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Technical Conference Paper

Full Geomechanical Modeling and Data Management of a Gas-Storage Facility Using LOCAS 3D

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FULL GEOMECHANICAL MODELING AND DATA MANAGEMENT OF A GAS-STORAGE FACILITY USING LOCAS 3D

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Abstract

LOCAS is a huge software suite that has been developed continuously for 20+ years, especially for the purpose of analyzing salt caverns. LOCAS is able to couple cavern thermodynamics and rock-salt complex geomechanics properly. This is of upmost importance for problems such as gas-storage management, caverns stability analysis, subsidence calculation, or cavern-abandonment.

LOCAS provides a very 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 salt caverns: for brine production, liquid storage or gas storage -including all type of gases. The new 3D version allows collection of numerous data related to a facility in one single place.

Some features of LOCAS 3D are shown through the example of a gas-storage facility. The whole history of the facility since its creation is modeled and a quick stability analysis is performed.

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

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, especially gas 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 caverns). This limitation in Abaqus was the starting point of the development of LOCAS (Brouard et al., 2006) for the purpose of abandonment studies (Brouard, 2020).

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 is 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 (see References).

1.2.1 Physical 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 or Lemaitre-Menzel-Schreiner constitutive laws (see example in Figure 1).
- Dislocation creep and pressure-solution creep can be considered (Brouard, 2020).
- 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 for liquid-hydrocarbon-filled caverns (Gatelier et al., 2008).
- Brine micro-permeation through rock salt.
- Increase of salt permeability due to the onset of tensile effective stresses (Brouard, 2020).

1.2.2 Type of salt caverns that can be modeled

Gas and liquid-hydrocarbon storage caverns can be modeled. Any gas, including hydrogen or air for instance, is suitable. Analysis of the mechanical stability of a whole brine-production facility is also possible. LOCAS 3D can hold data from more than 20 caverns of different types.

1.2.3 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 (Brouard, 2020). For the latter 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.

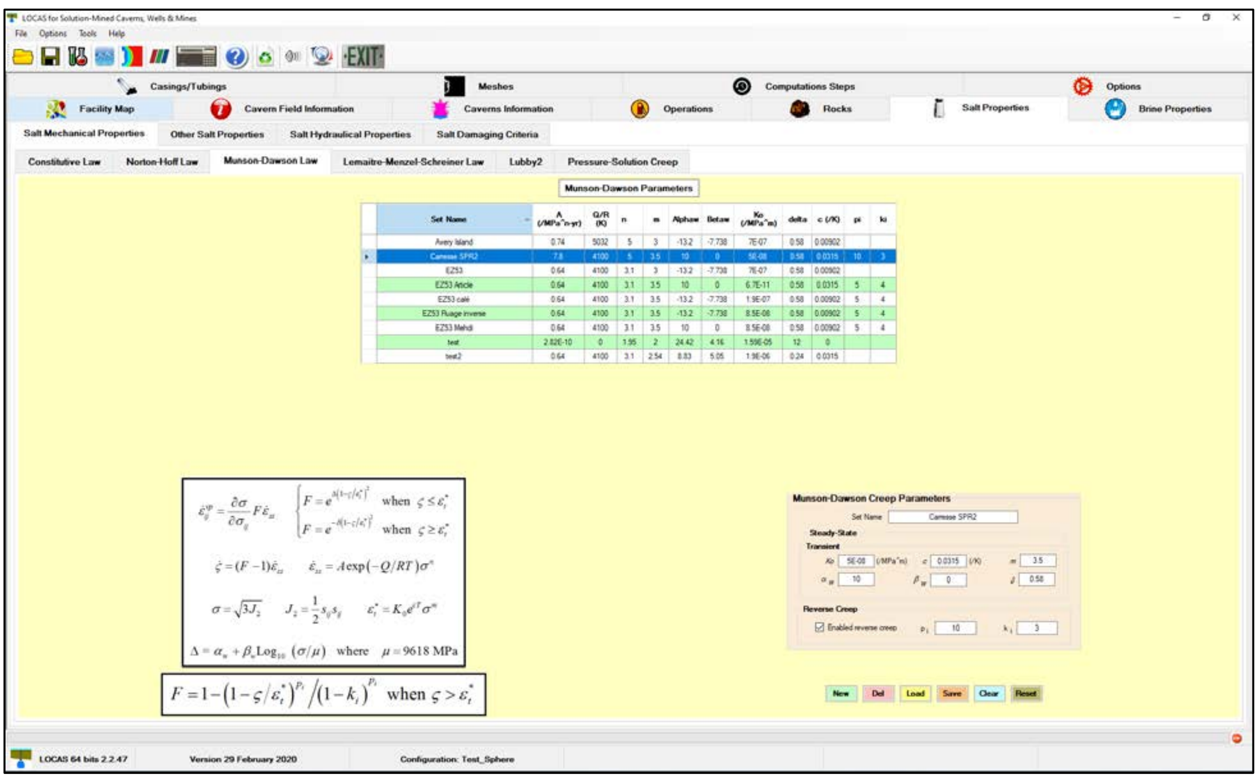

Figure 1 – LOCAS tab dedicated to the Munson-Dawson constitutive law.

1.2.4 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, Flodim or Sonar Wire files can be loaded directly in LOCAS.
- Logs (temperature, interface, GR, etc.).
- Leaching data.
- Tightness tests data.
- Pictures (see Figure 5).

A tab and many sub-tabs are dedicated to each cavern. Adding a new cavern from the cavern database (Figure 6) will create new tabs dynamically.

Figure 2 shows an example of facility overview through a Google map embedded in LOCAS. The meshed zone is highlighted in a transparent rectangle.

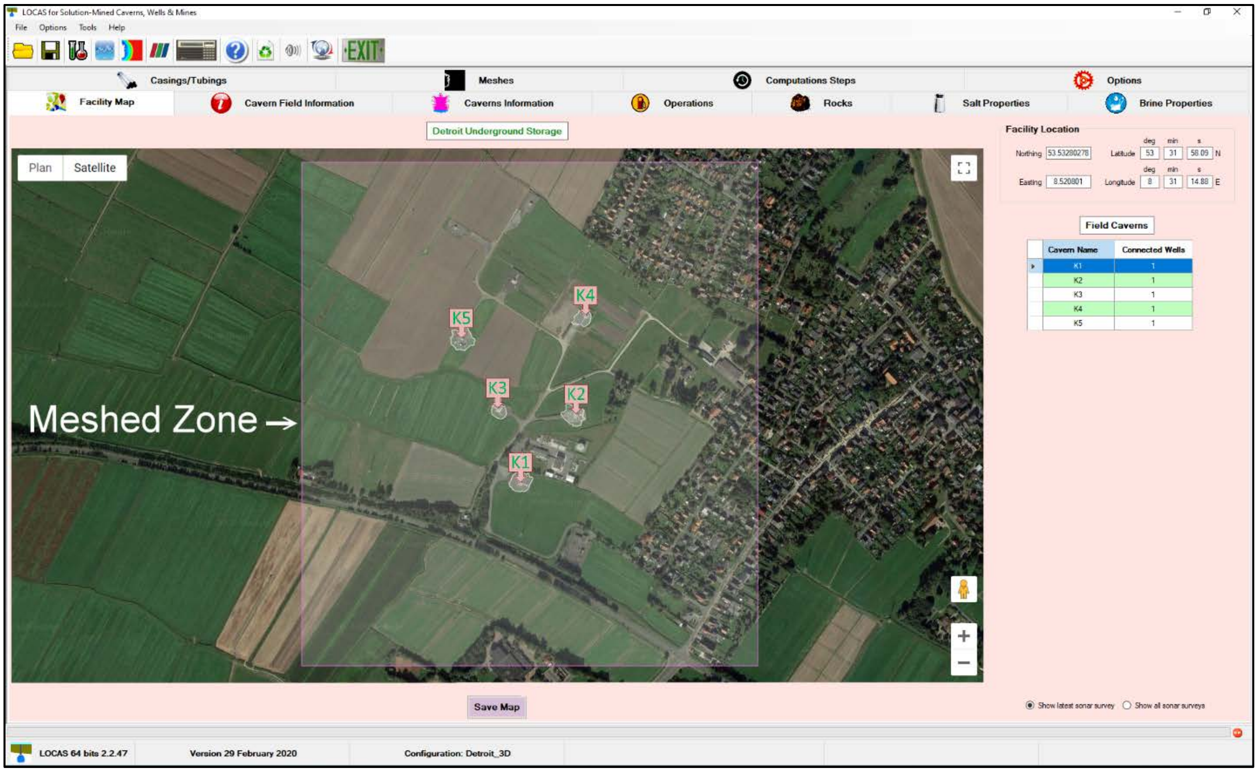

Figure 2 – LOCAS overview of a facility with cavern contours and meshed area.

1.2.5 Ability to monitor the status of a facility

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

- ✓ product mass and energy inventory in each cavern;
- ✓ facility inventory of stored products;
- ✓ creep closure of each cavern;
- ✓ casing-shoe pressures and pressure gradient evolutions; and
- ✓ subsidence rate.

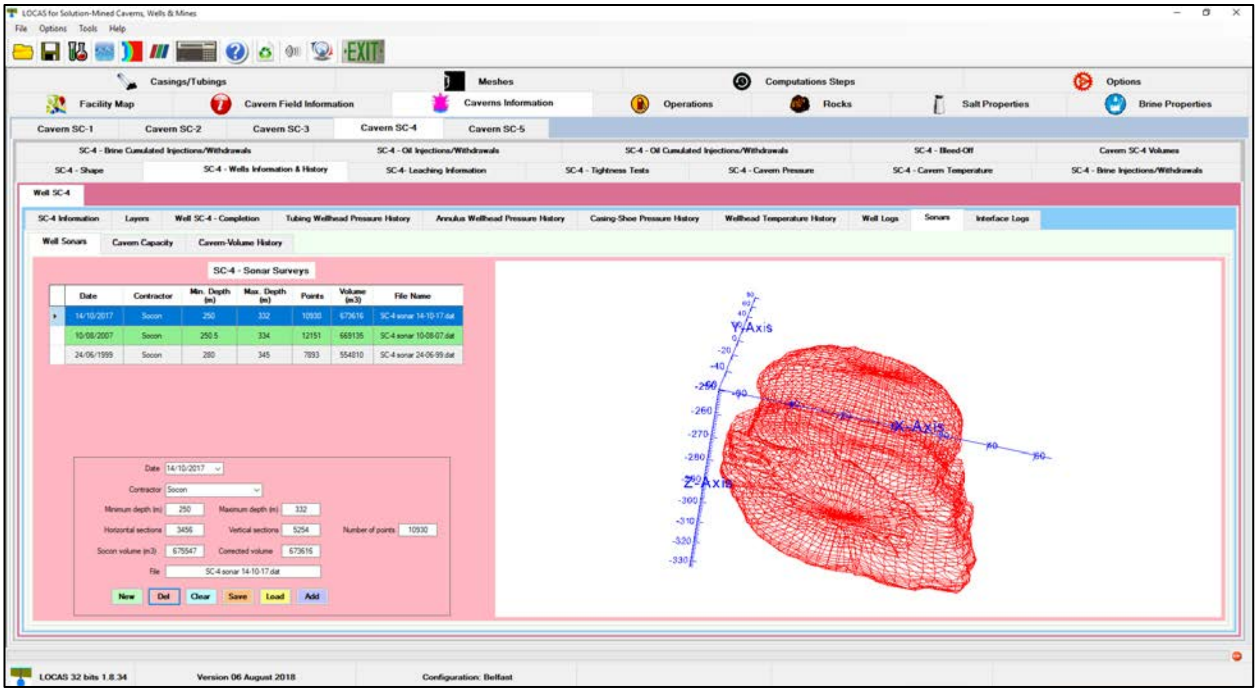

Figure 3 – Example of the sonar-survey database for a given cavern.

