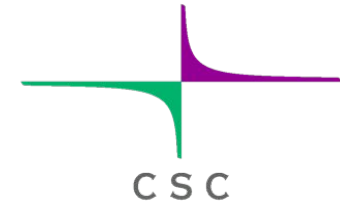


Laboratoire de Glaciologie et Géophysique de l'Environnement



A real world application

Tête Rousse Glacier

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LGGE - Grenoble - France

Tête Rouse Glacier

✓ Context

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

✓ Step 1

- Tête Rouse Glacier flow without a water filled-cavity (diagnostic)

✓ Step 2

- Influence of an empty cavity below Tête Rouse Glacier (diagnostic)

✓ Step 3

- Rate of closure of the cavity for a given drainage scenario (prognostic)

Location (Mont Blanc Area, France Alps)



Location (Mont Blanc Area, France Alps)

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

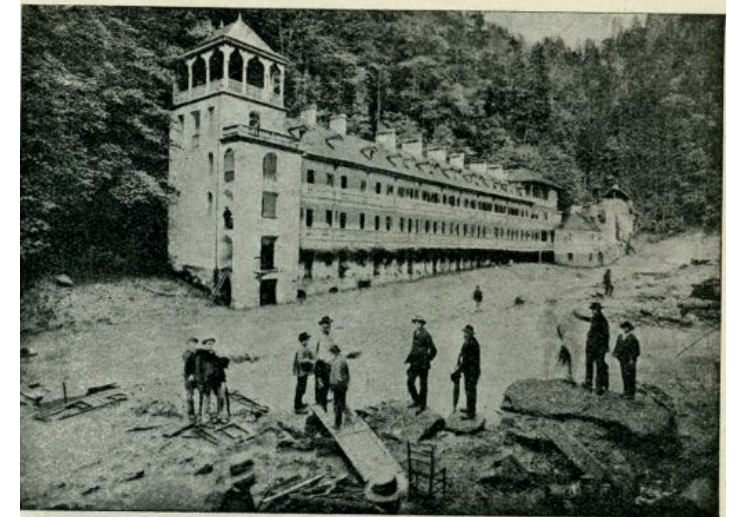
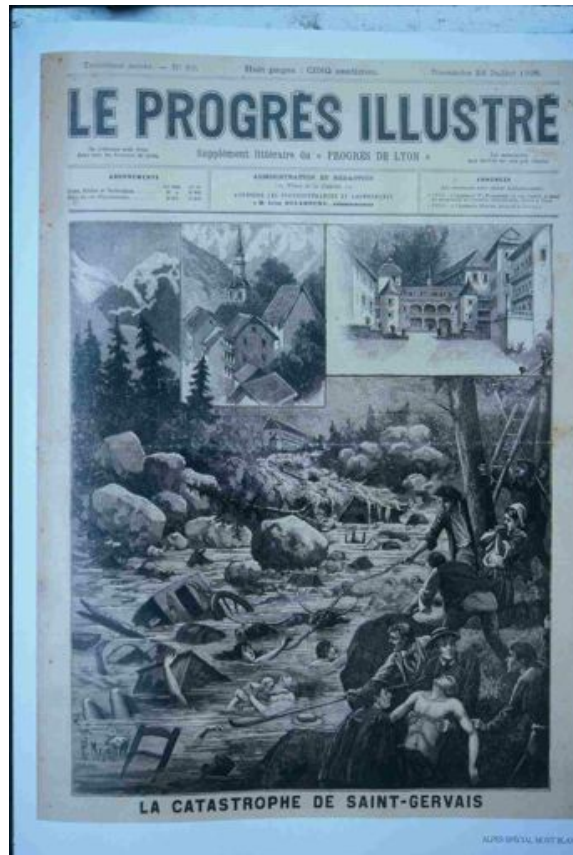
11 July 1892

