A real world application
Tête Rousse Glacier

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Tête Rousse Glacier

✓ Context
  - The history of Tête Rousse Glacier
  - The 2010 water filled-cavity
  - Analysis of the cavity roof stability (Autumn 2010)

✓ Step 1
  - Tête Rousse Glacier flow without a water filled-cavity (diagnostic)

✓ Step 2
  - Influence of an empty cavity below Tête Rousse Glacier (diagnostic)

✓ Step 3
  - Rate of closure of the cavity for a given drainage scenario (prognostic)
Location (Mont Blanc Area, France Alps)
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Tête Rousse glacier
3100 to 3300 m
0.08 km² (2007)
Chronology

The Past History – The 1892 catastrophe

Contemporary history:

2007-10 - Studies to answer the question about the necessity to maintain the tunnel

07/2010 - A water filled cavity under pressure is discovered
- Crisis – Artificial drainage

2011 - Small research program to understand the formation of the cavity
- New crisis – Artificial drainage

2012 - New Artificial drainage needed
The 1892 catastrophe

11 July 1892

175 fatalities

100 000 m$^3$ of water

Flood produced

800 000 m$^3$ of sediment

@Vincent, LGGE
The 1892 catastrophe
Is there still a risk at Tête Rousse?

Question asked by authorities in 2007

@Vincent, LGGE
Glaciological studies

- Topographic measurements
- Radar measurements
- Temperature measurements
- Mass balance measurements
The radar measurements showed a zone (volume) with an anomaly.
Glaciological studies

In Sept 2009, geophysical survey using the Magnetic Resonance Imaging (LTHE, Grenoble)
Glaciological studies

Water volume of 65,000 m³

Report given to public authorities in March 2010
Pressure measurements

20 hot-water drillings performed from 29 June to 8 July 2010

Confirm the presence of a cavity and that

the cavity is under pressure!
Decisions

The hydrostatic pressure exceeded the ice pressure due to the weight of the ice column

We could expect that the water contained in the glacier would be released suddenly

The public authorities have been warned immediately (13 July, 2010)

It has been decided to drain the subglacial lake as soon as possible, because 3000 people were threatened in the valley.
A difficult field work
Drainage of the cavity

The artificial drainage started the 26 of August
A new risk?

But was stopped the 1st September:

What was the risk of breakout of the cavity roof induced by the artificial drainage?
The 2010 cavity

Pumping of 47 700 m$^3$ from 25 August to 8 October 2010

**Question** (addressed end of August 2010):
What is the risk of break-up during the pumping phase?

right

upstream

h ~ 50 m
l_y ~ 80 m
l_x ~ 30 m

left
Timing for answering

Sonar data

Meeting with the mayor of St Gervais
Proposed application

Construct a model of the flow of Tête Rousse Glacier

- Step 1: Without the cavity (normal state)
- Step 2: Add an empty cavity (stress analysis)
- Step 3: Rate of closure of the cavity
  (surface deformation analysis)
Data for ice flow modelling

- Bedrock DEM
- 2007 Surface DEM
- Cavity topography from sonar measurements
- Few surface velocities, without the cavity (0.6 m/a at the centre of the glacier)
- 27 Stakes to measure surface displacement during drainage
Data: Contour_TR_cavity.dat, Contour_TR_glacier.dat, DEM_TR_bed.dat, DEM_TR_cavity.dat, DEM_TR_surf.dat

PROG: USF_TR.f90

Step1a: Makegeo.m, teterousse.geo, teterousse1a.sif

Step1b: teterousse1b.sif

Step2a: Makegeo_2.m, teterousse.geo, teterousse2a.sif

Step2b: teterousse2b.sif

Step3a: teterousse3a.sif

Step3b: teterousse3b.sif
Modelling Tête Rousse Glacier

✓ Step 1

- 1a Tête Rousse Glacier flow without a water filled-cavity (diagnostic)
- 1b Add Stress Solver to get the stress
  Compute the Eigenvalues of the stress tensor

✓ Step 2

- 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
- 2b Apply a water pressure in the cavity

