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A WORKFLOW FOR BUILDING AND CALIBRATING 3D PRE-INJECTION AND 4D GEOMECHANICS MODELLING TO ASSESS CAPROCK AND FAULT INTEGRITY FOR GEOLOGIC CO_2 STORAGE

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Abstract

Carbon capture and storage (CCS) has been established as a viable technology for the mitigation of climate change caused mainly by anthropogenic greenhouse gas emissions into the atmosphere. Ever since the publication of the special report on CCS by the Intergovernmental Panel on Climate Change in 2005, there has been an increased research and development in all areas of CCS. Some of these research involves use of numerical methods and models for optimizing storage and ensuring effective long term containment. In this paper, we propose a workflow for building and calibrating 3D pre-injection and 4D geomechanics modelling to assess caprock and fault integrity for geologic carbon dioxide storage. The workflow presented here describes a seamless end-to-end process which combines a transparent flow of data with an easy-to-use graphical user interface. The workflow can conduct 3D static and 4D flow-, pressure-, and temperature-coupled calculations for rock deformations, failure and stresses. In highly heterogeneous and complex models, the workflow is capable of modelling multiple hundred faults, and multiple thousand discrete fractures. It allows the geological model, despite its high degree of complexity to be maintained throughout the geomechanical analyses process.

Keywords: Workflow; Caprock; Fault; CO_2 storage; Bunter sandstone formation.

1. Introduction

To store CO_2, apart from determining a formation's ultimate containment capacity, it is a prerequisite to ensure the presence of an effective caprock [1] atop the storage formation to prevent leakage of stored CO_2 back to surface. Argillaceous rocks such as mudstones, shales and clays, and evaporites such as salts and anhydrites are some of the commonly identified effective caprocks for a CO_2 storage site [2].

However, for effective CO_2 containment, there are important rock properties that could determine caprock sealing ability. These properties could include (although not limited to) high capillary entry pressure, low permeability, high iron exchange capacity, high sorption capacity, and high swelling ability [3-4]. Geomechanical modelling can help to better our understanding on the behavior of a reservoir and caprock under tectonic stress [5] field because of injecttion and storage of CO_2.

In this paper, we present a workflow which can be used in building 3D pre-injection and 4D geomechanics modelling to assess caprock and fault seal integrity for geologic CO_2 storage. The work presented here is a seamless end-to-end workflow which combines a transparent flow of data with an easy-to-use graphical user interface. The workflow is capable of performing 3D static or 4D flow-, pressure- and temperature-coupled calculations for rock deformations, failure and stresses. In highly heterogeneous and complex models, the workflow is capable of modelling multiple hundred faults, and multiple thousand discrete fractures. More so,

the workflow allows the geological model, with its high degree of complexity, to be maintainnned throughout the geomechanical analyses process.

2. General Workflow

To conduct reservoir geomechanical modelling, it is important to follow several stages (Figure 1). These stages include creating geomechanical grid; creating materials and functions; populating properties; modelling discontinuities, faults and discrete fracture networks (DFNs); defining pressures, temperatures and saturations; defining boundary conditions; defining simulation case; and analysing and visualising the results.

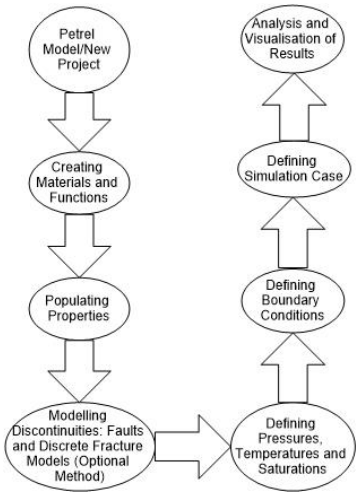

Figure 1. Summary of workflow used for building 3D/4D reservoir geomechanical models

With a new Petrel project or an already existing reservoir simulation model, it is possible to build, calibrate and simulate information derived from large scale data collections to use these for geomechanical studies. Some of the advantages of the simulator is that it reduces non-productive time during exploration activities in a fields' early life by enabling developers to assess potential for risks in drilling, avoiding unexpected problems such as increased well costs, and reducing non-productive time. Equally possible is the ability to in-corporate time as a fourth dimensional space into the model and to use it in the prediction of stress changes, rock failure, and deformation, which might happen in the later life of a field. In other words, the simulator allows geoscientists and engineers to understand different levels of formation compaction and overburden movements which can affect well- and cap-rock integrity, inadvertent loss of reservoir containment or out-of-zone injection, potential to produce solids, changes in reservoir performance and characteristics, risks of seismicity and induced rock failure following fault activation or fracturing.

