



RÉPUBLIQUE
FRANÇAISE

*Liberté
Égalité
Fraternité*



*maîtriser le risque
pour un développement durable*

RISK ASSESSMENT OF OPEN PIT LAKE USING IN SITU OBSERVATIONS AND ADVANCED NUMERICAL MODELLING – APPLICATION ON MOST LAKE

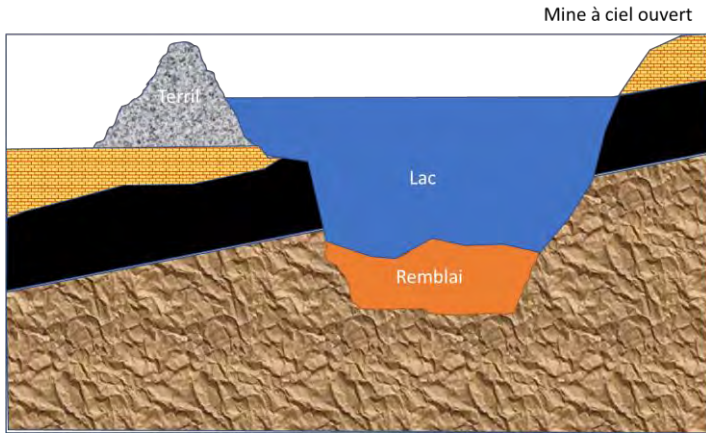
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- Introduction
- Risk analysis and assessment
- Slope stability methodology – lac Most case study
- Conclusion

Lake creation: morphology and risk assessment

Three specific characteristics of open pit lakes:

- Complex structure: geology, hydrogeology, geotechnical, **pollution**, etc.
- Recent structure: new and artificial creation
- Reuse and valorisation: industrial, agriculture, sport, etc.



Morphology

Water: inflow and outflow - hazards

Cause of Death on Abandoned Mines in USA (2001-2017)

Drowning	201
ATV accident	23
Fall	24
Asphyxiation/suffocation	9
Other	21
Total	278

Note – during the same period, there were 63,648 drowning deaths in the USA

Risk can causes:

- Fatalities, Missing people, Injuries
- Compromised transport routes including roads, bridges and railways, Illness
- River pollution, Flora and fauna damage and contamination
- Power disruption, Utility damage, Drainage contamination, Flooding, Water contamination, Mud slides and spills
- Villages submerged, Homes lost

State of flooded open pit mine

Open pit lakes due to flooded mines are young and therefore are typically in a non-equilibrium state with respect to their rate of filling, water quality, and biology.

The **long-term stability** depends on different aspects of open pit lakes, including their **morphometry**, geology, **hydrogeology**, **geochemistry**, and **biology**.



Objectives:

Elaboration of an assessment methodology of risks which may affect flooded open pit mines.

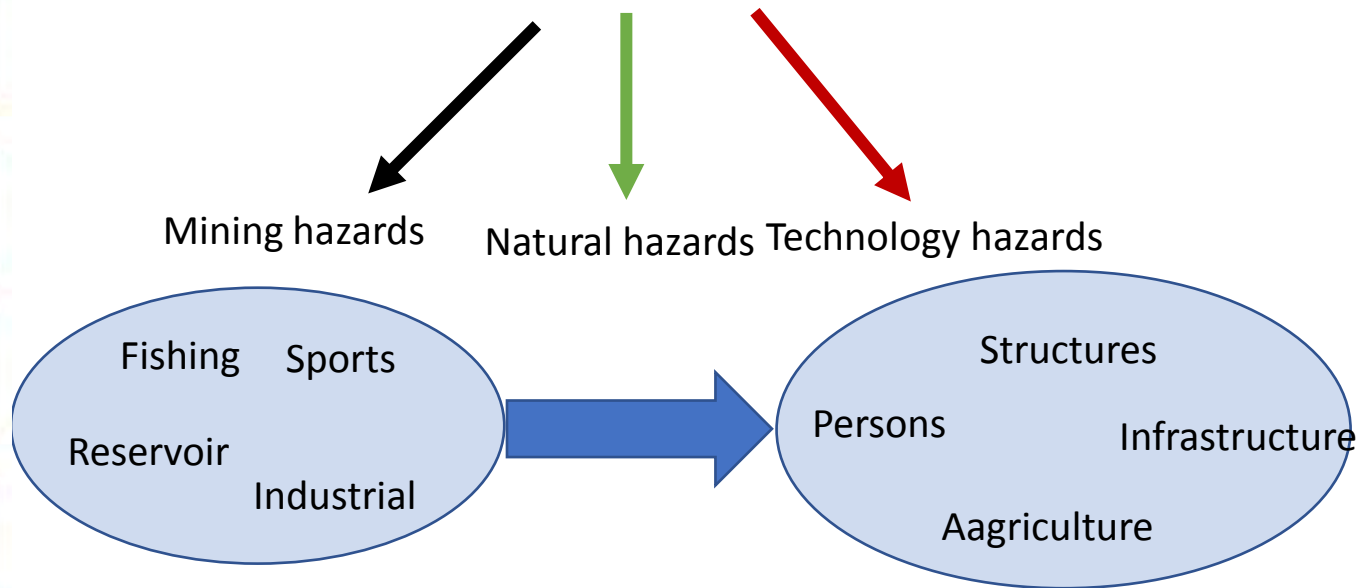
- **Development** of a reliability methodology for assessing the long-term stability of flooded open pit mines
- **Elaboration** of a comprehensive risk assessment methodology of flooded open pit mines
- **Elaboration** of guidelines for risks assessment during and after flooding of final pit

