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Sequential Geomechanical-Flow Coupling Using FLAC® and STARS®

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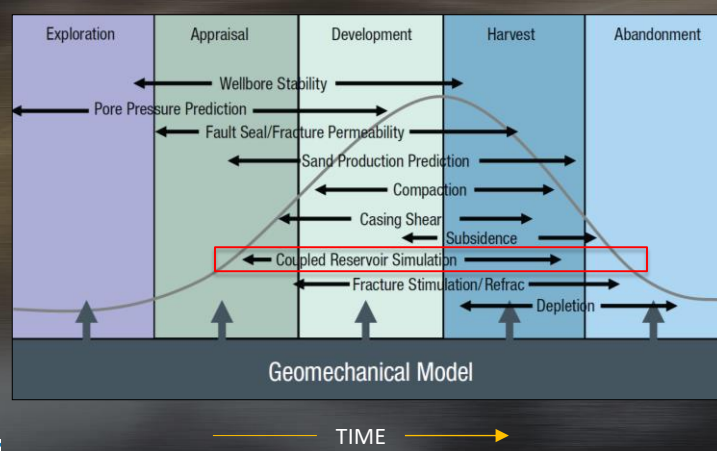
Geomechanical Issues

Geomechanics Issues arise during each phase of development cycle from exploration to abandonment



From: Reservoir Geomechanics: Current Capabilities and Future Trends
By: Zoback et al.

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Outlines

- FLAC: Quick Review
- STARS: Quick Review
- Iterative Geomechancial-Flow Simulation
- Fortran Coding
- Example: Shallow SAGD Simulation

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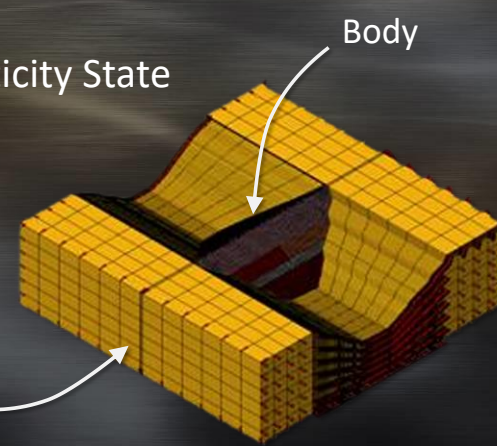
Geotechnical Example: Dam Model

Results of geomechanical solutions:

- Stress
- Strain
- Plasticity/Elasticity State
- Pore Pressure
- Displacement



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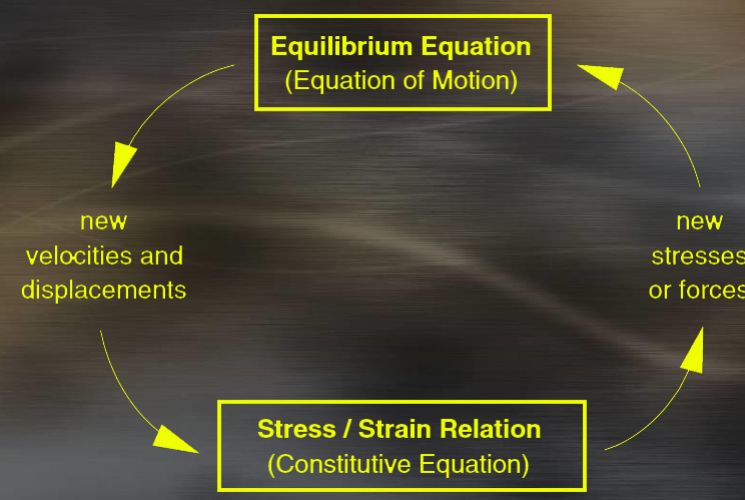
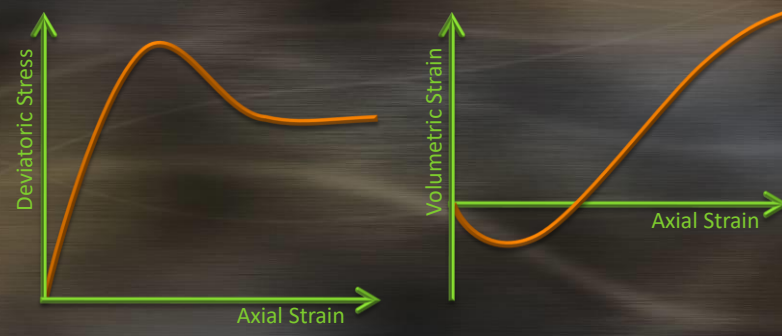
FLAC – Itasca

- FLAC is a two-dimensional explicit finite difference code
- For soil, rock or other materials that may undergo plastic flow when their yield limits are reached.
- Materials are represented by elements, or zones, which form a grid.
- Each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The material can yield and flow, and the grid can deform (in large-strain mode) and move with the material that is represented.