2.1. Geomechanical grid

The process of creating a geomechanical grid may involve the addition of an overburden, underburden and sideburden grid cells to an already existing reservoir grid or by converting a pre-embedded model. In this workflow, we attempt to create a new geomechanical pillar grid model (Figure 2) using a simple input created by standard processes in Petrel. Using this method, a grid created is ideally free from bad cells such that it could be suitable to use in other workflow stages, but with an exception: not suitable for two-way coupling.

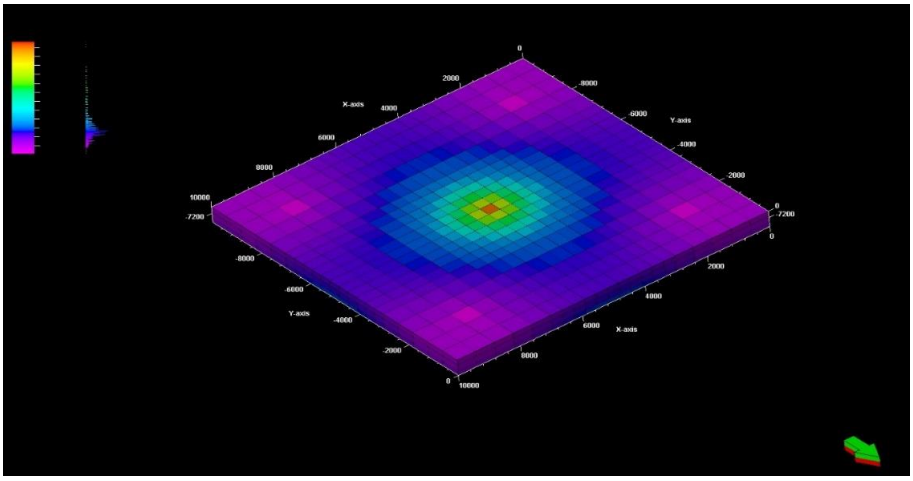

Figure 2. An oblique view of the reservoir horizon

When a simple grid is created, local grid refinements (LGRs) can be included in the geomechanical grid basically by two ways: in the first method, an already defined pre-existing LGR is used on the input grid (this can also be defined explicitly by the user); and in the second method, a standard Petrel process or method is used to make local grids after the creation of the geomechanical grid but prior to populating properties onto the grid. It is also required at this stage to control how sideburden, underburden, and overburden cells are generated by entering values into the extension settings of the Petrel software.

2.2. Materials and functions

Modelling of materials and creating functions are an important part of the workflow which is required to build a geomechanical model. Materials are usually any of the collection of named parameters which is assigned to one or more regions of a model; thus, material values are necessary inputs for the geomechanical simulation case. There are basically two types of materials: intact rock materials which are based in a range of elasticity models and yield criteria; and discontinuity materials for the modelling of faults and fractures. Once intact rock materials (which describe different rock types or other parameters of geomechanical importance) and associated parameters (which includes Poisson's Ratio, Young's Modulus, and bulk density) are created, materials are assigned to regions using techniques for populating properties. To create discontinuity, materials which describe faults and fractures as well as the definitions of their associated parameters which includes stiffness, spacing, and strength parameters, the materials are assigned to faults and fractures using an optional method for discontinuity modelling which is usually done after property population.

2.3. Populating properties

To conduct a geomechanics simulation, properties which describe material characteristics in each grid cell are required. However, these appropriate values for populating properties vary with respect to the type of geomechanical material which is present in a cell. The process of property population allows the creation of regions and assigning of materials on the grid using the material modelling process. A material usually has a set of parameters with defined values, and each parameter corresponds to a grid property which the populate property process creates. At each created grid property cell, the value is determined by the value of the related parameter in the assigned material e.g., when we assume that a region which encompasses the entire grid is created, and that such region is assigned a simple default elastic material which is not associated with a yield criterion. It is also safe to assume that the default elastic material has six parameters: Poisson's Ratio, Young's Modulus, Bulk Density, Porosity, Biot Elastic Constant, and Linear Thermal Expansion Coefficient. In this case, given the mentioned assumptions, the populate properties process will create six grid properties, all having the same name as the material parameters. Each of the property's cells are then assigned values that are associated with values in the corresponding material parameters. If a Young's Modulus of a material is 10 GPa, a Young's Modulus grid property with a value of 10 GPa will be created and assigned to every cell.