1.2.6 Ability to calculate cavern-gas temperature

Most of time no downhole temperature is set permanently in gas caverns; therefore, evolution of cavern-gas temperature can only be estimated through computations. When some data as wellhead gas pressure and gas inventory are available, LOCAS can compute cavern-gas temperature (Figure 7). This computation is performed using AGA-8 formulas (Starling and Savidge, 2003) when gas natural composition is known. An example of such a temperature evolution computed during a few years is given in Figure 8.

When only initial inventory and gas pressure at wellhead are available, LOCAS is also able to compute downhole gas pressure and temperature, but through finite-elements computations that take into account the heat fluxes exchanged between the gas, the rock mass and the brine sump. This type of computation may take a few hours depending on the number of caverns and the duration of the considered time period. Computations not only provided cavern pressure and temperature but also temperature and stresses in the rock mass that are used to assess caverns stability.

Note that computations can be much faster when using the restart feature of LOCAS, see Section 1.2.8.

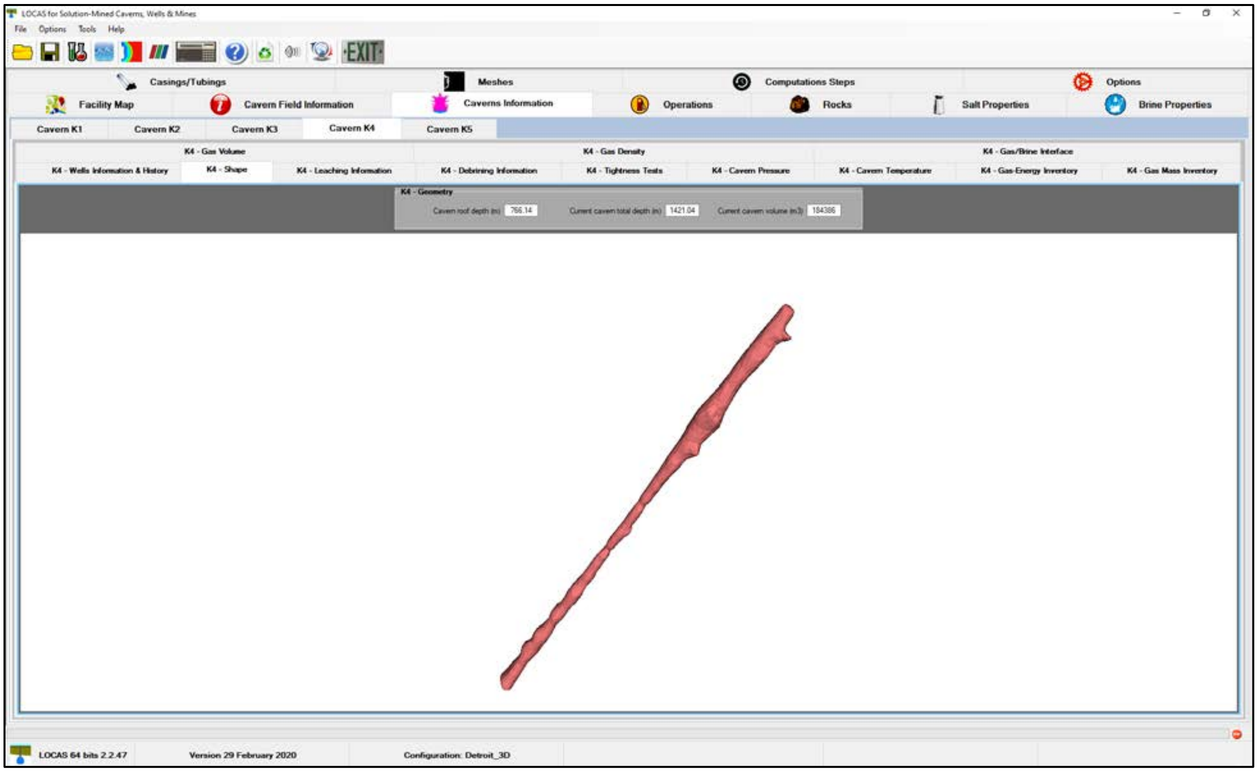

Figure 4 – LOCAS display of cavern current shape from the latest sonar survey.

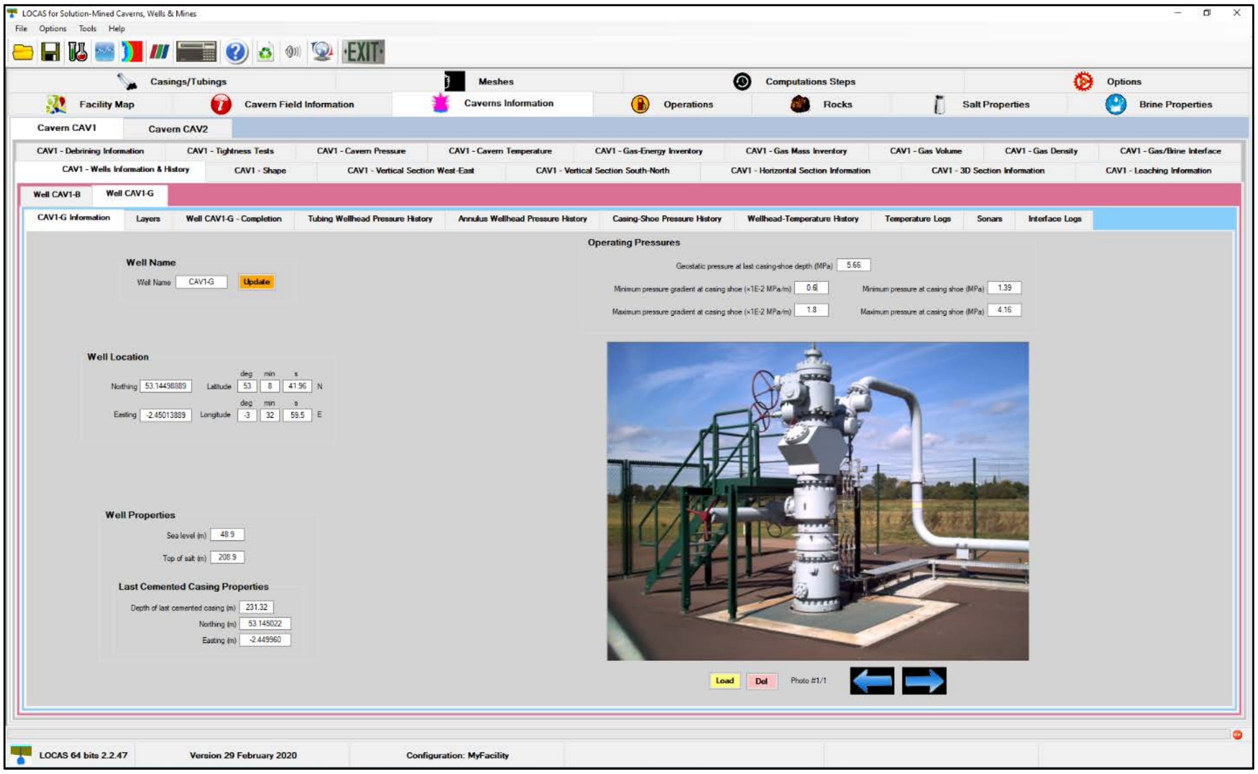

Figure 5 – Example of a tab dedicated to some well properties.

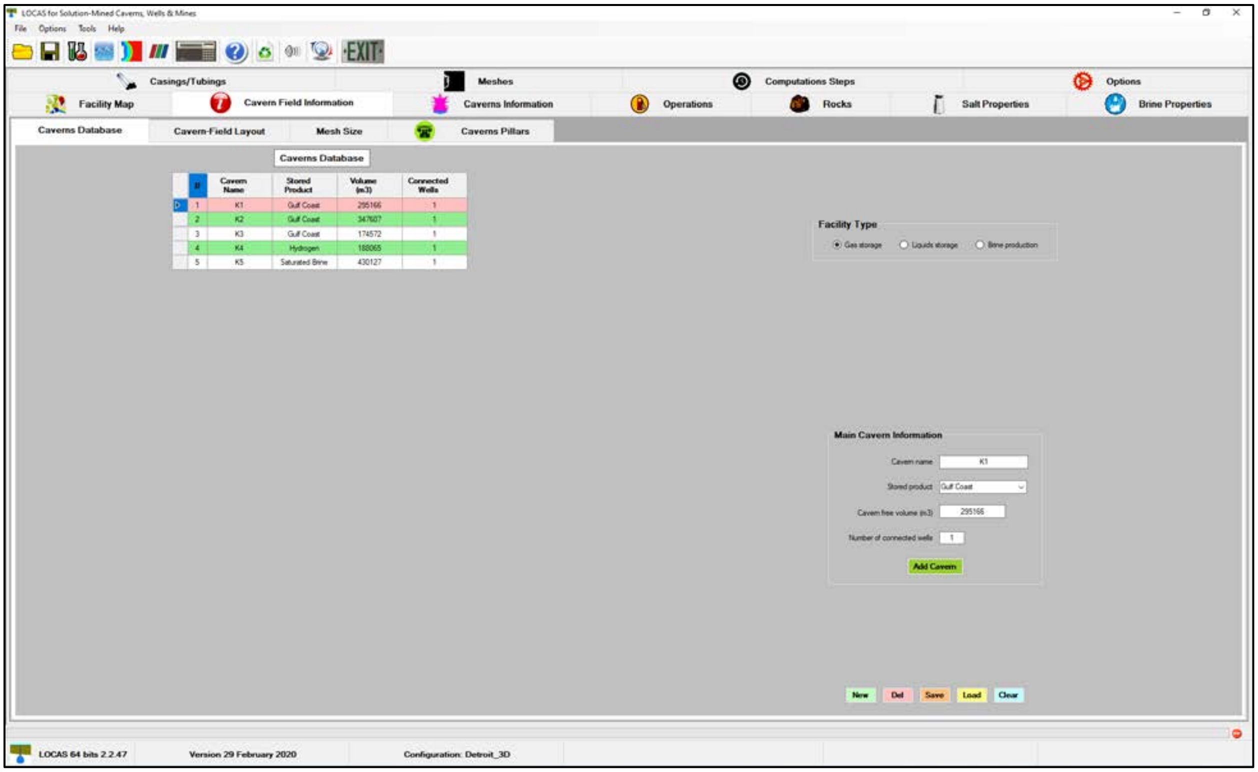

Figure 6 – Cavern database in LOCAS that allows easy addition of new caverns.