✓ Step 3

- 3a Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3b Add a drainage scenario
Step 1a: Work to do

- create the mesh
- impose the boundary conditions in the SIF file
- test other BCs on the lateral boundary
- test sliding at the base of the glacier
Step 1a: steps to make the mesh

1/ build the teterousse.geo file (input file of gmsh, footprint of the glacier)

2/ gmsh to get teterousse.msh (still footprint of the glacier)

3/ ElmerGrid to transform into Elmer format (still footprint of the glacier)

4/ we will use the internal extrusion feature in Elmer to create a volume from this footprint
clear;
lc_out=18.0;    % (size of the element in the plane)

A=dlmread('Contour_TR_glacier.dat');    % (Read contour points)
fid1=fopen('teterousse.geo','w');
fprintf(fid1,'Mesh.Algorithm=5; \n');    % (delaunay algorithm)

As=size(A,1);

np=0;
for ii=1:As
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,A(ii,1),A(ii,2),lc_out);
end

fprintf(fid1,'Spline(1)={
');
for ii=1:As
    fprintf(fid1,'%g,',ii);
end
fprintf(fid1,'%g}; \n',1);

fprintf(fid1,'Line Loop(2)={1}; \n');
fprintf(fid1,'Plane Surface(3) = {2}; \n');
fprintf(fid1,'Physical Line(4) = {1}; \n');
fprintf(fid1,'Physical Surface(5) = {3}; \n');

fclose(fid1)
Step 1a: Makegeo.m

% create teterousse.msh using gmsh
!gmsh teterousse.geo -1 -2

% convert teterousse.gmsh in an Elmer type mesh
!ElmerGrid 14 2 teterousse.msh –autoclean
Step 1a: gmsh (create a .msh file)

gmsh teterousse.geo -1 -2

help: http://www.geuz.org/gmsh/

line commands:
"-1 -2" performs 1D and 2D mesh generation and then exit
Step 1a: In the sif file

Define the number of vertical layers (Simulation section):

Simulation
   Coordinate System = Cartesian 3D
   Simulation Type = Steady
   Extruded Mesh Levels = Integer 16
...
End

The first solver to be executed is the StructuredMeshMapper

Solver 1
   Equation = "MapCoordinate"
   Procedure = "StructuredMeshMapper" "StructuredMeshMapper"
   Active Coordinate = Integer 3
   Mesh Velocity Variable = String "dSdt"
   Mesh Update Variable = String "dS"
   Mesh Velocity First Zero = Logical True
End
Step 1a: In the sif file

Define the top and bottom surfaces (BC section):

! cavity roof and Bedrock
Boundary Condition 2
Bottom Surface = Variable Coordinate 1
   Real Procedure "./USF_TR" "BottomSurface"
End

! Upper Surface
Boundary Condition 3
   Top Surface = Variable Coordinate 1
      Real Procedure "./USF_TR" "TopSurface"
End

BottomSurface and TopSurface are two user functions (in USF_TR.f90) that read the bottom and top DEM and interpolate for each node the altitude.
Step 1a: User Function USF_TR.f90

BottomSurface:
- load the file DEM_TR_bed.dat in ../Data
- for each node, use InterpolateDEM to get the altitude(x,y) of the bedrock

TopSurface:
- load the file DEM_TR_surf.dat in ../Data
- for each node, use InterpolateDEM to get the altitude(x,y) of the upper surface

Compilation: elmerf90 ../PROG/USF_TR.f90 → USF_TR
Step 1a: Hypothesis of the modelling

Solve only the Stokes equation in a diagnostic way

3 boundary conditions

Upper Surface BC:
stress free surface
(natural BC)