175 fatalities

100 000 m³ of water

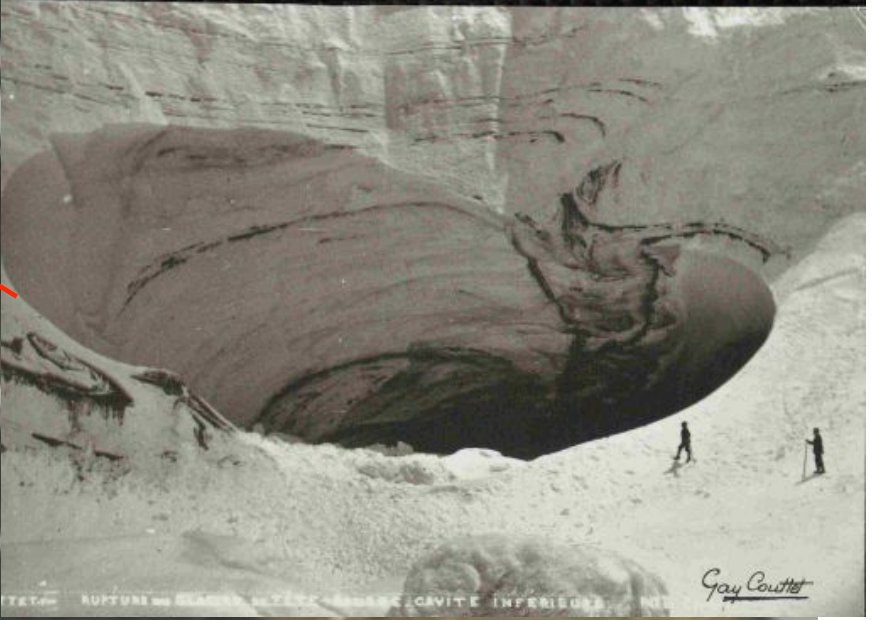
Flood produced

800 000 m³ of sediment



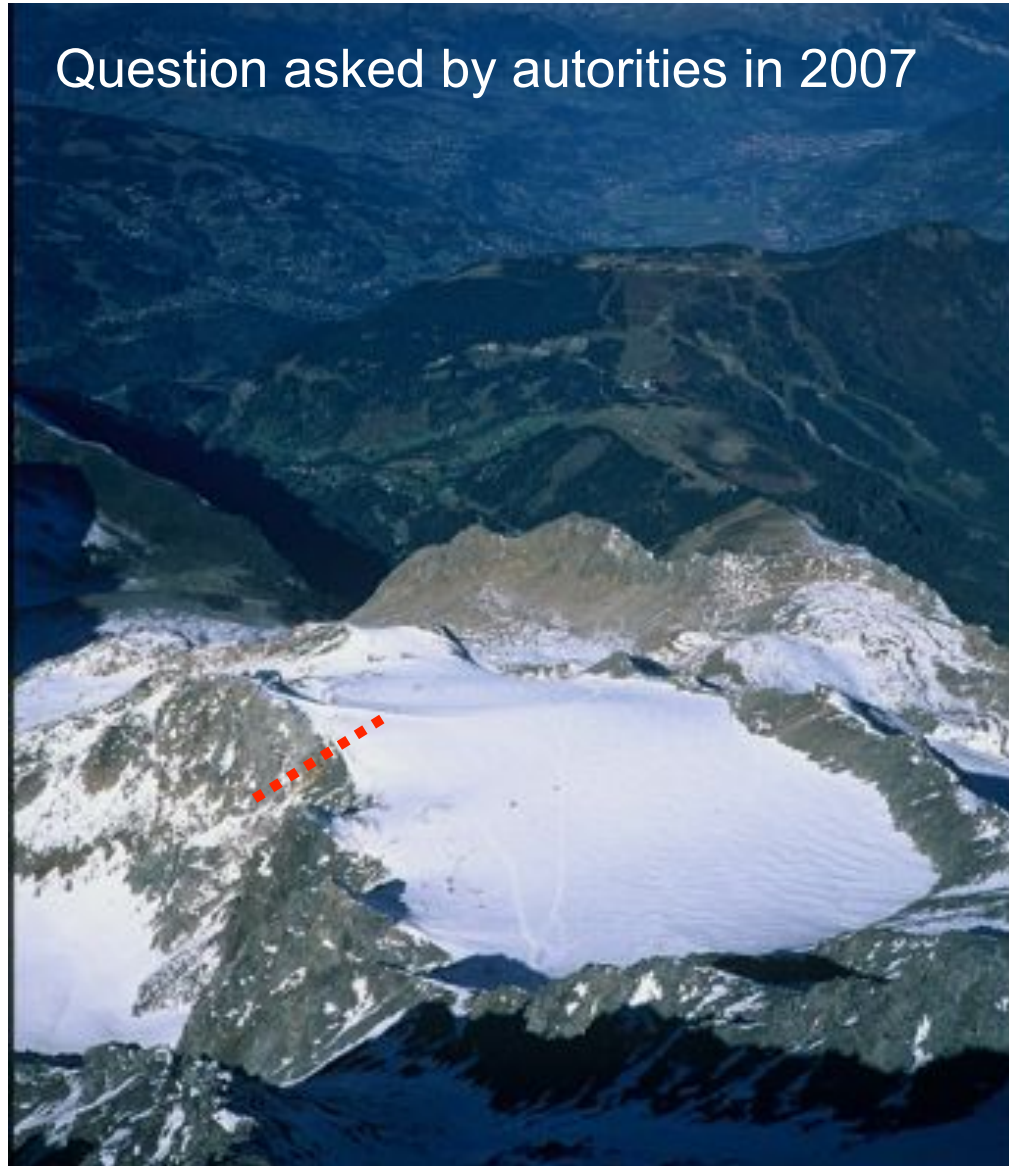
@Vincent, LGGE

The 1892 catastrophe



Is there still a risk at Tête Rousse ?

Question asked by authorities in 2007



@Vincent, LGGE

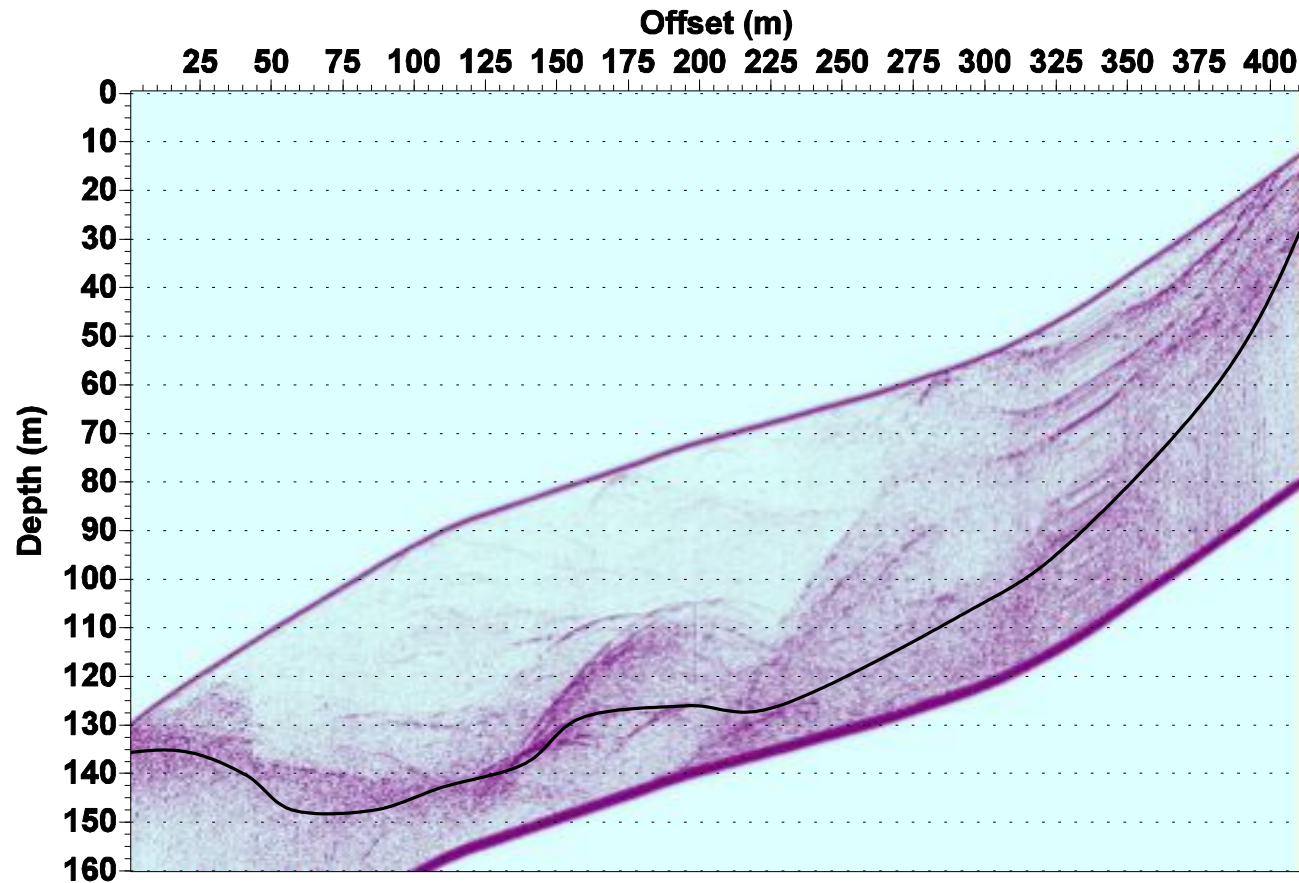
Glaciological studies

- . Topographic measurements
- . Radar measurements
- . Temperature measurements
- . Mass balance measurements



@Vincent, LGGE

Glaciological studies



@Vincent, LGGE

The radar measurements showed a zone (volume) with an anomaly.

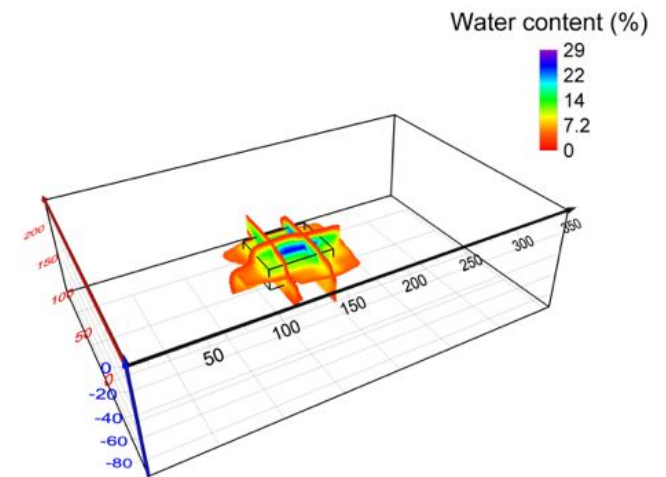
Glaciological studies

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



@Vincent, LGGE

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



A new risk ?

