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Technical Conference Paper

Introducing LOCAS 3D
Application to the Geomechanical Modeling of an Oil-Storage Facility

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Introducing LOCAS 3D

Application to the Geomechanical Modeling of an Oil-Storage Facility

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Abstract

Brouard Consulting has developed a 3D addition to its software package LOCAS which is dedicated to salt caverns. LOCAS has been enhanced continuously for 20+ years and, to date, LOCAS is still the only commercially available software that has been designed especially for salt-cavern modeling that is able to couple cavern thermodynamics and rock-salt complex geomechanics properly. Furthermore, LOCAS is also user-friendly software that exhibits numerous features, including facility data management.

Some features of the new 3D version of LOCAS are shown using the example of an oil-storage facility. The entire history of the facility since its creation is modelled. This example investigates the geomechanical stability of the facility during workover operations, which implies periods of low pressure in the caverns.

Key words: Computer Software, Computer Modeling, Rock Mechanics, Storage Cavern

1 Introduction

1.1 Existing software limitations

They are few software packages, commercially available or not, that can be used to perform relevant rock-mechanics computations related to salt caverns. The programs FLAC3D and Abaqus are probably the most used worldwide, but they have some important limitations when working with salt caverns.

Salt cavern specifics — No well-known software packages were designed initially for salt caverns; they have to be adapted by the end user because salt exhibits an unusual behavior compared to other rocks — a very complex mechanical behavior. Generally, no, or a limited number of, constitutive laws for rock salt are available in software packages. For instance, an extra creep package must be purchased for FLAC3D, and sometimes end users need to create coding on his or her own using the built-in scripting language called FISH to implement some additional constitutive laws (Liu et al., 2015). Therefore, the use of such a software package is limited to some rock-mechanics experts.

Not all involved phenomena are considered: No coupling — Most of the time, cavern thermodynamics, salt geomechanics and hydraulics cannot be calculated simultaneously. Some software packages (such as FLAC3D and Plaxis) are limited only to rock/soil mechanics and thermal computations — they include no cavern thermodynamics. When cavern-fluid behavior (compressibility, dissolution/crystallization, etc.) cannot be considered, a third-party software package such as SCTS (Nieland, 2004) is required; in that case, numerical computations between the inside and outside of the caverns cannot be coupled. This means, for instance, that a change in cavern volume through transient salt creep is not very accurately considered, because thermodynamics calculations are performed separately in advance.

There is another type of limitation: Abaqus, which is a huge software suite for finite-element analysis and computer-aided engineering, is unable to compute rock-salt thermal and hydraulic behavior simultaneously, which is necessary in some problems (e.g., cavern abandonment or stability analysis of liquid-hydrocarbon storages). This limitation in Abaqus was the starting point of the development of LOCAS (Brouard et al., 2006) for the purpose of abandonment studies.

Unsuitable meshers — Embedded meshers may not be suitable for gas-cavern problems where very fine meshes are needed; an additional mesher must be purchased. Fast pressure changes in gas caverns implies strong temperature gradients at the cavern wall and then very fine meshes — i.e., element size of the order of a couple of cm or inches (Brouard et al., 2011). Using a standard mesher would provide results, but they might be incorrect if the considered mesh were inadequate.

Limited support from vendors — Because salt caverns expose some particular characteristics, it would be fair for end users to get some support from the software vendors to adapt or to add new features. Most of the time, the support is relatively poor, as salt-cavern behavior is very complex and the salt-cavern business is limited.

1.2 LOCAS — Special features

Simulation of the non-linear and time-dependent mechanical behavior of salt caverns requires advanced constitutive models and accurate numerical computations. LOCAS (Brouard et al., 2006) is a finite-element code that provides 2D axisymmetric analysis as well as 3D analysis of the short- and long-term behavior of solution-mined caverns. It is a fully coupled thermo-hydro-mechanical program that has been developed by Brouard Consulting with assistance from Laboratoire de Mécanique des Solides (Ecole Polytechnique), tested widely against closed-form solutions, and used for numerous studies and articles.

1.2.1 Phenomena that can be taken into account

The physical phenomena that can be considered in LOCAS include the following.

- Salt creep using Norton-Hoff, Munson-Dawson, Lubby2 and Lemaitre-Menzel-Schreiner constitutive laws (Figure 1).
- Heat flux to or from the rock mass, heat exchange between gas and brine.
- Mechanical and thermal expansion/contraction of cavern liquids (Bérest et al., 1999).
- Real gas thermodynamics for gas caverns.
- Brine complementary dissolution/crystallization.
- Adiabatic compression of the liquids (Gatelier et al., 2008).
- Brine micro-permeation through rock salt.
- Increase of salt permeability due to the onset of tensile effective stresses (2D version).

1.2.2 Ability to predict cavern pressure and temperature evolution

The prediction of cavern pressure and temperature evolution is a critical component in the simulation of cavern abandonment, a capability that exists, for instance, in few, if any, software packages used to simulate the long-term behavior of salt caverns.

In LOCAS, pressure and temperature can be either fixed or released. For the second case, LOCAS computes the contributions of all involved phenomena to provide a step-by-step prediction of the evolution of cavern pressure and/or temperature.

For example, in the case of a gas cavern, the simulation of choked flow was found to be a critical component in the simulation of a blowout event (Brouard Consulting & RESPEC, 2013). Most software like SCTS do not have yet the capability to simulate unrestricted flow. LOCAS can compute cavern and wellbore complex thermodynamics during a blowout.

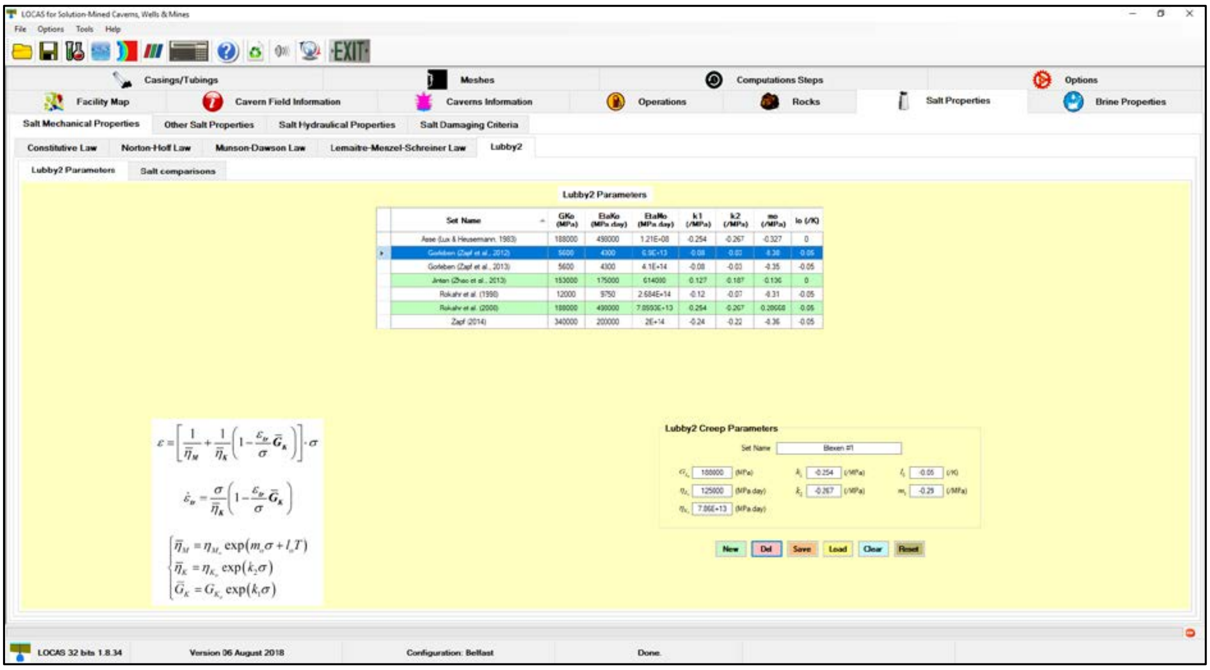

Figure 1 – LOCAS Tab dedicated to the Lubby2 constitutive law.