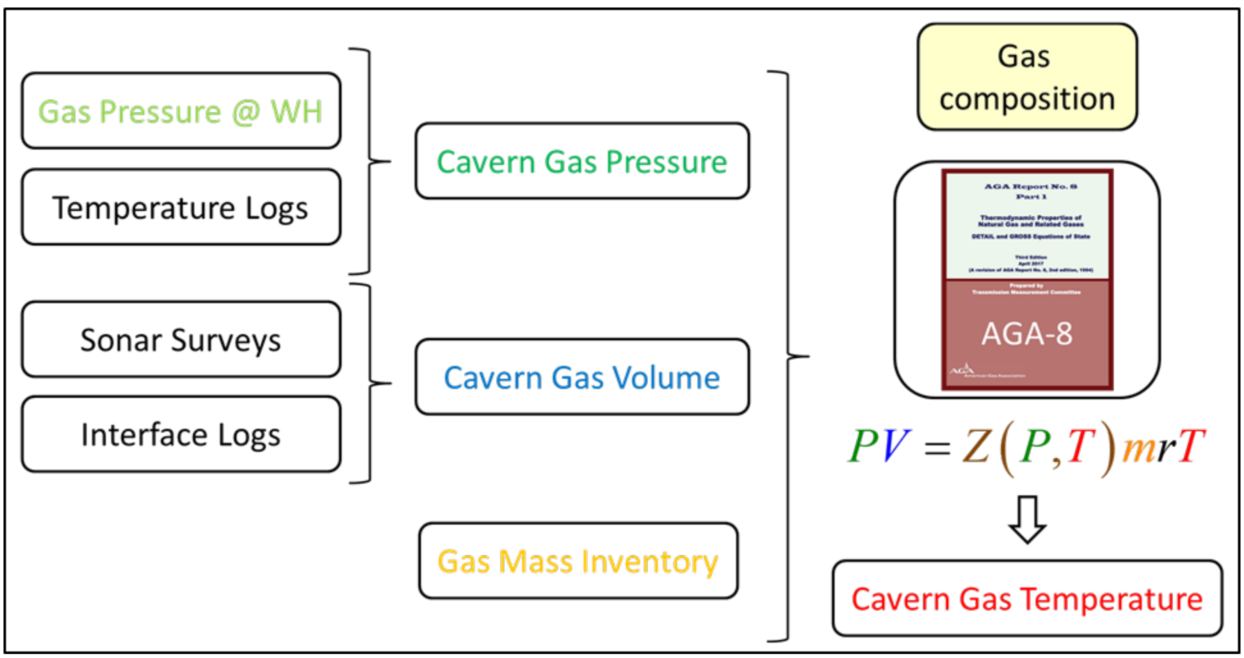

Figure 7 – Workflow for the calculation of cavern-gas temperature.

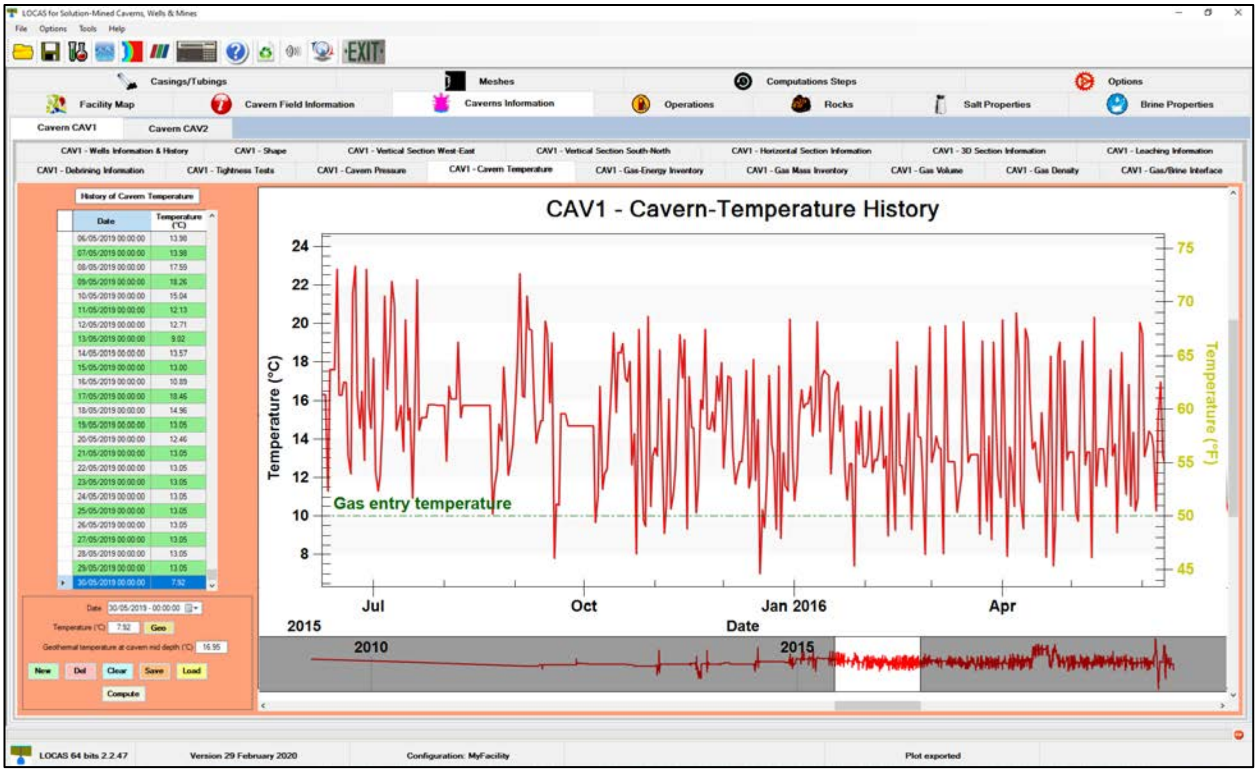

Figure 8 – Example of computed cavern-gas temperature.

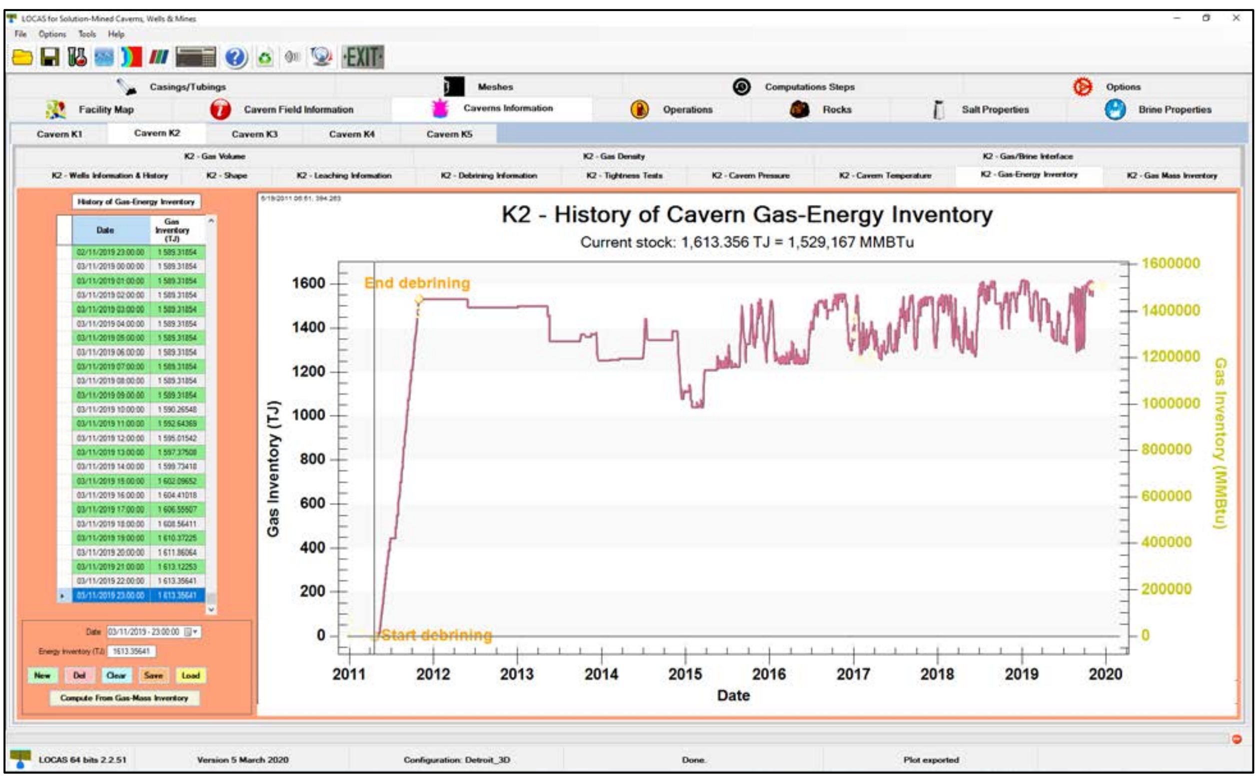

Figure 9 – Example of computed energy inventory.

1.2.7 Ability to calculate energy inventory

When only mass inventory, in MNm3 or MMscf, is known, it is possible to compute energy inventory through calculation of the mass-basis gross calorific value that has been implemented in LOCAS (British Standards Publication, ISO 6976:2016). An example is provided in Figure 9. Conversely, it is possible to compute mass inventory from energy inventory.

1.2.8 Ability to restart computation for quick prediction

LOCAS 3D has the ability to restart computations. At a given point in time during the computation stresses and temperatures withing the model can be saved. It is then possible afterwards to add new input data, and to restart the computations from the saved point.

An example is shown in Figure 10. A former computation has been performed until day 2588 (February 2, 2017) and the results of this computation have been saved. The new computation restarts from that day and runs until day 3593 (November 3, 2019). The new period (days 2588-3593) can be related to new measurements added (wellhead pressures, inventory), or, for instance, to a period when only cavern pressure is imposed. In the latter case, it allows testing a scenario. For instance, the stability of the caverns during a workover, or for gas injections/withdrawals completed at a higher rate than usual, can be verified. Furthermore, there is no need to be an expert in rock mechanics to determine is something goes wrong as, for instance, potentially damaged zones are colored in magenta.

Simulating the whole lifetime of a cavern field can be rather time consuming, in the order of 1 day of computation, but computing only a few additional hours or days is rapid. From that perspective, LOCAS can be used as a day-to-day tool for decision support.

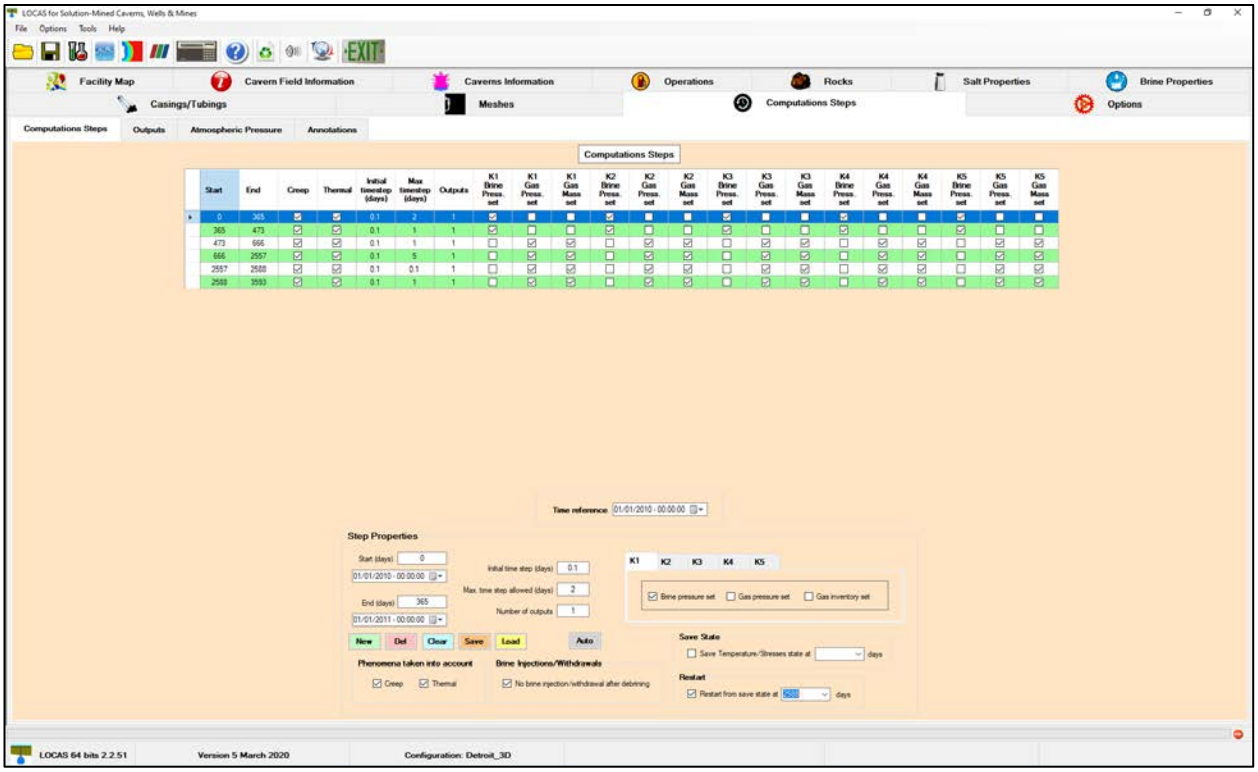

Figure 10 – Computations steps tab – Case of a restart.