But was stopped the 1st September :

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

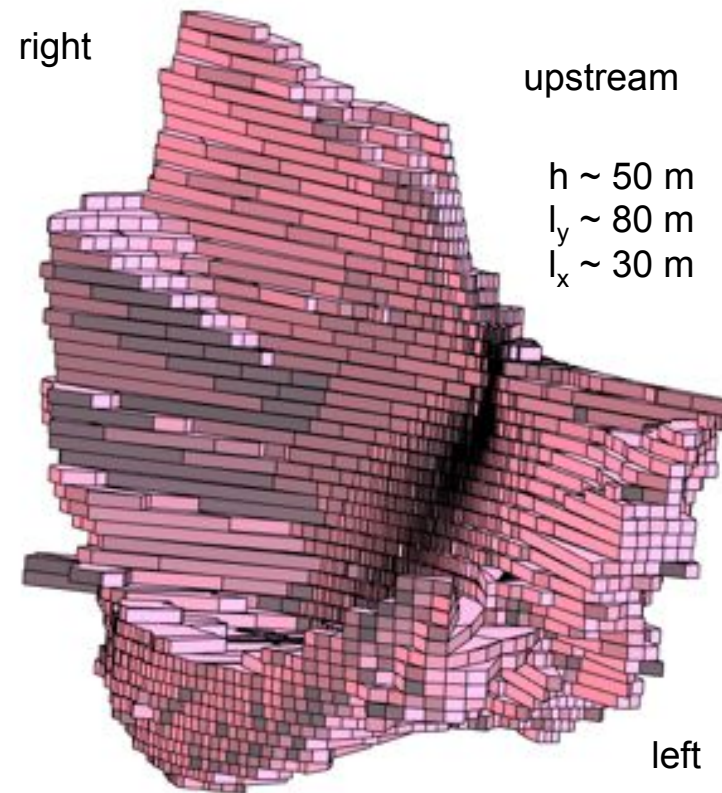


The 2010 cavity

Pumping of 47 700 m³ from 25 August to 8 October 2010

Question (addressed end of August 2010):

What is the risk of break-up during the pumping phase?



Timing for answering

Sonar data

Septembre

D	L	M	E	J	V	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

Meeting with the
mayor of St
Gervais

Proposed application

Construct a model of the flow of Tête Rousse Glacier

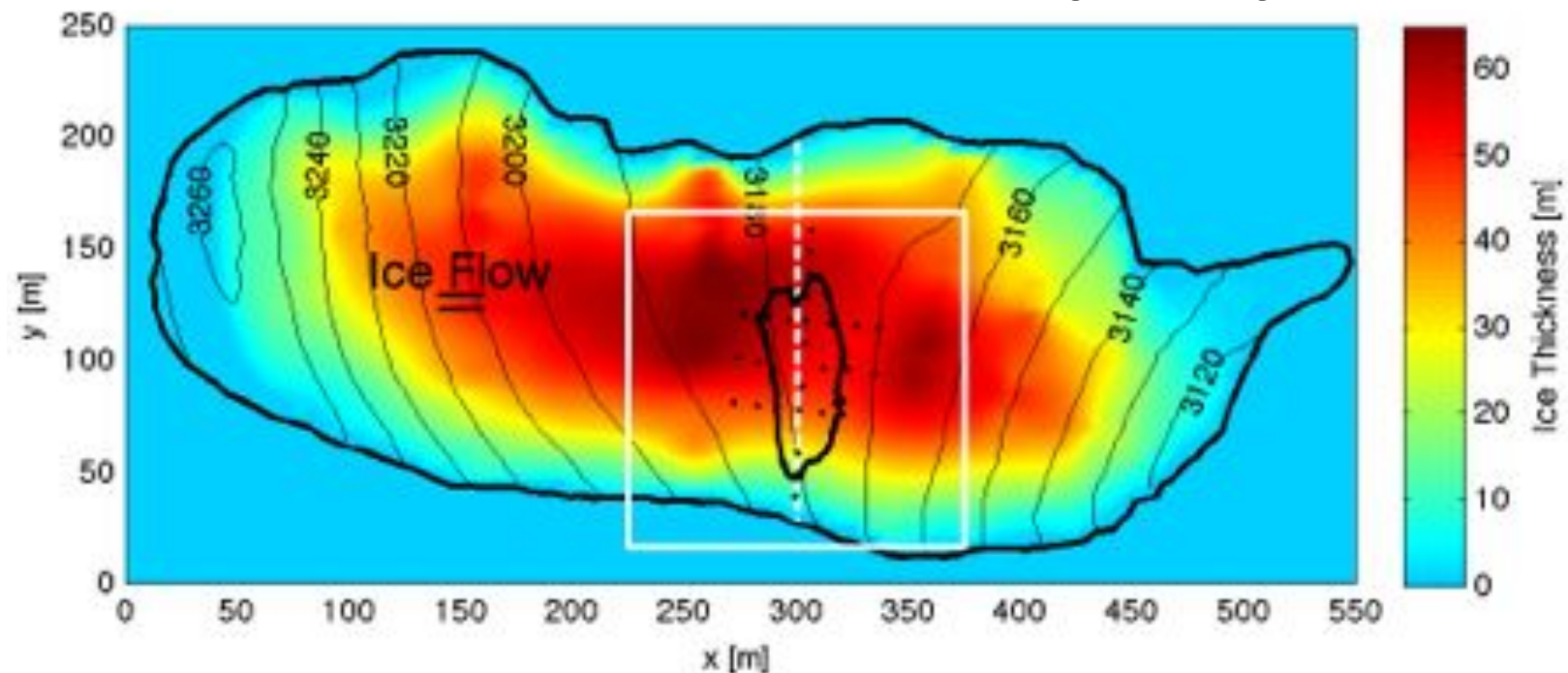
- Step 1: Without the cavity (normal state)
- Step 2: Add an empty cavity (stress analysis)
- Step 3: Rate of closure of the cavity

(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



Modelling Tête Rouse Glacier

✓ Step 1

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

✓ Step 2

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

✓ Step 3

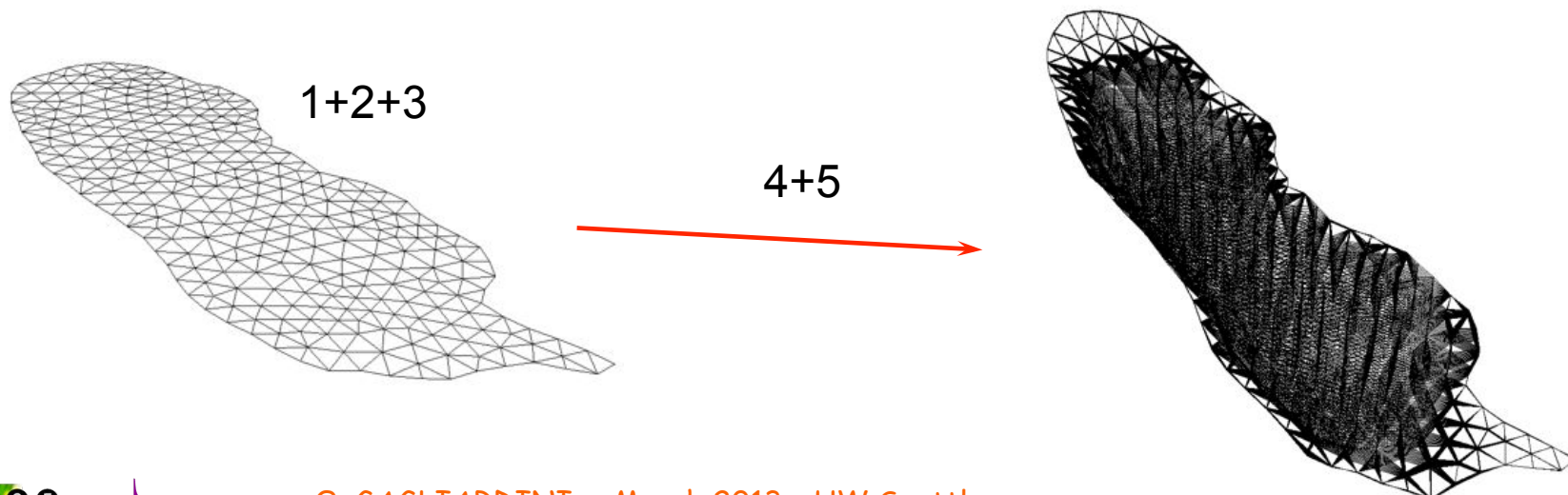
- 3 Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3.1 Add a drainage scenario