Bedrock BC:
No sliding condition

Lateral BC:
zero horizontal velocities
Step 1a: use Glen’s law

\[ D_{ij} = A \tau_c^{n-1} S_{ij} \quad ; \quad S_{ij} = A^{-1/n} I_{D_2}^{(1-n)/n} D_{ij} \]

\[ A = A(T') = A_0 \exp^{-Q/RT'} \]

\[ A = A_1 = 2.89 \times 10^{-13} \text{ s}^{-1} \text{ Pa}^{-3} \text{ if } T \leq -10^\circ \text{C} \]
\[ A = A_2 = 2.43 \times 10^{-2} \text{ s}^{-1} \text{ Pa}^{-3} \text{ if } T \geq -10^\circ \text{C} \]

\[ Q = Q_1 = 60 \text{ kJ mol}^{-1} \text{ if } T \leq -10^\circ \text{C} \]
\[ Q = Q_2 = 115 \text{ kJ mol}^{-1} \text{ if } T \geq -10^\circ \text{C} \]

Cuffey and Paterson (2010)

assume a constant temperature of -1°C
Step 1a: use Glen’s law

\[
\text{\$yearinsec = 365.25*24*60*60} \\
\text{\$rhol = 900.0/(1.0e6*yearinsec^2)} \\
\text{\$rhow = 1000.0/(1.0e6*yearinsec^2)} \\
! \text{Prefactor from Paterson (1994) in MPa^{-3} a^{-1}} \\
\text{\$A1 = 3.985e-13*yearinsec*1.0e18} \\
\text{\$A2 = 1.916e3*yearinsec*1.0e18} \\
\text{\$gravity = -9.81*yearinsec^2} \\
\]

Material 1
- Density = Real \$rhol
- Viscosity Model = String "glen"
- Viscosity = 1.0 ! Dummy but avoid warning output
- Glen Exponent = Real 3.0
- Limit Temperature = Real -10.0
- Rate Factor 1 = Real \$A1
- Rate Factor 2 = Real \$A2
- Activation Energy 1 = Real 60e3
- Activation Energy 2 = Real 139e3
- Glen Enhancement Factor = Real 1.0
- Critical Shear Rate = Real 1.0e-10

Constant Temperature = Real -1.0
End
Step 1a: Boundary Conditions

! lateral side of the glacier
Boundary Condition 1
   Target Boundaries = 1
   Velocity 1 = real 0.0
   Velocity 2 = real 0.0
End

! Bedrock
Boundary Condition 2
   Bottom Surface = Variable Coordinate 1
   Real Procedure "./USF_TR" "BottomSurface"
   Velocity 1 = Real 0.0
   Velocity 2 = Real 0.0
   Velocity 3 = Real 0.0
End

! Upper Surface
Boundary Condition 3
   Top Surface = Variable Coordinate 1
   Real Procedure "./USF_TR" "TopSurface"
End

Null horizontal velocities

No sliding

Natural BC, nothing to do!
Step 1a: Other BCs for the lateral boundary

Boundary Condition 1
Target Boundaries = 1
End

Natural BC

! lateral side of the glacier
Boundary Condition 1
Target Boundaries = 1
Velocity 1 = real 0.0
Velocity 2 = real 0.0
Velocity 3 = real 0.0
End

zero velocity

Conclusion ?
Step 1a: Add sliding on the bedrock

Friction law in Elmer:
\[ C_i u_i = \sigma_{ij} n_j \quad (i = 1, 2) \]
\[ C_t u_t = \sigma_{nt} ; C_n u_n = \sigma_{nn} \]

where \( n \) is the surface normal vector

! Bedrock BC
Boundary Condition 2

Flow Force BC = Logical True
Normal-Tangential Velocity = Logical True

Velocity 1 = Real 0.0e0
Slip Coefficient 2 = Real 0.1
Slip Coefficient 3 = Real 0.1
End

How to evaluate the Slip Coefficient?
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    Compute the Eigenvalues of the stress tensor

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  - 2a Influence of an empty cavity below Tête Rousse Glacier (diagnostic)
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  - 3a Rate of closure of the cavity for a given drainage scenario (prognostic)
  - 3b Add a drainage scenario
Step 1b: Add the Stress Solver

Objective: compute the stress field as

$$\int_V S_{ij} \Phi \, dV = 2 \int_V \eta D_{ij} \Phi \, dV$$

where \( D_{ij} \) and \( \eta \) are calculated from the nodal velocities using the derivative of the basis functions