1.2.3 Ability to archive data from an entire facility

Many salt caverns were leached out in the 1970s or '80's, when no electronic archiving was possible. Old data often are scattered in paper archives, and sometimes not easily accessible. LOCAS offers the capability to collect all available data in a single place. It allows safe storage of a huge amount of data that can be used easily afterward to improve the knowledge about a given facility and the predictability of its behavior. A non-comprehensive list of data that can be collected for each cavern of a facility is as follows.

- Wellhead pressure data (brine/product), no limitation regarding the number of data points.
- Volume/Flowrate of liquid/gas pumped in or out.
- Bleed-off data.
- Sonar surveys (see Figure 3 and Figure 4). Socon files can be loaded directly in LOCAS.
- Logs (temperature, interface, GR, etc.).

- Leaching data.
- Tightness tests data.

A tab and many sub-tabs are dedicated to each cavern. Adding a new cavern from the cavern database (Figure 5) will create new tabs dynamically.

Figure 2 shows an example of facility overview through a Google map embedded in LOCAS.

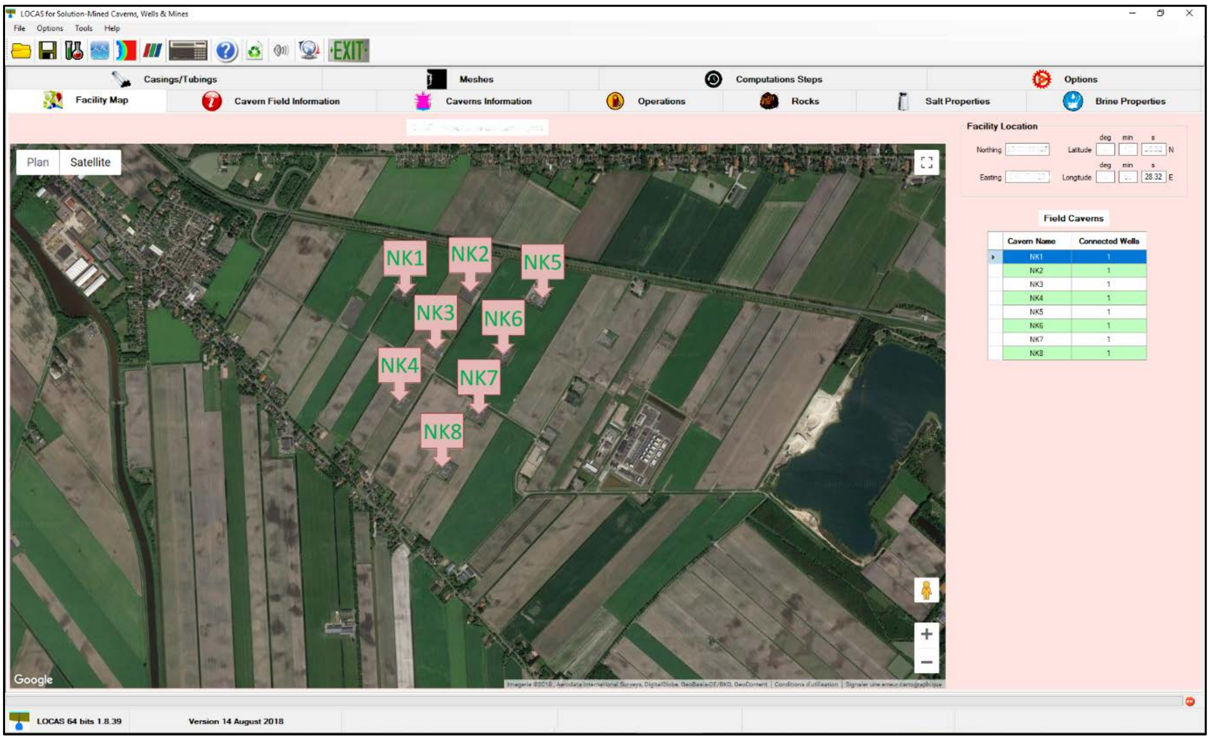

Figure 2 – LOCAS overview of facility with cavern contours – Google map embedded.

1.2.4 Ability to monitor the status of a facility

Using the huge amount of available data, LOCAS is able to monitor the status of a facility through accurate calculation, providing indicators tables and plots, such as:

- ✓ product stock in each cavern;
- ✓ facility stock of stored products;
- ✓ creep closure of each cavern; and
- ✓ casing-shoe pressures and pressure gradient evolutions.

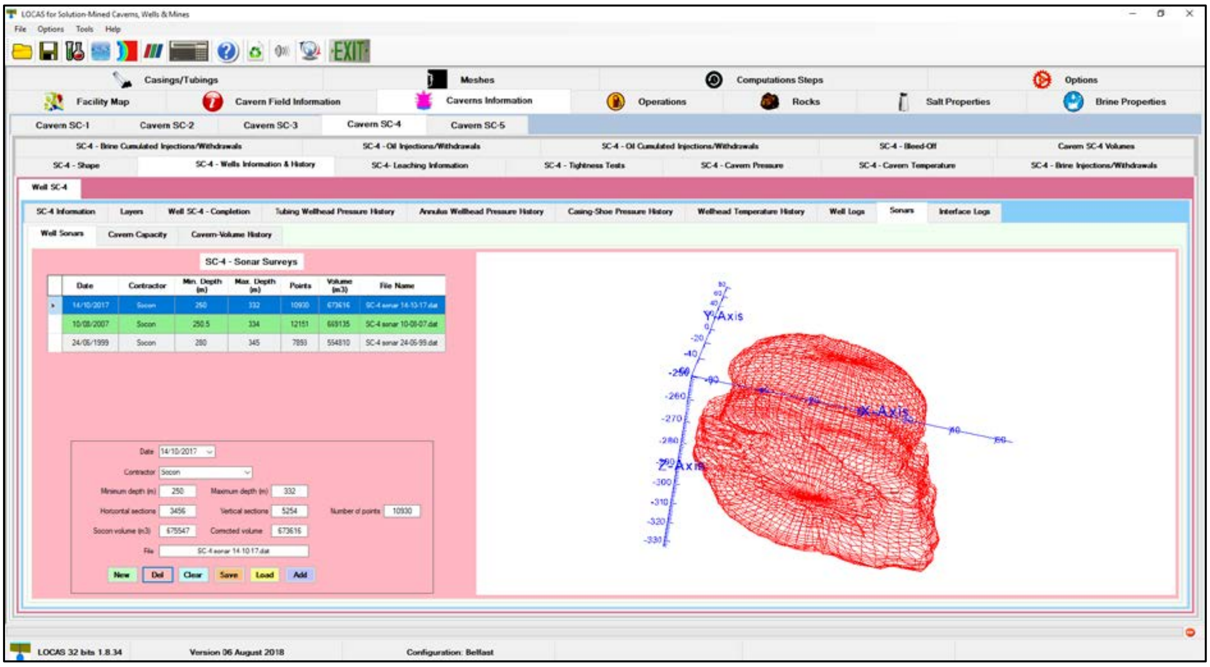

Figure 3 – LOCAS example of the sonar-survey database for a given cavern.

