Appendix A 2 - User manual Location Specific SHRA tooling (SRIMA)

Introduction

This document is a practical user manual for the Seismic Hazard and Risk Analysis (SHRA) part of the Seal and Reservoir Integrity through Mechanical Analysis (SRIMA) tool[1]. SRIMA covers the following elements of the SHRA:

1. Determining the potential for fault reactivation, or SCU (shear capacity utilization).
2. Calculating the largest credible magnitude (M_{LCE}) and PGV (PGV_{LCE}, peak ground velocity) of an unlikely seismic event.

This document does not describe the calculation methods or the equations behind it. The report 'Seismic Hazard and Risk Assessment for geothermal projects in the Netherlands', p. 62-72, gives a first order description of these methods. A detailed description of the SRIMA program and the analytical solutions and equations used is presented in the report 'SRIMA: Background information of the Python tool' (Fokker et al., 2023).

The next sections give a short description of the different tabs in the program and a very brief parameter listing. A complete parameter listing with description is given in Appendix I. Appendix II gives a listing of all the plots with calculation results available in the SRIMA program. Please note that parameter values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values.

Manual

Installation
The SRIMA tool can be downloaded from [SDRA & Integriteit afdichtend pakket | NLOG](). Download the zip file and unzip it. The package contains a folder called 'SRIMA', containing the program files. Double click on the 'SRIMA' application file in the 'SRIMA' folder to start the program.

Changing the size of the user interface
Due to the scaling of several visualizations in the tool, it is not possible to maximize or change the screen. The user interface will be scaled according to the screen size you are using. If you work with multiple screens, you can scale the tool to your preferred screen:
- Right-click on your desktop screen and go to Display settings.
- Select your preferred screen so it turns blue.
- Under 'Multiple displays', check the box 'Make this my main display'.
- Close and restart the app. It will open on your preferred screen and be scaled accordingly.

User interface
SRIMA contains two main windows (Figure 1):
1. The input window on the left. This window contains different tabs with parameter fields per category (*General, Geometry, Thermal & Flow, Mechanics, Operational* and *Seismicity*). The parameter fields are filled with default values upon opening the tool but need to be edited by the user.

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[1] This document does, for the time being, not describe parts of the SRIMA-tool related to seal integrity evaluation, as the processes to develop and approve the SHRA and Seal Integrity parts are with different (groups of) parties and have (had) different timelines. If and when both methodologies are final and approved, the user manuals for both aspects will be merged where relevant.

2. The results window on the right. This window contains different tabs:
    a. *Log:* a log which prints the status of calculations or other procedures.
    b. *Geometry input:* a simplified map showing the injection well, the projected mid reservoir location of the injection well and the fault.
    c. *Profiles input:* profiles for pressure and stress at the start of production, used for calculating profiles after a certain time of production.
    d. *Calculated input:* values of parameters calculated from input parameters, used for other calculations.
    e. *Profiles (available after running a calculation):* profiles for:
        i. Pressure and stress
        ii. Temperature.
    f. *Plots (available after running a calculation):* graphical representation of the calculation results, including SCU and largest credible magnitude and PGV. The plots are explained further in *Results window - Plots*.
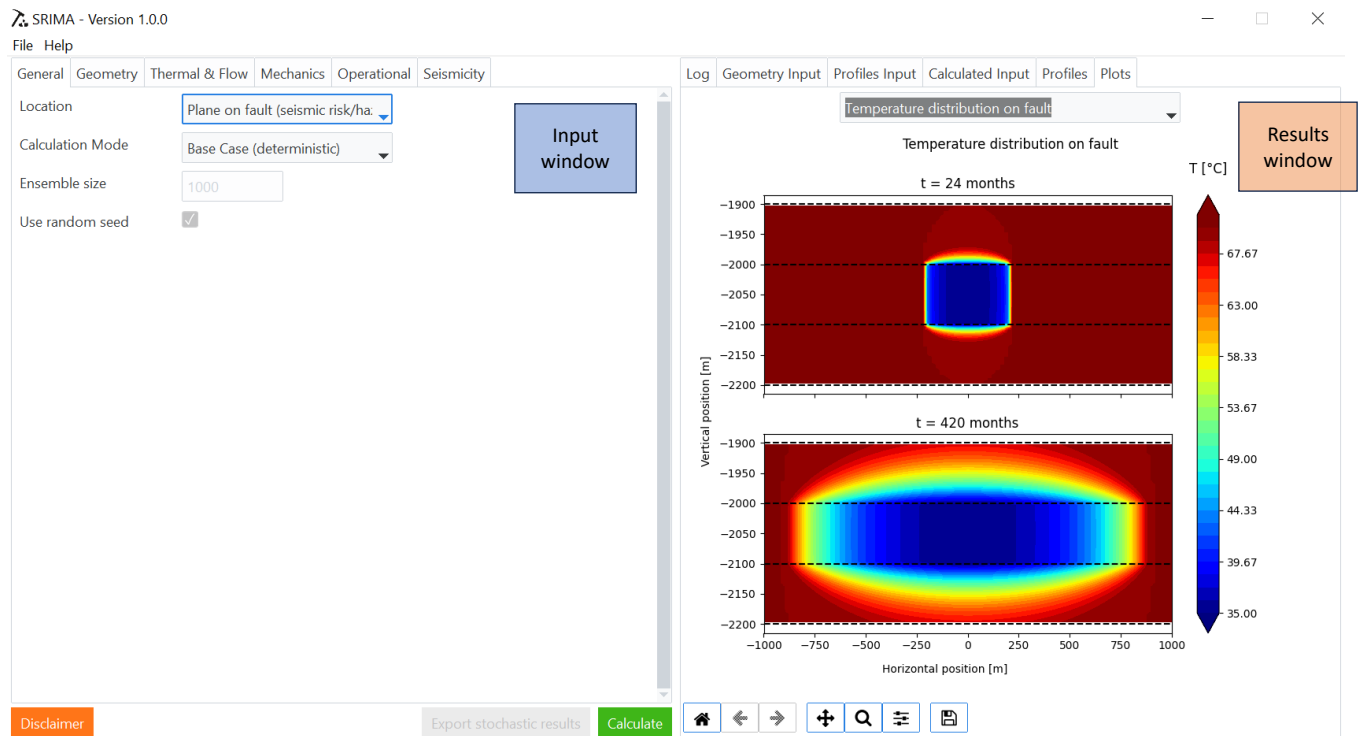

Figure 1: Overview of the SRIMA interface. The input window is displayed on the left, the results window on the right.

Input window
Input parameters can be edited in the parameter fields. Important things to note are:
- Units can be chosen in the drop-down menu.
- Indicate whether a parameter must be stochastically calculated by checking the box after the parameter name (indicated with the symbol ⟁). Enter most likely (indicated with *Value/Likely*), minimum and maximum values for given parameter. These values will be used when running a stochastic calculation (see *1. General – Calculation mode*) For a deterministic calculation, the most likely value will be used as the only parameter.

- The full list of input parameters, units and a description are given in *Appendix I: Input parameters.*

Under *File* (Figure 2), there are a couple of options for parameters:
- Reset: resets all the parameters to the default values.
- Toggle expert mode: this enables some extra options, such as the possibility to run the calculation on a horizontal line at mid reservoir and to view extra stress plots for a calculation run on a fault. These options are not necessary for SHRA purposes but might be of interest to expert users.
- Import configuration: import a project csv file with parameters into SRIMA. **Note**: when filling in the parameter fields for the first time, the easiest way to do this is within the tool and then export the values to a csv file. The file can then be imported into SRIMA at a later time.
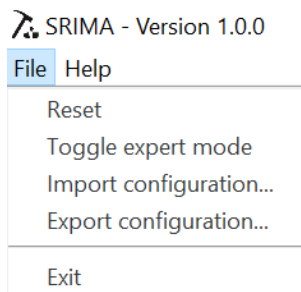- Export configuration: export a csv file with parameters as filled in within the tool.

Figure 2: Options under 'File'.

1. General

Upon opening, the SRIMA tool displays the input window on the first tab: *General* (Figure 3). Here, the user is able to indicate how the calculation should be run.

- Choose *Location* in the drop-down menu.
  - *Plane on fault (seismic risk/hazard)*: this option is used for SHRA purposes.
  - *Vertical line at injection well (seal integrity).* **Note**: this option is for calculating seal integrity and will not be discussed in this manual.
- Choose *Calculation mode* in the drop-down menu.
  - *Base Case (deterministic)*: this calculation mode will use the most likely value given for parameters (the value under *Value/Likely*).
  - *Uncertainty (stochastic)*: this calculation mode will use a range of parameters (the values under *Value/Likely, Minimum* and *Maximum*). This calculation will take longer than a deterministic calculation (a deterministic calculation will take a couple of seconds whereas a stochastic calculation with 500 runs will take around 5 minutes).
  - *Sensitivity (tornado diagram)*: this calculation mode will produce a sensitivity plot, which indicates the influence of all parameters on the final result of the largest credible magnitude (at a certain time after production).
- *Ensemble size*: fill in the number of stochastic runs for a calculation. In order to achieve adequate results, use a minimum of 500 stochastic runs.
- *Use random seed*: check this box to run a stochastic calculation with a random seed number. Uncheck the box to give a seed number that ensures the same output for successive runs using the same parameter set.

Tip: a stochastic calculation takes longer than a deterministic calculation. In order to check that your parameters are correct, and the results are satisfactory, first run a deterministic calculation or a stochastic calculation with fewer runs (e.g., 10 iterations). When satisfied with the parameters and results, run a stochastic calculation with more iterations.

Figure 3: Input parameters under 'General' tab.

2. Geometry

The *Geometry* tab contains input parameters that define the location of the geothermal well and fault, well diameter, information on the reservoir and seal depth and thickness and the reservoir radius (Figure 4). The description of all parameters is given in Appendix I.