Step 1: 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 1: 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/ ExtrudeMesh to extrude vertically the footprint (now we have a 3D mesh)
- 5/ MshGlacierDEM to deform vertically the mesh using the surface and bedrock DEMs by modifying the mesh.nodes Elmer file



Step 1: Makegeo.m (create a .geo file)

```
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 1: Makegeo.m (Extrude)

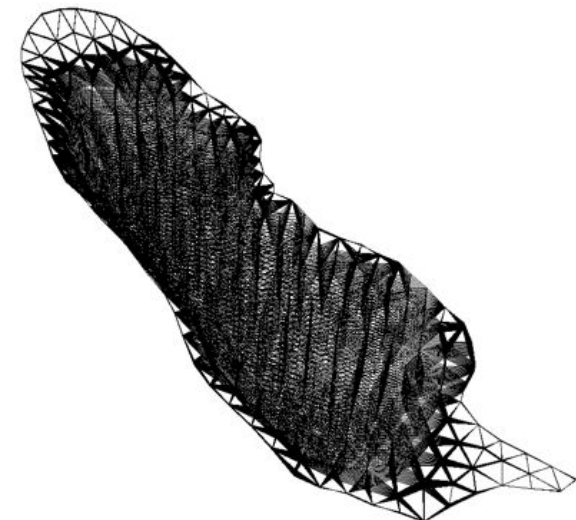
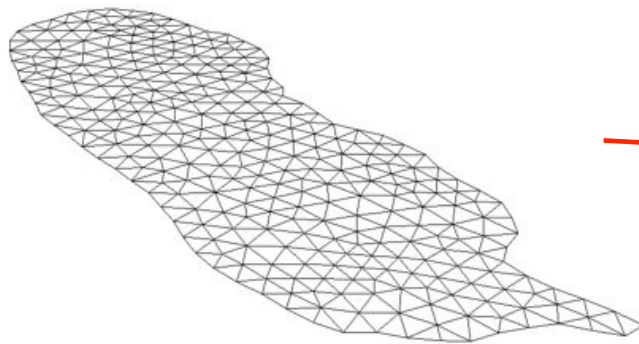
```
% create teterousse.msh using gmesh
!gmsh teterousse.geo -1 -2

% convert teterousse.gmsh in an Elmer type mesh
!ElmerGrid 14 2 teterousse.msh -autoclean

% Extrude vertically the mesh (1m thick)
!ExtrudeMesh teterousse WithOutCavity 14 1 1 0 0 0

% Deform vertically using the surface and bedrock DEM
% Input data are in mesh_input.dat
!./MshGlacierDEM

% Make a .ep to visualize in ElmerPost the mesh
!ElmerGrid 2 3 WithOutCavity
```



Step 1: 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 1: ExtrudeMesh

Get ExtrudeMesh in `elmerice/Meshers/`

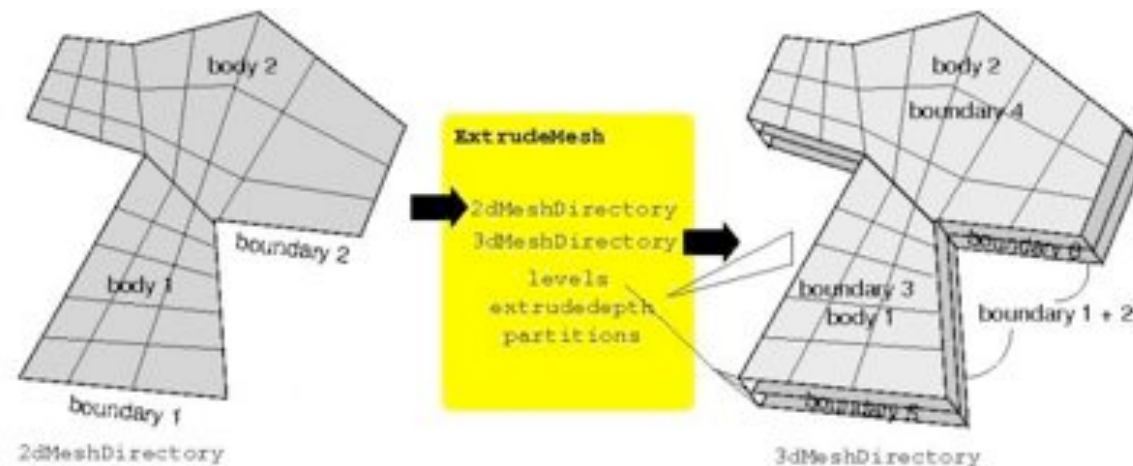
Compile it:

```
> cc ExtrudeMesh.c -o ExtrudeMesh -lm
```

Execute

```
ExtrudeMesh teterousse WithoutCavity 14 1 1 0 0 0 0
```

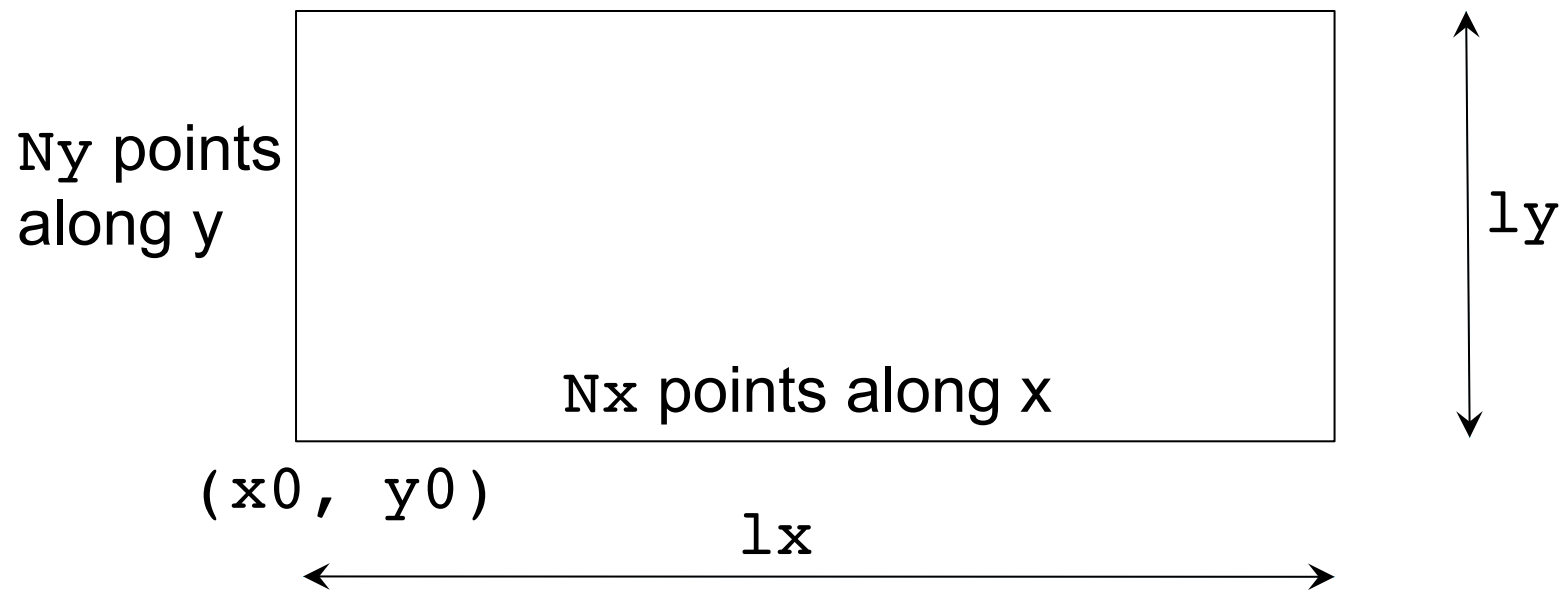
14 layers, 1m thick in total, 1 partition



Step 1: MshGlacierDEM

From surface and bedrock DEMs, deforms vertically the initial 1m height mesh.

Here surface and bedrock are given on a regular grid



Where data are missing : -9999

Step 1: MSH_Glacier3DGrille

Compile MSH_Glacier3DGrille