FLAC



Oil Sand – Geomechanical Behavior



- Plastic - Strain Softening Behavior

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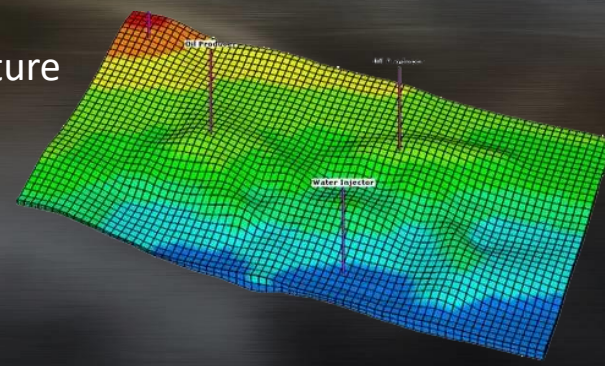
Reservoir Example: Water Flooding

Results of flow simulations:

- Flow rates (injection and production)
- Saturations
- Pressure
- Temperature
- …



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STARS – CMG

- STARS is CMG's advanced finite difference process simulator for modelling the flow of three-phase, multi-component fluids.
- STARS is usually employed for thermal analysis of EOR techniques.

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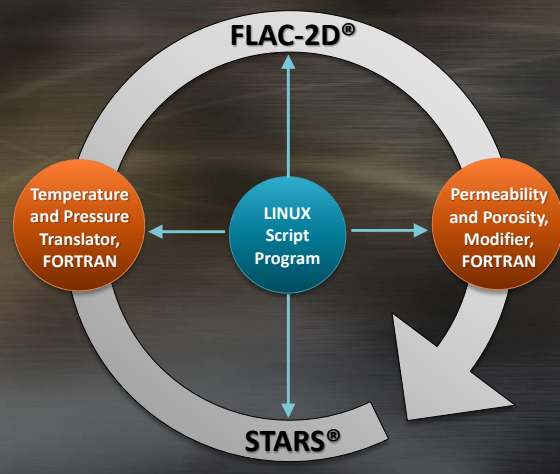
Geomechanical-Flow Coupling

Iterative Approach



$$\ln\left(\frac{K}{K_0}\right) = \frac{n}{\phi_0}\varepsilon_v$$

$$\phi = \frac{\phi_0 + \varepsilon_v}{1 + \varepsilon_v}$$

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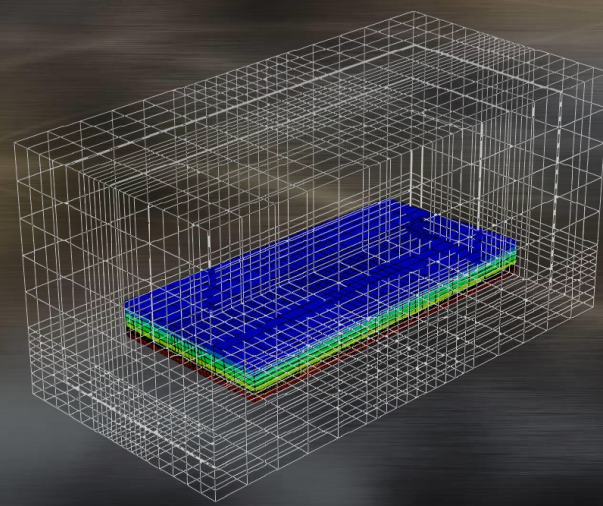
Geomechnical vs. Flow Grid



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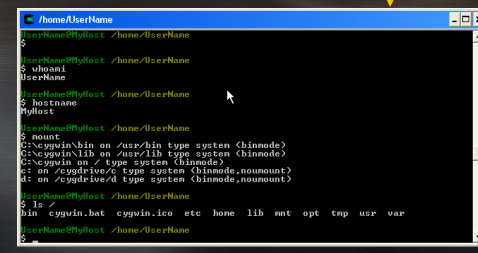
Tools

- FLAC 2D – Itasca International Inc.
- STARS – Computer Modelling Group
- Fortran Compiler
  (or other languages that can provide .exe files)
- Windows-Based Linux, Cygwin
  download for free from: *www.cygwin.com*