1.2.9 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 or on the cavern wall, can be plotted for the following variables:

(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 (brine and gas); cavern compressibility (for brine production or liquid-storage cavern); cavern volume (creep closure), and comparison with field data (sonars for instance) whenever available.

1.2.10 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.

1.2.11 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 (Intel i9 processor with 128GB RAM or

AMD Ryzen with 256GB RAM). Access to the cloud version has been tested successfully for a few years. It works smoothly and securely through any firewall via rdp, Citrix, or browser-based access.

Note that the cloud version can be run from any operating system, such as Microsoft Windows, macOS or Linux. It can also be accessible from any smartphone using RDP protocol.

2. Example of application to the geomechanical modeling of a gas-storage facility

2.1 Introduction

The following example is not real but is inspired by existing gas-storage facilities. The geomechanical study consisted in gathering available data, performing finite-element analysis, 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 are used to assess the stability of the caverns, with special attention paid to the possible onset of effective tensile stresses and salt dilation.

2.2 Considered facility

The considered facility is composed of 5 caverns: 3 caverns are filled with natural-gas, one is half-filled with hydrogen and the last one is kept filled with brine. In LOCAS caverns are located both through their GPS coordinates, and also through their relative coordinates in the mesh. A tab called "Mesh Size" is dedicated to the coordinates (Figure 11). In fact, a very precise location of caverns in the model is mainly needed when the pillar size between two caverns is a concern. For that purpose, another tab is dedicated to the calculation of the minimum distance between two caverns, the distance can be calculated from selected sonar surveys, or from caverns location in the mesh (Figure 12). Note that each cavern may be connected to the ground through one or more wells, all these wells may be deviated and their trajectories can be loaded in LOCAS.

2.2.1 Geology

For simplicity bedded salt caverns are considered in the example. A much more complex geology can be considered whenever needed. An example of a salt dome including faults is presented in Brouard et al. (2018). Figure 13 gives an overview of the 1000-m × 1000-m × 1500-m (3000-ft × 3000-ft × 4500-ft) domain modeled for the 3D numerical computations.

2.2 Meshing

Figure 14 shows the meshed model. A typical mesh is composed of about 500,000 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 gas cavern or 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, especially when considering gas caverns, the finer the mesh must be (Brouard et al., 2011). The meshing process is very important and can be complex in some cases. Brouard Consulting offers complimentary support to customers when creating meshes.

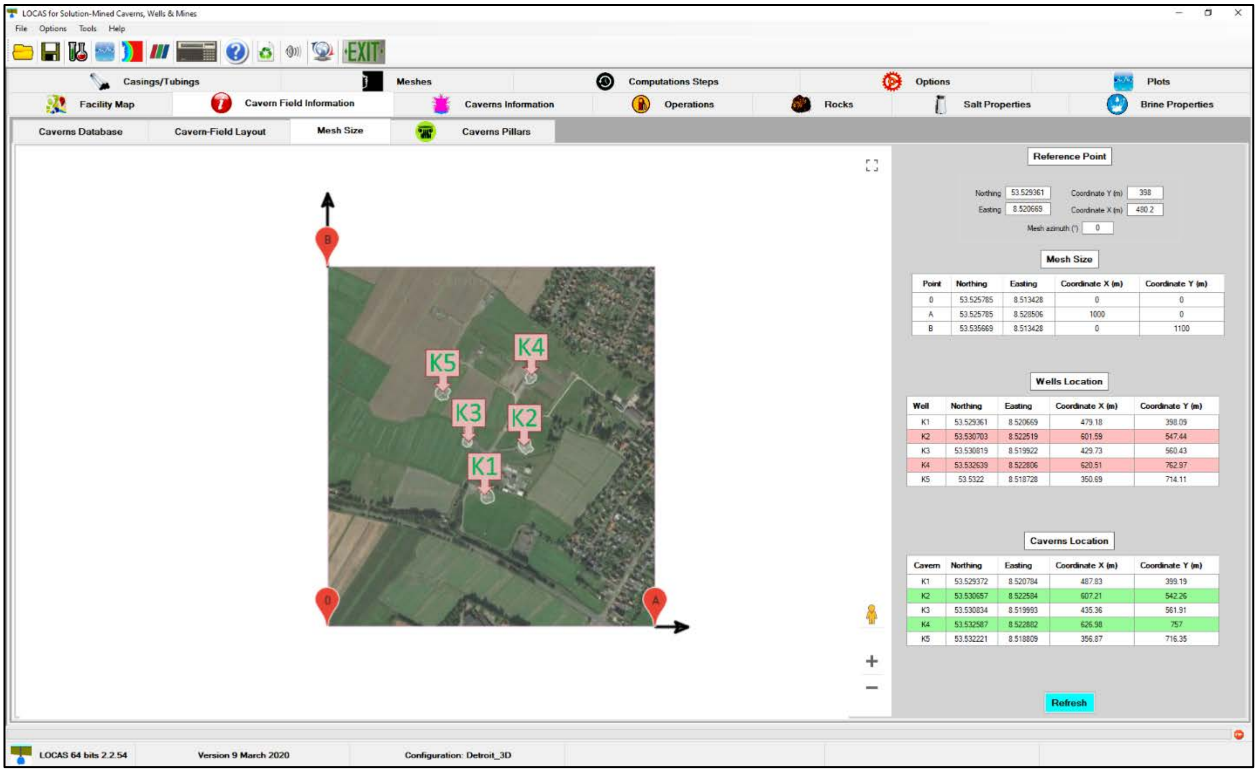

Figure 11 – Size of meshed area.

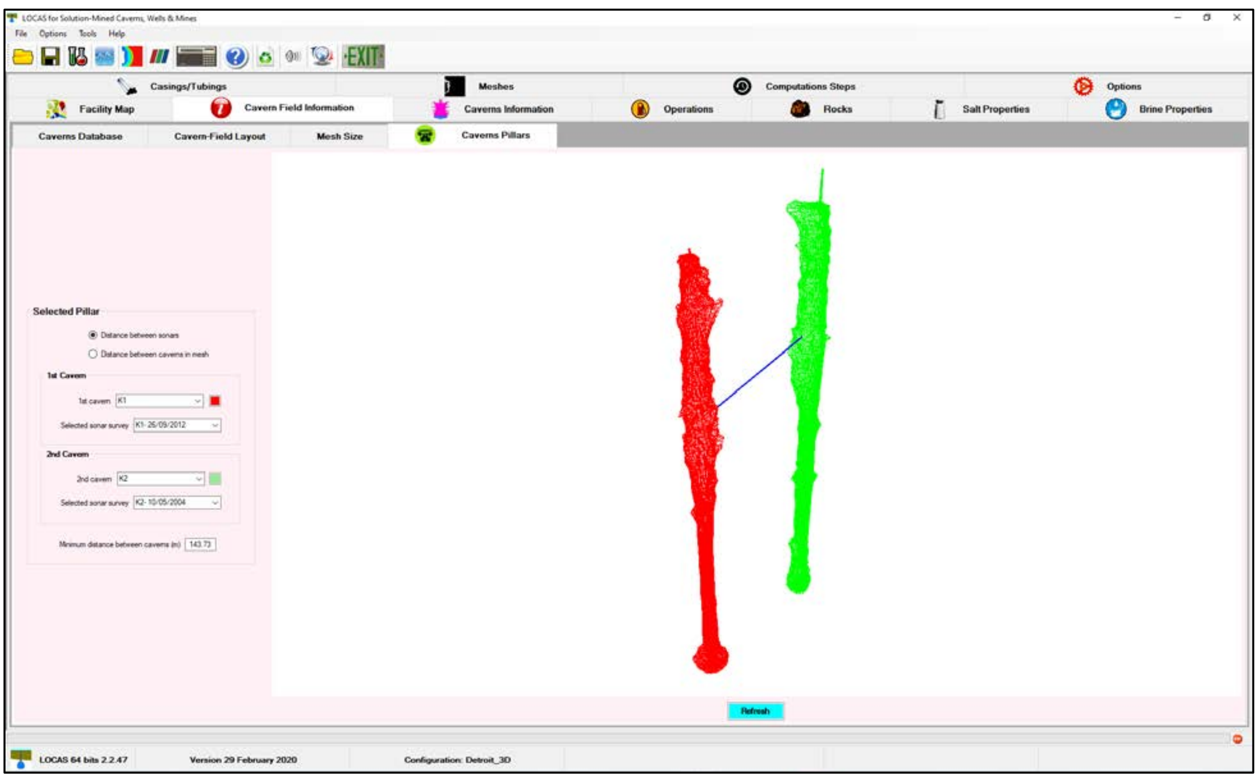

Figure 12 – Calculation of the minimum distance between two caverns.