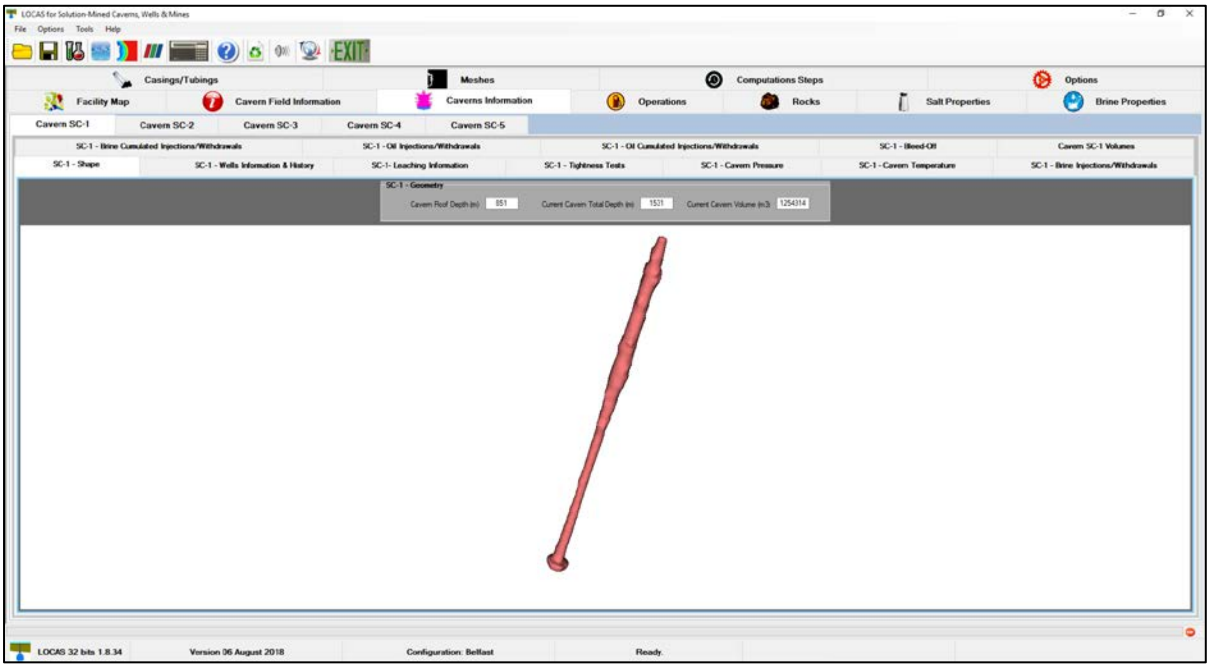

Figure 4 – LOCAS display of cavern shape from the latest sonar survey.

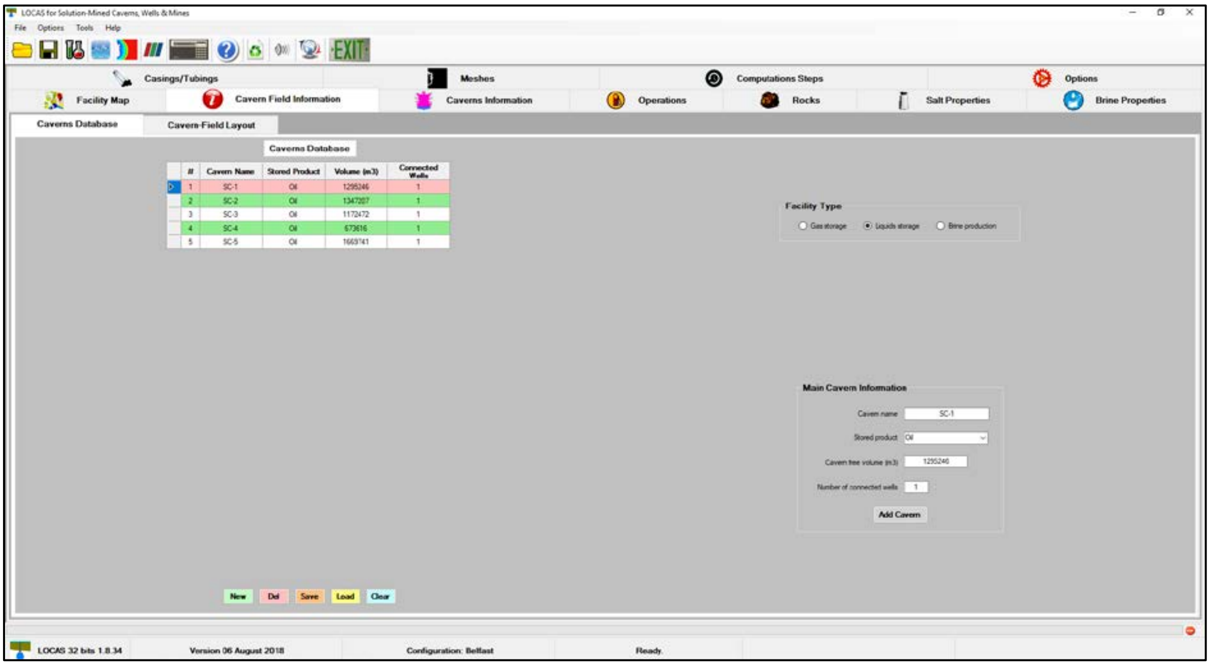

Figure 5 – Cavern database in LOCAS that allows easy addition of a new cavern.

1.2.5 Comprehensive embedded post-processing features

LOCAS 3D provides numerous embedded post-processing features, allowing easy data analysis even for a non-expert. Exportation of computation results to post-processing external tools such as ParaView (developed by Sandia) is possible. Contours in horizontal and vertical cross-sections of the following variables can be plotted:

(1) displacements, including subsidence;
(2) principal stresses, effective stress;
(3) pore pressure;
(4) dilation Factor of Safety (FOS); and
(5) Coulomb criterion for the onset of fault slip.

For each cavern of a facility, temporal evolutions of the following variables are provided: cavern pressure and temperature; cavern compressibility (for brine production or liquid-storage cavern); and cavern volume and creep closure, comparison with field data (sonars).

1.2.6 User-friendly software package — Complimentary support

From the very beginning, LOCAS has been designed to be a very user-friendly software package that can be used by non-experts with almost no training. It also was designed to facilitate sensitivity analysis, which is a key point when working with salt-cavern problems. LOCAS has been used by dozens of students worldwide and has led to the publication of numerous journal and conference papers [See, for example, Karimi-Jafari et al. (2006) or Djizanne et al. (2012, 2014).]

Brouard Consulting offers complimentary support for users, either paid users or those testing a trial version, as understanding user problems helps in designing a more intuitive interface. LOCAS has been developed continuously since the 1990s, and updates are made on a timely basis.

All facilities are different, and the way in which people work often is different from one place to another. This is why Brouard Consulting complimentary offers the possibility of adapting LOCAS to special needs — for instance, giving the ability to load sonar surveys from a new service provider whenever needed.

LOCAS also aims also to remain at the cutting edges of research. New features are implemented when further progress is made in cavern modeling or the modeling the mechanical behavior of salt.

1.2.7 Software technology for the long term

LOCAS has been developed within the .NET framework from Microsoft. Brouard Consulting received direct support from Microsoft through its BizSpark program. LOCAS uses the best technology available, including the Fortran compiler recently developed by Intel for its finite-element computation core.