After filling in these parameters, the well and fault geometry can be checked in the *Geometry Input* tab in the results window (see *Results window – Geometry Input*). Click on *Refresh* to display the geometry with new parameters.

Parameter name	Unit	Value/Likely	Minimum	Maximum	⋀
Injection well x-coordinate	m	0			
Injection well y-coordinate	m	0			
Thickness seal	m	100	80	120	☐
Thickness reservoir	m	100	50	150	☑
Thickness base	m	100	80	120	☐
Net to gross reservoir	-	0.7	0.6	0.8	☑
Top depth reservoir	m	2000			
Well diameter	in	8.5			
Reservoir radius	m	1500			
Fault dip	deg	60	50	70	☐
Fault dip direction	deg	40	30	50	☐
Fault center x-coordinate	m	0	-50	50	☐
Fault center y-coordinate	m	0	-50	50	☐
Fault length along strike	m	2000	1500	2500	☐
Fault cell size along strike	m	20			
Fault cell size along dip	m	5			

Figure 4: Input parameters under 'Geometry' tab (note that values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).

3. Thermal & Flow

This tab contains parameters that are needed for the calculation of the cooled area formed by the progressive injection of water (Figure 5). Properties including *pore pressure gradient, permeability, total porosity, bulk density, specific heat capacity of the rock* and *thermal conductivity* are hidden behind buttons. Click the button to unfold the parameter fields. The pressure gradient can be entered separately for seal, reservoir and base, or one gradient can be used for all layers. Rock properties should be entered separately for each layer. The *Pore pressure top reservoir* is the anticipated reservoir pressure at top reservoir and subsequently serves as the anchor point for the pore pressure gradient (Figure 6).

For the property *fluid salinity* and related parameters, it is possible to check the box *Use empirical fluid properties*. In this case, only *fluid salinity* should be entered and the parameters below (*reservoir fluid viscosity, fluid heat capacity, injection viscosity* and *injection density*) are calculated from the fluid salinity. The calculated values are displayed in the *Calculated input* tab in the results window (Figure 7). Click on *Refresh* to display the calculated values with new parameters. When the box is unchecked, the user is able to fill in these parameters themselves. This can be done when the user feels that specific parameter values are available for their project.

Figure 5: Input parameters under 'Thermal & Flow' tab (values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).
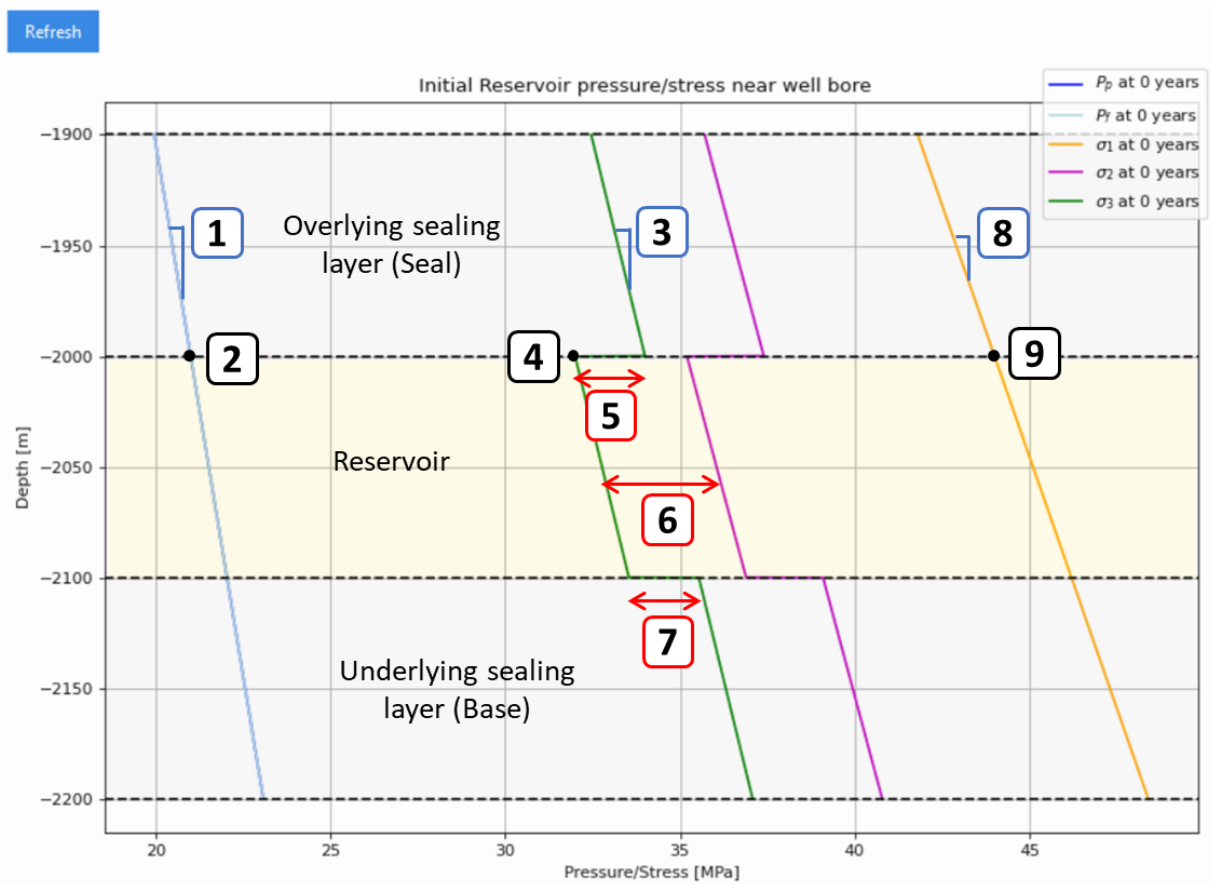
Figure 6: Example of the plot in the Profiles Input tab. By hovering your cursor over the curves, the value is displayed in the lower right of the screen. 1) Increase in pore pressure (P_p) with depth (parameter: Pore pressure gradient). 2) Pore pressure (P_p) at the top of the reservoir (parameter: Pore pressure top reservoir). 3) Increase in minimum horizontal stress (σ_3) with depth (parameter: Min horizontal stress gradient). 4) Minimum horizontal stress (σ_3) at the top of the reservoir (parameter: Min. horizontal stress top reservoir). 5) Stress contrast as observed from the overlying sealing layer into the reservoir, which can offset the minimum horizontal stress gradient (parameter: Stress contrast seal to reservoir). 6) Difference between the minimum (σ_3) and maximum horizontal stress (σ_2), which is constant with depth (parameter: Max. hor. / min. hor. stress ratio). 7) Stress contrast as observed from the reservoir into the underlying sealing layer, which can offset the minimum horizontal stress gradient (parameter: Stress contrast reservoir to base). 8) Increase in vertical stress (σ_1) with depth (parameter: Vertical stress gradient). 9) Vertical stress (σ_1) at the top of the reservoir (parameter: Vertical stress top reservoir).

Log | Geometry Input | Profiles Input | Calculated Input | Profiles | Plots

Refresh

Well radius: 4.25 in

Mid reservoir depth: -2050.0 m

Top reservoir pressure: 21.0246 MPa

Injection density: 1.1490e+03 kg/m3

Injection viscosity: 1.0342e-03 Pa.s

Reservoir fluid viscosity: 1.5204e-04 Pa.s

Reservoir fluid heat capacity: 4.8305e+03 J/kg/K

Thermoelastic stress constant seal: 2.1538e+05 Pa/K

Thermoelastic stress constant reservoir: 1.6000e+05 Pa/K

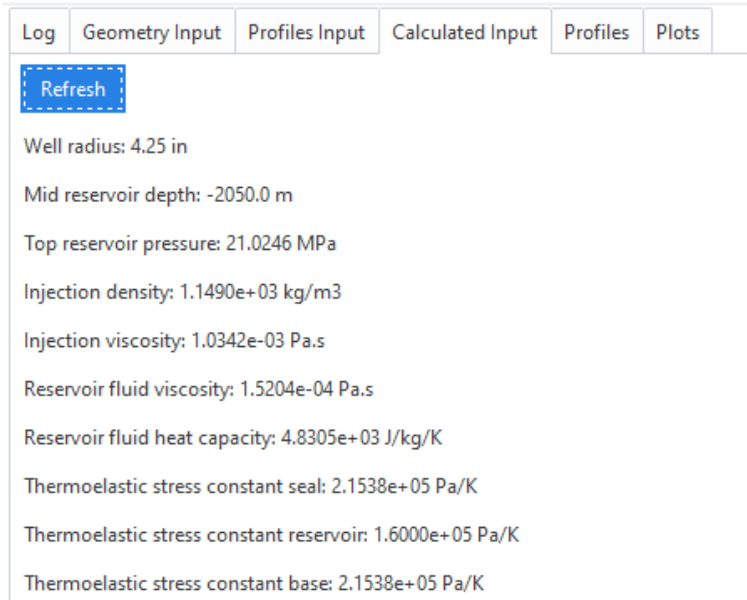Thermoelastic stress constant base: 2.1538e+05 Pa/K

Figure 7: Calculated input values (note that values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).

4. Mechanics

This tab contains geomechanical parameters that are needed for the calculation of the stress field and the change in stresses (Figure 8). The vertical stress and minimum horizontal stress gradient, and maximum horizontal stress azimuth can be entered separately for seal, reservoir and base, or one gradient can be used for all layers. Geomechanical properties should be entered separately for each layer. Geomechanical properties include max horizontal stress azimuth, Young's modulus, Poisson's ratio, Biot constant and linear thermal expansion coefficient are hidden behind buttons. Click the button to unfold the parameter fields.

The *Min. horizontal stress top reservoir* and the *Vertical stress top reservoir* are the anticipated subsurface stress state of top reservoir and subsequently serve as the anchor points for the minimum horizontal stress gradient and vertical stress gradient. The initial stress situation as given by the input is visualised in the tab *Profiles input* showing the anticipated pressures and stresses at the near injection wellbore location (Figure 6).