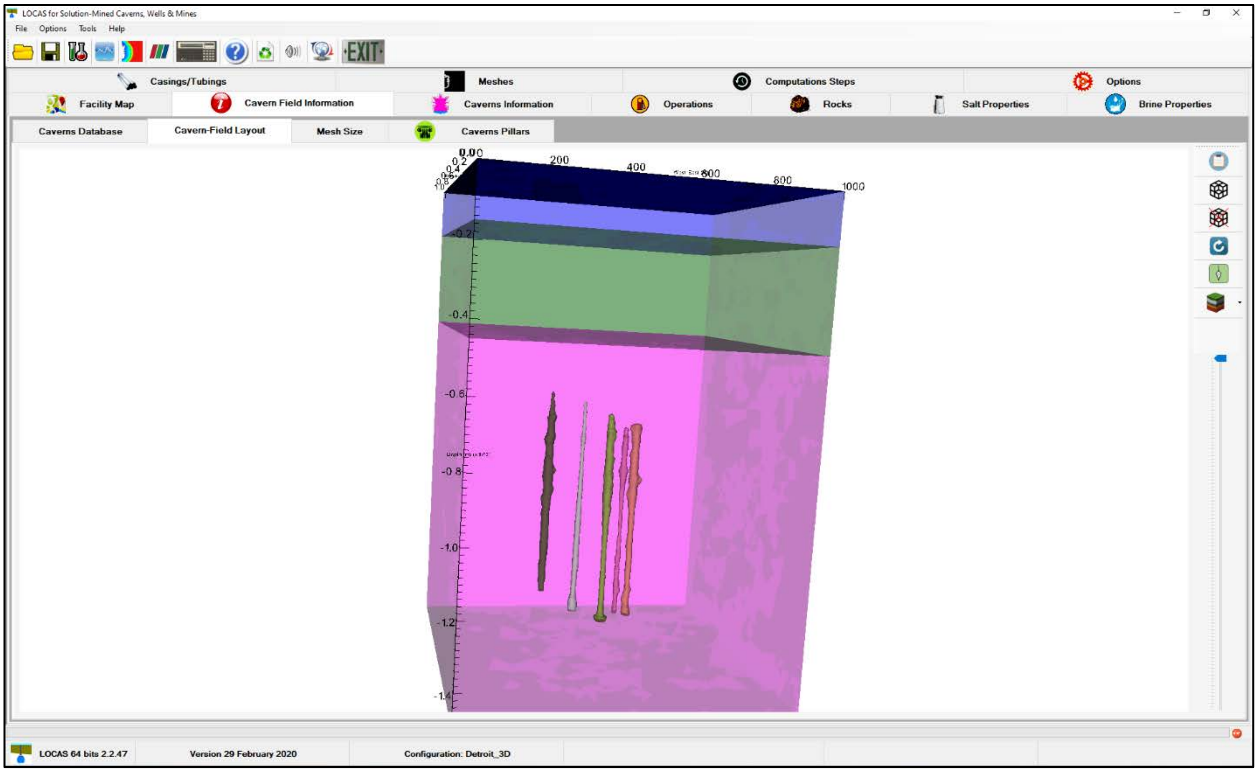

Figure 13 – Cavern-field layout as displayed in LOCAS.

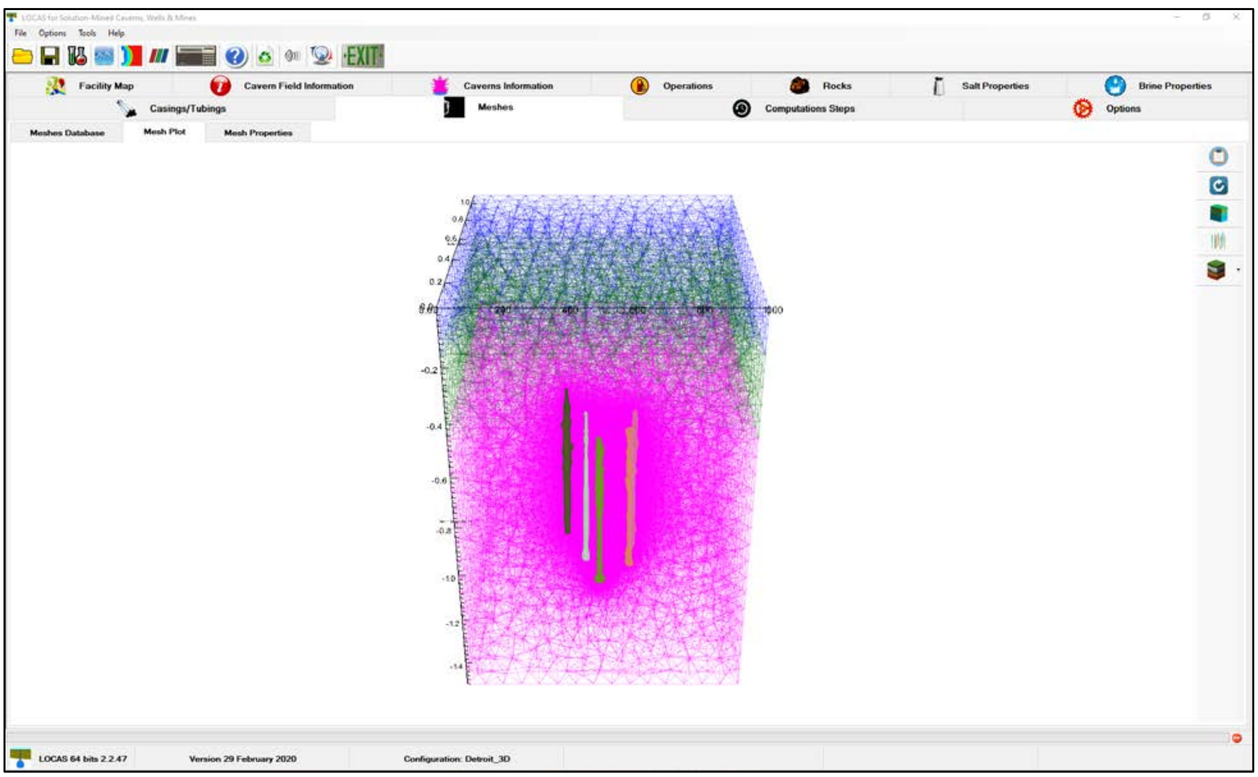

Figure 14 – Meshed model.

2.3 Initial conditions

2.3.1 Initial stress field

Computations in LOCAS are always performed since the start of mining because stresses redistribution all along caverns lifetime must be carefully calculated. The initial stress field is back calculated in order to be relevant with geology and rocks densities.

2.3.2 Initial temperature field

When geological structure of a facility is complex, including several rock units that exhibit different thermal conductivities, it may be challenging to determine the distribution of geothermal temperature to be considered as initial conditions and/or boundary conditions in the model. A dedicated calibration 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 cavern. This procedure helps determining the relevant initial temperature field within the model. In the considered example, a 48 °C (118 °F) temperature is obtained at first cavern mid-depth for a geothermal flux equal to 62 mW/m^2 (5.5×10^{-6} $Btu/s\text{-}ft^2$).

2.4 Historical data

A huge amount of historical data can be loaded in LOCAS. There is almost no size limit as LOCAS is a 64-bit software that can hold a huge amount of memory. The most common data are wellhead-pressure data and inventory data. In this example, hourly data during several years were loaded.

Data can be historical; i.e., from actual measurements, or set by the user for the purpose of prediction. Figure 15 for instance shows the considered hydrogen-pressure evolution in cavern K4. Monthly cycles for 3 years are assumed. Hydrogen pressure is kept at the maximum pressure, 150 bar or 2175 psi, for 10 days, then hydrogen is withdrawn in 5 days to lower the pressure down to the minimum, 90 bar or 1300 psi. The pressure is kept at the minimum for 5 days, and then hydrogen is injected to go back to the maximum pressure in 10 days. According to the initial hydrogen inventory at the end of debrining, LOCAS computes the resulting evolution of gas mass and gas temperature in the cavern. The 36 cycles were automatically generated using an embedded tool.

The gas compressibility factor, or Z, is calculated at each time step during computation assuming the most accurate constitutive law available; i.e., AGA-8 formulas (Starling and Savidge, 2003) in the case of natural gas, and Younglove (1982) and Lemmon et al. (2008) for hydrogen.

Evolution of pressure, and pressure gradient (Figure 17), at the last cemented casing shoe (LCCS) for the five caverns can be computed from wellhead pressures, injection/withdrawal flowrates and from temperature logs -whenever available. It can be easily checked that the downhole pressure remains below the maximum allowable pressure; i.e., 1 psi/ft at the LCCS in this example.

A table of daily gas nominations can be generated (Figure 18). It is used to determine field mass/energy inventory and to plot the working gas capacity for each cavern or for the whole facility (Figure 19).

Figure 15 – Close-up of hydrogen-cavern pressure.

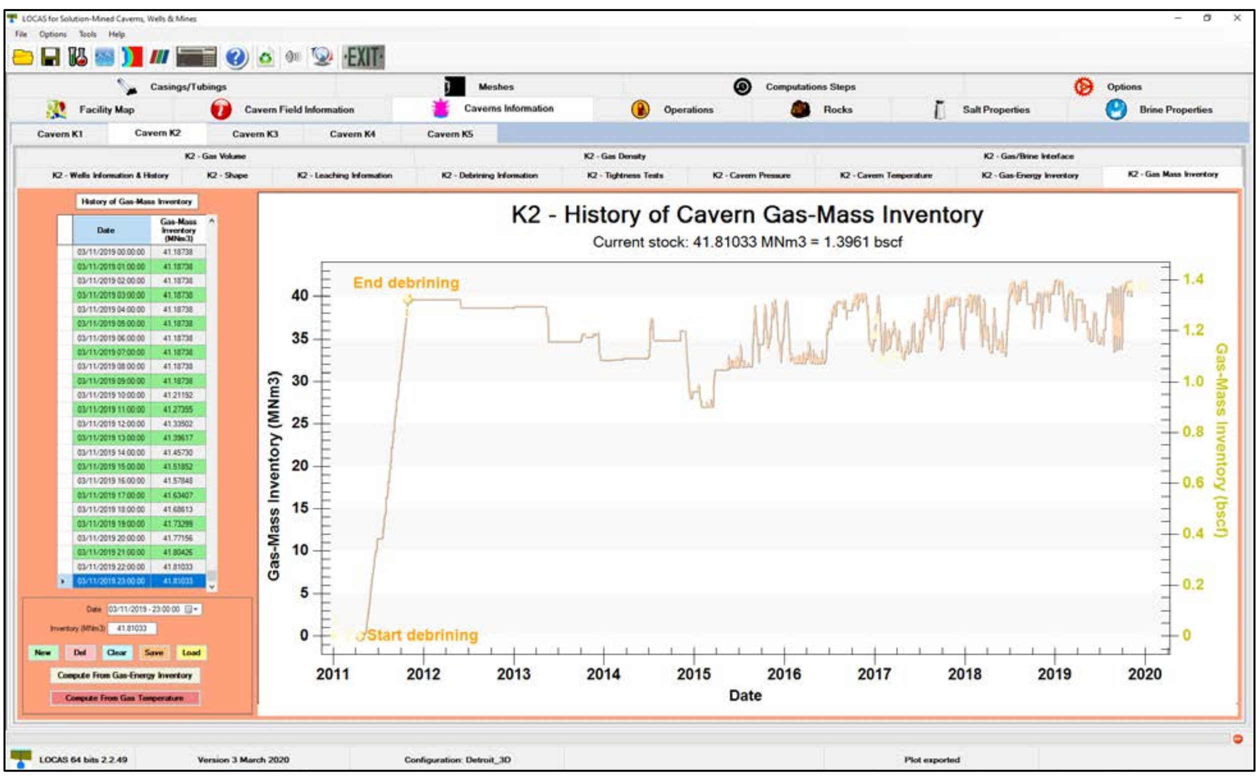

Figure 16 – Gas-mass inventory.