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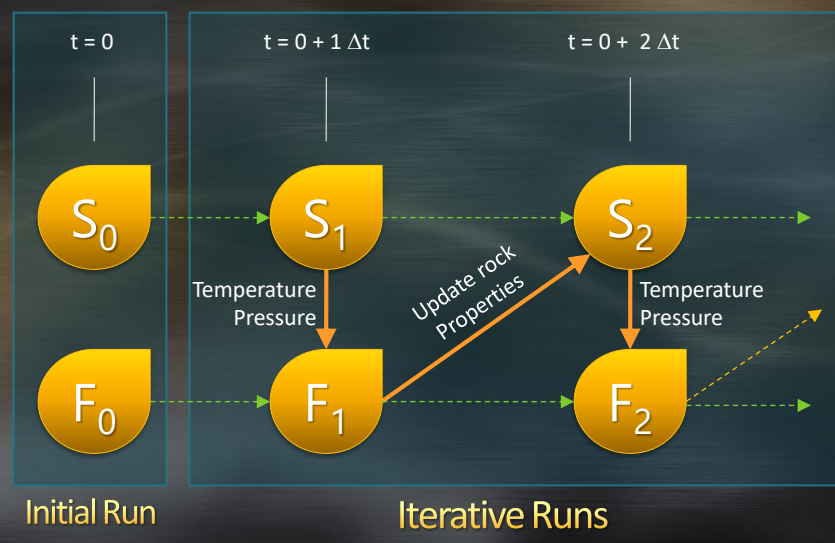
Solution's Steps



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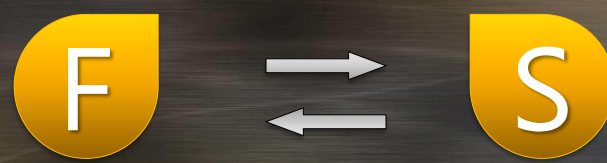
Reference

- Stability, Accuracy, and Efficiency of Sequential Methods for Coupled Flow and Geomechanics (2011)
  Authors: J. Kim, H.A. Tchelepi (Stanford University), and R. Juanes (MIT)
  SPE Journal, 16(2): 249-262

- A Comparison of Techniques for Coupling Porous Flow and Geomechanics (2006)
  Authors: R.H. Dean, X. Gai, (U. of Texas), C.M. Stone, and S.E. Minkoff (U. of Maryland)
  SPE Journal, 11(1): 132-140

Features: FLAC vs. Stars



- Run a model using input file
- Extract results using FISH functions
- Call a property file
- Save the solution for next step
- Restore previous step

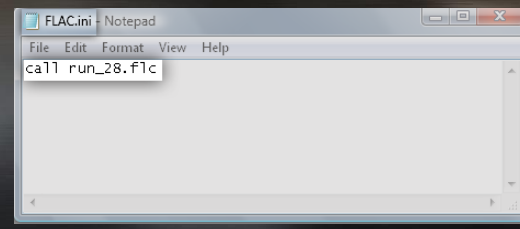
- Note: Results at grid points

- Run a model using input file
- Extract results using REPORT
- Include a property file
- Write the solution for next step
- Restart the model in the next step

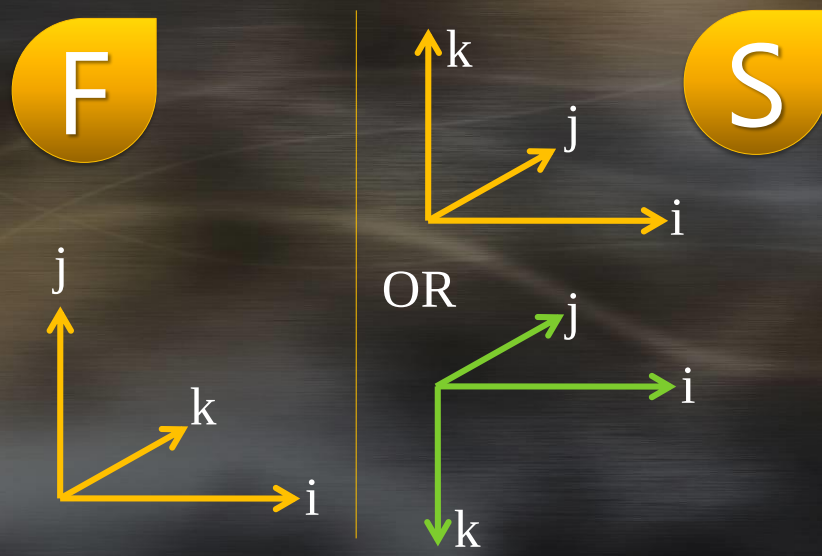
- Results at the centre of zones

FLAC tips

- To run FLAC, create the file 'FLAC.ini' and type the line below within the file:
  Call 'filename'
- Then, run the exe file.
- FLAC automatically reads 'FLAC.ini' and as a result calls the 'filename'



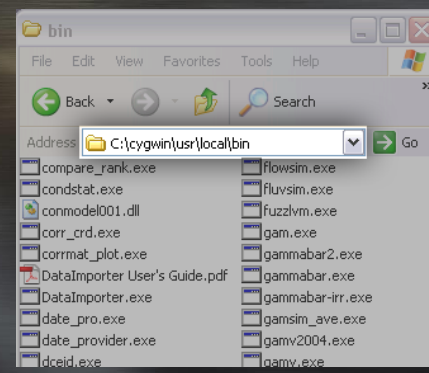
Coordinate Systems



Cygwin Tips

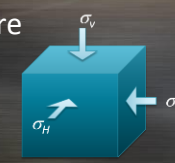
Copy all the '.exe' files you need to run into 'cigwin' working directory including:

- FLAC files
- STARS files
- REPORT files



Why initial runs?