There are dozens of 2D and 3D zoomable plots in LOCAS that are displayed using the best charting components available — i.e., ProEssentials from Gigasoft Inc. (TX) and the 3D OpenGL VTK Visualization tool kit. The 64-bit architecture allows very large models to be constructed, limited only by computer RAM. LOCAS is available as a stand-alone program and also is available in the Azure cloud from Microsoft. The cloud version is extremely secure, and it simplifies initial set-up and, later, maintenance, while offering very high computational capabilities (i9 processor, 128 RAM). Access to the cloud version has been tested successfully for a few years. It works smoothly and securely through any firewall via browser-based access.

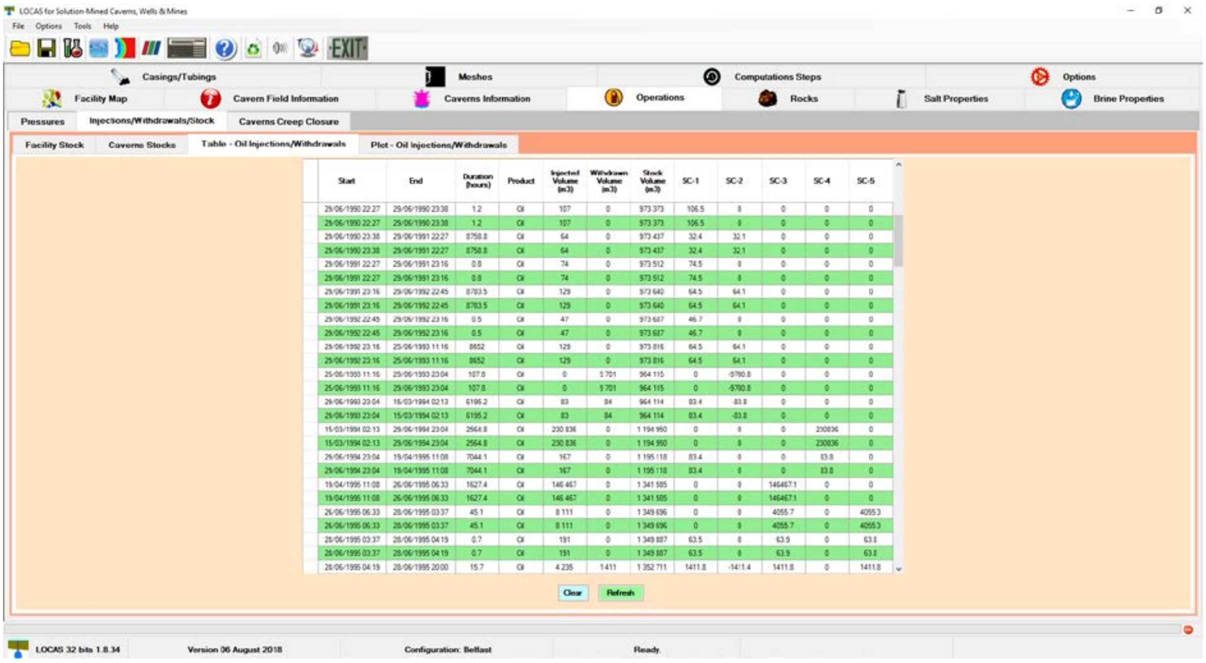

Figure 6 – Example of LOCAS table for product injection/withdrawal history.

Figure 7 – Example of bleed-off history in LOCAS.

2 Application to the geomechanical modeling of an oil-storage facility

2.1 Background

The example of an actual oil-storage facility is presented. The workovers that were conducted involve significantly lower cavern pressure, therefore the geomechanical stability of the caverns had to be carefully investigated. The geomechanical study consisted of performing finite-element analyses, simulating the entire history of the caverns and determining the evolution of stresses in the vicinity of the caverns as accurately as possible. The results of the computations then were used to assess the stability of the caverns during the workovers, with special attention paid to the possible onset of effective tensile stresses, salt dilation and fault slip.

2.2 Geology - Modeling at dome scale

The salt structure is a domal salt feature. It is covered by Mesozoic (Upper and Lower Cretaceous) and Cenozoic (Quaternary and locally Tertiary) sediments. The sedimentary overburden is faulted and the Tertiary has been eroded above the northwestern caverns. Regional Quaternary thickness variations indicate upward salt movement until the beginning of Quaternary period (2.6 my). The main strike direction of the salt accumulation is NNW – SSE, dipping WSW.

Figure 8 gives an overview of the 900-m × 1400-m × 1500-m domain modeled for numerical 3D computations.

Figure 9 to Figure 11 show views of the meshed model. Some meshing difficulties arose due to the existence of the faults that created discontinuities. A typical mesh is composed of about 600,000 ten-node tetrahedral elements. The degree of refinement of the mesh around each cavern can be adapted easily depending on the needs. For instance, a refined mesh usually is selected in the vicinity of a cavern that needs to be analyzed during a workover, while a less fine mesh is considered for remote caverns. The faster the pressure variations, the finer the mesh must be (Brouard et al., 2011).

Faults were meshed, but no slipping mechanisms were considered. All wellhead-pressure data and cavern-temperature measurements available since the 1970s were loaded in LOCAS.

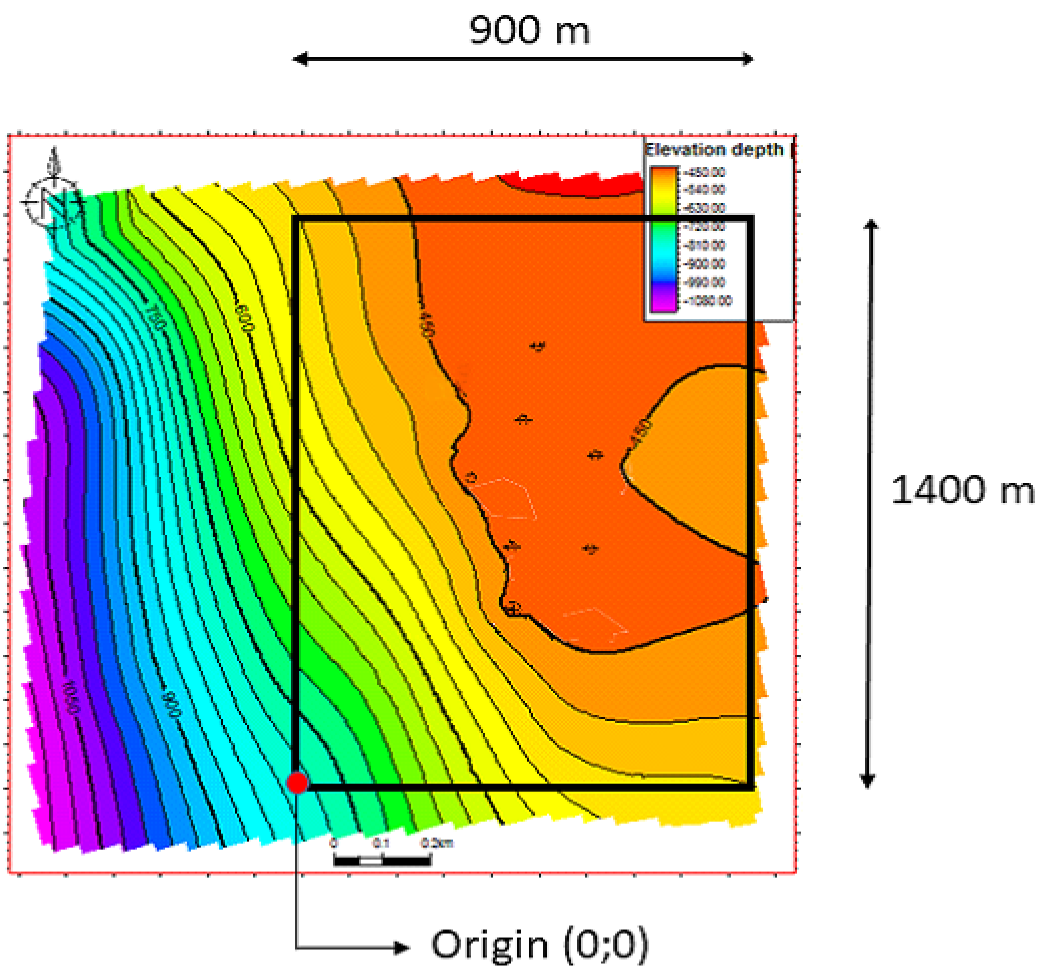

Figure 8 – Top-of-salt contours. Overview of modeled domain.