```
elmerf90-nosh ../elmerice/Meshers/MshGlacierDEM.f90 -o MshGlacierDEM
```

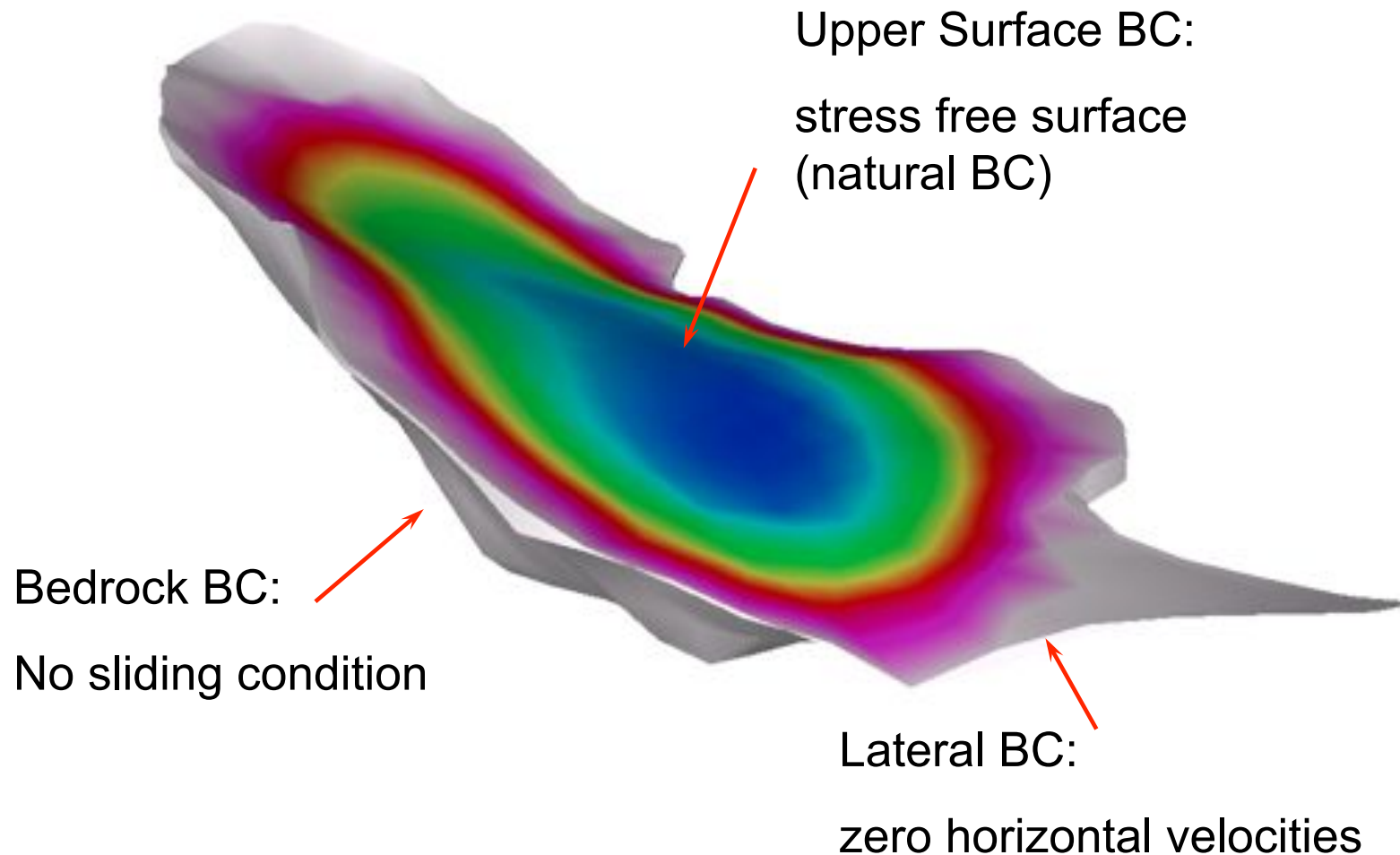
MshGlacierDEM reads mesh_input.dat

```
! Name of the mesh directory (should exist)
WithoutCavity
! Surface DEM name file
DEM_TR_surf.dat
! Nsx, Nsy
268 118
! xs0, ys0
947700.0 2104850.0
! lxx, lyy
800.0 350.0
! Bedrock DEM name file
DEM_TR_bed.dat
! Nbx, Nby
301 176
! xb0, yb0
947700.0 2104850.0
! lbx, lby
600.0 350.0
! Minimum ice thickness
1.0
```

Step 1: Hypothesis of the modelling

Solve only the Stokes equation in a diagnostic way

3 boundary conditions



Step 1: use Glen's law

$$D_{ij} = A \tau_e^{n-1} S_{ij} \quad ; \quad S_{ij} = A^{-1/n} I_{D_2}^{(1-n)/n} D_{ij}$$

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

$$A = A_1 = 2.89 \times 10^{-13} \text{ s}^{-1} \text{ Pa}^{-3} \text{ if } T \leq -10^\circ\text{C}$$

$$A = A_2 = 2.43 \times 10^{-2} \text{ s}^{-1} \text{ Pa}^{-3} \text{ if } T \geq -10^\circ\text{C}$$

$$Q = Q_1 = 60 \text{ kJ mol}^{-1} \text{ if } T \leq -10^\circ\text{C}$$

$$Q = Q_2 = 115 \text{ kJ mol}^{-1} \text{ if } T \geq -10^\circ\text{C}$$

Cuffey and Paterson (2010)

assume a constant temperature of -1°C

Paterson 2010		
A*	3.50000E-25	s ⁻¹ Pa ⁻³
A1	2.89165E-13	s ⁻¹ Pa ⁻³
A2	2.42736E-02	s ⁻¹ Pa ⁻³
Q1	60000	J/mol
Q2	115000	J/mol

T [°C]	A [s ⁻¹ Pa ⁻³]	A [s ⁻¹ MPa ⁻³]
0	2.4029E-24	75.830
-1	1.9945E-24	62.942
-2	1.6533E-24	52.173
-3	1.3685E-24	43.286
-4	1.1312E-24	35.698
-5	9.3370E-25	29.465
-6	7.6958E-25	24.286
-7	6.3339E-25	19.988
-8	5.2054E-25	16.427
-9	4.2716E-25	13.480
-10	3.5000E-25	11.045
-10	3.5000E-25	11.045
-11	3.1520E-25	9.947
-12	2.8363E-25	8.951
-13	2.5502E-25	8.048
-14	2.2910E-25	7.230
-15	2.0564E-25	6.490
-16	1.8444E-25	5.820
-17	1.6528E-25	5.216
-18	1.4798E-25	4.670
-19	1.3238E-25	4.177
-20	1.1831E-25	3.734
-21	1.0565E-25	3.334
-22	9.4260E-26	2.975
-23	8.4019E-26	2.651
-24	7.4822E-26	2.361
-25	6.6570E-26	2.101
-30	3.6580E-26	1.154
-35	1.9602E-26	0.619
-40	1.0225E-26	0.323
-45	5.1843E-27	0.164
-50	2.5496E-27	0.080

Step 1: use Glen's law

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

Material 1