Establish *in situ* stresses and initial pressure/temperature



Load FISH functions for next steps

Allow STARS to write information for next RESTART steps

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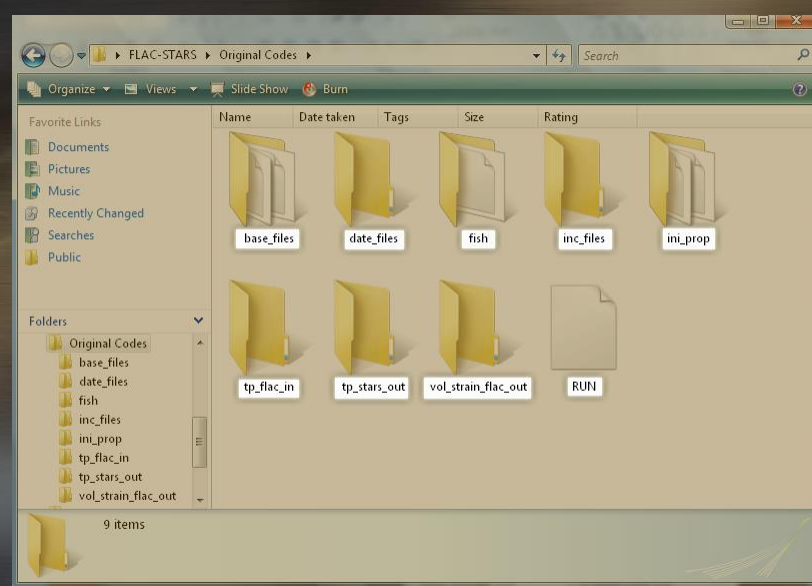
Working Folders



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FLAC: Initial Stage Input File

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```
; ---------- Initialize ----------
config ats thermal ex 15
grid 120,35

; ---------- Settings ----------
set grav = 9.81
set echo off
call fish\functions.fis

; ---------- Define Grid ----------
gen 0.0,70.0 0.0,210.0 150.0,210.0 150.0,70.0 ratio 0.8,1.5 i=1,11 j=26,36
gen 150.0,70.0 150.0,210.0 250.0,210.0 250.0,70.0 ratio 1.0,1.5 i=11,111 j=26,36
gen 250.0,70.0 250.0,210.0 400.0,210.0 400.0,70.0 ratio 1.25,1.5 i=111,121 j=26,36

; ---------- Define Material Properties -------
group 'over'  j=26,35
model elastic th_i group 'over'
prop d=2200  b=208e6  s=96.2e6  group 'over'
prop cond=1 spec=1 thexp=2.00E-05  group 'over'

; ---------- Fluid Properties ----------
water den 1000 bulk 2e9

; ---------- Define Initial Stresses ----------
ini sxx  -4620000 var 0,4620000   j=1,36
ini syy  -4620000 var 0,4620000   j=1,36
ini szz  -9240000 var 0,9240000   j=1,36
.
.
.

; ---------- Pore Pressure
ini pp  0                         j=34,36
ini pp  1300e3 var 0,-1300e3      j=1,34
ini pp  650e3                     j=6,26

; ---------- Temprature
ini temp 10

; ---------- Define Boundary Condition ----------
fix x y          j=1
fix x            i=1
fix x            i=121

; ---------- solve and initialize ----------
solve

; ---------- Save For the Next Step ----------
save run_0.sav
quit
```


STARS: Initial Stage Input File

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```
RESULTS SIMULATOR STARS 200900
**NOLIST
**
INUNIT *SI
WSRF GRID TIME
WSRF WELL TIME
REWIND 0
**$  Distance units: m
RESULTS XOFFSET         0.0000
RESULTS YOFFSET         0.0000
RESULTS ROTATION        0.0000  **$  (DEGREES)
RESULTS AXES-DIRECTIONS 1.0 -1.0 1.0
*WRST TIME

**$ Property: Porosity  Max: 0.3  Min: 0.3
POR CON         0.32
*mod
INCLUDE 'inc_files/poro_0.inc'

**$ Property: Permeability I (md)   Max: 4000  Min: 2000
PERMI CON       1000
*mod
INCLUDE 'inc_files/permi_0.inc'
.
.
.

**$ Property: Permeability J (md)   Max: 2000  Min: 2000
PERMJ CON       1000

*mod
INCLUDE 'inc_files/permj_0.inc'

**$ Property: Permeability K (md)   Max: 2000  Min: 2000
PERMK CON       1000

*mod
INCLUDE 'inc_files/permk_0.inc'

AUTOHEATER ON  50:50     1:1     17:17
AUTOHEATER ON  50:50     1:1     20:20

*********
** DATES
**********
DATE 1901 1  5
STOP
```