- Add a Solver
Solver 3
  Equation = Sij
  Procedure = "ElmerIceSolvers" "ComputeDevStress"
  Variable = -nooutput "Sij"
  Variable DOFs = 1
  Exported Variable 1 = Stress
  Exported Variable 1 DOFs = 6

  Flow Solver Name = String "Flow Solution"

  Linear System Solver = Direct
  Linear System Direct Method = umfpack

End
Step 1b: Add the Stress Solver

- Add this solver in the Equation Section
  Active Solvers(3) = 1 2 3

- Tell you want the Cauchy stress to be computed (Material Section)
  Material 1
  Cauchy Stress = Logical True
  End

- Output:
  negative stress = Compressive stress
  positive stress = Tensile stress

Stress.1 → S_{xx}    Stress.4 → S_{xy}
Stress.2 → S_{yy}    Stress.5 → S_{yz}
Stress.3 → S_{zz}    Stress.6 → S_{xz}
Step 1b: Add the Eigenvalues Solver

Objective: compute the eigenvalues of the Cauchy stress tensor

- Add a Solver
  Solver 4
  Equation = "EigenStresses"
  Procedure = "ElmerIceSolvers" "ComputeEigenValues"
  Variable = -nooutput dumy
  Variable DOFs = 1

  ! The 3 eigenvalues
  Exported Variable 1 = EigenStress
  Exported Variable 1 DOFS = 3

  ! The 3 eigenvectors (Option)
  Exported Variable 2 = EigenVector1
  Exported Variable 2 DOFS = 3
  Exported Variable 3 = EigenVector2
  Exported Variable 3 DOFS = 3
  Exported Variable 4 = EigenVector3
  Exported Variable 4 DOFS = 3

End
Step 1.3: Add the Eigenvalues Solver

- Add this solver in the Equation Section
  Active Solvers(4) = 1 2 3 4

- Output:
  negative stress = Compressive stress
  positive stress = Tensile stress
  ordered → Eigenstress.3 gives the maximal tensile stress

  Eigenstress.1 → S_1
  Eigenstress.2 → S_2
  Eigenstress.3 → S_3
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Step 2a: Add the cavity (empty)

The initial problem

The new problem

Two BCs for the base:

\[ u = 0 \text{ if } z_b = b \]

\[ \sigma_{nn} = p_w \text{ if } z_b > b \]

\[ p_w = 0 \text{ if the cavity is empty of water} \]

!!! The ice bottom surface is not anymore given by the bedrock DEM !!!
Step 2a: new Bottom Surface definition

The bottom surface is now given by the BottomSurface function in USF_TR.f90 (and not anymore the bedrock function)

Change the boundary condition 2:

Boundary Condition 2
  Bottom Surface = Variable Coordinate 1
    Real Procedure "./USF_TR" "BottomSurface"
End
Step 2a: Make a new mesh

We will use the cavity contour to have smaller size elements in the vicinity of the cavity

Work to do: modify the Makegeo.m file to create this new mesh.
Step 2: Make a new mesh

```matlab
clear;
lc_out=18.0;
lc_in=6.0;
A=dlmread('Contour_TR_glacier.dat');
B=dlmread('Contour_TR_cavity.dat');
fid1=fopen('teterousse.geo','w');
As=size(A,1);
Bs=size(B,1);
np=0;
for ii=1:As
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,A(ii,1),A(ii,2),lc_out);
end
for ii=1:Bs
    np=np+1;
    fprintf(fid1,'Point(%g)={%14.7e,%14.7e,0.0,%g}; \n',np,B(ii,1),B(ii,2),lc_in);
end
fprintf(fid1,'Spline(1)={');
for ii=1:As
    fprintf(fid1,'%g,',ii);
end
fprintf(fid1,'%g}; \n',1);
fprintf(fid1,'Spline(2)={');
for ii=1:Bs
    fprintf(fid1,'%g,',As+ii);
end
fprintf(fid1,'%g}; \n',As+1);
```
Step 2a: Make a new mesh

```matlab
fprintf(fid1,'Line Loop(3)={1}; \n');
fprintf(fid1,'Line Loop(4) = {2}; \n');
fprintf(fid1,'Plane Surface(5) = {3, 4}; \n');
fprintf(fid1,'Plane Surface(6) = {4}; \n');
fprintf(fid1,'Physical Line(7) = {1}; \n');
fprintf(fid1,'Physical Surface(8) = {5,6}; \n');
fclose(fid1)

% create teterousse.msh using gmsh
!gmsh teterousse.geo -1 -2

% convert teterousse.gmsh in an Elmer type mesh
!ElmerGrid 14 2 teterousse.msh –autoclean
```
Step 2a: Change in the basal BC