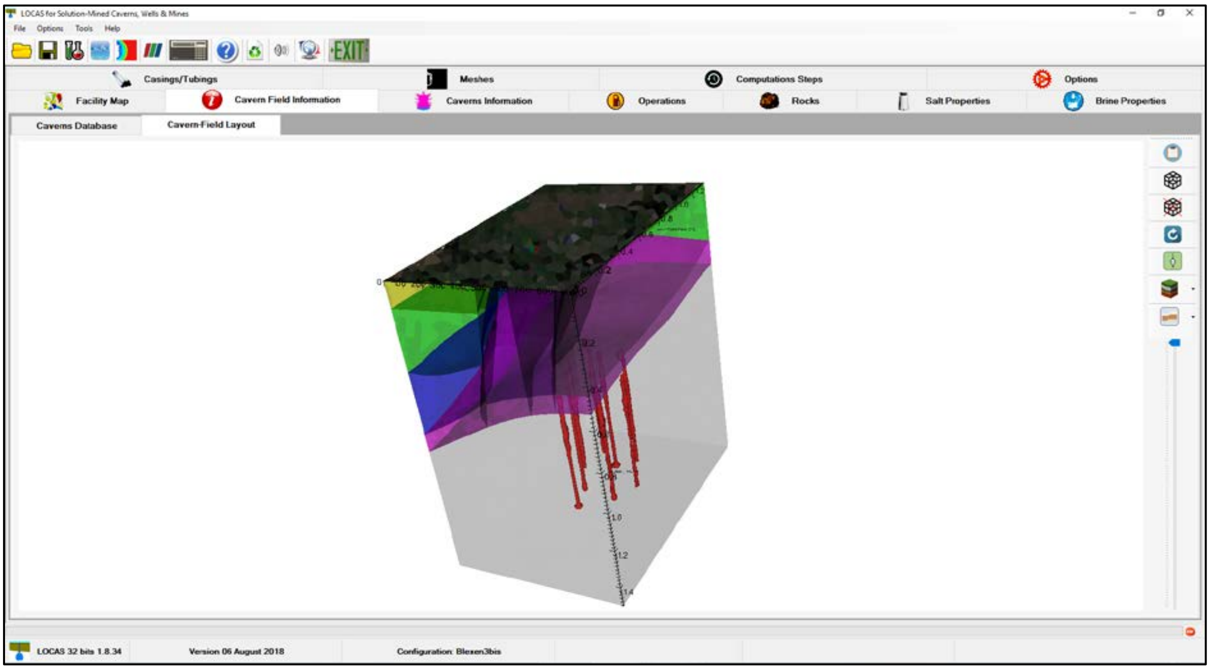

Figure 9 – Cavern-field layout as displayed in LOCAS.

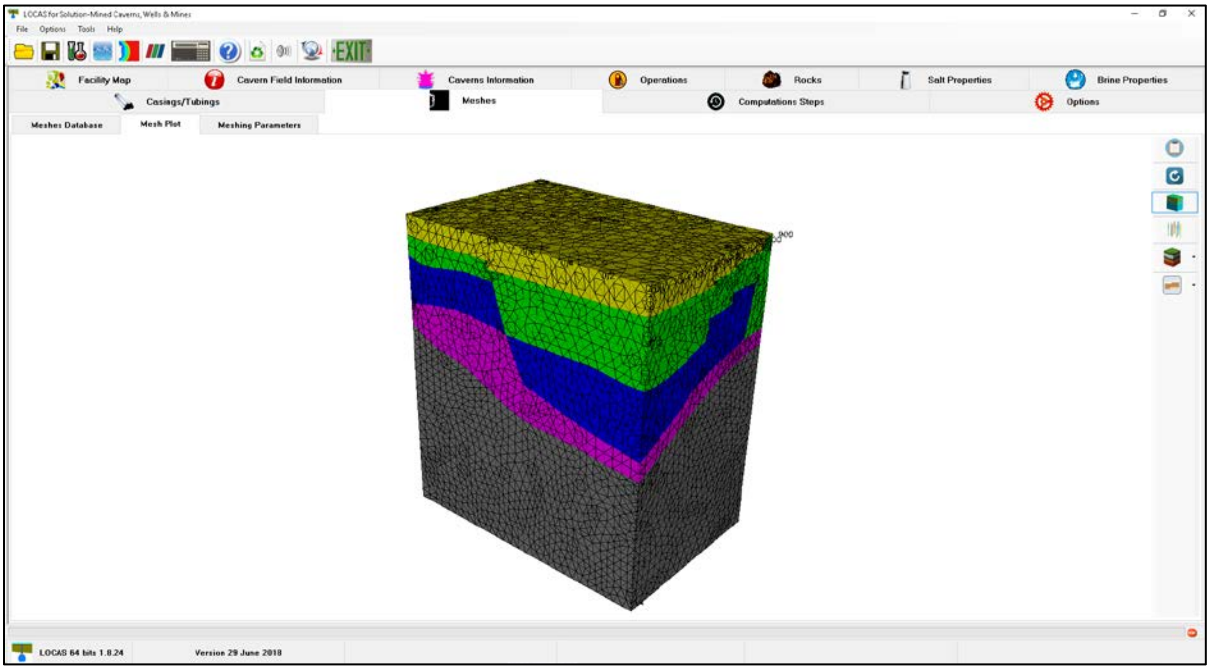

Figure 10 – Outer mesh view created by LOCAS.

