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Advanced Simulation Environment for Induced Seismicity Mitigation and Integrated Control (ASEISMIC)

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Summary

Efforts to quantify induced-seismicity (IS) risk and to develop mitigation strategies are hampered by a dearth of numerical schemes that can accommodate realistic Earth models, while capturing the full spectrum of applicable physics. ASEISMIC is a new computational toolbox to aid in generating quantitative mitigation and response strategies, by combining reservoir-simulation methods with advanced geomechanical and seismological computational tools. The toolbox includes modules for site-specific IS operational risk assessment, by augmenting relevant public data sources with additional site-specific information. Case studies from western Canada are used to evaluate the applicability of this approach for unconventional oil and gas development as well as for gigaton-scale carbon dioxide storage.

Method

The University of Calgary and the Southern Alberta Institute of Technology (SAIT) have partnered in the development of ASEISMIC, as part of the Global Research Initiative in Sustainable Low Carbon Unconventional Resources funded by the Canada First Research Excellence Fund (CFREF). A minimum viable product (MVP) has been developed to obtain feedback from industry and the scientific community. The aim is to create a toolbox that could aid in producing site-specific quantitative mitigation and response plans by combining reservoir-simulation methods with advanced geomechanical and seismological computational tools.

There are currently various tools that have been developed to address individual areas of this problem. However, while many of these tools are supported by strong scientific logic, none of them fully integrates all aspects of the problem that need to be addressed in order to fully and satisfactorily model induced seismicity in such a way that would be useful to successfully mitigate against it. The aim of this project is to address all areas of the problem, and integrate these into the toolbox. Ultimately, this could lead to a product which can successfully used by industry and regulators to mitigate induced seismicity hazard, and would also be of interest to academia.

For the prototype version, development of ASEISMIC is concentrated on the Duvernay of the Western Canadian Sedimentary Basin, due to the availability of public and private data from this region to the developers. However, the toolbox will also be tested with an abundance of data from the Montney basin, and aims to be able to be applied globally. The toolbox is broken down into separate modules which will be integrated into a workflow.