The basal BC will be of the form:

\[
\begin{align*}
\text{Velocity 1} &= \text{Real 0.0} \\
\text{Velocity 1 Condition} &= \text{Variable Coordinate 1} \\
\text{Real Procedure} &= \text{"./USF_TR" "MaskCavity"}
\end{align*}
\]

And the same for Velocity 2 and Velocity 3.

The user function MaskCavity returns +1 where \( z_b = b \), -1 where \( z_b > b \). \( z_b \) is the node altitude, \( b \) is given by the bedrock DEM.

use the same interpolation function (InterpolateDEM) than the other DEM functions.

Visualize the results in ElmerPost.
What does it change in term of velocity and stress?
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Step 2.1: Add a water pressure

Modify the SIF to add a water pressure

\[ p_w = \rho_w g (h_w - z) \]

$hw = 3170.0$

the water load

In the bedrock BC

Flow Force BC = Logical True
External Pressure = Variable Coordinate 3
Real MATC ",-rhow*gravity*(hw-tx)"

will only apply where a Dirichlet BC is not applied
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Step 3a: Move to prognostic

Will do it in two steps
- Move to prognostic assuming the cavity is empty of water at $t=0$
  (big step, need 2 new solvers!)
- Prescribe the observed drainage scenario for the water pressure

To move from a diagnostic to a prognostic simulations:
- Add the FreeSurface solver (here 2 times, since we have 2 FS)
- Add one body per FS (new Initial Condition and Equation Sections)
- Modifications in the Simulation and Boundary Condition Sections

Only shown for the upper free surface here
Step 3a – Steady to transient

The simulation Section has to be modified:

Simulation Type = Transient

Timestepping Method = “bdf”
BDF Order = 1
Output Intervals = 1
Timestep Intervals = 200
Timestep Sizes = 1.0

Steady State Min Iterations = 1
Steady State Max Iterations = 1

Backward Differences Formulae
Save in .ep file

To control the “implicity” of the solution over one time step (here 1 means explicite)
Step 3a – Sketch of a transient simulation

Geometry + Mesh → Degrees of freedom

Linear System: \( A \cdot x = b \)
- Direct
- Iterative \( \varepsilon_L \)

Non Linear iterations: \( A = A(x) \)

Coupled iteration over \( dt \) (implicit scheme)

\[ t = t + dt \]

\( \varepsilon_L < \varepsilon_{NL} < \varepsilon_C \)
Step 3a – Free surface Solver

The free surface solver only apply to the boundary 3 (upper surface)

Define a 2nd body which is the boundary 3.

Body 2
   Equation = 2
   Body Force = 2
   Material = 1
   Initial Condition = 2
End

where Equation 2, Body Force 2 and Initial Condition 2 are defined for the free surface equation of the upper surface.

Tell in BC2 that this is the body 2:
   Boundary Condition 3
   Body Id = 2
   ...
End
Step 3a – Add the Free surface Solver

Solver 4
Equation = "Free Surface Top"
Variable = String "Zs Top"
Variable DOFs = 1
Exported Variable 1 = String "Zs Top Residual"
Exported Variable 1 DOFs = 1

Procedure = "FreeSurfaceSolver" "FreeSurfaceSolver"
Before Linsolve = "EliminateDirichlet" "EliminateDirichlet"

Linear System Solver = Iterative
Linear System Max Iterations = 1500
Linear System Iterative Method = BiCGStab
Linear System Preconditioning = ILU0
Linear System Convergence Tolerance = Real 1.0e-9
Linear System Abort Not Converged = False
Linear System Residual Output = 1