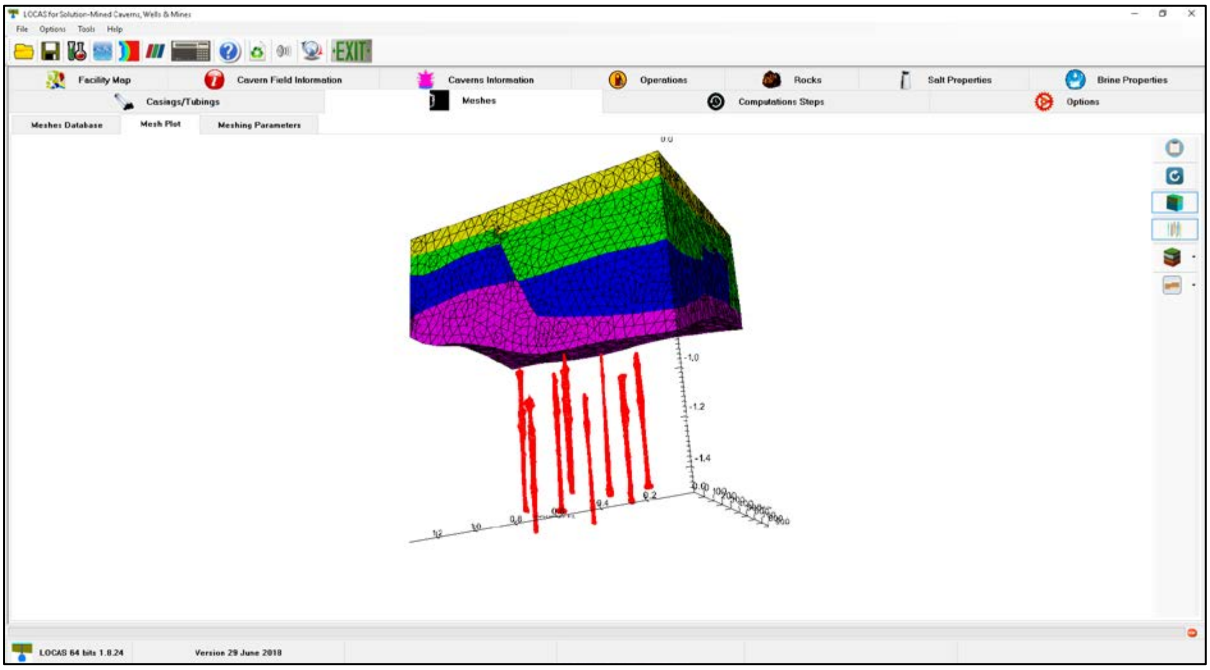

Figure 11 – LOCAS mesh view including caverns.

2.3 Histories of cavern pressure and temperature

2.4 Initial conditions

Because the geological structure of a facility is often complex, including several rock units that exhibit different thermal conductivities, it is challenging to determine the distribution of geothermal temperature to be considered as initial conditions in the model. A dedicated fitting procedure has been implemented in LOCAS to back-calculate the geothermal flux to be applied on the bottom surface of the model to obtain a given steady-state temperature at the mid-depth of a given cavern. This procedure helps determining the initial temperature field within the model.

Also set in the model was the initial pore pressure, which was assumed to be halmostatic in the salt body and hydrostatic in the overburden (Figure 12). A rather small permeability (10^{-21} m²) and Darcy's law were considered for the micro-permeation computations.

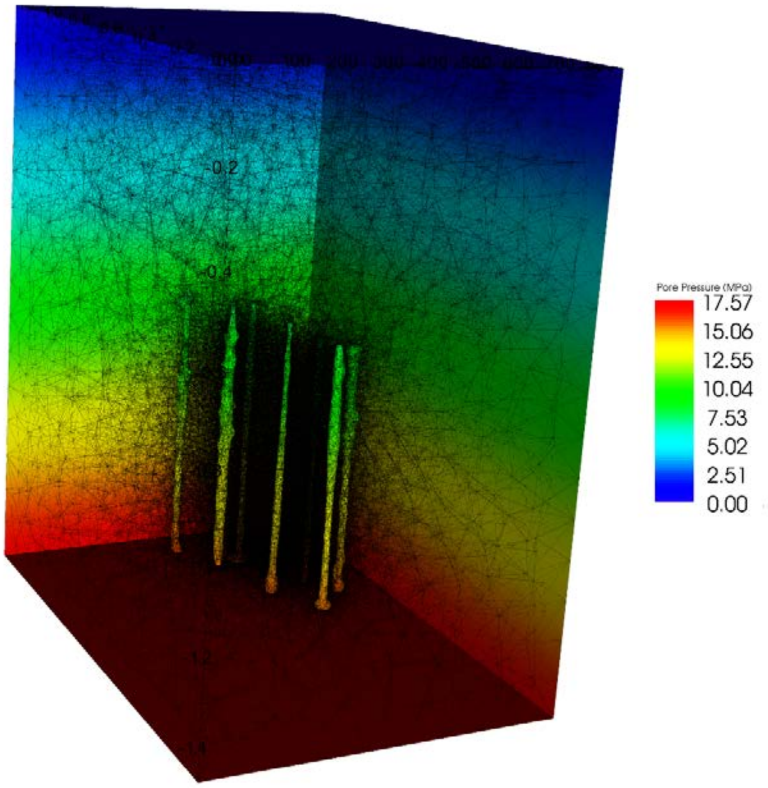

Figure 12 – Initial pore-pressure field in the entire model.

Figure 13 shows a screen shot of the table dedicated to computation steps. It has been designed to provide a precise breakdown of each phase of interest during the entire history of the facility.

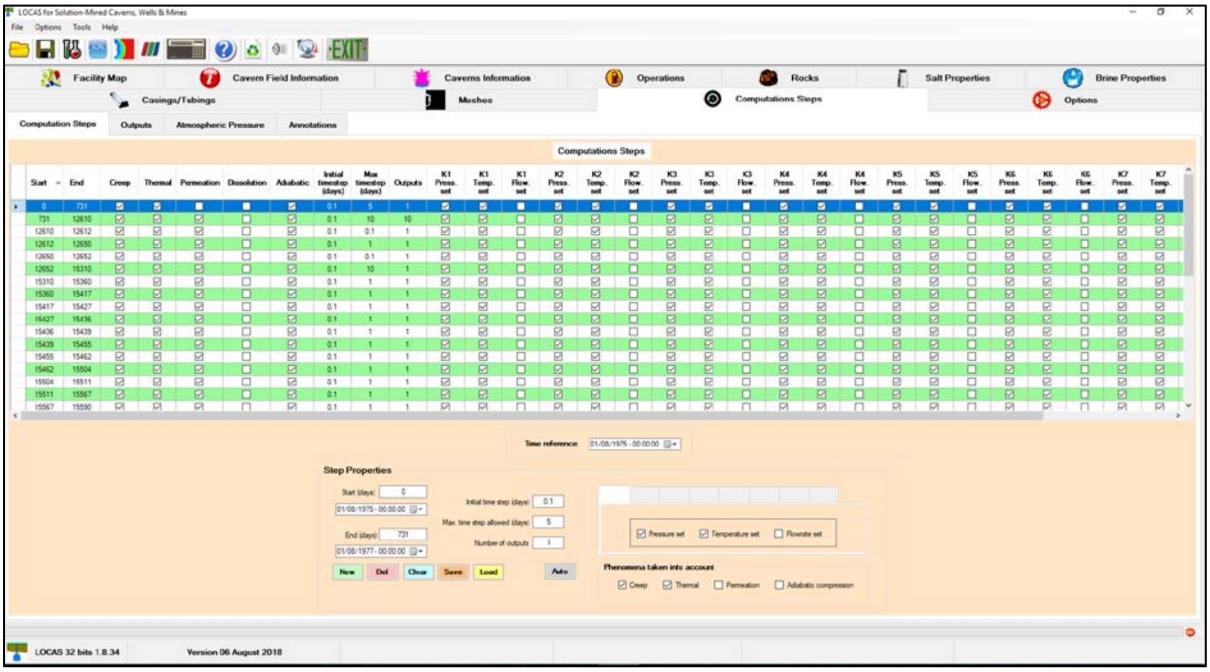

Figure 13 – Table of computation steps.

2.5 Stability criteria

When assessing the stability of the caverns during workovers, four criteria were examined:

(1) onset of tensile stresses in the rock mass at the vicinity of caverns;
(2) onset of effective tensile stresses in the rock mass at the vicinity of caverns;
(3) onset of salt dilation; and
(4) onset of a fault slip.

2.5.1 Onset of tensile stresses

Tensile zones must be avoided, as the tensile strength of salt is low, of the order of 1-2 MPa. Assuming zero tensile stress would be on the safe side, large tensile stresses are assumed to lead to the creation of fractures. Roof or wall spalling may be caused by deep fractures. In a salt cavern, stresses in the rock mass generally are compressive, and no tensile stresses appear at the cavern wall.