Figure 8: Input parameters under 'Mechanics' tab (note that values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).

5. *Operational*

This tab contains operational parameters (Figure 9). The parameters are divided into three sections:

1. Injection rate, injection temperature, skin factor and time steps (after start of production) used to show the result of the calculation.
2. Shear failure stochastic thresholds. Fill in the shear capacity cut-off and peak ground velocity according to the requirements in the SHRA methodology (e.g., shear capacity cut-off = 1, peak ground velocity = 3 mm/s).
3. Seal and base integrity norm. These values are not used for calculating seal integrity and will not be discussed in this manual. The values can be left as is.

Parameter name	Unit		Value/Likely	Minimum	Maximum	
Average injection rate	m3/hr	▾	300			
Maximum injection rate	m3/hr	▾	400			
Injection temperature	C	▾	35			
Skin factor	-	▾	0.0			
Time steps (comma sep.)	yr	▾	2, 35			
Shear failure stochastic thresholds						
Shear capacity cutoff	-	▾	1			
Peak ground velocity	mm/s	▾	3			
Seal and Base integrity norm						
Minimum intact layer thickness	m	▾	30			
Minimum intact layer share	%	▾	50			
Safe realizations share	%	▾	95			

Figure 9: Input parameters under 'Operational' tab (note that values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).

6. *Seismicity*

This tab contains seismicity related parameters that are used to determine the shear capacity utilization and magnitude and PGV for the largest credible earthquake (Figure 10).

The user can define how the calculation is done in two ways:
- Choose how the critical fault area is calculated
    - Based on shear capacity, SCU > threshold. This means the critical fault area is calculated based on the area where the shear capacity utilization is higher than the threshold defined under the tab *Operational*.
    - Based on temperature change, dT > 0.5°C. The critical fault area is calculated based on the area where the change in temperature is more than 0.5°C.
- Choose how the stress drop is defined
    - User defined: the user can define the stress drop in the designated parameter field.
    - Calculate from stresses: the parameter field for stress drop is greyed out and will be calculated from the parameters under the tab *Mechanics*.

Note: for a user defined stress drop, do not enter a value that is higher than 5 MPa. This is the value used for magnitude calculations in small gas fields[2] and should not be higher for geothermal operations. The stress drop calculated from stresses will never be higher than 5 MPa.

General	Geometry	Thermal & Flow	Mechanics	Operational	Seismicity			
Parameter name		Unit		Value/Likely		Minimum	Maximum	⋀
Mohr-Coulomb friction		-	▾	0.6		0.5	0.7	☑
Mohr-Coulomb cohesion		MPa	▾	0		0	2	☐
Residual friction		-	▾	0.3		0.3	0.3	☐
Stress drop		MPa	▾	1.7		0.1	4	☑
Critical fault area mode		Based on shear capacity, SCU > threshold	▾					
Stress drop mode		User defined	▾					

Figure 10: Input parameters under 'Seismicity' tab (note that values shown in the figures of this user manual should be considered random example values and neither these, nor the default values in the tool should be taken as recommended values).

7. *Run the calculation*
After having filled in all parameters, click the green *Calculate* button at the bottom right corner of the input window to start the calculation.

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[2] Staatstoezicht op de Mijnen – Methodiek voor risicoanalyse omtrent geïnduceerde bevingen door gaswinning.

Results window

1. Log

The status of calculations is displayed here. Also, if there is an error in the imported csv, it will be displayed here.

2. Geometry Input

The mid-reservoir position of the injection well and fault geometry as defined in the input tab *Geometry* is displayed here (Figure 11). Click *Refresh* to update the figure if new input parameters are entered.

- The position of the injection well is indicated with a blue marker.
- The closest point on the fault (at mid reservoir) relative to the injection well is indicated with a black marker.
- The fault center at mid reservoir is indicated with a green marker.
- The fault plane is indicated with three lines: yellow for the position of the fault at top seal, black for the position of the fault at mid reservoir and red for the position of the fault at bottom base.
- The perpendicular distance between the injection well and the projected mid reservoir location of the injection well is indicated with a thin black dotted line.
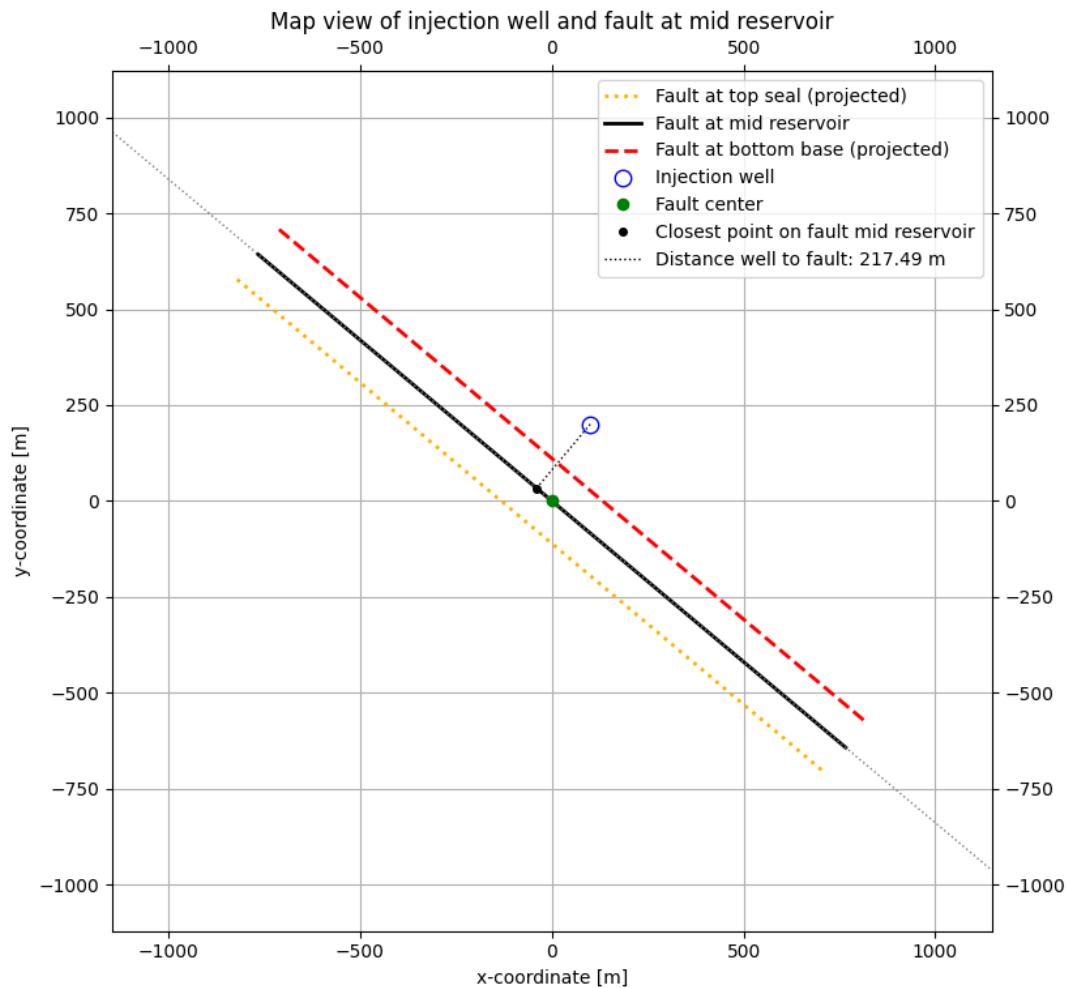

Figure 11: Top view of well and fault geometry (example).

3. Profiles input

Profiles for pressure and stress at the start of production are displayed here. These are created based on the input parameter values and can be used to view the initial stress profiles. The initial profiles are used for calculating profiles after a certain time of production.

4. Calculated input

Parameters calculated from certain input values are displayed here. These values are used in calculations the result of which are finally displayed in the plots.

5. Profiles

Several profiles are calculated and displayed here. Note that these are calculated based only on the most likely parameter values, and do not take into account stochastic parameters.

- Pressure and stress profiles:
  - Pressure (Figure 12)
    - Pp is the pore pressure in the reservoir. At t=0 it will be the virgin pressure, at t>0 the virgin pressure plus the calculated injection pressure.
    - Pf is the same as Pp in the reservoir but also extended into the seal where it would occur if an open fracture would be present.
  - σ_v (σ_1) is the vertical stress gradient at t=0 or the changed gradient as consequence of the geothermal operation at t>0.
  - σ_{hmax} (σ_2) is the maximum horizontal stress gradient at t=0 or the changed gradient as consequence of the geothermal operation at t>0.
  - σ_{hmin} (σ_3) is the minimum horizontal stress gradient at t=0 or the changed gradient as consequence of the geothermal operation at t>0.
- Temperature profile (Figure 13): gives the temperature gradient over the studied interval at t=0 or the changed gradient profile as consequence of the geothermal operation at t>0.