```
Density = Real $rhoi
```

```
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 1: Boundary Conditions

```
! Bedrock
Boundary Condition 1
  Target Boundaries = 1

  Velocity 1 = Real 0.0
  Velocity 2 = Real 0.0
  Velocity 3 = Real 0.0
End

! Upper Surface
Boundary Condition 2
  Target Boundaries = 2
End

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

No sliding

Natural BC, nothing to do!

Null horizontal velocities

Step 1: Other BCs for the lateral boundary

```
! lateral side of the glacier  
Boundary Condition 3  
  Target Boundaries = 3  
End
```

Natural BC

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

zero velocity

Conclusion ?

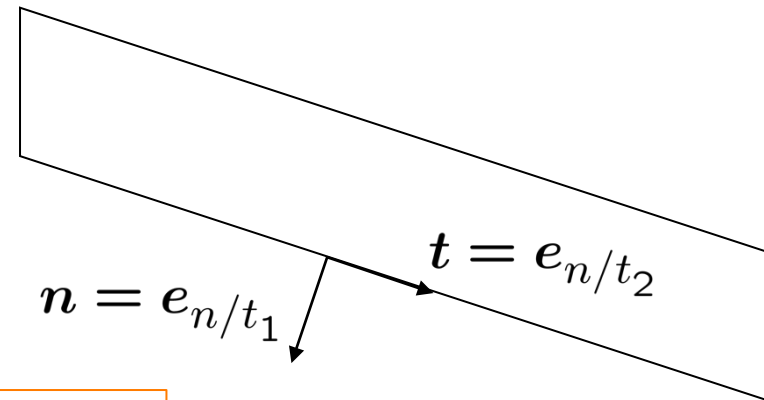
Step 1: Add sliding on the bedrock

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 1

Target Boundaries = 1

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 ?

Modelling Tête Rouse Glacier

✓ Step 1

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

✓ Step 2

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

✓ Step 3

- 3 Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3.1 Add a drainage scenario

Step 1.2: 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 η are calculated from the nodal velocities using the derivative of the basis functions

- Add a Solver

Solver 2

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 1.2: Add the Stress Solver

- Add this solver in the Equation Section

```
Active Solvers(2) = 1 2
```

- 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 → Sxx           Stress.4 → Sxy  
Stress.2 → Syy           Stress.5 → Syz  
Stress.3 → Szz           Stress.6 → Sxz
```

Modelling Tête Rouse Glacier

✓ Step 1

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✓ Step 2

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✓ Step 3

- 3 Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3.1 Add a drainage scenario

Step 1.3: Add the Eigenvalues Solver

Objective: compute the eigenvalues of the Cauchy stress tensor

- Add a Solver

Solver 3

```
Equation = "EigenStresses"
```

```
Procedure = "ElmerIceSolvers" "ComputeEigenValues"
```

```
Variable = -nooutput dummy
```

```
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(3) = 1 2 3

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

Eigenstress.1 \rightarrow S_1
Eigenstress.2 \rightarrow S_2
Eigenstress.3 \rightarrow S_3

Modelling Tête Rouse Glacier

✓ Step 1

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

✓ Step 2

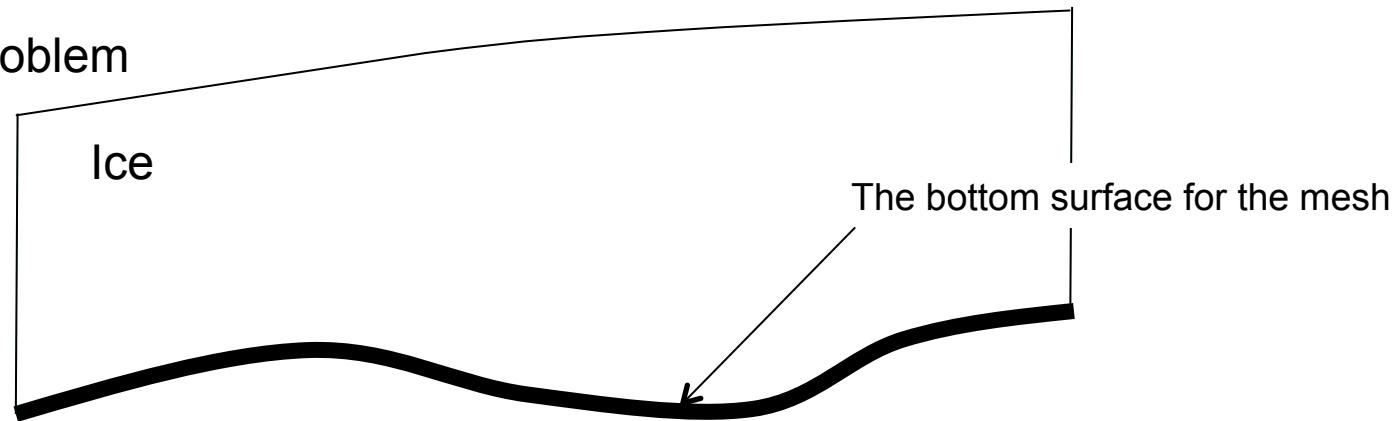
- 2 Influence of an empty cavity below Tête Rouse Glacier (diagnostic)
- 2.1 Apply a water pressure in the cavity

✓ Step 3

- 3 Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3.1 Add a drainage scenario

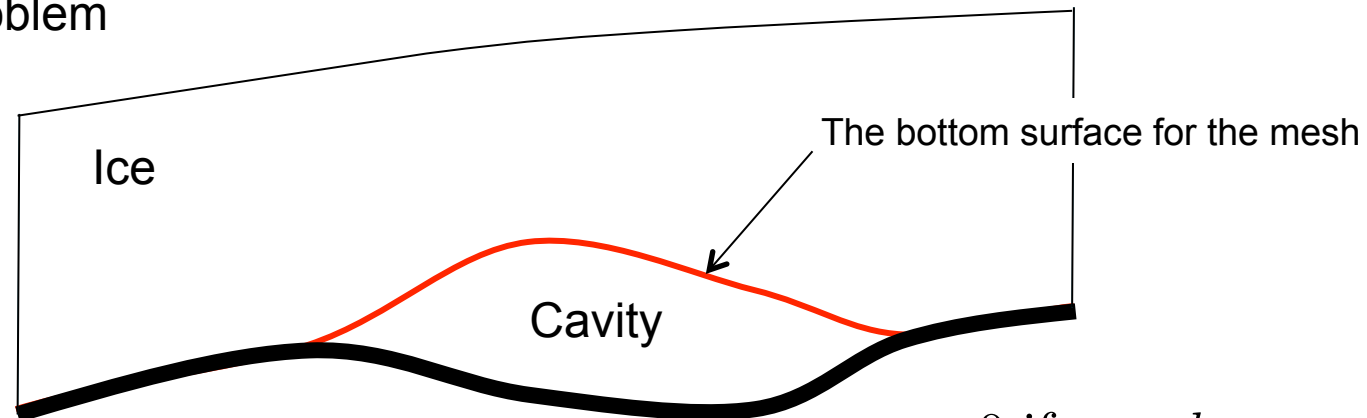
Step 2: Add the cavity (empty)

The initial problem



Only one BC for the base: no sliding

The new problem



Two BCs for the base:

$$\mathbf{u} = 0 \text{ if } z_b = b$$

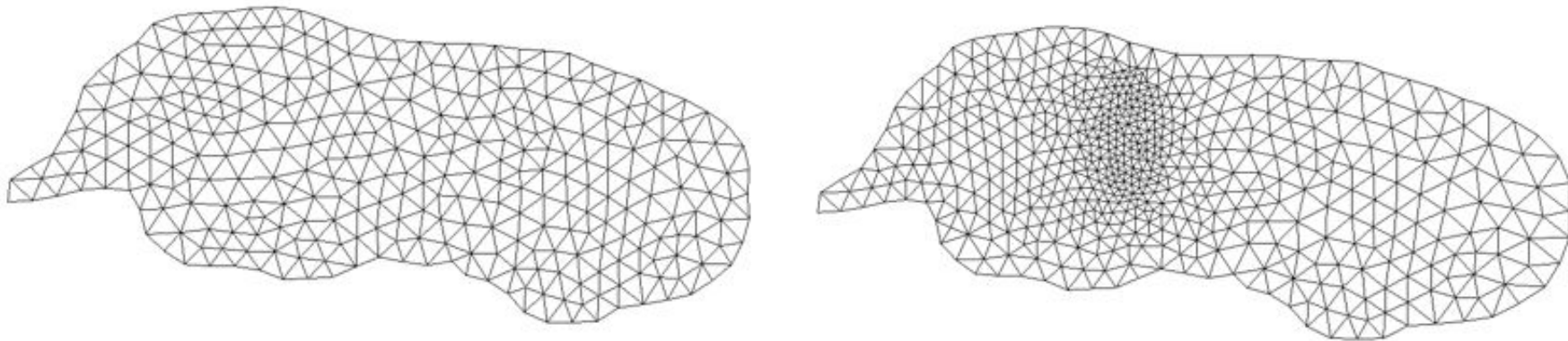
$$\sigma_{nn} = p_w \text{ if } z_b > b$$

$p_w = 0$ if the cavity is empty of water

Step 2: Make a new mesh

The bottom surface is now given by the DEM `DEM_TR_cavity.dat`

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.
Don't forget to modify the `mesh_input.dat`

Visualize the mesh in ElmerPost, you should see the cavity !
What does it change in term of velocity and stress?

Step 2: Make a new mesh

The new mesh_input.dat