2.5.2 Onset of effective tensile stresses

The notion of effective stress applies to any porous rock and commonly is used in Reservoir Engineering. The effective stress equals the actual stress (Compressive stresses are negative.) plus a part of the fluid pressure in the rock pores:

$$\underline{\underline{\sigma}}_{eff} = \underline{\underline{\sigma}} + bP\,\underline{\underline{1}} \qquad (1)$$

where b is Biot's coefficient and P is pore pressure. Whether this notion applies to rock salt is a question still open to discussion, as salt permeability and porosity are exceedingly low. However, at a cavern wall, the effective stress simply is the actual stress plus the cavern pressure (Brouard et al., 2007; Djizanne et al., 2012). Consider the case of an axisymmetric cavern. At the cavern wall, three actual stresses must be considered: the normal stress; the tangential stress; and the circumferential stress. In a perfectly cylindrical cavern, the tangential stress is the vertical stress. By definition, the effective normal stress is zero, as the actual normal stress is equal to minus the cavern pressure. The two other effective stresses may be positive (tensile) or negative (compressive).

It generally is accepted that when the effective stress is larger than a certain positive quantity, often called the rock tensile strength, T_{salt}, hydro-fracturing is possible. The related criterion can be written

$$\sigma_{\max} + P_c < T_{salt} \qquad (2)$$

where $\sigma_{\max}$ is the least compressive stress (Compressive stresses are negative.), and P_c is the cavern pressure. When this criterion is not met, micro-fracturing occurs, permeability increases drastically, and salt softens. In some cases, discrete fractures appear (Bérest et al., 2001; Rokahr et al., 2003; Düsterloh and Lux, 2012).

The tensile strength of salt is a couple of MPa or so. Selecting $T_{salt} = 0$ (to be on the safe side), the criterion can be stated simply: The effective stress must be negative — i.e., "no tensile effective stress" must exist:

$$\sigma_{\max} + P_c < 0 \qquad (3)$$

When considering effective stress inside the rock mass, it is conservative to consider a Biot's coefficient equal to 1 and to check that the effective remains negative:

$$\sigma_{\max} + P < 0 \tag{4}$$

2.5.3 Onset of salt dilation

An irreversible increase in salt volume can occur under certain compressive stress states. This volume increase is due to micro-fracturing in the salt, a phenomenon called dilation. Salt dilation must be avoided, as it may cause an increase in salt permeability and a reduction in salt strength. Several dilation criteria can be found in the literature, and ten are available in LOCAS. The Ratigan/RESPEC criteria were considered for this study: (1) the Ratigan dilation criterion (Ratigan et al., 1991),

$$\sqrt{J_2}_{\,dil} = -0.27 I_1 \tag{5}$$

and the RESPEC or RD dilation criterion (DeVries et al., 2003),

$$\sqrt{J_2}_{\,dil} = \frac{D_1\left(\dfrac{I_1}{sign(I_1)\sigma_0}\right)^{\bar{m}} + T_0}{\left(\sqrt{3}\cos\psi - D_2\sin\psi\right)} \tag{6}$$

where $I_1 < 0$ is equal to three times the mean stress ($I_1 = 3\sigma_m$), and J_2 are the first and second invariants of the stress tensor. Salt parameters D_1, D_2, and m can be determined from laboratory tests. The lode angle (ψ) describes the relation between the principal stresses, and ranges between – 30° and + 30°. Dimensional constant σ_0 is equal to 1 MPa (145 psi), T_0 is the unconfined tensile strength, and $\bar{m}$, D_1, and D_2 are parameters that must be determined for each salt formation. The RD criterion can predict both linear and nonlinear relations for the dilation boundary in the $\sqrt{J_2}$ and I_1 stress spaces.

For all the considered dilation criteria, the **factor of safety** (FOS) is defined as

$$FOS = \sqrt{J_2}_{\,dil} \Big/ \sqrt{J_2} \tag{7}$$

where $\sqrt{J_2}$ is the computed deviatoric stress, and $\sqrt{J_2}_{\,dil}$ is the value of the dilatant deviatoric stress. Dilation may develop when FOS < 1.

2.5.4 Onset of a fault slip

The mechanical behavior of faults is a very complex topic. Some mechanisms can be found in the literature for fault slip, but they are purely speculative, and no set of parameters is available for these mechanisms at the considered site. For this study, it has been considered more reasonable to analyze the possible onset of a fault slip at the post-processing stage using a Mohr-Coulomb failure criterion:

$$\tau = \sigma \tan(\phi) + C \tag{8}$$

where τ is shear strength, σ is normal stress, ϕ is angle of internal friction, and C is the cohesion.

Parameters are site-specific, and there are no available data for the angle of internal friction and cohesion of overburden layers. Therefore, a conservative approach was preferred, and the following parameters were considered (Lux et al., 2004):

$$\begin{cases} \phi = 35° \\ C = 0 \end{cases}$$

2.6 Post-processing examples

Figure 14 gives an example of Factor-of-Safety contours in the vertical cross-section between two caverns at the end of a phase at low pressure during a workover. It can be easily observed that there is no significant dilatant zone in the pillar ($FOS > 1$).

Figure 15 gives an example of effective-stress contours in a horizontal cross-section at the end of a workover. Cavern-shape shadows above the horizontal cross-section are shown. It can be observed that some tensile effective stresses may appear at cavern wall if the pressure build-up at the end of a workover is too rapid following a period at low pressure. This phenomenon has been discussed in the literature (see Djizanne et al., 2012). In this case, cavern stability is not a concern, as the extension of possible fractures is limited to a few meters and is in the horizontal direction.

Figure 16 shows the Coulomb-criterion contours plotted on all the faults. “Coulomb-criterion contours” correspond to contours of $\tau - \sigma \tan(\phi) - C$ according to Equation (8). Onset of a fault slip is likely when this quantity is positive. The Coulomb criterion is everywhere negative, except in very small areas close to surface (only a few meters thick) for one of the faults, therefore excluding any risk of a fault slip. The onset of a fault slip would be likely only if there were a significantly large part of the fault exhibiting positive values of the Coulomb criterion (magenta areas), but this is clearly not the case here.

Figure 17 provides an example of subsidence contours.