Click on the blue button *Figure pop-out* to open the visualization in a separate window. By hovering your cursor over the Profiles visualizations, the x/y values of the plot can be viewed at the bottom right corner of the visualization.
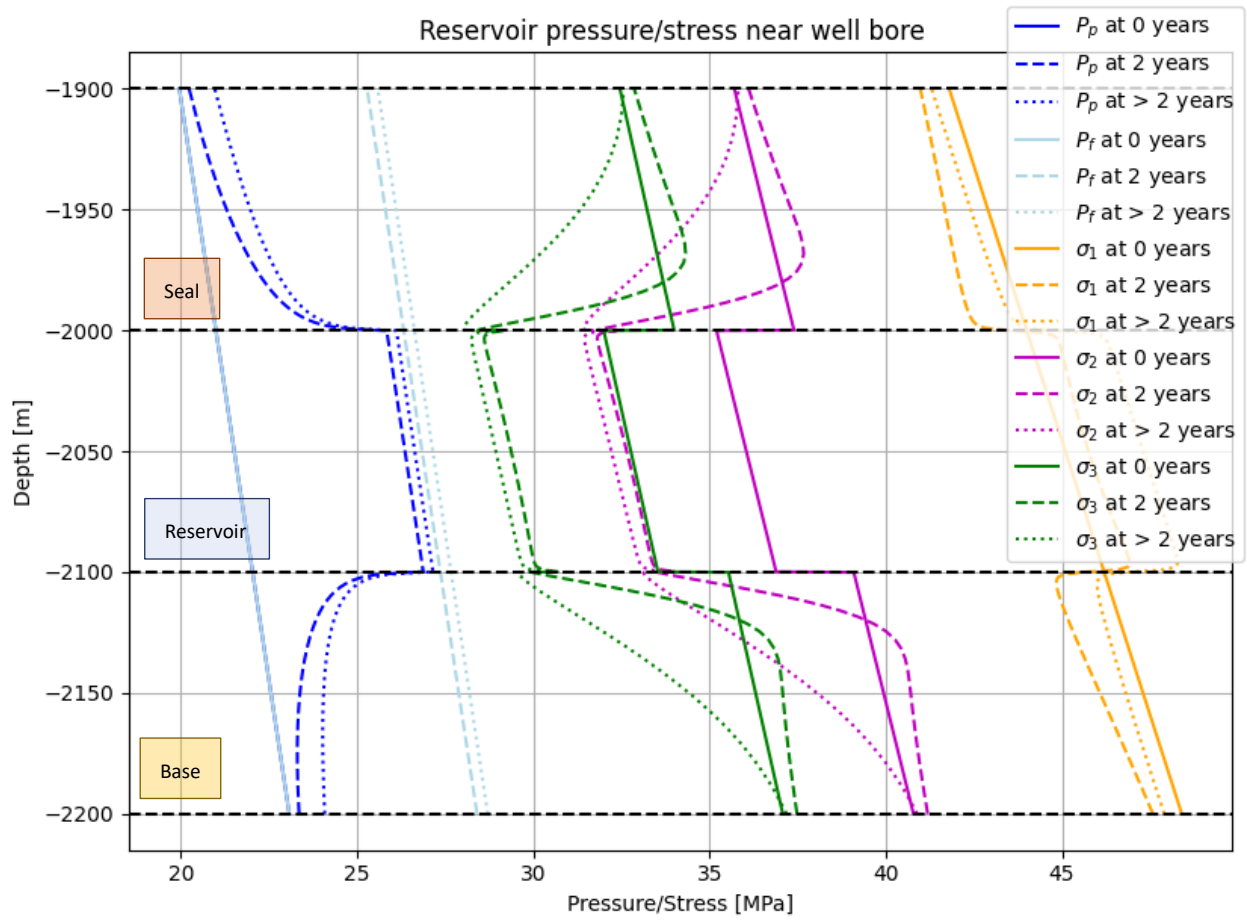
Figure 12: Pressures and stress profile (example, calculated at the start of operation and after 2 and 35 years). The black dotted lines indicate the boundary between seal, reservoir and base.
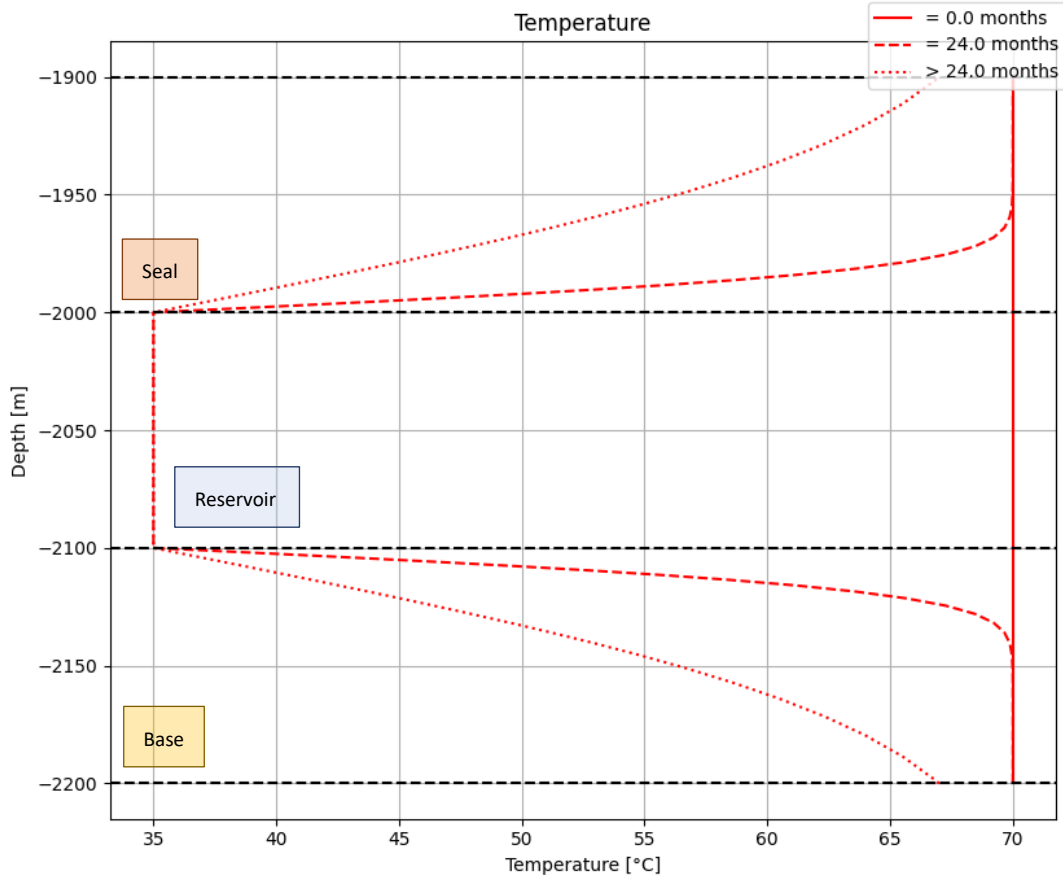
Figure 13: Temperature profile (example calculated at the start of operation and after 2 and 35 years). The black dotted lines indicate the boundary between seal, reservoir and base.

6. Plots

Plots can be displayed for different calculation modes chosen in the tab *General*: Base case, Uncertainty and Sensitivity. The full list of possible plots is given in *Appendix II: Plots*.

6.1 Base case (deterministic calculation)

To check whether the parameters and results are satisfactory, it is recommended to run a deterministic calculation before running a stochastic calculation (the run time is shorter than that of a stochastic calculation). In order to generate these results, choose *Base Case (deterministic)* for *Calculation mode* in the *General* tab.

After running the calculation, go to the *Plots* tab in the results window to view the results:

1. Cold front propagation
2. Temperature distribution on fault
3. Pressure increase on fault
4. Pressure on fault
5. Normal stress on fault
6. Shear stress on fault
7. Shear capacity on fault

These plots display the change of several parameters over time. An example for temperature distribution is given in Figure 14.
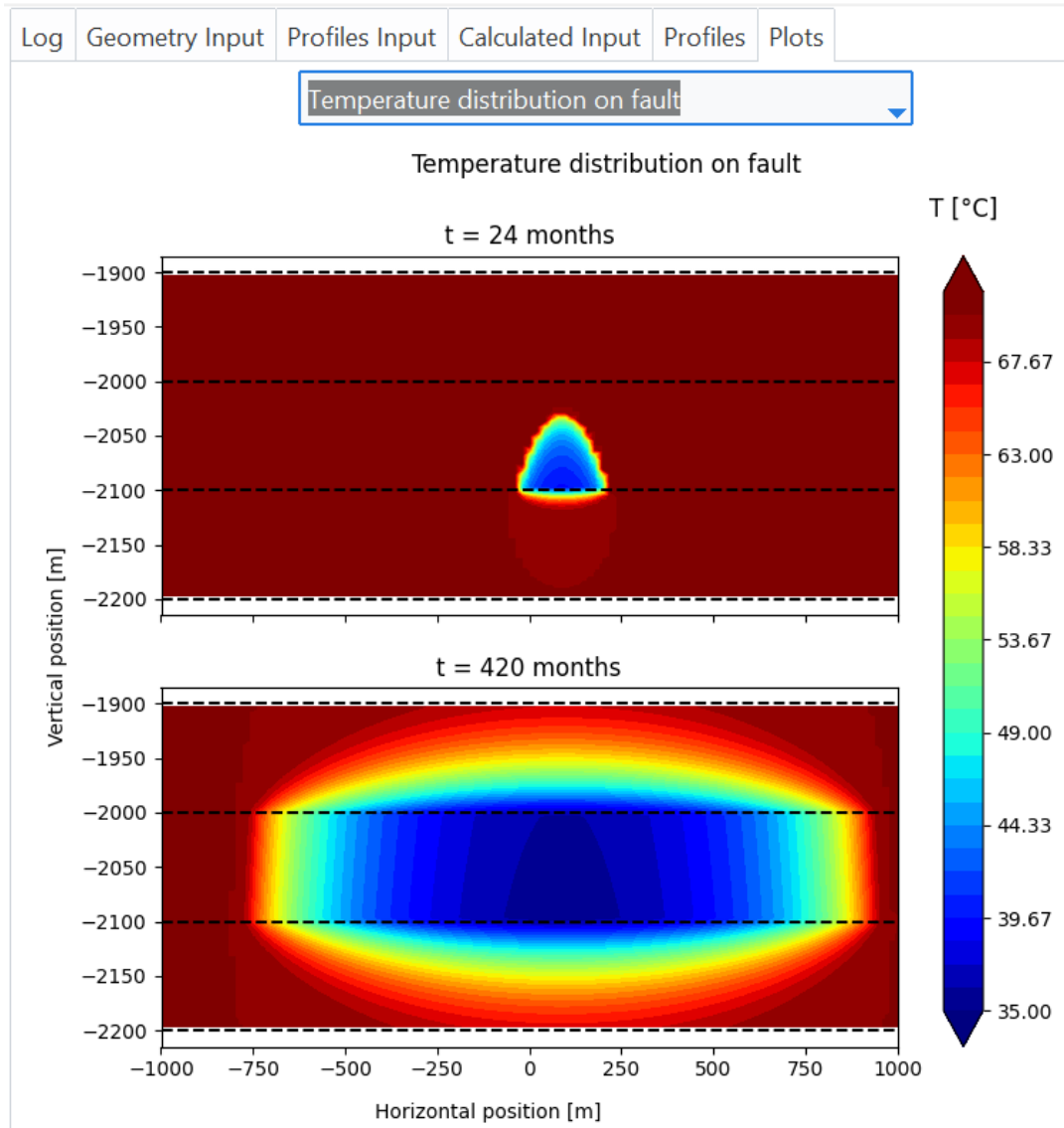
Figure 14: Temperature distribution across the fault plane for 2 and 35 years after operation (example).