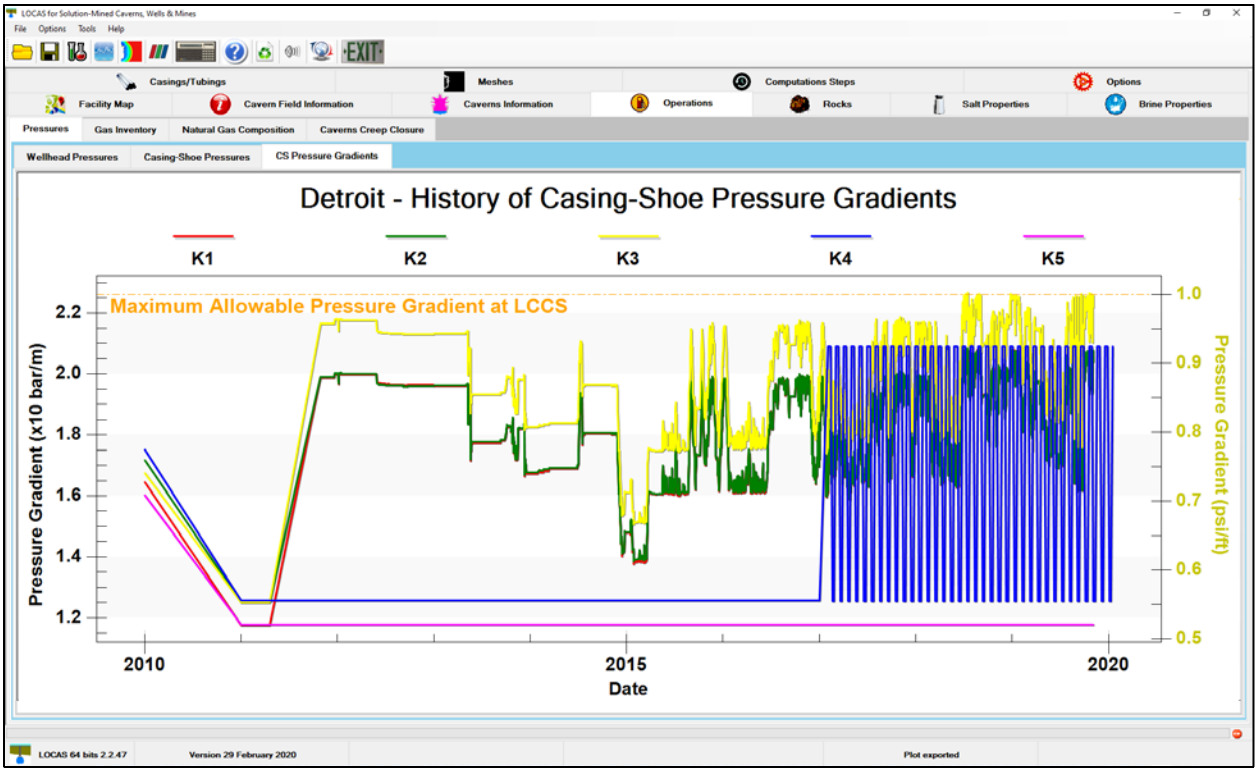

Figure 17 – Example of evolution of casing-shoe pressure gradients.

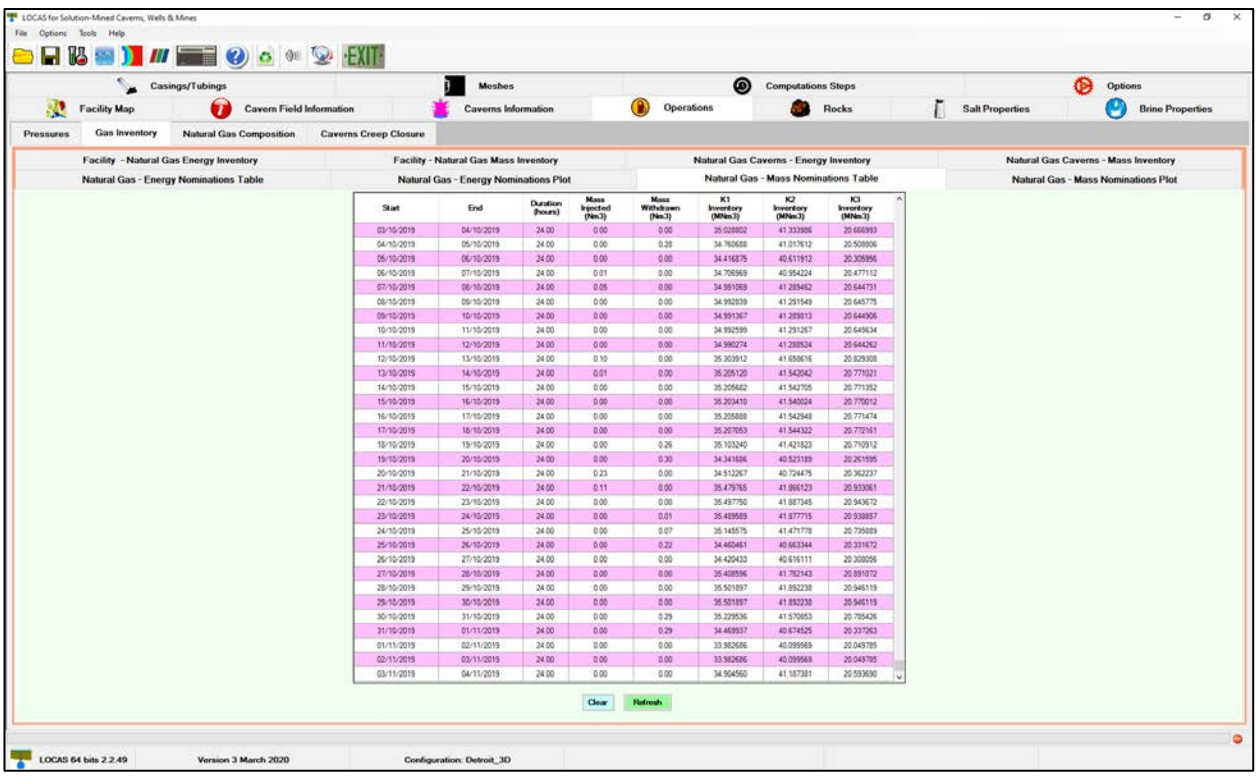

Figure 18 – Example of natural-gas daily nominations table.

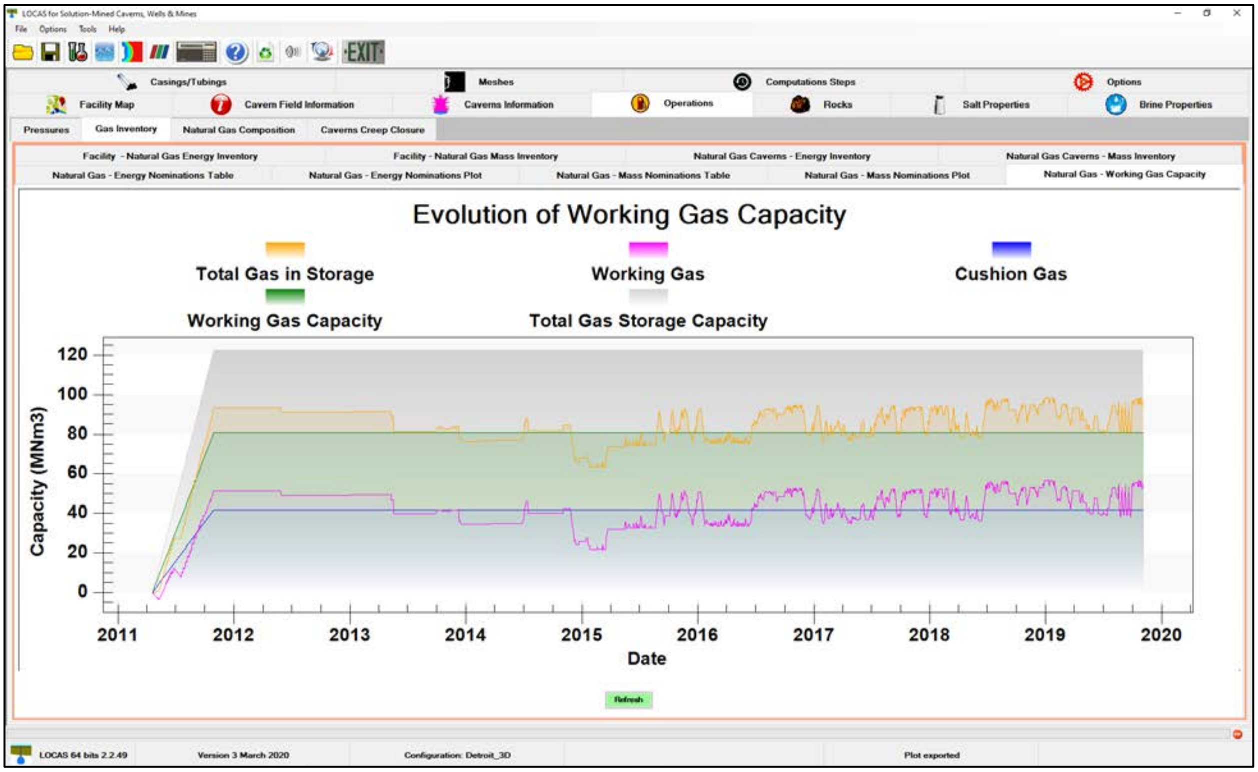

Figure 19 – Working gas capacity for the whole facility.

2.3 Stability criteria

When assessing the stability of gas caverns, three criteria must be examined (Bérest et al., 2012):

(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; and
(3) onset of salt dilation.

Loss of volume due to creep closure and subsidence must also be calculated.

2.3.1 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.

2.3.2 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 gas-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

$$\sigma_{\max} + P_c < T_{salt} \tag{2}$$

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 $T_{salt} = 0$ is conservative.

2.3.3 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),

$$\sqrt{J_2}_{\,dil} = -0.27 I_1 \tag{3}$$

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

$$\sqrt{J_2}_{\,dil} = \frac{D_1 \left(\dfrac{I_1}{sign(I_1)\sigma_0} \right)^{\bar{m}} + T_0}{\left(\sqrt{3}\cos\psi - D_2 \sin\psi \right)} \tag{4}$$

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

$$FOS = \sqrt{J_2}_{\,dil} \Big/ \sqrt{J_2} \tag{5}$$

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.

A tab in LOCAS is dedicated to the RD dilation criterion (Figure 20). Several sets of parameters can be saved in a database, this is especially helpful for sensitivity analysis.