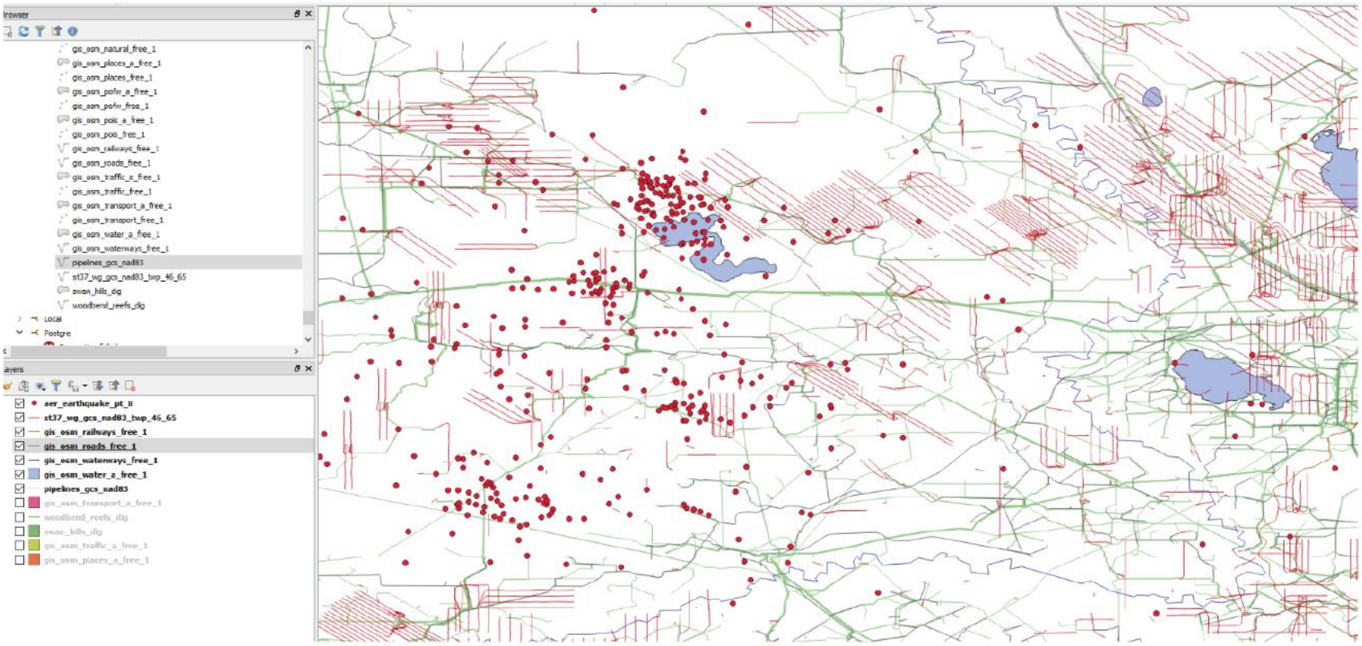

Figure 1. Screenshot showing an example from the interactive GIS map viewer used to display data from the database module. Map shows a region around Crooked Lake and Fox Creek, Alberta. Water bodies are shown in blue, roads in grey, wells as red lines, pipelines in green and seismicity (from the Alberta Energy Regulator database) as red circles.

Modules

Database Module

A prototype of the first module is complete. This module consists of an SQL database which will be accessed by future modules, and an interface for viewing the data on maps (Figure 1). Data already contained includes public well information and completions data, regional seismicity, infrastructure locations (e.g. pipelines), geographical information (e.g. roads, water bodies), and geological information. The database is set up such that it is relatively straightforward to add more data if necessary.

Simulation Module

The aim of the simulation module is to perform a full simulation from hydraulic fracturing to induced seismicity. To do this, initially the local initial stress field must be defined, including the regional stress field and any perturbations caused by pre-existing faults. Hydraulic fracturing stages can then be simulated, and the stress and pore pressure pertubations caused by each can be modeled. Finally, any slip along pre-existing faults caused by these perturbations can be modeled. This module has therefore been broken down into four components. Work is currently nearing completion on the first of these (PReSS).

Poroelastic Regional Stress Simulation (PReSS)

The PReSS module produces a gridded regional stress model for a region of the order of a township. First, 1D stress models are created for each well with suitable log data in the defined region assuming isotropic poroelasticity. To do this, logs are first preprocessed, and the dynamic moduli obtained from the logs are converted to static moduli using relationships defined in Slota & Valim (2015). The pore pressure field with depth can then be defined assuming *a priori* knowledge of the quasi-static pore pressure distribution. The stress profile is calculated assuming uniform elastic strain, i.e. the static strain in each layer is the weighted average of the far-field strain and uniform horizontal strain (there is no slip at layer boundaries) (Roche &

van der Baan, 2015) (Figure 2a). If there are multiple stress profiles in the region, 1D stress profiles are interpolated between them. Mohr circles can be constructed at any location within the region.

The 3D stress perturbation generated by each individual planar fault segment located within the region covered by the stress model is then calculated. Faults are treated as finite-width damage zones subject to locally reduced horizontal stress, which leads to stress shedding to the surrounding rockmass (Figure 2b). Fault perturbation horizontal principal stress components are defined by a smooth differential (Gaussian) function. Once calculations are complete, the layered stress model is summed with the perturbations calculated for all fault segments in the region to produce a full poroelastic regional stress model for the region prior to fluid injection. Currently, the code works for a strike-slip faulting regime.

Hydraulic Fracture Model

Allows the user to import simulation results for each stage from hydraulic fracture modelling software e.g. FracMan. The results are input to the overall model so that the percolation model can be run.

Percolation Model

Simulates the change in stress and/or pore-pressure on the pre-existing faults caused by the HF stimulation, using a discrete fracture network.

Fault Slip Model

This incorporates rate and state friction modeling to simulate rupture on a pre-existing fault based on an exceedance criterion, due to the stress and pore-pressure pertubations from the percolation model.

<u>Stochastic Module</u>

In order to analyse the hazard and risk in a probabilistic sense, the simulation module is run a large number of times using a stochastic approach. During each iteration, each unknown parameter in the simulation (e.g. pore pressure distribution, permeability, fault location) can be varied between reasonable values to produce a large number of outcomes which can be analysed probabilistically. The simulation module must therefore run quickly in order for the software to produce a result within a reasonable timeframe.

<u>Hazard Module</u>

This module will use a probabilistic seismic hazard assessment (PSHA) approach (and/or the statistical approach of Mignan et al. (2017)) to perform probabilistic hazard analysis using the results of the stochastic module. It will generate hazard maps for the likelihood of occurrence and uniform hazard spectra.

<u>Risk Module</u>

This module will calculate the risk by convolving hazard spectra from the hazard module with fragility curves and consequence data in order to generate a risk report for the operation, which may be useful to industry and regulators. This risk report can give estimates of the likelihood of costs/damage associated with induced seismicity.