Click on the blue button *Figure pop-out* to open the visualization in a separate window. By hovering your cursor over the Plots visualizations, the x/y values of the plot can be viewed at the bottom right corner of the visualization.

6.2 Uncertainty (stochastic calculation)
For SHRA purposes the following plots should be generated:

1. The potential for fault reactivation, or SCU (shear capacity utilization).
2. Largest credible magnitude and PGV (peak ground velocity).

In order to generate these results, choose *Uncertainty (stochastic)* for *Calculation mode* in the *General* tab.

After running the calculation, go to the *Plots* tab in the results window to view the results:

1. *Largest credible earthquake* shows the M_{LCE} at the selected time steps (Figure 15). An overview is displayed in the lower left corner of the graph for the P10, P50, P90 and P_{mean} values of the last time step.
2. *Stress drop* shows the stress drop on the fault at the last time step (Figure 16). An overview is displayed in the lower left corner of the graph for the P10, P50, P90 and P_{mean} values of the last time step.
3. *PGV at epicenter* shows the largest credible PGV value at the epicenter of the seismic event at the selected time steps (Figure 17). An overview is displayed in the lower left corner of the graph for the P10, P50, P90 and P_{mean} values of the last time step.
4. *P(PGV > x mm/s) at epicentral distance* shows the probability of exceedance of the largest credible PGV, larger than x mm/s, at a certain distance from the epicenter. The value for x can be entered in the *Operational* tab: '*Peak ground velocity*'. The epicentral distance indicates where a PGV of x mm/s would occur as a consequence of the largest credible magnitude at the hypocentre (Figure 18).
An overview is displayed in the lower left corner of the graph for the P10, P50, P90 and P_{mean} values at the last time step. Also, the average percentage of damaged buildings (built before and after 1940) is displayed here. These percentages are required to calculate the damage claim provision (see the report 'Seismic Hazard and Risk Assessment for geothermal projects in the Netherlands', p. 77-79).
5. *Shear capacity* shows in how many iterations there is a potential for fault reactivation. This is given in percentages where SCU < 1 (no fault reactivation possible) or where SCU ≥ 1 (fault reactivation possible) (Figure 19).

Click on the blue button *Figure pop-out* to open the visualization in a separate window. By hovering your cursor over the Plots visualizations, the x/y values of the plot can be viewed at the bottom right corner of the visualization.

