttings re-injection or disposal of solids produced by the drilling processes
- Produced or waste water disposal
- Well-bore integrity assessment or reducing fluid loss during drilling
- Fault stability and slippage assessment

Recent articles (Ref. 5-9) describe these workflows in detail along with numerical results using the newly developed technologies in Abaqus.

Figure 7 depicts the shear bands near a bore-hole predicted using the newly implemented orthotropic clay plasticity material model. This analysis is for a vertical bore-hole subjected to in-ground horizontal compressive stresses, but not sufficient mud pressure to support the rock. The rock fails in shear as the mud pressure is reduced.

Figure 8 shows the pore pressure contours in a hydraulic fracture stimulation analysis based on the new pore pressure cohesive elements that exhibit smooth transition between Darcy flow and Poiseuille flow. Gravity effects are included in the element formulation. Fluid pipe elements have been used to drive the fracturing fluid into the formation.

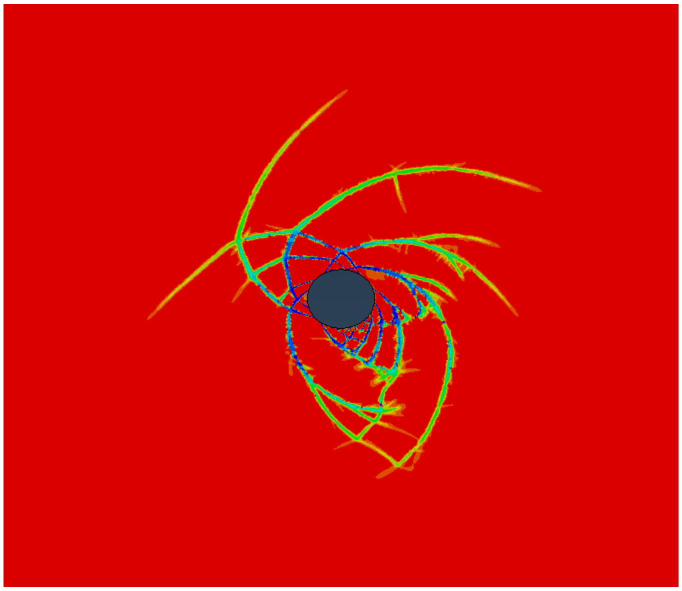

Figure 7: Shear band pattern computed using the newly implemented orthotropic clay plasticity model. The analysis is for a bore-hole model subjected to in-ground stress and insufficient mud pressure to support the rock. The rock fails in shear as the mud pressure is reduced.

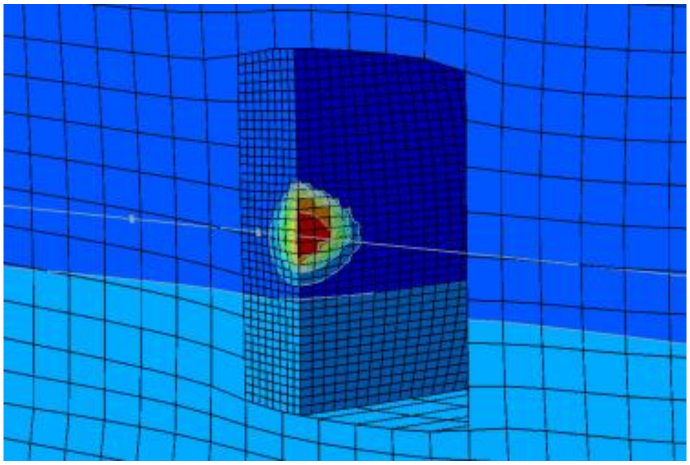

Figure 8: Pore pressure contours in a hydraulic fracture stimulation analysis based on the new pore pressure cohesive elements that exhibit smooth transition between Darcy flow and Poiseuille flow. Gravity effects are included in this element formulation.

Figure 9 shows a formation expected to undergo hydraulic fractures, colored light blue, and the surrounding rock, colored green. The well-bore is placed vertically, starting from the ground level, and turns to a horizontal level at a depth of about 2700 m. Two initial fractures created by explosive charges are positioned as shown on the right. The fluid pressure in the well-

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bore is then increased to drive the fractures further using the extended finite element (XFEM) technique. A coupled pore fluid flow displacement formulation is used. Fluid pipe connectors are used to control the fluid flow allowed to enter the formation at the locations shown. Initially, the fracture on the right is allowed to propagate, and then the one on the left.