Nonlinear System Max Iterations = 100
Nonlinear System Convergence Tolerance = 1.0e-6
Nonlinear System Relaxation Factor = 1.00

Steady State Convergence Tolerance = 1.0e-03

Stabilization Method = Bubbles
Apply Dirichlet = Logical False

! How much the free surface is relaxed
Relaxation Factor = Real 1.00

! Is there a maximum step-size for the displacement
! use/or not accumulation
Use Accumulation = Logical True

! take accumulation to be given normal to surface/as vector
Normal Flux = Logical False

End
Step 3a – Upper Surface

Body Force 2:

```
Body Force 2
  Zs Top Accumulation Flux 1 = Real 0.0e0
  Zs Top Accumulation Flux 2 = Real 0.0e0
  Zs Top Accumulation Flux 3 = Real 0.0e0
End
```

Equation 2:

```
Equation 2
  Active Solvers(1) = 2
  Flow Solution Name = String "Flow Solution"
  Convection = String Computed
End
```

Initial Condition 2: (tell that \( z_s(x, 0) \) is given by the surface DEM)

```
Initial Condition 2
  Zs Top = Variable Coordinate 1
    Real Procedure "./USF_TR" "TopSurface"
End
```
Step 3a - StructuredMeshMapper

We know say in StructuredMeshMapper that the top (and bottom) surface is defined by the variable zs top:

Solver 1
   Equation = "MapCoordinate"
   Procedure = "StructuredMeshMapper" "StructuredMeshMapper"

   Active Coordinate = Integer 3
   Mesh Velocity Variable = String "dSdt"
   Mesh Update Variable = String "dS"
   Mesh Velocity First Zero = Logical True

   Top Surface Variable Name = String "Zs Top"
   Bottom Surface Variable Name = String "Zs Bottom"
End

And delete from the BC the initial definition of the top (and bottom) surface:

Boundary Condition 3
!!! this BC is equal to body no. 2 !!!
   Body Id = 2

   — Top Surface = Variable Coordinate 1
   —— Real Procedure "./USF_TR" "TopSurface"
End
Step 3a – Same for the bedrock

Name of the variable: Zs Bottom
Add solver: Solver 5
Add equation: Equation 3

Modify the the Bottom surface BC (3):

Boundary Condition 2
Body Id = 3
Bottom Surface = Variable Coordinate 1
Real Procedure "./USF_TR" "BottomSurface ">
End

Add a limiter to ensure that $z_b \geq b$
In the material section

Min Zs Bottom = Variable Coordinate 1
   Real Procedure "./USF_TR" "Bedrock"
Max Zs Bottom = Real +1.0e10

+ in the Free Surface solver: Apply Dirichlet = Logical True
Step 3a – Newton linearization

If you want to use Newton linearization for the non-linear iterations, don’t forget to reset the conditions used to move from Picard to Newton at each time step, by adding:

Solver 1

Nonlinear System Reset Newton = Logical True

End
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Step 3b – Add a drainage scenario

Add an evolution of the water load of the form:

\[ h_w = 3170.0 - t \cdot \Delta h_w / \Delta t \]

Work to do: 
write a MATC function hw to prescribe the water load evolution
Step 3b – Add a drainage scenario

MATC function $hw$ to prescribe the water load evolution:

! Water load function of time (in year)
! Decrease by DH in DT
$ function hw(t) \{ \$
   DH = 70.0;\$
   DT = 20.0;\$
   _hw = 3170.0 - t*365.25*DH/DT ;\$
 }$

Call in the bedrock BC

External Pressure = Variable time, Coordinate 3
Real MATC "rhow*gravity*(hw(tx(0))-tx(1))"
More Steps ???

Some idea:

- go to parallel

- add the Savedata solver to get upper and lower surfaces output

- add the StructuredProjectToPlane solver

Solver 2
  Equation = "HeightDepth"
  Procedure = "StructuredProjectToPlane" "StructuredProjectToPlane"
  Active Coordinate = Integer 3

  Operator 1 = depth
  Operator 2 = height

End
References