Note: it is possible that one or more of the probability values (P10, P50, P90, P_{mean}) for magnitude, stress drop or PGV will read 'no occurrence'. For P90, this means that in 90% of the calculations, an earthquake will not occur.
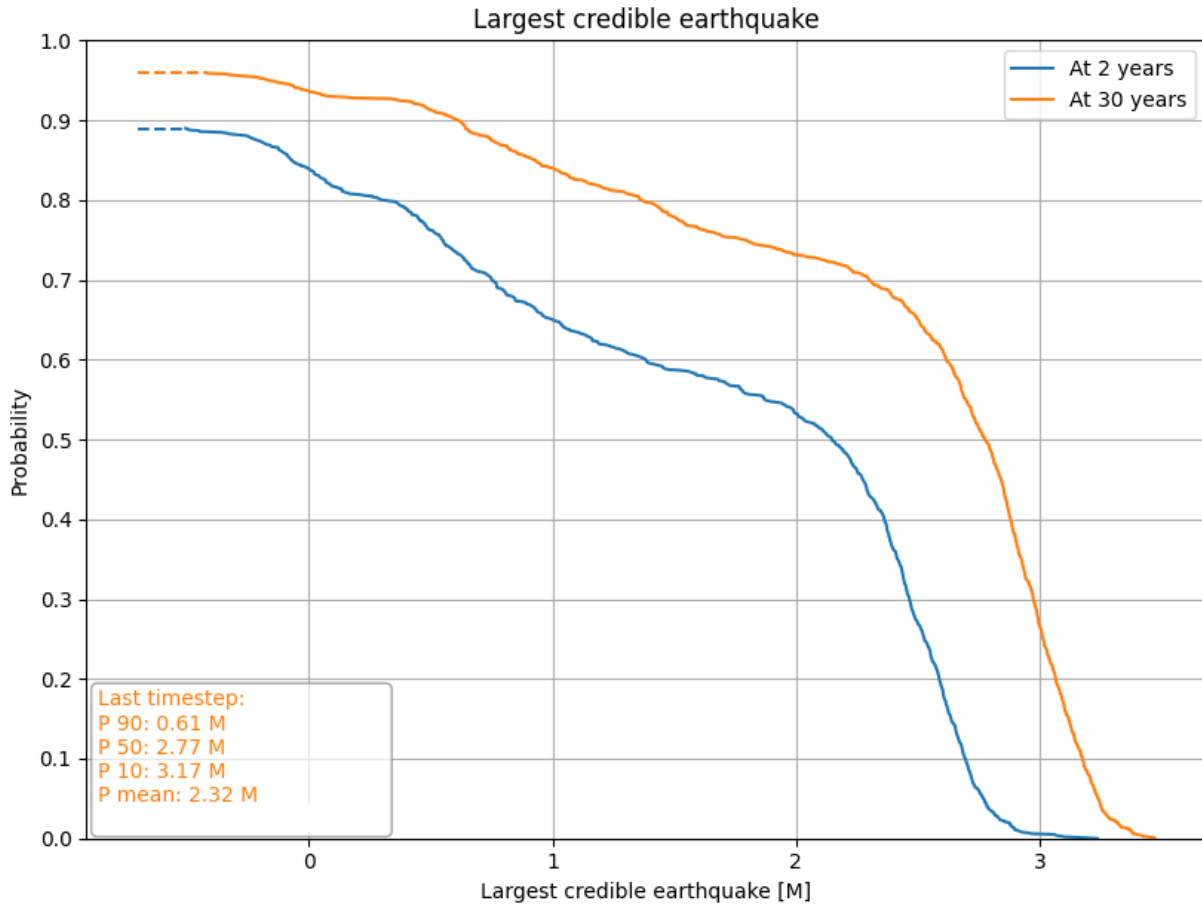
Figure 15: Magnitude for the largest credible earthquake, for selected time steps (example calculated for 2 and 35 years after start of operation). P10, P50, P90 and P$_{mean}$ for the largest credible magnitude at the last time step are displayed at the bottom left corner.
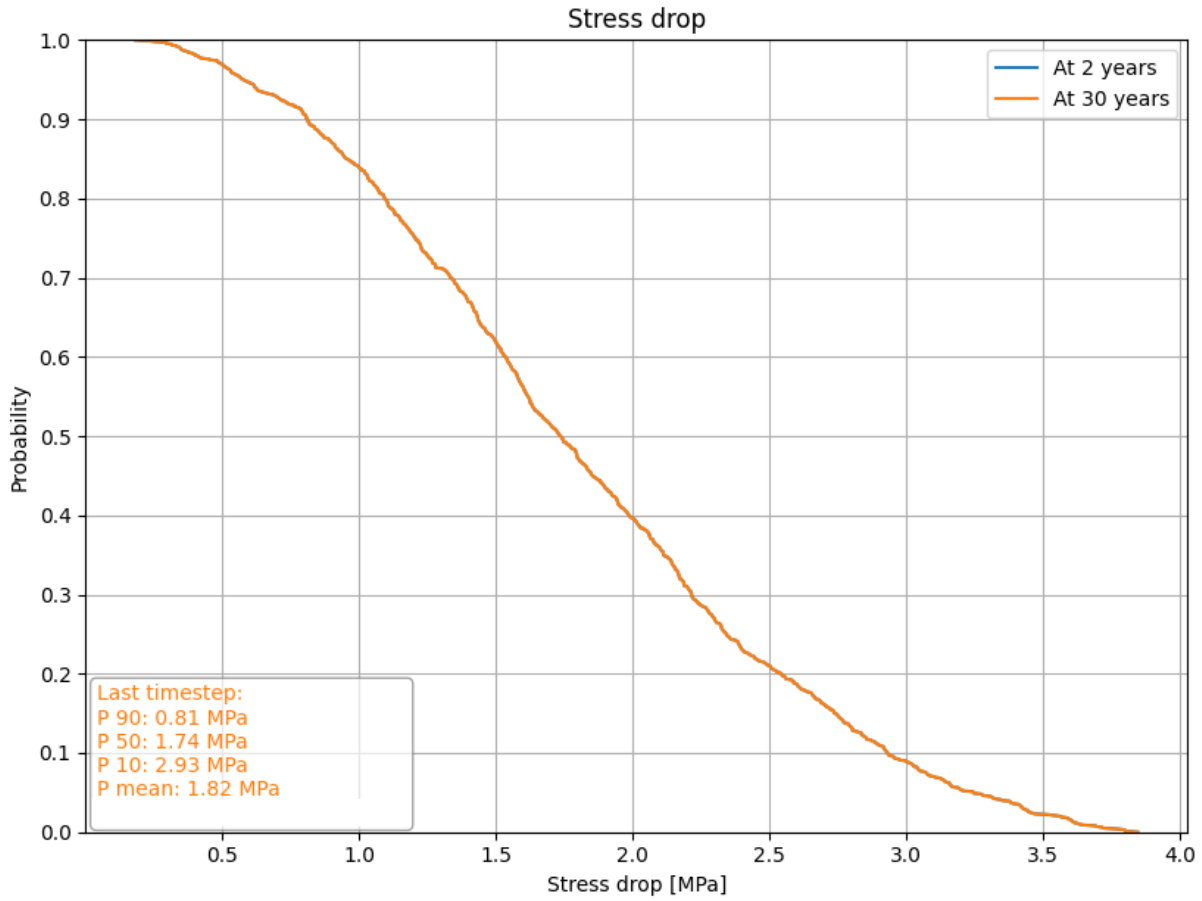
Figure 16: Stress drop on the fault at the last time step. P10, P50, P90 and P_{mean} values for the stress drop at the last time step are displayed at the bottom left corner.
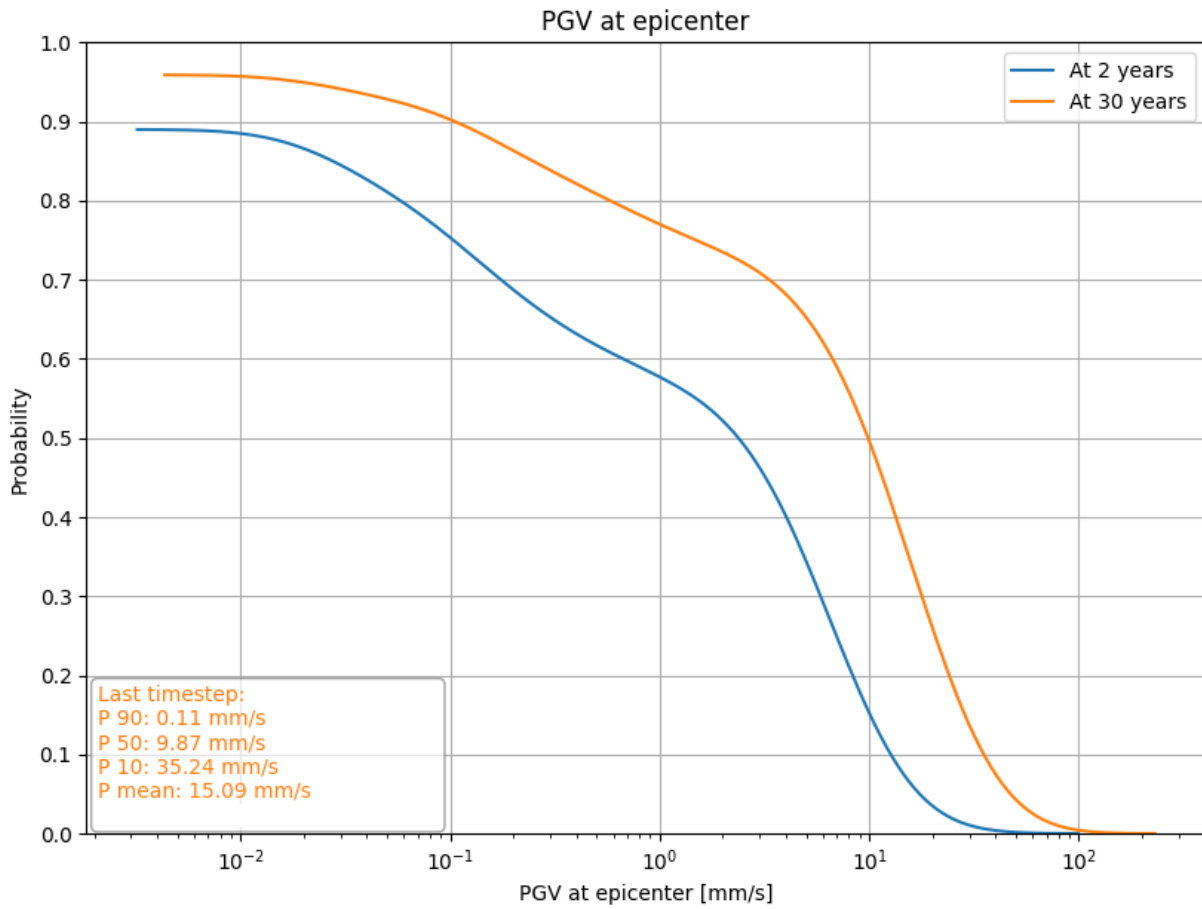
Figure 17: PGV at the epicenter of the seismic event for selected time steps (example calculated for 2 and 35 years after start of operation). P10, P50, P90 and P$_{mean}$ values for PGV at the last time step are displayed at the bottom left corner.
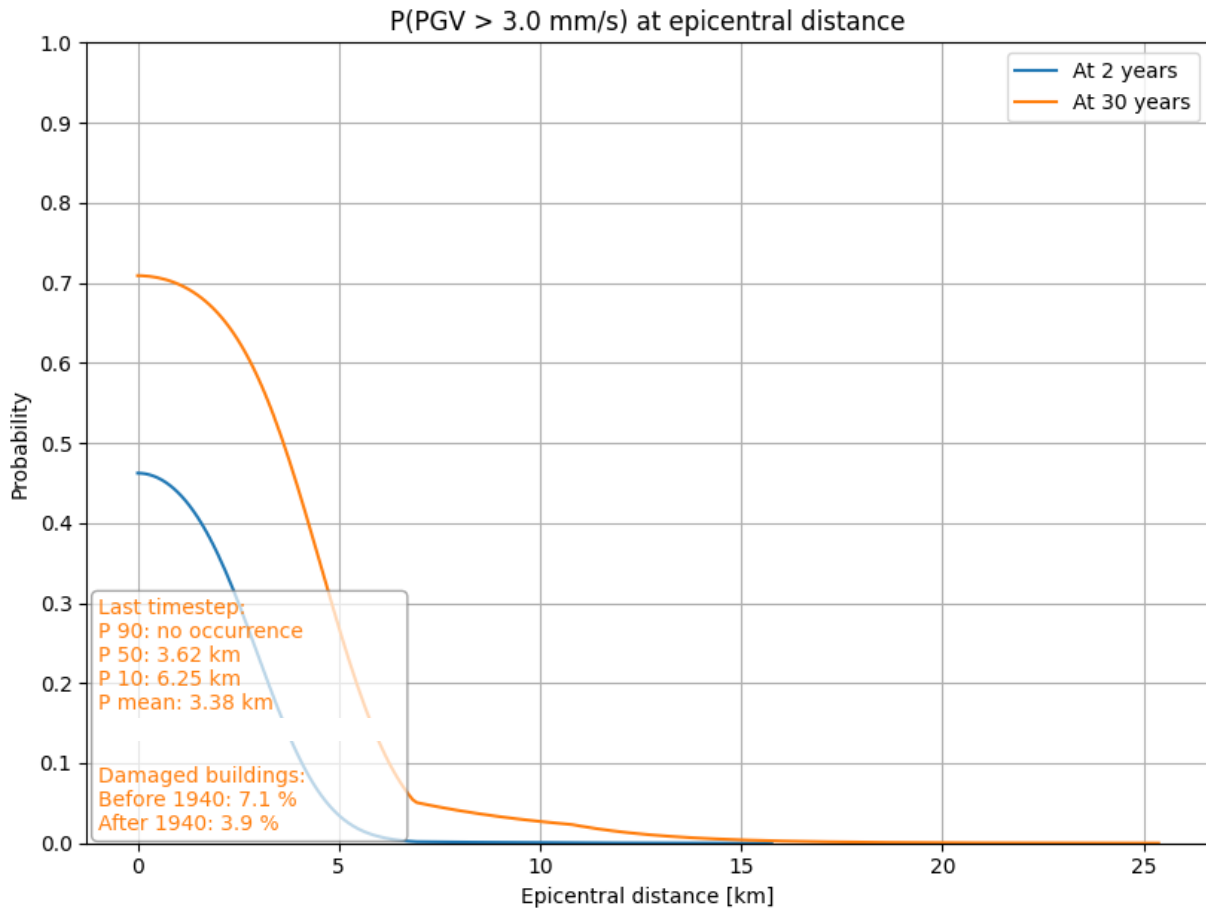
Figure 18: PGV > 3 mm/s at epicentral distance at the selected time steps (example calculated for 2 and 35 years after start of operation). P10, P50, P90 and P_{mean} values for distance from epicenter at the last time step are displayed at the bottom left corner. Also, the average percentage of damaged buildings (built before and after 1940) is displayed here.
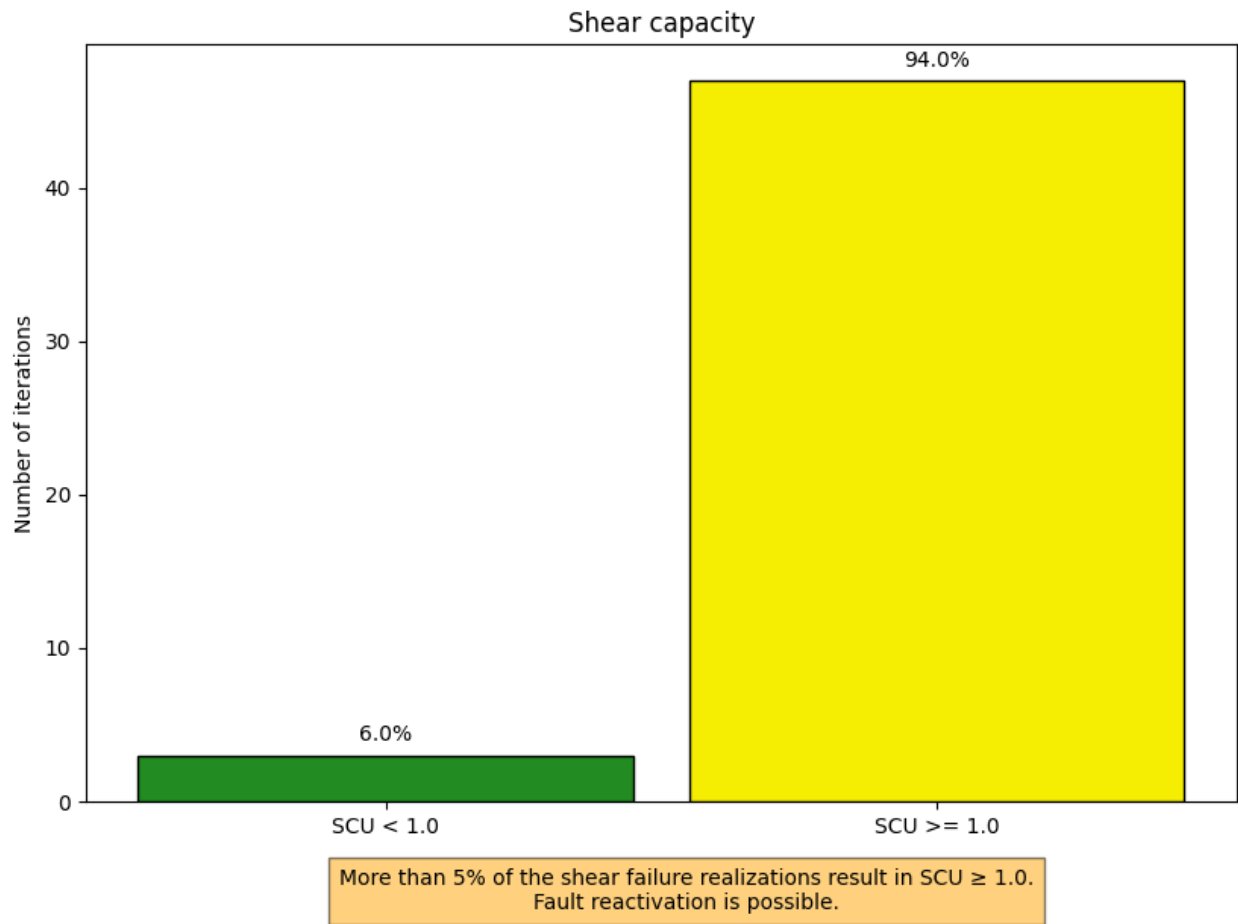
Figure 19: Shear capacity on fault (example calculated for 1000 iterations). The histogram shows what percentage of the iterations has a SCU smaller or greater than 1.