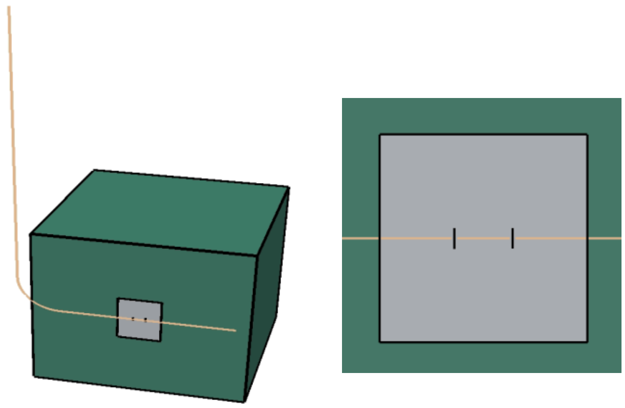

Figure 9: The rock formation expected to undergo hydraulic fractures, colored light blue, and the surrounding rock, colored green. The well-bore is placed vertically, starting from the ground level, and turns to a horizontal level at a depth of about 2700 m. Two initial fractures created by explosive charges are shown on the right.

Figure 10 shows the hydraulic fractures in the formation after the propagation of the right fracture, shown on the left, and then the propagation of the left fracture, shown on the right. The fractures are seen to propagate upwards due to the reduction in the lateral stress in the rock at higher elevations.

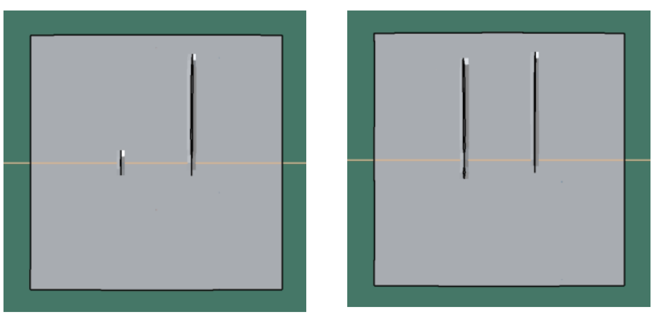

Figure 10: Hydraulic fractures in the formation after the propagation of the right fracture, shown on the left, and then the propagation of the left fracture, shown on the right. The analysis has been done using the extended finite element method (XFEM) and using a coupled pore fluid flow displacement formulation. The fractures are seen to extend vertically upwards due to the reduction in the lateral stress at higher elevations.

Figure 11 shows slippage at faults due to changes in pore pressure near a geological fault. The undeformed shape is shown in Figure 4. General contact with friction has been assumed at the faults. The pore pressure is increased at a few nodes in the interior of the model, which leads to a reduction in the effective stress in the neighborhood of the nodes. As the nodes are near a fault, this reduction in effective stress reduces the frictional forces at the fault, leading to fault slip and uplift of some regions in the ground.

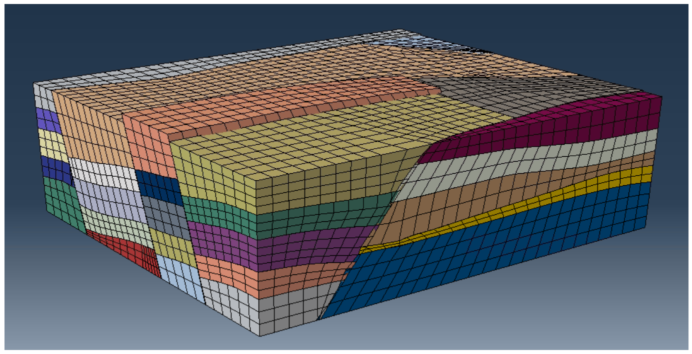

Figure 11: Fault slippage due to changes in pore pressure near a geological fault. Compare with Figure 4, which shows the undeformed configuration.

SUMMARY

We are strongly engaged to have a digital continuity for reservoir geomechanics, at the solver side for the multi-scale challenges, and at the business side with connection to the process management apps. We are also fully engaged to enhance our openness where it is important, for example, for co-simulation.

This digital continuity will provide a complete workflow, from building up reservoir geomechanics models, to analyze them, and then to interpret the results for making sound and profitable business decisions in the oil and gas extraction industry

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