2.4. Modelling discontinuities: Faults and discrete fracture networks

The discontinuity modelling for faults and discrete fracture networks (DFNs) is an optional process which involves introducing pre-existing faults and DFNs models into a geomechanics simulation. This process allows the production of two distinct types of objects: firstly a fault mapping object which describes how set of faults are associated with the current model such that each object created would contain a given list of cells which will intersect with the fault and set of fault properties; and secondly a DFN mapping object which describes how DFNs are associated with the current model such that each object created would contain a given list of cells which will intersect with the DFN and set of DFN properties.

2.5. Pressures, temperatures and saturations

Definition of pressures, temperatures, and saturations for simulation can be set using different methods. Prior to running the reservoir geomechanics simulation, initial pore pressure is defined, however, setting temperature conditions is an optional task. Also optional is setting the saturation except when certain chalk models with water weakening, or the use of saturation with property updating is to be conducted. When pressures, temperatures, and saturations are defined, it is required to also define one-way coupling since it is intended that a defined and submitted simulation case will be coupled with VISAGE using a one-way coupled approach after which results are imported for analysis and visualisations. In one-way coupled method, simulations make use of pressures, temperature, and saturations which were generated at specific dates and times as input to the geomechanics simulation to generate stress state causing rock deformations at each date and time. It is also worthy of note that a one-way coupled simulation is carried out in a step-wise manner in an order defined by rows in a pressure, temperature, and saturation coupled data table. As a caveat for the simulation, all pressure, temperature and saturation must have valid date and time associated with it, and these must be attached to the geomechanical grid, even though most pressure, temperature, and saturation properties which are imported from reservoir simulations will expectedly have date and time associated with it, but additionally, when any other properties are supplied, it is necessary to add dates and times to it.

2.6. Boundary conditions

It is important to use the step-wise workflow to define boundary conditions by assigning stress boundary conditions on the geomechanical grid. The process for defining boundary conditions contains various options for setting up the boundary which are applied to the model to define initial stress for a simulation. Some of the options used in the process for defining boundary conditions include: gravity/pressure method (simulates initial stress using global tectonic stresses which is given at boundary and stress due to gravity from density); initialisation method (calculates initial stress using ratio of tectonic stress and vertical compressive stress); explicit initialisation (even though similar to initialisation method, in this case initial stress is provided through one of two methods, that is either by stress tensor or by horizontally rotated stress); and strain (simulates initial stress using strain given at boundary and gravity).

2.7. Simulation case

At this stage, a reservoir simulation case is defined by naming it accordingly (from its default name 'Case'), and assigning other model configurations and input before the reservoir geomechanics simulation case is submitted and allowed to run on VISAGE. For this study, the options for running VISAGE for one-way coupling method for execution was utilised. It is also at this point that the VISAGE simulator version (which, usually set as default is the latest version installed) is selected.

2.8. Analyzing and visualizing results

When a simulation case is defined, and submitted onto VISAGE simulator for running, at the end of a run, results are imported as output of the VISAGE simulation to the Petrel environment. This importation enables the provision of data for several post-processing uses.

3. The Reservoir model

The workflow outlined above is applied to study the Bunter Sandstone Formation (BSF) which belongs in the Sherwood Sandstone Group comprising pebbly sandstones and sandstones intercalated with few amounts of conglomerates, mudstones, and siltstones. The BSF reservoir is typically 200 m or more thick, with fair to good porosity and permeability, and is found at depths of between 1000 and 3000 m [6]. Distributed in Eastern England and the UK sector of the Southern North Sea, the BSF is thought to have been deposited between 230 and 260 million years during the late Permian and Triassic periods.