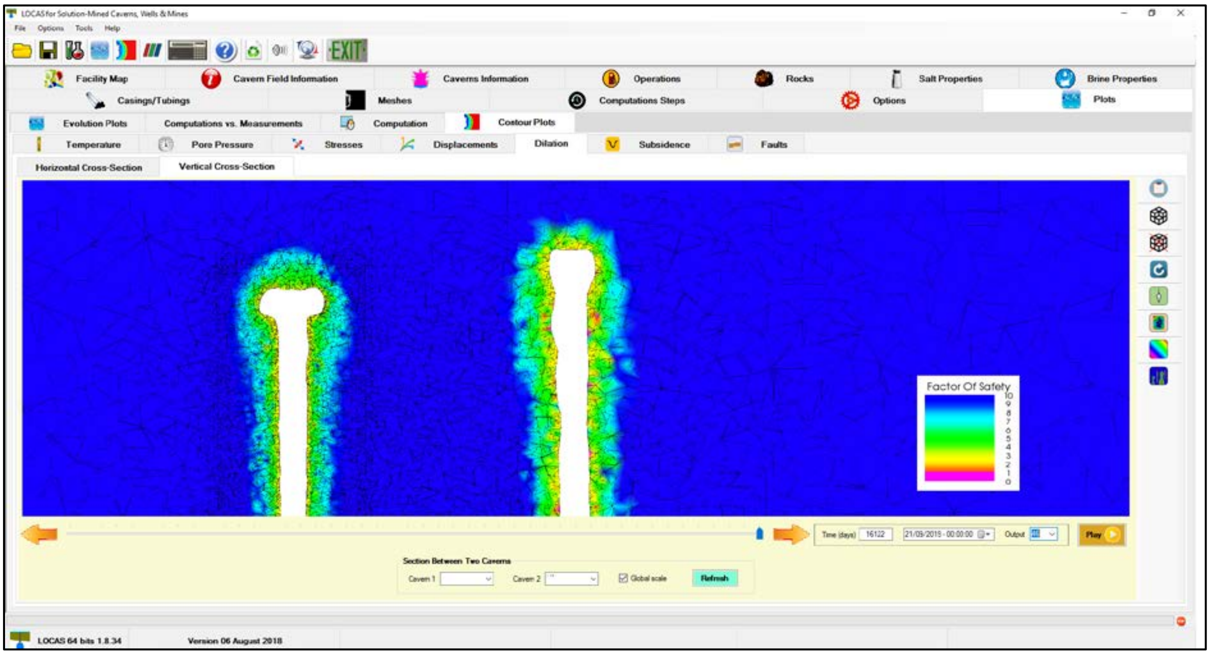

Figure 14 – Example of LOCAS Factor-of-Safety contours and mesh in the vertical cross-section between two caverns during a workover.

Figure 15 - Example of LOCAS effective-stress contours at a 1000-m depth.

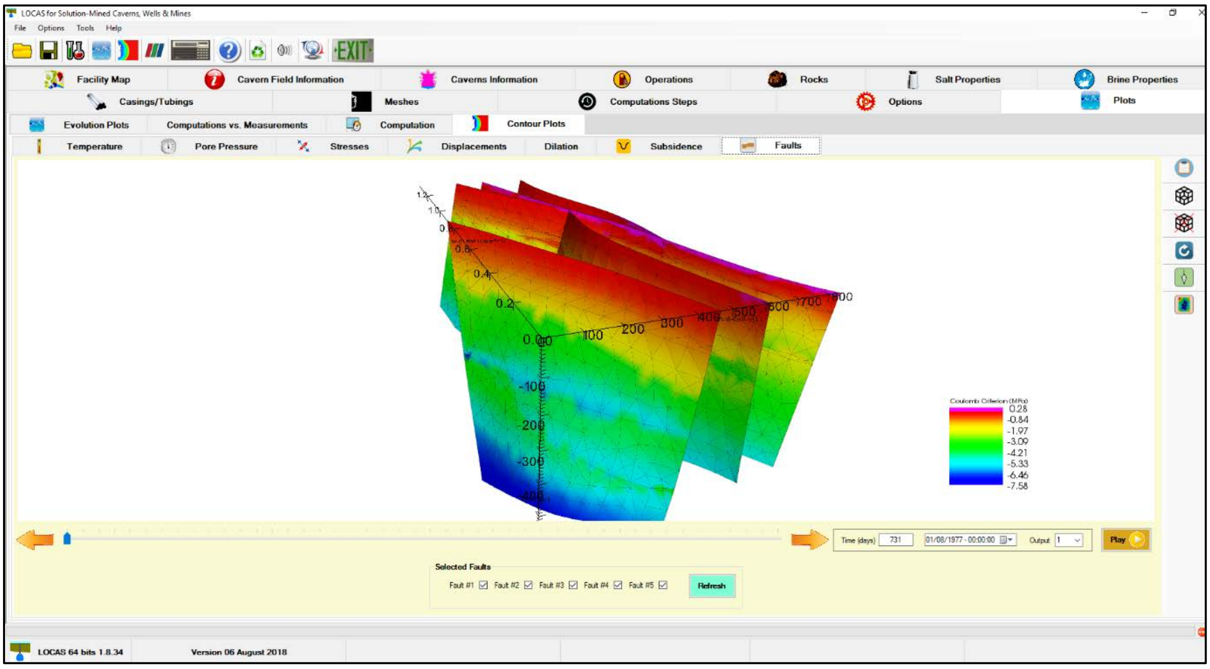

Figure 16 – LOCAS analysis of faults stability: example of Coulomb-criterion contours.

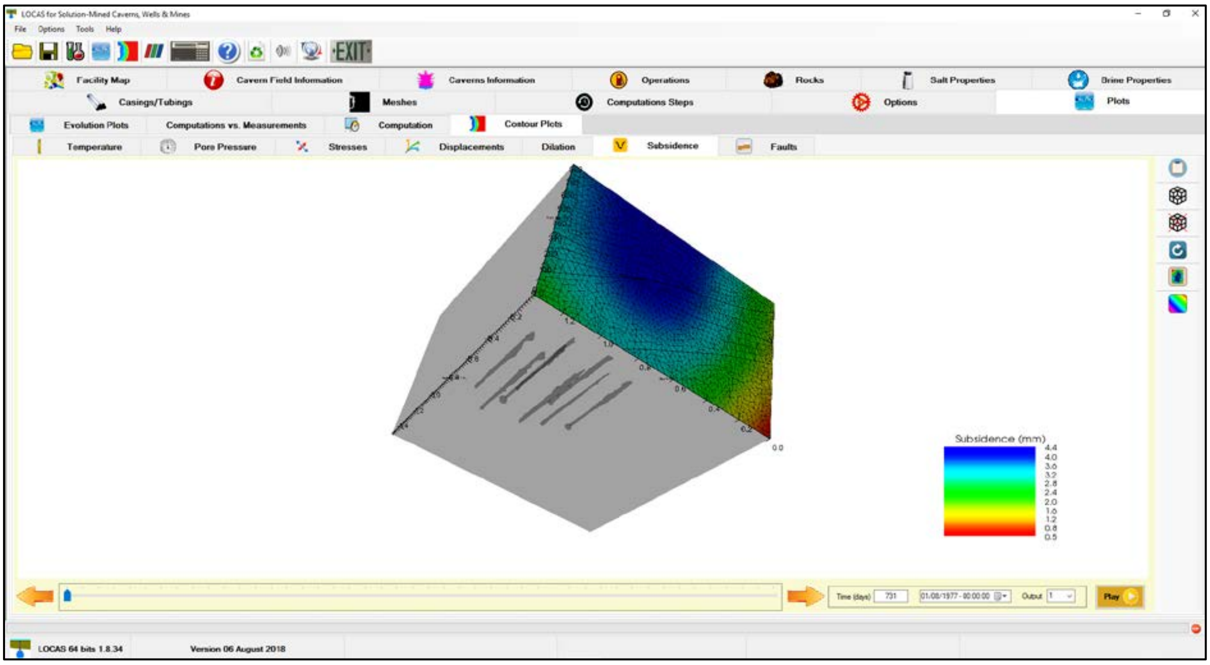

Figure 17 – LOCAS example of subsidence contours.

3 Conclusion

LOCAS is a huge software suite that has been developed continuously for 20+ years, especially regarding behavior analysis of salt caverns. LOCAS is the only commercially available software that is able to couple cavern thermodynamics and rock-salt complex geomechanics properly. This is of upmost importance for problems such as cavern-abandonment.

LOCAS provides a user-friendly interface, usable by non-experts, which allows input of field data and calculations parameters, and also a very powerful finite-element core for stability analysis of caverns in the short or long term. LOCAS has been designed for all type of caverns (gas/liquid storage and brine production), and the new 3D version allows collection of all available data from a facility in one place.

LOCAS exists in both stand-alone and cloud versions.

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