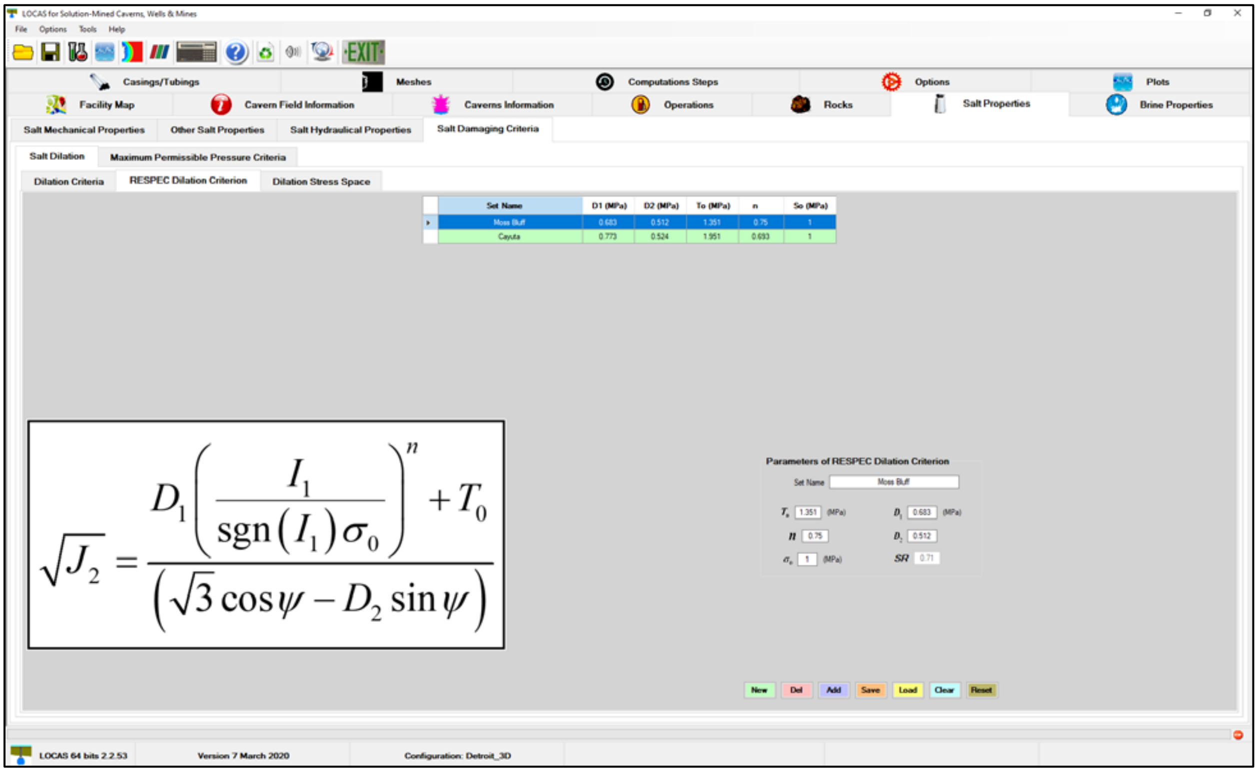

Figure 20 – Tab dedicated to RESPEC or RD dilation criterion.

2.4 Post-processing examples

The post-processing features are numerous in LOCAS and cannot all be presented in a short paper. Variables such as pressures, temperatures and volumes in the cavern can be plotted as a function of time. Note that brine and gas are considered as two different fluids with their own temperature. Variables such as stresses, rock temperature, rock pore pressure (in the case of liquid-filled caverns), or displacements can be plotted as contours or distributions, both in horizontal or vertical direction.

After a computation, a dedicated plot provides information about RAM usage, CPU usage, and also on computational speed (Figure 21). In this example, the duration of the computation was 22 hours. The average speed (orange line) is approximately 3 real days computed per minute. It means that, in the case of a restart computation from that state, LOCAS is able to predict in a very short period of time the evolution of the cavern field in the next days.

Figure 22 shows volume variation due to creep closure for hydrogen cavern K4. The considered monthly pressure cycling, at a moderate rate and with a rather high minimum pressure, equal to halmostatic pressure, does not produce a significant increase of creep closure compared to the former period, before 2017, when the cavern was only used for brine production.

Figure 23 gives an example of Factor-of-Safety contours in the vertical cross-section between natural-gas caverns K1 and K2 caverns at the end of computation (day 3593, 3 November 2019). It can be easily observed that there is no dilatant zone in the pillar ($FOS > 1$); any dilatant zone would be colored in magenta.

Figure 24 gives an example of a vertical distribution. The considered location is either selected though its GPS coordinates, or directly by clicking on the Google map. As for any contour plot (Figure 23), a time cursor allows to select the point in time when the variable must be plotted.

Figure 25 gives an example of effective-stress contours in a horizontal cross-section. Effective stress remains compressive anywhere in the considered section, including the cavern wall where onset of tensile effective can be a concern in a gas cavern (Brouard et al., 2007, 2011; Bérest et al., 2013).

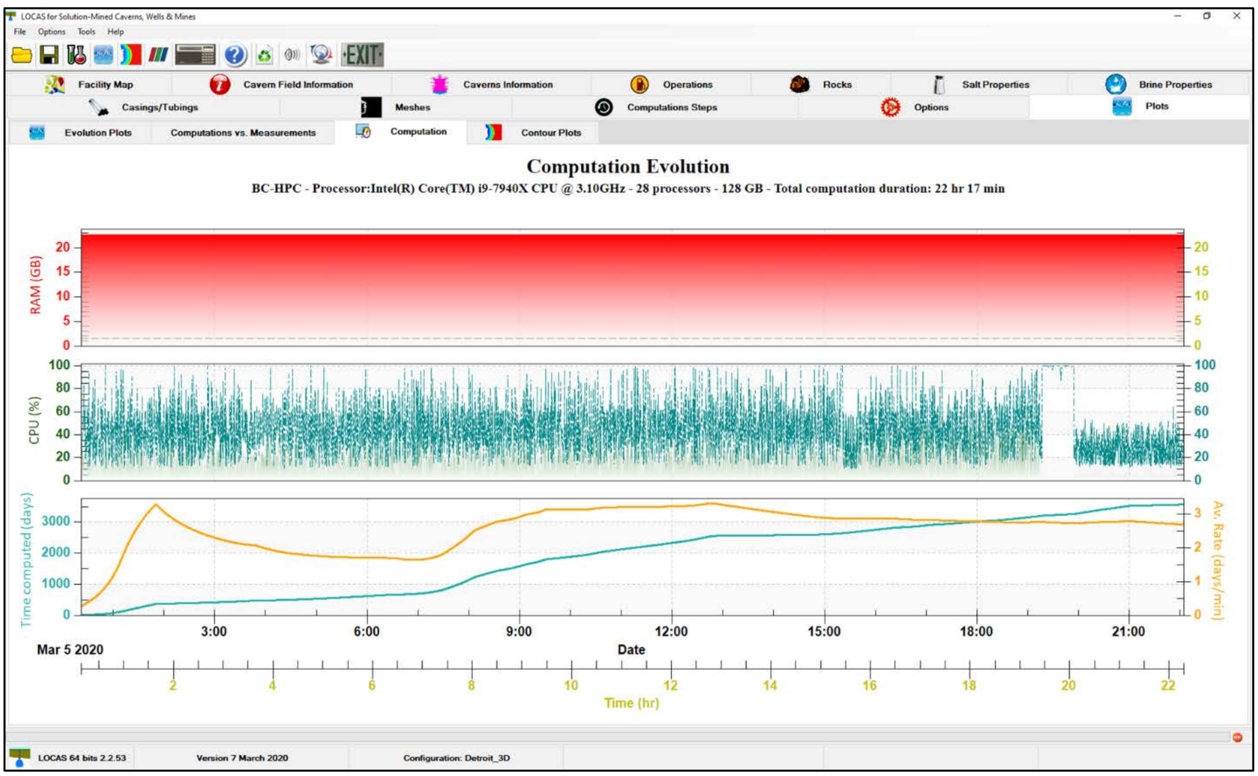

Figure 21 – Evolution of RAM, CPU usage and computational speed.

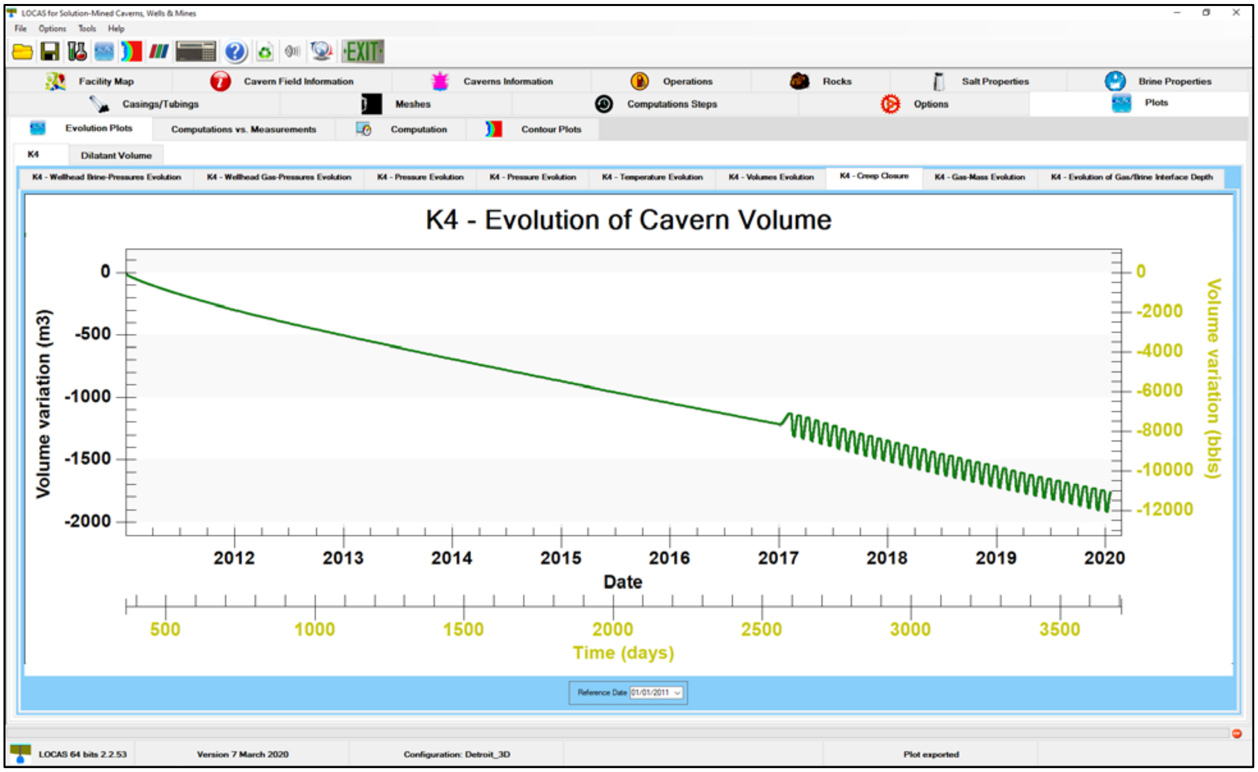

Figure 22 – Evolution of volume loss due to creep in hydrogen-filled cavern K4.

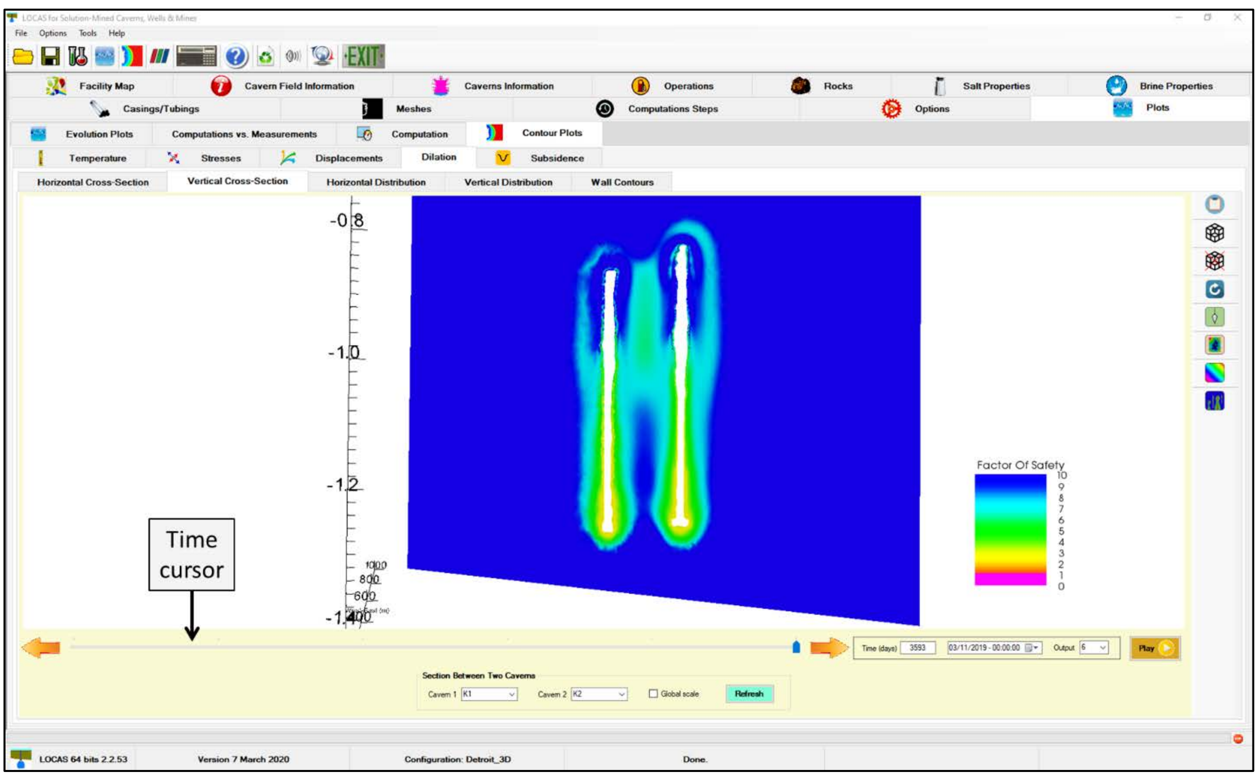

Figure 23 – Example of Factor-of-Safety contours in the vertical cross-section between natural-gas caverns K1 and K2.