FLAC: Iterative Input File Template

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```
;-----Restore previous step
restore run_0.sav

; ---- Define Plastic Properties for the reservoir -------
model m th_i group 'reservoir'
prop cond=1 spec=1 thexp=2.00E-05  group 'reservoir'
prop dil=15 fric=45  group 'reservoir'

; --------- Update Temprature and Pressure and material properties
call tp_flac_in\temp_1.flc
call tp_flac_in\pres_1.flc

; ------------------- Solve and initialize ---------------------
set mech on thermal off flow off     ; Mechanical only calculation
solve

; ------------------- Extract Results---------------------
SET _fil_name 'vol_strain_flac_out\ev_1.out'
ev_out

; ------------------- Save For the Next Step -------------------
save run_1.sav
quit
```

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REPORT Input File

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- *FILE 'run_1.irf'
- *OUTPUT 'tp_stars_out/temp_1.inc'
- *PROPERTY-FOR 'Temperature' 100
- *XYZLAYER 0

- *FILE 'run_1.irf'
- *OUTPUT 'tp_stars_out/pres_RN.inc
- '*PROPERTY-FOR 'PRES' 100
- *XYZLAYER 0

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STARS: Iterative Input File Template

```
RESULTS SIMULATOR STARS 200900
FILENAMES INDEX-IN 'run_0.irf'
**NOLIST
**
WSRF WELL TIME
RESTART

REWIND 0
**$  Distance units: m
RESULTS XOFFSET         0.0000
RESULTS YOFFSET         0.0000
RESULTS ROTATION        0.0000  **$  (DEGREES)
RESULTS AXES-DIRECTIONS 1.0 -1.0 1.0
*WRST TIME

**$ Property: Porosity  Max: 0.3  Min: 0.3
POR CON         0.32
*mod
INCLUDE 'inc_files/poro_0.inc'

**$ Property: Permeability I (md)   Max: 4000  Min: 2000
PERMI CON       1000
*mod
INCLUDE 'inc_files/permi_0.inc'

**$ Property: Permeability J (md)   Max: 2000  Min: 2000
PERMJ CON       1000

*mod
INCLUDE 'inc_files/permj_0.inc'

**$ Property: Permeability K (md)   Max: 2000  Min: 2000
PERMK CON       1000

*mod
INCLUDE 'inc_files/permk_0.inc'

AUTOHEATER ON  50:50    1:1     17:17
AUTOHEATER ON  50:50    1:1     20:20

*********
** DATES
**********

INCLUDE 'date_files/date_1.inc'
```


FLAC: Temp/Press Input Files

```
initial  pp           716901.800000   i   11   j   6
initial  pp           781276.800000   i   11   j   7
initial  pp           776151.000000   i   11   j   8
initial  pp           770884.500000   i   11   j   9
initial  pp           765486.000000   i   11   j   10
initial  pp           759967.800000   i   11   j   11
initial  pp           754344.800000   i   11   j   12
initial  pp           748634.800000   i   11   j   13
initial  pp           742857.800000   i   11   j   14
initial  pp           737035.000000   i   11   j   15
initial  pp           731189.300000   i   11   j   16
initial  pp           725343.300000   i   11   j   17
initial  pp           719520.300000   i   11   j   18
initial  pp           713743.000000   i   11   j   19
initial  pp           708032.800000   i   11   j   20
.
.
.
```

```
initial  temperature  10.055200   i   11   j   6
initial  temperature  10.113450   i   11   j   7
initial  temperature  10.119170   i   11   j   8
initial  temperature  10.124250   i   11   j   9
initial  temperature  10.128830   i   11   j   10
initial  temperature  10.132950   i   11   j   11
initial  temperature  10.136630   i   11   j   12
initial  temperature  10.139780   i   11   j   13
initial  temperature  10.142350   i   11   j   14
initial  temperature  10.144350   i   11   j   15
initial  temperature  10.145700   i   11   j   16
initial  temperature  10.146330   i   11   j   17
initial  temperature  10.146180   i   11   j   18
initial  temperature  10.145200   i   11   j   19
initial  temperature  10.143350   i   11   j   20
.
.
.
```

STARS: Petrophysics Include File

```
1   1   20      =       5000
2   1   20      =       5000
3   1   20      =       5000
4   1   20      =       5000
5   1   20      =       5000
6   1   20      =       5000
7   1   20      =       5000
8   1   20      =       5000
9   1   20      =       5000
10  1   20      =       5000
11  1   20      =       5000
12  1   20      =       5000
13  1   20      =       5000
14  1   20      =       5000
```

-
-
-

FLAC: FISH Functin

```
def ev_out
    num=1
    float ev_for_k
    array ev_for_k(2000)
    loop j (6,25)
        loop i (11,110)
            ev_for_k(num)=string(vsi(i,j))
            num=num+1
        endloop
    endloop
    status=open(_fil_name,1,1)
    status=write(ev_for_k,2000)
    status=close
end
```

STARS: Date Include File