<u>Mitigation Module</u>

This module will be able to simulate a scenario event using the simulation module (with a focus on yellow light events assigned by the regulator (Shipman et al., 2018)). The simulation and stochastic modules can be used to assess the best approach for risk mitigation (e.g. reduce pumping pressure, skip a stage, etc.).

Conclusion

Fault activation by hydraulic-fracturing is a highly complex geomechanical problem that is as yet not fully understood. ASEISMIC is the first tool aiming to address all areas integral to modeling and mitigating induced seismicity, from injection to rupture simulation to ground motion prediction and hazard analysis, using advanced numerical methods currently available for each. Development is currently at an early stage but is moving forward rapidly through the partnership with SAIT, which is enabling rapid generation of thoroughly tested code.

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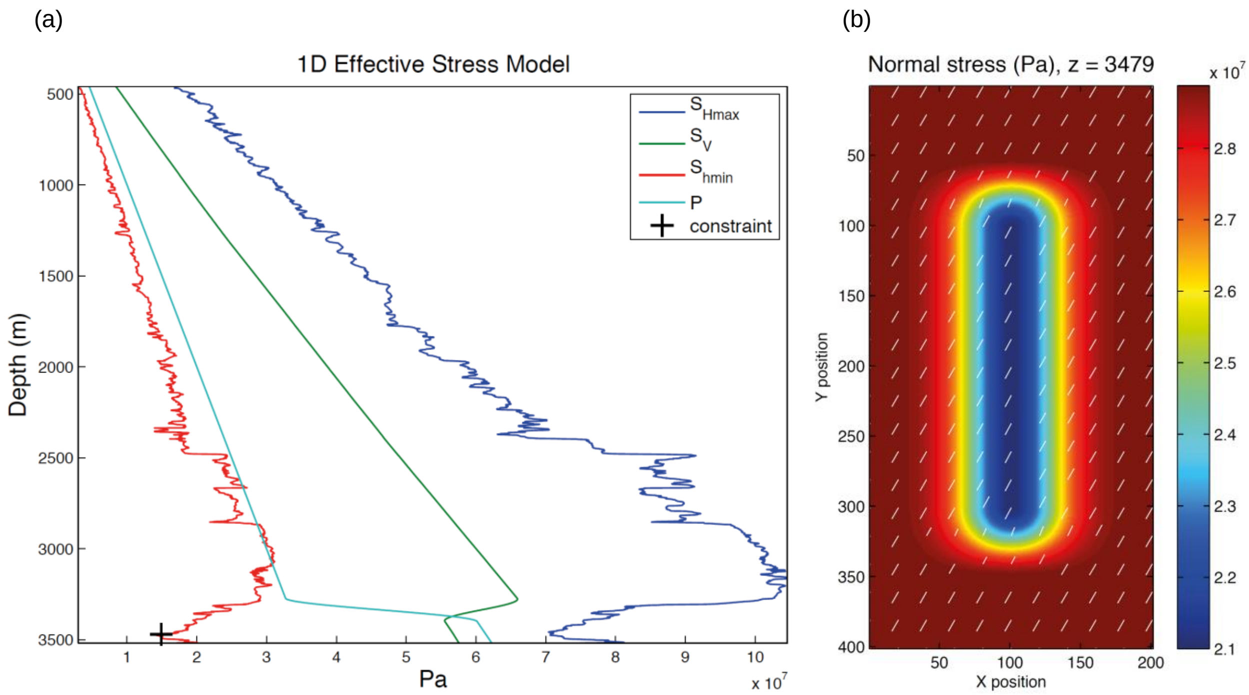

Figure 2. (a) Stratified effective stress model computed for a well in western Canada (01-36-61-22 W5). Mechanical properties (Young's modulus, Poisson's ratio and density) were derived from well logs and converted from dynamic to static values using the regression parameters from Slota & Valim (2015). A fault slip margin of 4.0 MPa and Biot parameter $\alpha = 0.5$ were assumed. The pore-pressure profile (P) is based on Eaton & Schultz (2018) and the constraint on S_{hmin} was calculated using a regional gradient of 22 kPa/m from Fox & Soltanzadeh (2015). (b) Normal and shear stress acting on a N-S fault, obtained by superimposing the 1D model with the fault perturbation model. The white arrows show the local S_{Hmax} direction. Where the arrows are shorter, the principal axes are tilted. The model predicts unphysical stress concentrations at the fault tips. Stress rotations are most pronounced close to these areas of stress concentration.

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