```
! Name of the mesh directory (should exist)
WithCavity
! Surface DEM name file
DEM_TR_surf.dat
! Nsx, Nsy
268 118
! xs0, ys0
947700.0 2104850.0
! lxx, lyy
800.0 350.0
! Bedrock DEM name file
DEM_TR_cavity.dat
! Nbx, Nby
301 176
! xb0, yb0
947700.0 2104850.0
! lbx, lby
600.0 350.0
! Minimu Ice Thickness
1.0
```

Step 2: Make a new mesh (Makegeo_2.m) 1/2

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

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

fprintf(fidl,'Spline(2)={');
for ii=1:Bs
    fprintf(fidl,'%g,',As+ii);
end
fprintf(fidl,'%g}; \n',As+1);
```

Step 2: Make a new mesh (Makegeo_2.m) 2/2

```
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

% Extrude vertically the mesh (1m thick)
!ExtrudeMesh teterousse WithCavity 14 1 1 0 0 0 0

% Deform vertically using the surface and bedrock DEM
% Input data are in mesh_input.dat
!./MshGlacierDEM

% Make a .ep to visualize in ElmerPost the mesh
!ElmerGrid 2 3 WithCavity
```

Step 2: Change in the basal BC

The basal BC will be of the form:

```
Velocity 1 = Real 0.0
```

```
Velocity 1 Condition = Variable Coordinate 1
```

```
Real Procedure "./USF_TR" "MaskCavity"
```

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

Work to do : modify the SIF (Bed BC + mesh name + name)

write the user function `USF_TR.f90` using the same interpolation as in `MSH_Glacier3DGrille.f90`

Compile it: `elmerf90 USF_TR.f90 -o USF_TR`

Visualize the results in ElmerPost.

What does it change in term of velocity and stress?

Step 2: MaskCavity

The user function has to do:

- Evaluate for the called node (x,y,z), the bedrock altitude (Copy and paste from MshGlacierDEM.f90)
- Then, if $z > \text{bed}$, return -1, else if $z = \text{bed}$ returns +1
- To save time, the reading of the DEM is done only the first time and x_b, y_b, z_b are saved.

```
x = Model % Nodes % x(nodenumbr)
y = Model % Nodes % y(nodenumbr)

znodenumbr = Model % Nodes % znodenumbr
IF (znodenumbr > Zbed+0.1) THEN
    Mask = -1.0
ELSE
    Mask = 1.0
END IF
```

Modelling Tête Rouse Glacier

✓ Step 1

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

✓ Step 2

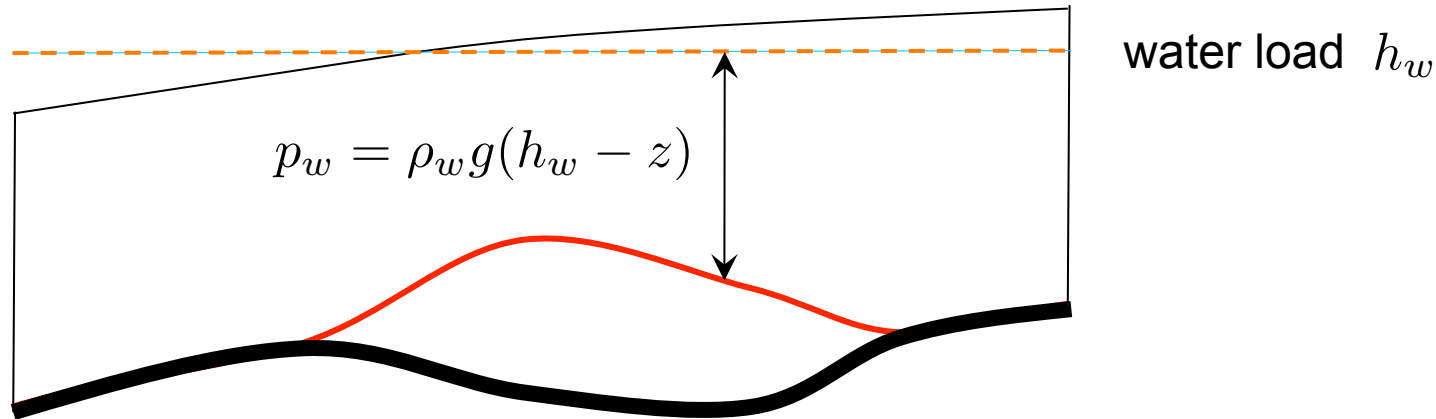
- 2 Influence of an empty cavity below Tête Rouse Glacier (diagnostic)
- 2.1 Apply a water pressure in the cavity