```
DATE        1901        1           11
DATE        1901        1           21
DATE        1901        1           31
DATE        1901        2           10
DATE        1901        2           20
DATE        1901        3           2
DATE        1901        3           12
DATE        1901        3           22
DATE        1901        4           1
OPEN 'Injector'
OPEN 'Producer'
HEATR   *CON 0
UHTR    *CON 0
DATE        1901        4           11
DATE        1901        4           21
STOP
```


STARS: Petrophysics Include File

```
1   1   20      =       5000
2   1   20      =       5000
3   1   20      =       5000
4   1   20      =       5000
5   1   20      =       5000
6   1   20      =       5000
7   1   20      =       5000
8   1   20      =       5000
9   1   20      =       5000
10  1   20      =       5000
11  1   20      =       5000
12  1   20      =       5000
13  1   20      =       5000
14  1   20      =       5000
```

-
-
-

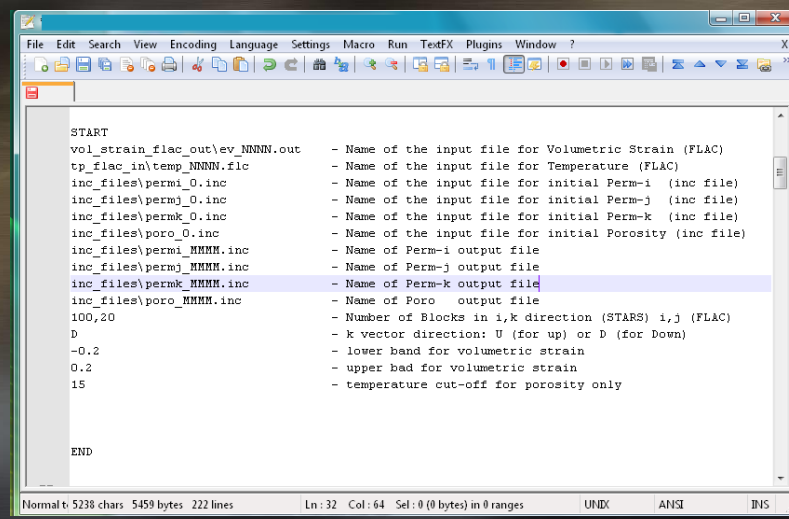
Fortran Codes

- Three codes has been developed for the following tasks:
  - Translating Temp/Press from STARS results to be readable for FLAC
  - Generating Prem/Poro updated files based FLAC results (volumetric strain)
  - Providing 'Include data files' at each iterative run for STARS

Coding Tips:

- Compile Fortran codes and generate .exe files
- Since we work with .exe files, there is no access to change the original code during each run. Therefore, an input-based coding should be considered to change some variables at each time step.

Example:
Input file for Updating Perm/Poro



```
START
vol_strain_flac_out\ev_NNNN.out     - Name of the input file for Volumetric Strain (FLAC)
tp_flac_in\temp_NNNN.flc            - Name of the input file for Temperature (FLAC)
inc_files\permi_0.inc               - Name of the input file for initial Perm-i  (inc file)
inc_files\permj_0.inc               - Name of the input file for initial Perm-j  (inc file)
inc_files\permk_0.inc               - Name of the input file for initial Perm-k  (inc file)
inc_files\poro_0.inc                - Name of the input file for initial Porosity (inc file)
inc_files\permi_MMMM.inc            - Name of Perm-i output file
inc_files\permj_MMMM.inc            - Name of Perm-j output file
inc_files\permk_MMMM.inc            - Name of Perm-k output file
inc_files\poro_MMMM.inc             - Name of Poro   output file
100,20                              - Number of Blocks in i,k direction (STARS) i,j (FLAC)
D                                   - k vector direction: U (for up) or D (for Down)
-0.2                                - lower band for volumetric strain
0.2                                 - upper bad for volumetric strain
15                                  - temperature cut-off for porosity only