6.3 Sensitivity (tornado diagram)

The user is able to study the influence of parameters on the resulting magnitude of the largest credible earthquake. The sensitivity of parameters is visualized in a tornado diagram. In order to generate these results, choose *Sensitivity (tornado diagram)* for *Calculation mode* in the *General* tab.

After running the calculation, go to the *Plots* tab in the results window to view the results for either the top 10 parameters or all parameters (Figure 20). The parameter sensitivity is calculated for the last time step indicated by the user (under the *Operational* tab).

By hovering your cursor over the Plots visualizations, the x/y values of the plot can be viewed at the bottom right corner of the visualization.

maximum magnitude (last time step) - Top 10

0   1   2   3   4   5   6

36.0 MPa	Min. horizontal stress top reservoir (32.0 MPa)	28.0 MPa
8.0 GPa	Young's modulus reservoir (12.0 GPa)	16.0 GPa
5.000e-06 1/K	Linear thermal expansion coefficient reservoir (1.000e-05 1/K)	1.000e-05 1/K
0.1 MPa	Stress drop (1.7 MPa)	4.0 MPa
50.0 m	Thickness reservoir (100.0 m)	150.0 m
0.7 -	Mohr-Coulomb friction (0.6 -)	0.5 -
20.0 MPa	Pore pressure top reservoir (21.0 MPa)	22.0 MPa
0.2 -	Poisson's ratio seal (0.35 -)	0.4 -
0.2 -	Poisson's ratio base (0.35 -)	0.4 -
10.0 GPa	Young's modulus seal (14.0 GPa)	18.0 GPa
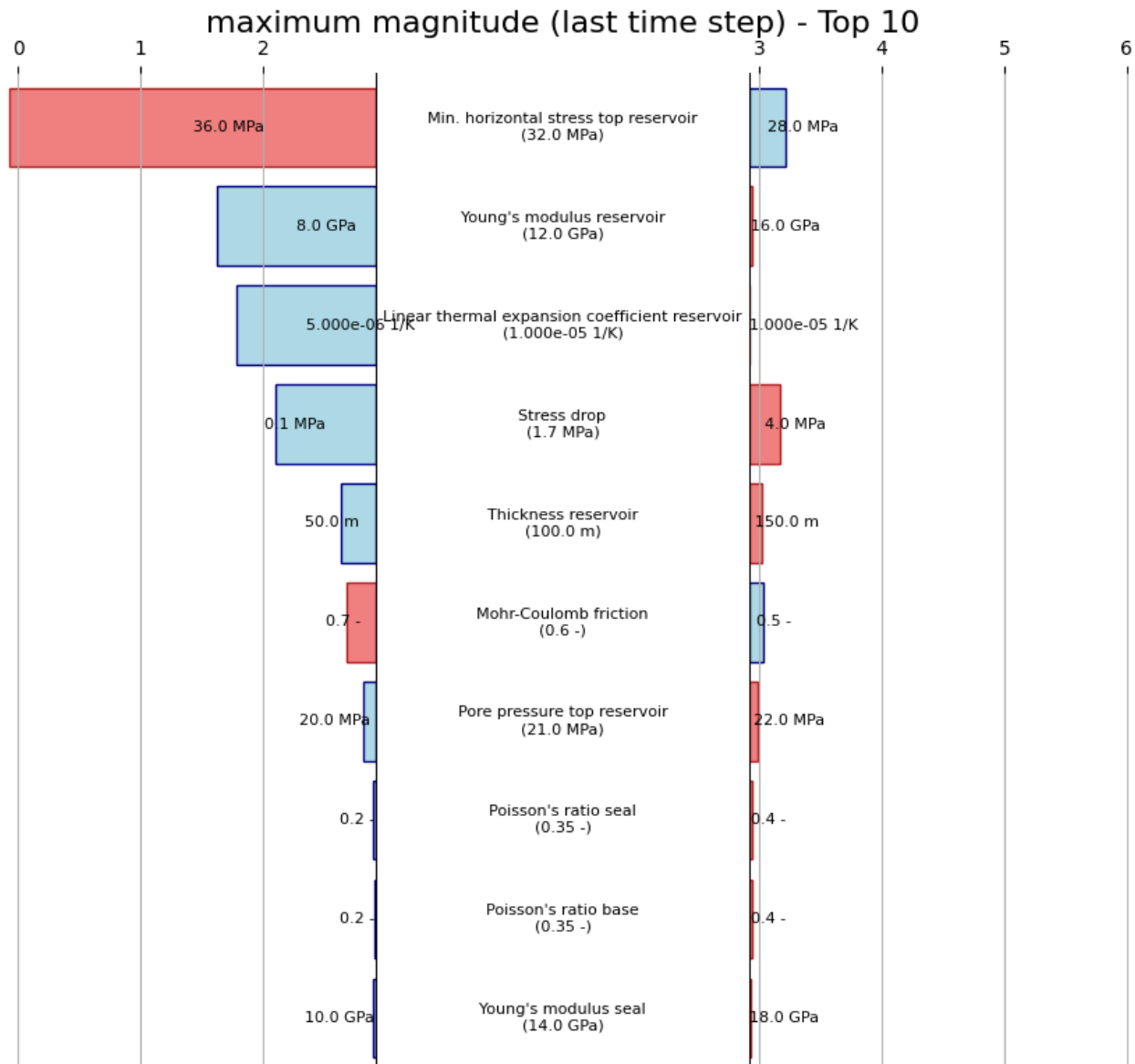
Figure 20: Tornado diagram displaying the influence of parameters (top 10) on the resulting largest credible magnitude at the last time step (example).

Note: when too many parameters are displayed on the screen, it is possible that the parameters overlap and are not readable. In this case, click the zoom icon on the bottom of the screen to zoom in on an area of the screen so the separate parameters are readable.

6.4 Exporting results
The results can be exported to a zip file by clicking the blue *Export results* button at the bottom right corner of the input window. These results include:
- Images with profiles and plots
- Parameter values
- Probabilities (P10, P50, P90 and P_{mean}) for M_{LCE}, stress drop and PGV

7. Batch mode

If desired, the SRIMA app can be run in batch mode. The batch mode can be found in the downloaded SRIMA zip file, within the 'SRIMA' folder under the name 'SRIMA_batch.exe'. It can be run in the command prompt with the following command: "srima_batch.exe -f SETTINGS_FILE -0 OUTPUT_FILE", where:

- SETTINGS_FILE is the location and file name of the csv file with parameter values (this is the same file as the one which is exported from the tool by clicking the *Export results* button or choosing File > Export configuration…). The user can choose the location and file name themselves.
- OUTPUT_FILE is the location and file name of the zip file where all the results will be saved. The user can choose the location and file name themselves.

Appendix I: Input parameters and default setting

Below, a short description is given for each of the input parameters of the SRIMA tool. Note that the default setting or value as implemented in the tool should not be taken as a recommended setting or value. In all cases, it is the responsibility of the user to choose the appropriate setting or value (and provide a justification) for the project under evaluation.

