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Large-scale 3D-modeling of a realistic cavern field within a salt dome – Combined application of *Griddle*, *FLAC3D* & Python

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1 INTRODUCTION

Predictions of subsidence and horizontal displacement over large cavern fields is most commonly performed using mathematical approaches correlating the underground convergence with a corresponding subsidence field on the surface (Zimmermann 2011). While conceptually simple and easy to perform, these approaches largely rely on mathematical fits and the applicability of the chosen subsidence transfer function, while inevitably not capturing the actual state of deformation in the underground.

Therefore, geomechanical 3D-modeling of large-scale cavern has been receiving more attention in the last decade (Sobolik & Ehgartner 2012), since they potentially offer more insights into the interactions between caverns and the general development of stresses and strains within the cavern field as well as aboveground. However, such models are generally associated with high computational cost due to the scale of the system (dozens to hundreds of caverns in a salt dome and surroundings of kilometer-scale) as well as the difficulties in generating a suitable mesh for the typically irregular and complicated geometry.

This paper presents the workflow employed for the predictions of subsidence, tilt and horizontal displacements/strains over a large-scale cavern field in *FLAC3D* (Itasca 2017) by using *Griddle* (Itasca 2016) for mesh generation and the embedded Python for some of the more complicated tasks associated with the modeling of typical storage cavern peculiarities and events such as regular volume increases due to oil withdrawal by injection of unsaturated water.

2 DESIGN AND ANALYSIS

The geomechanical model is first constructed in the CAD program Rhinoceros based on cavern sonar data and geological information on the salt dome and its surrounding rock layers (Fig. 1). Since no 3D-data on the internal structure of the salt dome was available, the rock salt was modeled as one homogeneous unit. Otherwise separating layers between different salt types could have been included. 2D-quad surface meshes were then created using the tools provided by *Griddle* to specify spatially-dependent mesh densities. The surface meshes were then used as boundaries for the volumetric quad-dominant mesh generation by *Griddle*. This allows for comparatively highly-resolved cavern shapes and contour regions, while creating larger elements in the outer regions of the model, so that the computational cost remains feasible.

Since some of the storage caverns were actively solution-mined in order to increase storage volume several years after they had been originally created, these secondary shapes – and therefore volumes – were already included in this pre-processing step. However, frequent smaller increases in volume due to oil withdrawal by injection of unsaturated water had to be incorporated differently using a Python-based method explained below.

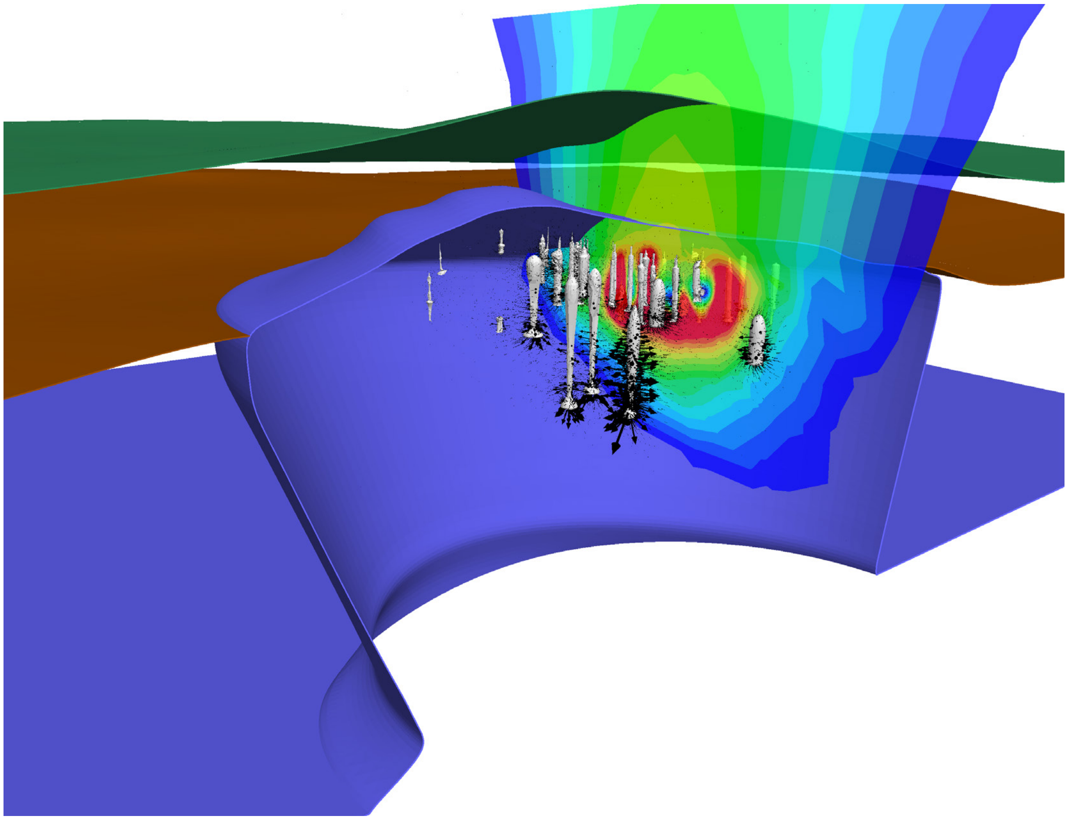

Figure 1. Cross-section through the salt dome model showing some of the embedded caverns. Perpendicular cross sections of total displacement through the cavern field.