END
```

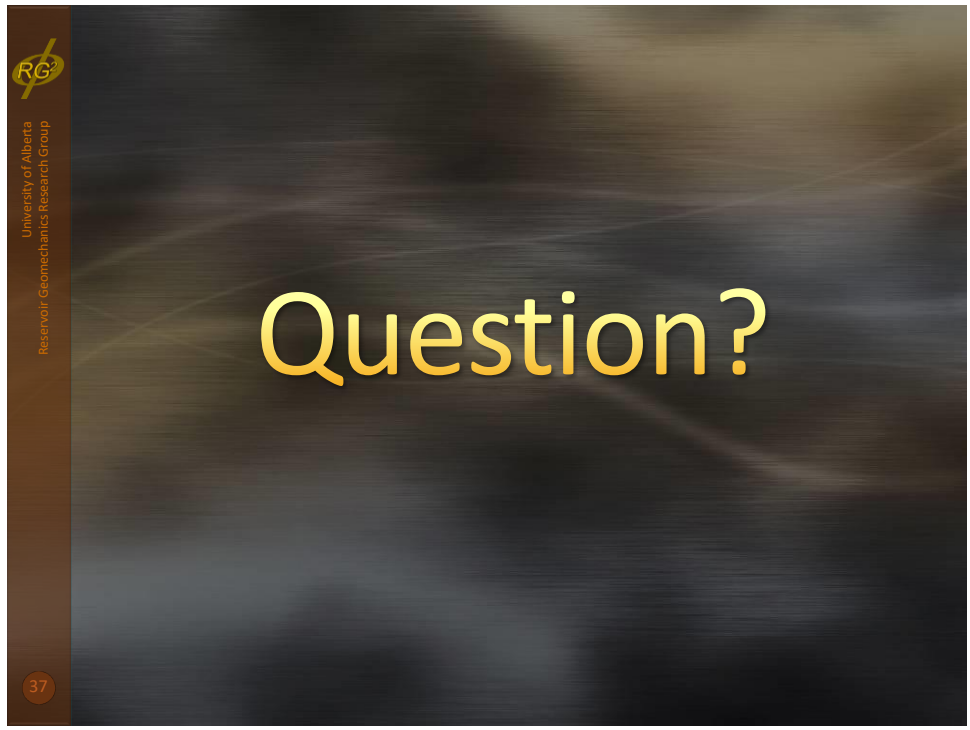

Review: Linux Scripting

- In general, we have some .exe that read their individual input files.
- At the beginning of simulation, we need to generate the input files as templates.
- In every time step, a copy of each template is reproduced: tokens are replace by appropriate values. For example:

INCLUDE 'date_files/date_AAA.inc'

At time step 1:

INCLUDE 'date_files/date_1.inc'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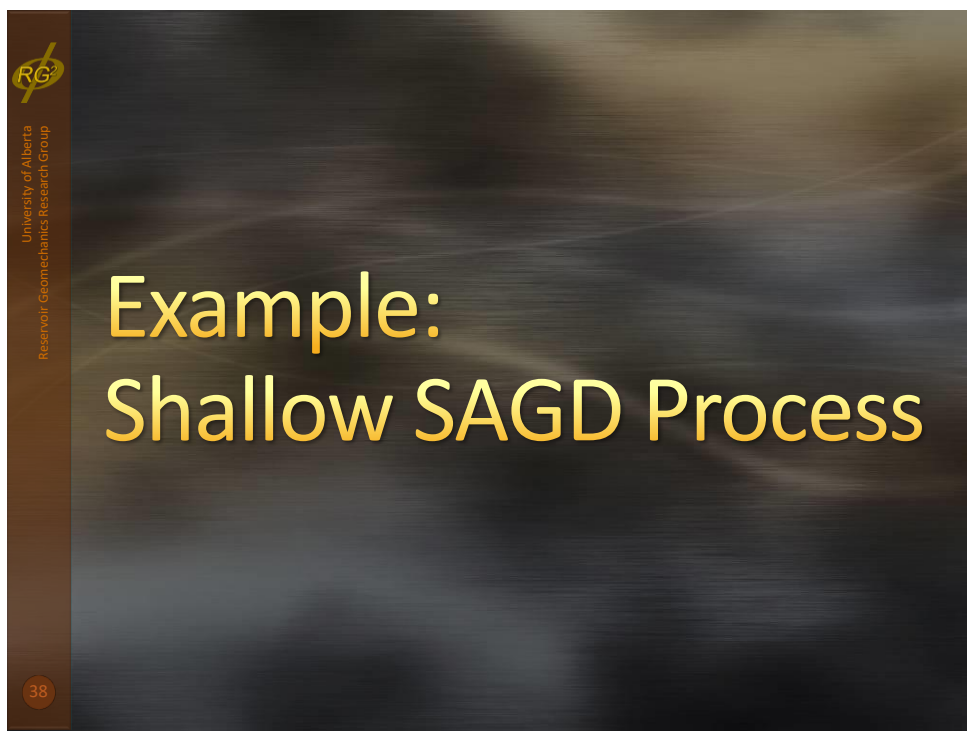