Parameters 'General'

Parameter	Short description
Location [-]	Choose the location for the calculation: Plane on fault (seismic risk/hazard). The option Vertical line at injection well (seal integrity) is used for seal integrity purposes and not discussed in this manual.
Calculation mode [-]	Choose the calculation mode: Base Case (deterministic), Uncertainty (stochastic) or Sensitivity (tornado diagram).
Ensemble size [-]	Number of runs or stochastic iterations. The more iterations, the more accurate the results, and the longer the calculation time.
Use random seed [-]	The seed is used to determine random values for stochastic calculations. Check the box to use a random seed, and to do a calculation that is different each run. Uncheck the box to fill in a set seed, and to do a calculation that is the same each run.

Parameters 'Geometry'

Parameter	Short description
Injection well x-coordinate [m]	Position of the intersection between the injection well and mid reservoir, projected at the surface, in the x direction.
Injection well y-coordinate [m]	Position of the intersection between the injection well and mid reservoir, projected at the surface, in the y direction.
Thickness seal [m]	Thickness of the seal, TST (true stratigraphic thickness).
Thickness reservoir [m]	Thickness of the reservoir, TST (true stratigraphic thickness).
Thickness base [m]	Thickness of the base (underlying non-reservoir interval), TST (true stratigraphic thickness).
Net to gross reservoir [-]	Ratio between net reservoir (sand) and total thickness of the reservoir.

Parameter	Short description
Top depth reservoir [m]	True vertical depth of the top of the reservoir at the position of the injection well.
Well diameter [in]	The diameter of the borehole at the injection interval.
Reservoir radius [m]	The area where the change in pressure is 0. The well distance at reservoir level is a good estimate for reservoir radius.
Fault dip [deg]	Angle between the fault plane and the horizontal. The max dip entered should not be higher than 70 degr (input should be truncated at that value).
Fault dip direction [deg]	The direction in which the fault dips.
Fault center x-coordinate [m]	x-coordinate of the center point of the fault at mid reservoir level.
Fault center y-coordinate [m]	y-coordinate of the center point of the fault at mid reservoir level.
Fault length along strike [m]	Length of the fault (segment). For this purpose not the whole mapped fault length should be used but only the part of the fault that overlaps the GT-AoI plus a ~20% buffer where the fault extends outside the GT-AoI.
Fault cell size along strike [m]	Size of the grid cells on the fault along strike. This determines the resolution. The smaller the cell size, the more detailed the calculation, and the longer the calculation time.
Fault cell size along dip [m]	Size of the grid cells on the fault along dip. This determines the resolution. The smaller the cell size, the more detailed the calculation, and the longer the calculation time.

Parameters 'Thermal & Flow'

Parameter	Short description
Temperature mid reservoir [°C]	Temperature at mid reservoir location.
Pore pressure @ top reservoir [MPa]	The pore pressure measured or calculated at the top of the reservoir. This is the anchor point of the pore pressure gradients.
Pore pressure gradient [kPa/m]	The change with depth of the pore pressure in seal, reservoir and base. Note that this gradient is not used by the program to calculate pore pressure at top reservoir. Pore pressure at top reservoir is manual input (see above).
Pressure contrast seal-reservoir [MPa]	The difference in pore pressure between the seal and reservoir. This is generally 0 MPa but it might be lower (in case of a neighbouring depleted gas field) or higher (in case of an overpressured aquifer).
Pressure contrast reservoir-base [MPa]	The difference in pore pressure between the reservoir and base. This is generally 0 MPa but it might be lower (in case of a neighbouring depleted gas field) or higher (in case of an overpressured aquifer).
□ *Use empirical fluid properties*	This box can be checked in order to use fluid salinity to calculate other fluid properties. This box can be unchecked in order to fill in fluid viscosity, density and heat capacity at different temperature domains.
Fluid salinity [ppm]	The salinity (in Na equivalents) as measured from the reservoir formation water in parts per million.

Parameter	Short description
Reservoir fluid viscosity [Pa·s]	Viscosity of the reservoir fluid at reservoir temperature. Is calculated based on fluid salinity, but can be filled in by unchecking 'Use empirical fluid properties'.
Fluid heat capacity [J/kg/K]	Heat capacity of the reservoir fluid. Is calculated based on fluid salinity, but can be filled in by unchecking 'Use empirical fluid properties'.
Injection fluid viscosity [Pa·s]	Viscosity of the injection fluid at injection temperature. Is calculated based on fluid salinity, but can be filled in by unchecking 'Use empirical fluid properties'.
Injection fluid density [kg/m^3]	Density of the injection fluid at injection temperature. Is calculated based on fluid salinity, but can be filled in by unchecking 'Use empirical fluid properties'.
Permeability [mD]	Permeability of seal, reservoir and base.
Total porosity [-]	Total porosity of seal, reservoir and base. The total porosity in the reservoir approaches the effective porosity for a good reservoir.
Bulk density [kg/m^3]	Bulk density of seal, reservoir and base.
Specific heat capacity rock [J/kg/K]	Heat capacity of seal, reservoir and base.
Thermal conductivity [W/m/K]	Thermal conductivity of seal, reservoir and base.
Total compressibility [Pa^{-1}]	The extent to which pores and water can be compressed. This influences the movement of the cold water front.

Parameters 'Mechanics'

Parameter	Short description
Hydraulic fracture overpressure [MPa]	Overpressure with respect to virgin (hydrostatic) reservoir pressure necessary to initiate and create a hydraulic fracture.
Minimum horizontal stress @ top reservoir [MPa]	The minimum horizontal stress measured or calculated at the top of the reservoir. Note that in general the Sh$_{min}$ is lower in the reservoir (sandstone) than in the overlying claystone. The stress contrast (see stress contrast seal – reservoir) addresses this issue.
Minimum horizontal stress gradient [kPa/m]	The change with depth of the minimum horizontal stress in the seal, reservoir and base. Sometimes referred to as the fracture gradient.
Vertical stress @ top reservoir [MPa]	The vertical stress measured or calculated at the top of the reservoir.
Vertical stress gradient [kPa/m]	The change with depth of the vertical stress in the seal, reservoir and base.
Maximum horizontal / minimum horizontal stress ratio [-]	The maximum horizontal stress divided by the minimum horizontal stress.
Stress contrast seal-reservoir [MPa]	The difference in minimum horizontal stress between the seal and reservoir.
Stress contrast reservoir-base [MPa]	The difference in minimum horizontal stress between the reservoir and base.
Maximum horizontal stress azimuth [deg]	The angle between the direction of the maximum horizontal stress and North.

Parameter	Short description
Young's modulus [GPa]	The static Young's modulus of the seal, reservoir and base. The static Young's modulus is determined from deformation experiments.
Poisson's ratio [-]	The Poisson's ratio of the seal, reservoir and base.
Biot constant [-]	Parameter which expresses how fluid pressure counterbalances in-situ stress in the seal, reservoir and base.
Linear thermal expansion coefficient [K^{-1}]	A measure of the change in length of the formation in response to temperature change.

Parameters 'Operational'

Parameter	Short description
Average injection rate [m^3/hr]	This is the anticipated average flow rate through the primary loop. The non-operational hours should be included in the average. This to calculate the proper extent of the cold front.
Maximum injection rate [m^3/hr]	This is the anticipated maximum flow rate through the primary loop.
Injection temperature [°C]	Temperature of the injected fluid at reservoir depth. May differ from the exit temperature at the heat exchanger due to heat loss or gain in the injection well.
Skin factor [-]	Measure of connection between the well and reservoir. This can be positive (in case of e.g. fracking) or negative (in case of e.g. clogging).
Time steps [hr, day, year]	The tool will present the results after this duration of continuous operation (simulated period). Different time steps may be calculated simultaneously by separating the time steps with commas.
	Shear failure stochastic thresholds
Shear capacity cut-off [-]	Cut-off used for the SCU calculations. The value indicates above what threshold a fault will be reactivated. For the standard SHRA-procedure, this value should be set to SCU = 1.
Peak ground velocity [mm/s]	Value is used for the PGV calculations, resulting in a specific PGV contour for this value. For the standard SHRA-procedure, this value should be set to PGV = 3 mm/s.
	Seal and base integrity norm: **not used for SHRA purposes**
Minimum intact layer thickness [m]	The minimum layer thickness not affected by potential seal failure conditions
Minimum intact layer share [%]	The minimum percentage of seal thickness not affected by potential seal failure conditions
Percentage of safe realisations [%]	The percentage of safe realisations in the stochastic evaluation

Parameters 'Seismicity'

Parameter	Short description
Mohr-Coulomb friction [-]	Coefficient of friction on the fault (static friction).

Parameter	Short description
Mohr-Coulomb cohesion [MPa]	Cohesion of the fault.
Residual friction [-]	Coefficient of friction on the fault after slip (used here to compute the stress drop).
Stress drop [MPa]	Difference in shear stress at a certain timestep and residual shear stress on the fault, averaged over the fault area where the fault strength has been exceeded.

Critical fault area mode	Choose the calculation mode to determine the critical fault area:
	    -Based on shear capacity, SCU > threshold or
	    -Based on temperature change, $dT > 0.5°C$

Stress drop mode	Choose the mode to determine stress drop:
	    -User defined or
	    -Calculate from stresses

Appendix II: Plots

Location	Type	Plots
Plane on fault	Base case (deterministic)	- Largest credible earthquake - Stress drop - PGV at epicenter - P(PGV > x mm/s) at epicentral distance - Shear capacity
Plane on fault	Uncertainty (stochastic)	- Cold front propagation - Temperature distribution on fault - Pressure increase on fault - Normal stress on fault - Shear stress on fault - Shear capacity on fault
Plane on fault	Sensitivity (tornado diagram)	- Maximum magnitude (last time step)