In order to calibrate the model, the previous history of cavern storage in this particular field was re-enacted based on the recorded data on cavern pressures (applied as internal boundary conditions), periodic sonar measurements and other events such as the volume increase due to withdrawal of oil by injection of unsaturated water. Especially the latter event occurred quite frequently in the first decades of storage and posed a challenge for the numerical modeling, since it effectively changes the shape of the numerical mesh. As discussed, larger changes in cavern shape or volume can be included at the pre-processing state, but these small volume adjustments (about 10,000 – 100,000 m³) are essentially too small and tend to create problems in the meshing procedure. Additionally, any change in these events – e.g. due to data corrections - would make it necessary to re-mesh the whole model. Therefore, a Python-based method was constructed, which basically nudges the mesh in opposite direction to the arisen displacement in order to model that uniform increase in volume. This has proven to work quite stable if the cavern shape is not overly irregular and comparative single-cavern modeling has shown that this does not introduce significant distortions in the stress field around the cavern in comparison to conventional element removal.

3 RESULTS AND DISCUSSION

The historic development of subsidence over this cavern field was successfully replicated using the *FLAC3D* model based on the real cavern shapes, positions and history (Fig. 2, subsidence values given in units relative to maximum subsidence for reasons of data confidentiality). The decisive calibration factors were the creep behavior of the rock salt and – to a lesser degree - overburden properties. Most interestingly, recent measurements of the horizontal displacements based on satellite measurements (Satellite Radar Interferometry – Ashrafianfar 2014) are in good agreement with the numerical modeling. The calculated values for the parameters relevant for the evaluation of mining-induced damage on infrastructure above ground can therefore be assumed to be accurately determined by the numerical simulation. In comparison. conventional mathematical approaches usually postulate the horizontal displacement to be proportional to the slope of the subsidence bowl (Zimmermann 2011), which – at least for Gaussian-shaped subsidence functions – appears to underestimate the horizontal displacements in the outer parts of the subsidence region.

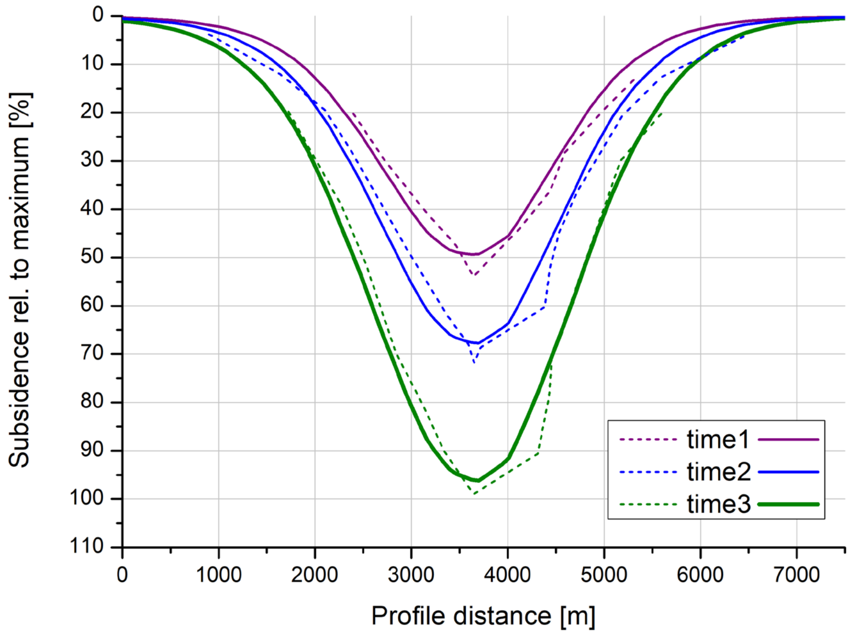

Figure 2. Measured (dashed lines) vs. modeled (solid lines) subsidence along a profile through the cavern field at different points in time.

Another interesting and rather positive aspect within the simulation results lies in the observation that both cavern convergence and subsidence are in good agreement with measured values without special treatment of creep properties around the caverns. Comparable studies using large-scale models of cavern fields were not able to achieve sufficient agreement for cavern convergence and subsidence within one parameter set and instead had to rely on the somewhat questionable approach of assigning cavern specific creep parameters separately around each cavern (Sobolik 2015 & Park 2017).

Different scenarios for the future of the cavern storage have been constructed, investigating the influence of changes in operating pressures or large-scale oil withdrawal by injection of unsatured water. Due to a further increase in cavern head pressures the already small subsidence rates are further decreased, therefore minimizing the impact on aboveground structures while at the same time reducing loss of cavern volume due to convergence.

4 CONCLUSIONS

This paper demonstrates the combined workflow using Itasca's *FLAC3D* & *Griddle* in combination with the embedded Python distribution for the generation and numerical modeling of a large-scale cavern field within a salt dome based on actual cavern shapes, volumes, types of operation and history.

The numerical model was successfully calibrated to replicate the previous land subsidence and cavern convergence and was then used to predict the development of subsidence and horizontal displacement within different future storage scenarios.

Such studies may supplement conventional mathematical subsidence predictions by allowing for a better understanding of the deformation processes within the salt dome and the interactions between cavern convergence and subsidence in dependence on operational parameters.

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