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Example:
Shallow SAGD Process
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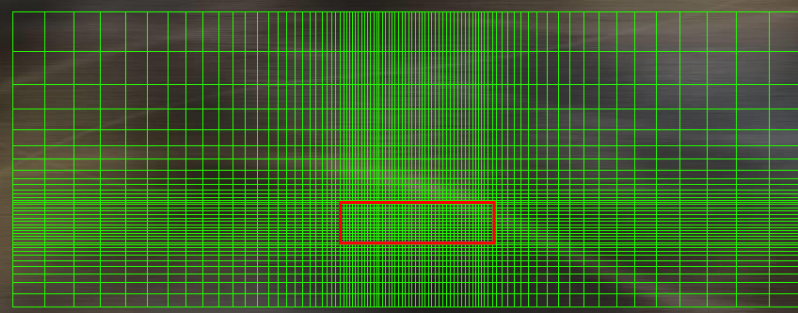
FLAC: Mesh



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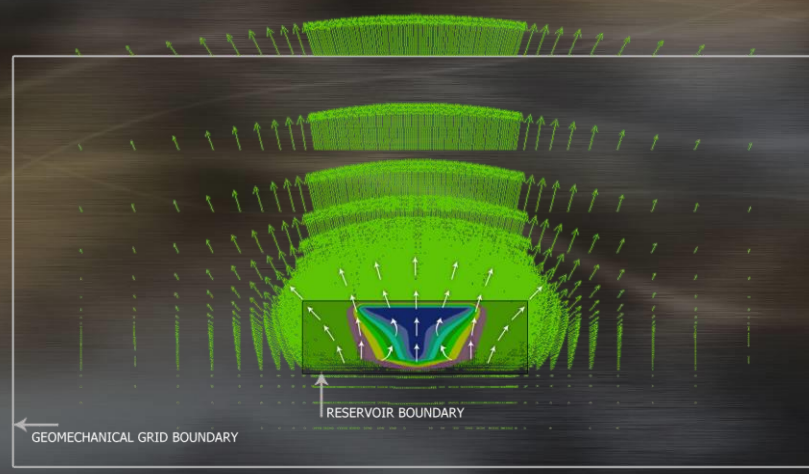
Resevoir Deformation



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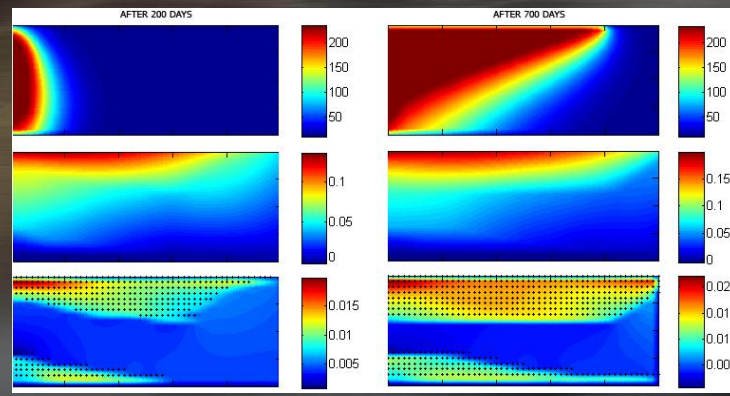
Injection Pressure = 3000 kPa



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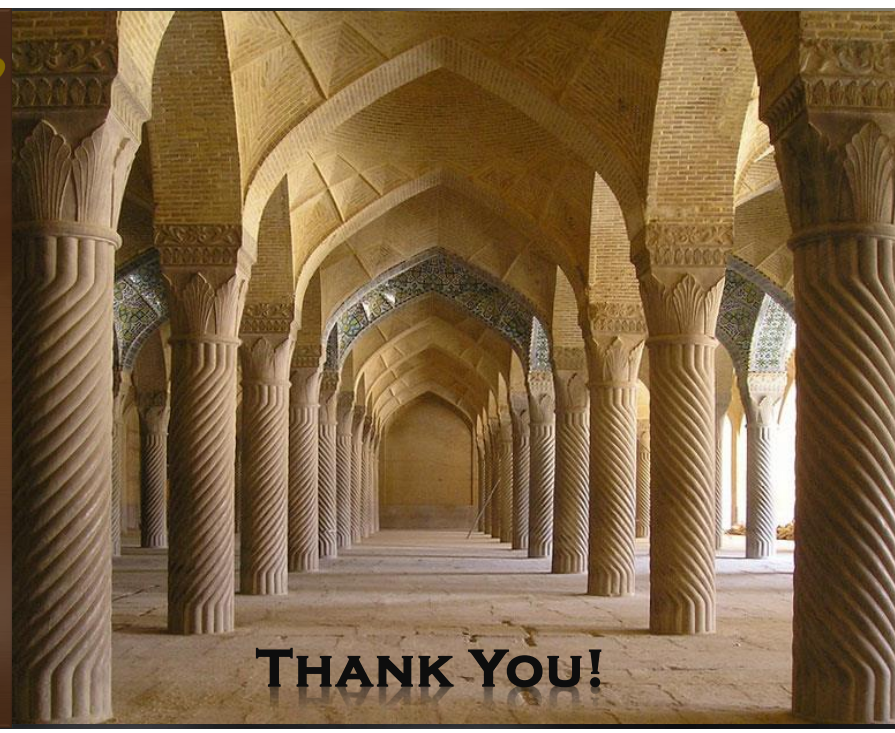

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