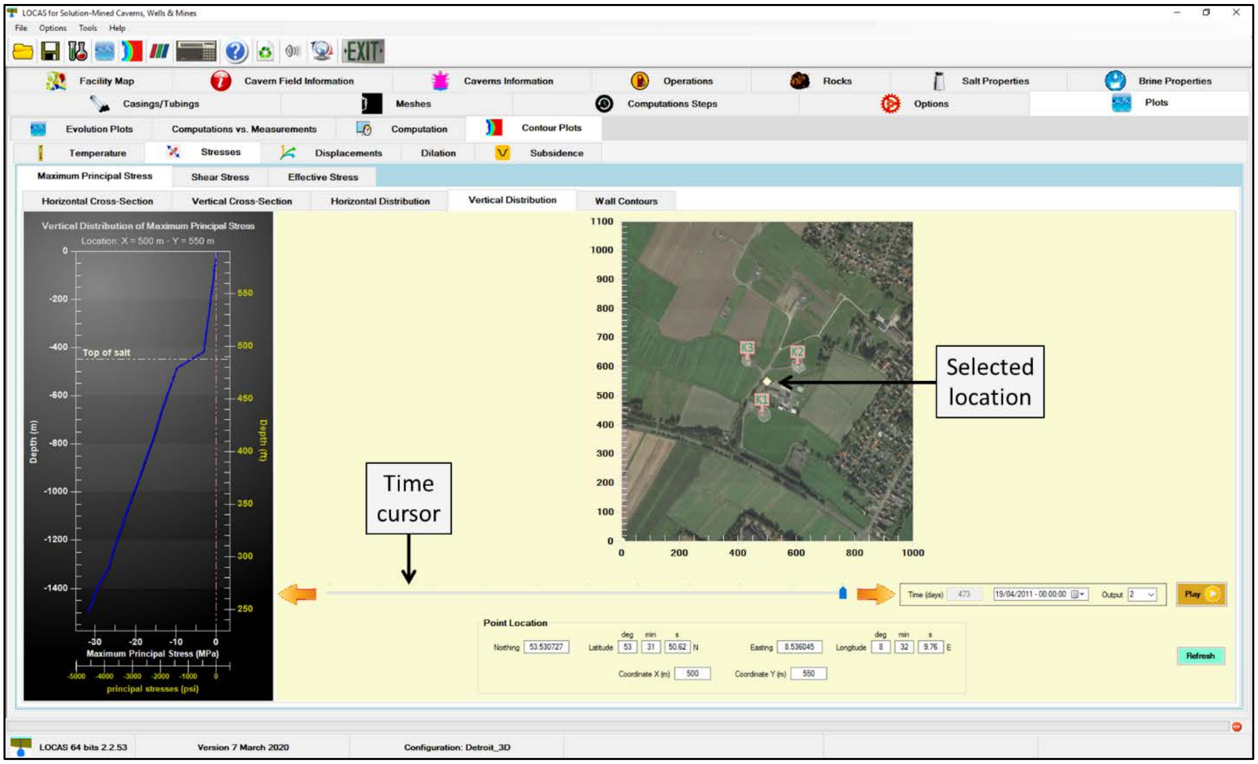

Figure 24 – Vertical distribution of maximum principal stress at a selected location.

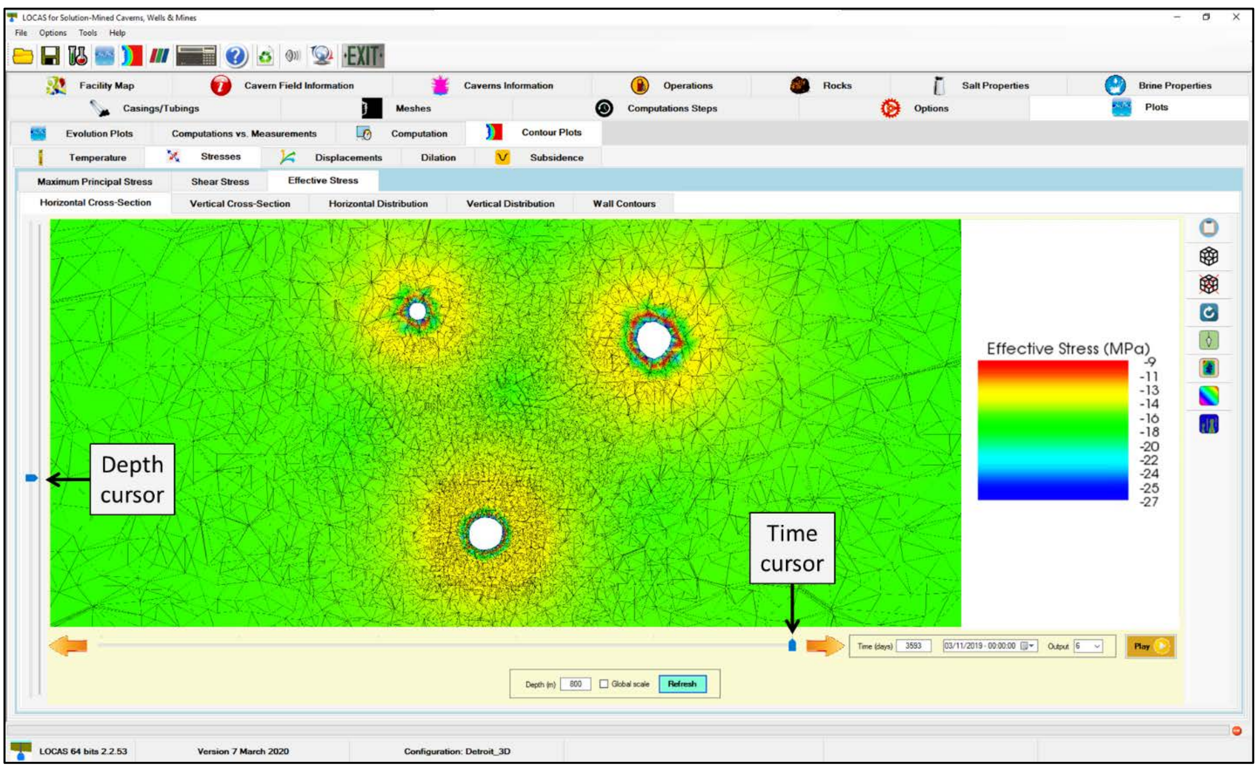

Figure 25 – Example of effective-stress contours in a horizontal section at a 800-m depth.

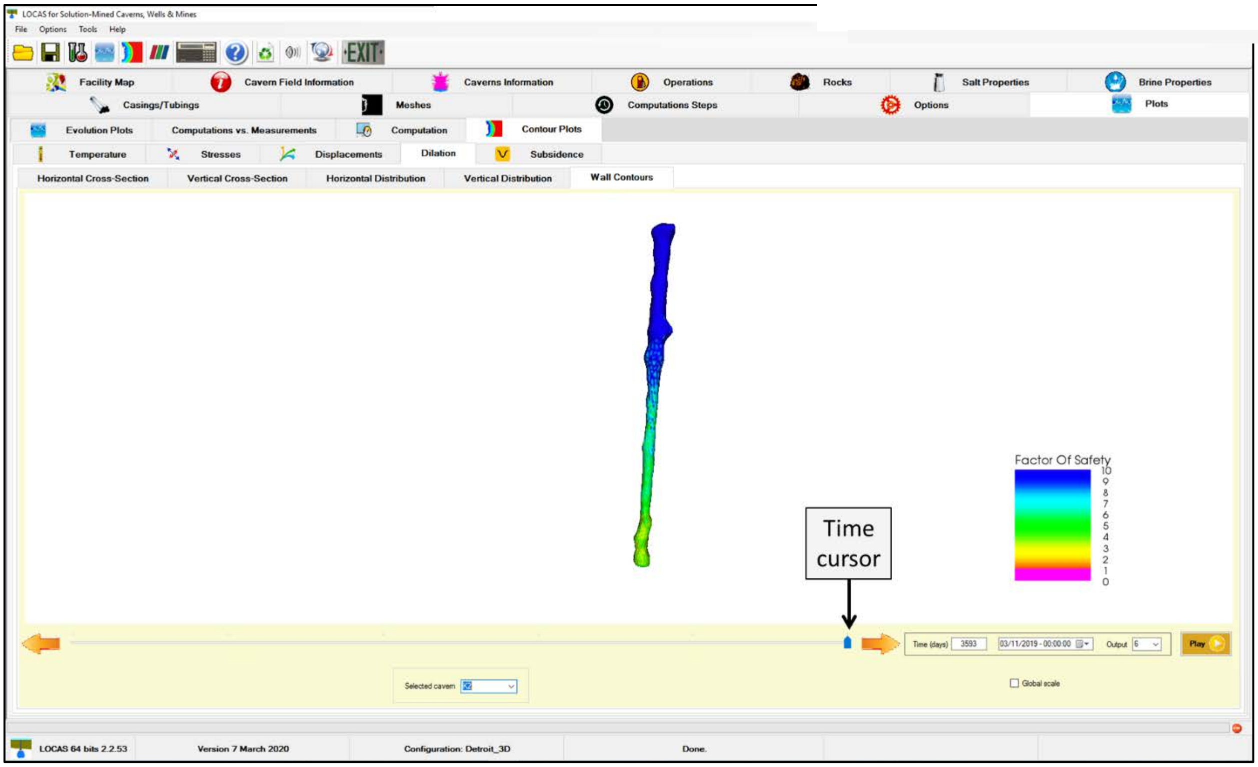

Figure 26 – Example of Factor-of-Safety contours on the K2 cavern wall.

3. Conclusions

LOCAS is a huge software suite that has been developed continuously for 20+ years, especially for the purpose of analyzing 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 gas-cavern stability or cavern abandonment analysis.

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

Thanks to its restart feature, LOCAS is able to predict, in a very short period of time, the evolution of a cavern field; in this way it can be used as a day-to-day tool for decision support.

LOCAS exists in both stand-alone and cloud versions.

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