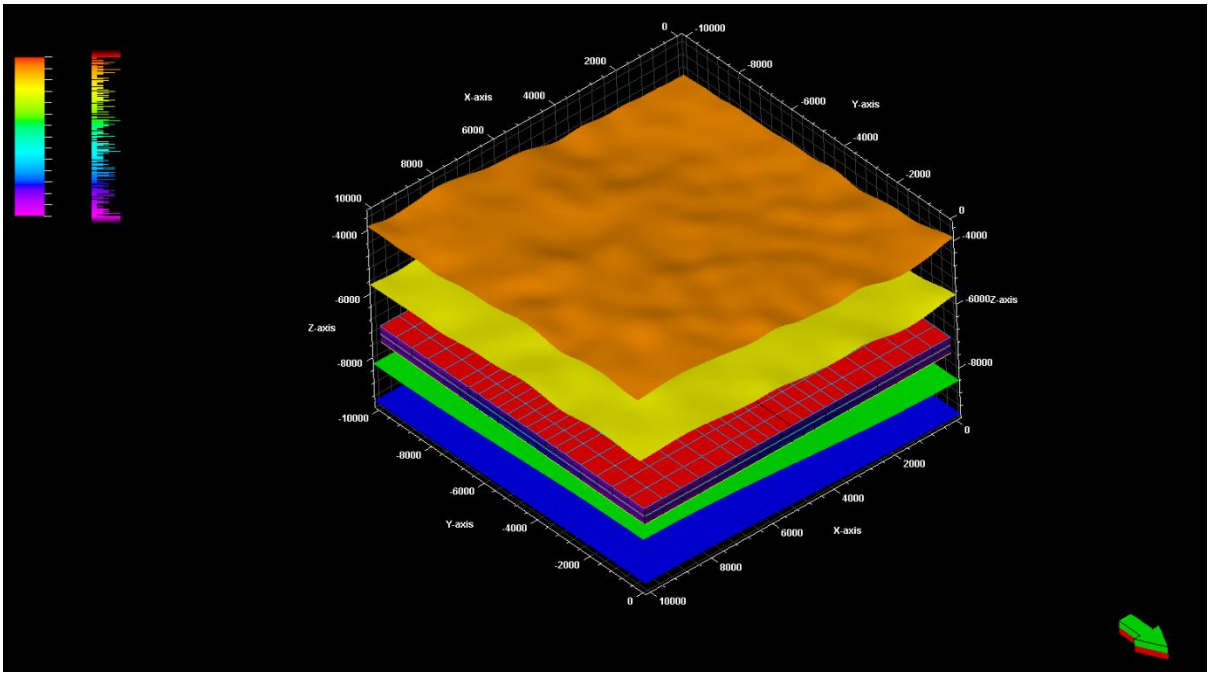

Figure 3. A simple geomechanical grid with different layers within the reservoir horizon

The objective of this workflow is for building a field-scale geomechanical reservoir model that encompasses the entire area of the reservoir. 3D seismic data were made available from the interpretation of lithostratigraphic horizons. Using a Petrel Reservoir Geomechanics ® project, a simple geological reservoir model was created from seismic data. The reservoir horizons (Figure 3) were embedded between overburden and underburden rock layers to avoid boundary effects on the area of study.

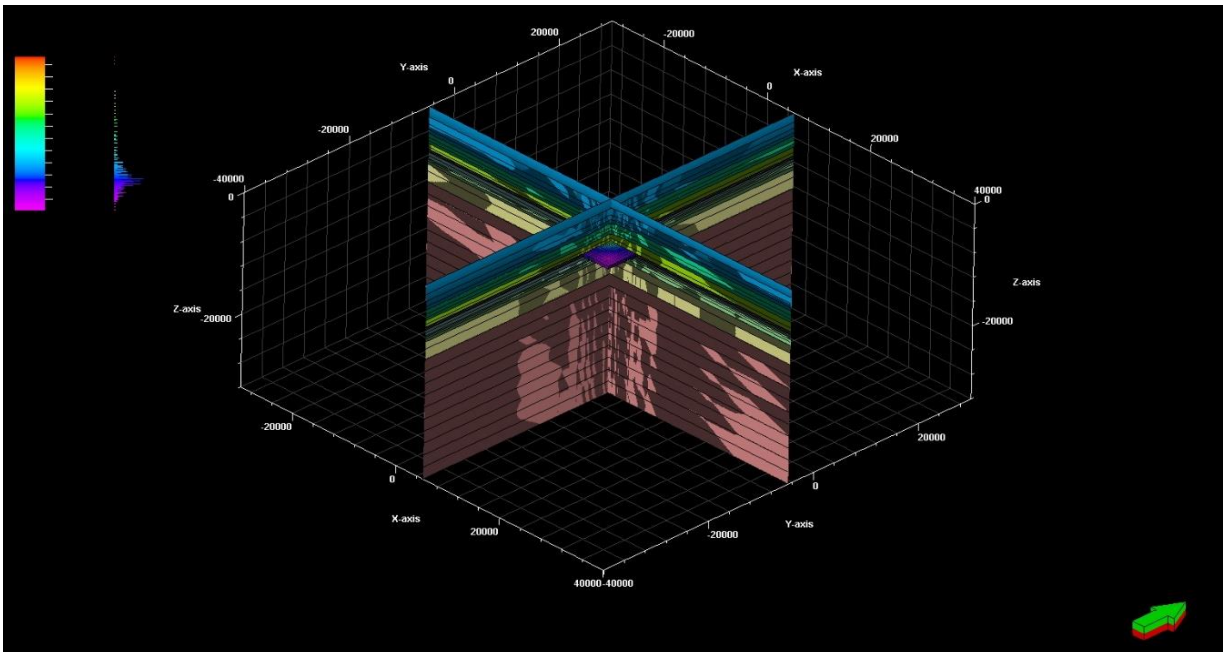

Figure 4. Intersections within the reservoir horizon.