✓ Step 3

- 3 Rate of closure of the cavity for a given drainage scenario (prognostic)
- 3.1 Add a drainage scenario

Step 2.1: Add a water pressure

Modify the SIF to add a water pressure



\$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 3: 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 3 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 the MeshUpdate solver to deform the mesh from the FS

displacements

- 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 3 – Steady to transient

The simulation Section has to be modified:

Simulation Type = Transient

Timestepping Method = "bdf" → Backward Differences Formulae

BDF Order = 1

Output Intervals = 1 → Save in .ep file

Timestep Intervals = 200

Timestep Sizes = 1.0

Steady State Min Iterations = 1

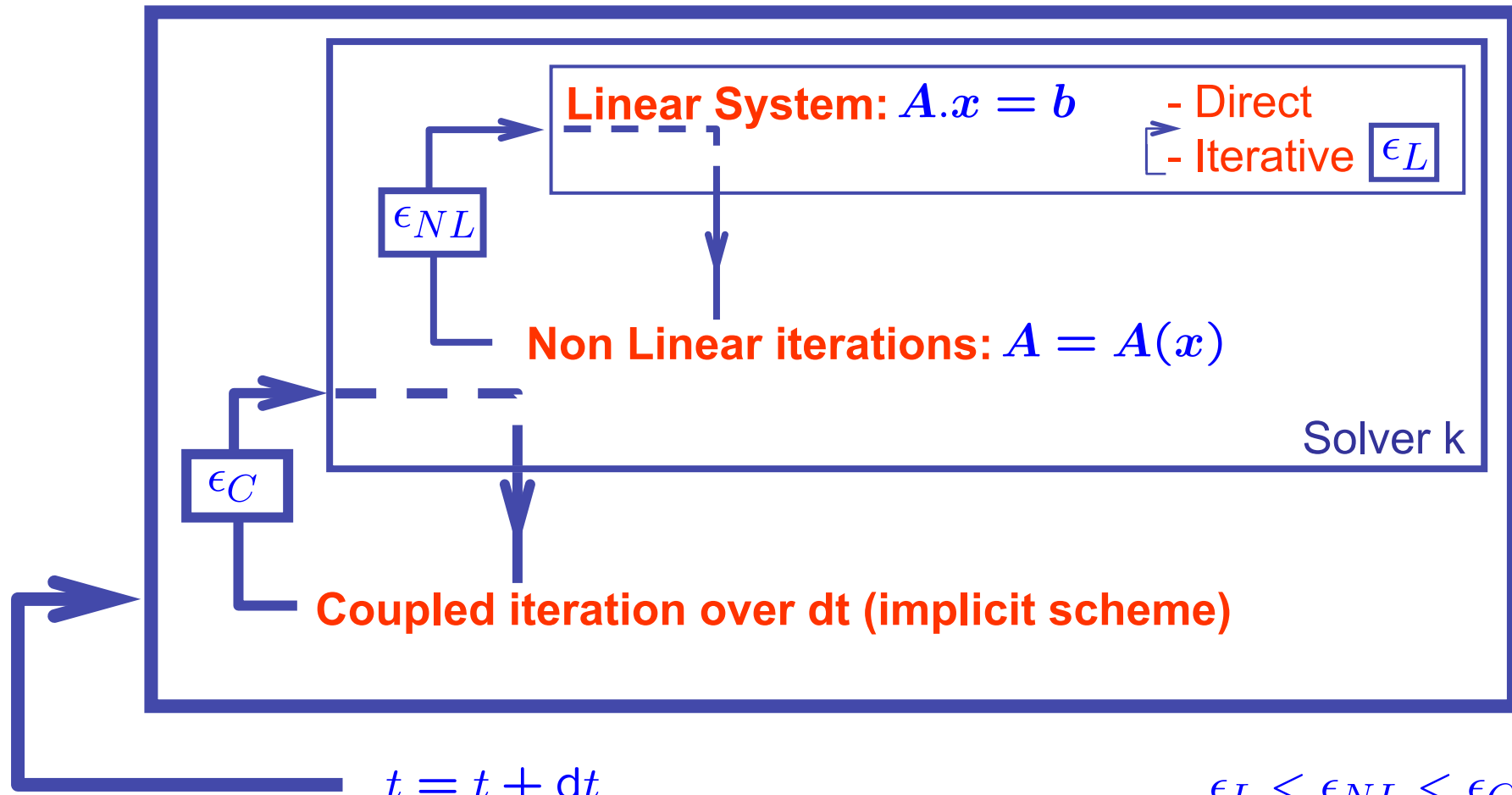
Steady State Max Iterations = 1 → To control the "implicitness" of the solution over one time step (here 1 means explicit)

Step 3 – Sketch of a transient simulation

Geometry + Mesh



Degrees of freedom



$$\epsilon_L < \epsilon_{NL} < \epsilon_C$$

Step 3 – 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 2
  Target Boundaries =2
  Body Id = 2
  ...
End
```

Step 3 – 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 3 – 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 $z_s(x, 0)$ = ordinate of the initial top surface)

```
Initial Condition 2
  Zs Top = Variable Coordinate 1
  Real Procedure "ElmerIceUSF" "ZsTopIni"
End
```

Have a look to this User
Function in
[elmerice/UserFunctions](#)

Step 3 – Mesh Update Solver

Add the Mesh Update Solver:

```
Solver 6  
Equation = "Mesh Update"  
Linear System Solver = "Direct"  
Linear System Direct Method = umfpack  
Steady State Convergence Tolerance = 1.0e-04  
End
```

Material parameter for this solver:

```
Mesh Youngs Modulus = Real 1.0  
Mesh Poisson Ratio = real 0.3
```

Force that Mesh Update 1 and 2 =0 everywhere:

```
Body Force 1  
Mesh Update 1 = Real 0.0  
Mesh Update 2 = Real 0.0  
End
```

Step 3 – Mesh Update Solver BC

In all Boundary conditions:

```
Mesh Update 1 = real 0.0
```

```
Mesh Update 2 = real 0.0
```

For the upper surface BC (2):

```
Mesh Update 3 = Variable Zs Top
```

```
Real Procedure "ElmerIceUSF" "ZsTopMzsIni"
```

Step 3 – Same for the bedrock

Name of the variable: Zs Bottom

Add solver : Solver 5

Add equation: Equation 3

For the Bottom surface BC (3):

```
Boundary Condition 1
```

```
Target Boundaries =1
```

```
Body Id = 3
```

```
Mesh Update 3 = Variable Zs Top
```

```
Real Procedure "ElmerIceUSF" "ZsBottomMzsIni"
```

```
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" "MinZsBottom"
```

```
Max Zs Bottom = Real +1.0e10
```

Same as MaskCavity
but return zbed

+ in the Free Surface solver : Apply Dirichlet = Logical True

Step 3 – 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 False
```

```
End
```

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Step 3.1 – Add a drainage scenario

Add an evolution of the water load of the form:

$$h_w = 3170.0 - t * \Delta h_w / \Delta t$$

Work to do:

write a MATC function h_w to prescribe the water load evolution

Step 3.1 – 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 "rho*gravity*(hw(tx(0))-tx(1))"
```

More Steps ???

Some idea:

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

References

Gagliardini O., F. Gillet-Chaulet, G. Durand, C. Vincent and P. Duval, 2011. Estimating the risk of glacier cavity collapse during artificial drainage: the case of Tête Rousse Glacier. *Geophys. Res. Lett.*, 38, L10505, doi:10.1029/2011GL047536.