Besides the layers of rock that form the overburden, underburden and sideburden, there are no faults incorporated in the reservoir horizon yet. Fault networks will be created during the calibration of the network prior to simulation. Incorporating the entire fault network will allow the complex interaction of those faults to be addressed in the model. Figures 4 and 5 shows intersections within reservoir horizon, and skeletal views of the reservoir respectively. The spatial resolution and grid cell size inside the reservoir region is 10000 m x 10000 m x 80000 m (length x width x depth).

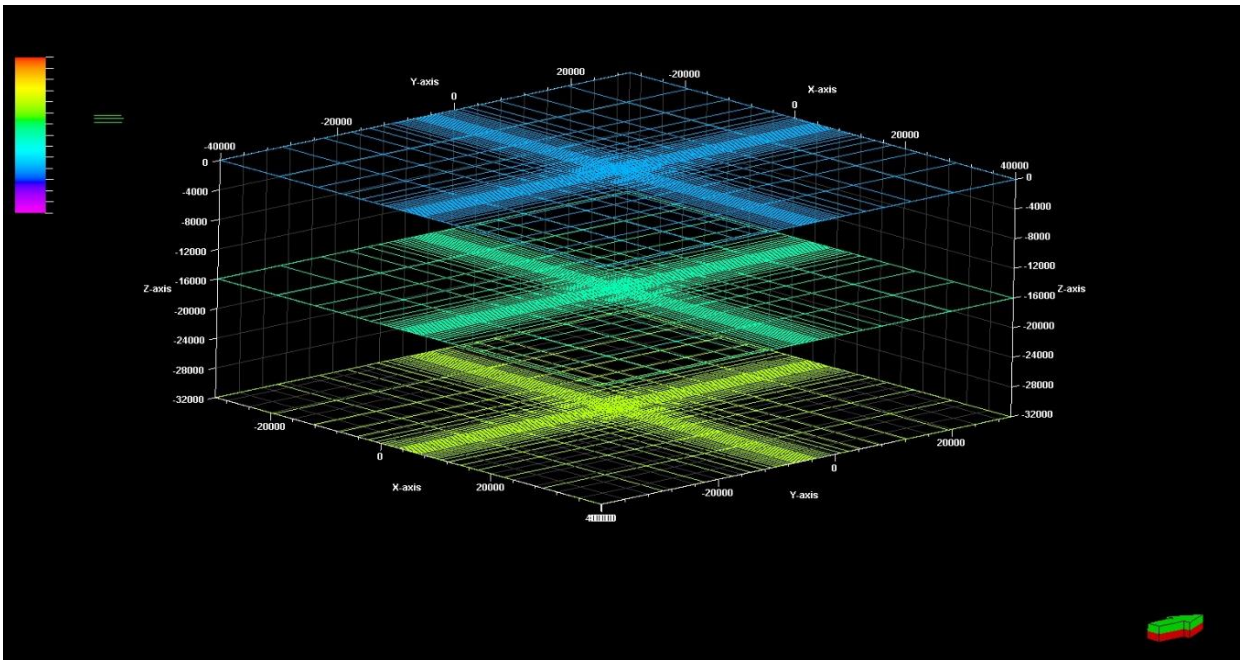

Figure 5. A skeletal view of the reservoir horizon

5. Conclusions

The workflow presented above can be used to build 3D pre-injection and 4D reservoir geomechanics model to assess caprock and fault integrity for geological CO_2 storage in the BSF, UK North Sea. The workflow can be used for modelling both field-scale as well as much smaller but highly detailed sub-models of specific reservoir horizons. All steps of the workflow have been explained in detail, incorporating mechanical grid creation; creating materials and functions; populating properties; modelling discontinuities (faults and DFNs); defining pressures, temperatures and saturations; defining boundary conditions; defining simulation case; and analysing and visualising of results. The geomechanical reservoir model created here will be calibrated against available field data such as from drilling events, in-situ stress measurements, surface observations. This information, provided in the workflow, can be used for a variety of reservoir applications and can also provide more insights into the reservoir drainage pattern [7]. Overall, this workflow provides a seamless end-to-end process which combines a transparent flow of data with an easy-to-use graphical user interface. In highly heterogeneous and complex models, the workflow is capable of modelling multiple hundred faults and multiple thousand discrete fractures, allowing the geomechanical analyses process to be maintained despite high degree of complexity.

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