Risk identification of open pit lake



Risks are related to public access and safety

Risk = hazard * vulnerability of elements at risks



Risk assessment: collect of the data

Geometry/geomorphology data:

- Average slope angle and the range of variation
- Shape and geometry of the excavation
- Excavation depth
- Excavation method
 - Blasting / mechanical
- Mine orientation

Geotechnical and geology data

- Soil/rock layers type
- Strength estimation
- Homogeneity degree
- Existing of local/major faults and characterization

Hydrogeology data

- Average water level
- Flooding date
- Water level variation
- Water resources
- Water seepage
- Drainage

Filling materials:

- Existing partial filling
- Depth
- Type of filling material

Monitoring and inspection

- Of ground movement
- Of water level
- Type of monitoring: periodic or continuous
- Analysis and reporting

Accidents and instability problems

- Local/global instability
- Volume and frequencies
- Damages and consequences
- Treatment and reinforcement

External factors:

Seismicity

Traffic

Flooding / heavy rain

Erosion

Human and industrial activities

Data reliability for risk assessment

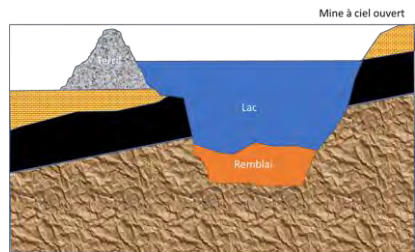
Analysis of the reliability of the data necessary for carry out risk assessment of pit lake. The data may be adopted, rejected or completed to establish geotechnical, hydrogeological hazard analysis

Table 1 Suggested target levels of data confidence by project stage (after Read 2009b)

Project stage						Depends on date of mine	
Project level status	Conceptual	Pre-feasibility	Feasibility	Design and construction	Operations	Closer mine	Pit lake
Geotechnical level status	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7
Geotechnical characterisation	Pertinent regional information	Assessment and compilation of initial mine-scale geotechnical data	Ongoing assessment and compilation of all new mine-scale geotechnical data	Refinement of geotechnical database and 3D model	Ongoing maintenance of geotechnical database and 3D model		
Target levels of data confidence for each model							
Geology	>50%	50–70%	65–85%	80–90%	>90%	>75	>90
Structural	>20%	40–50%	45–70%	60–75%	>75%	>75	>75
Hydrogeological	>20%	30–50%	40–65%	60–75%	>75%	>75	>75
Rock mass	>30%	40–65%	60–75%	70–80%	>80%	>80	>80
Geotechnical	>30%	40–60%	50–75%	65–85%	>80%	>80	>80

Lakes in Europe

Hazards identification related to open pit lake



Pollution and chemical hazards

Geohazards: dumps/open pit mine

Combustion hazards (dumps/ coal seam)

Hydrology and water hazards

Mining hazards

Earthquakes

Karst cavities

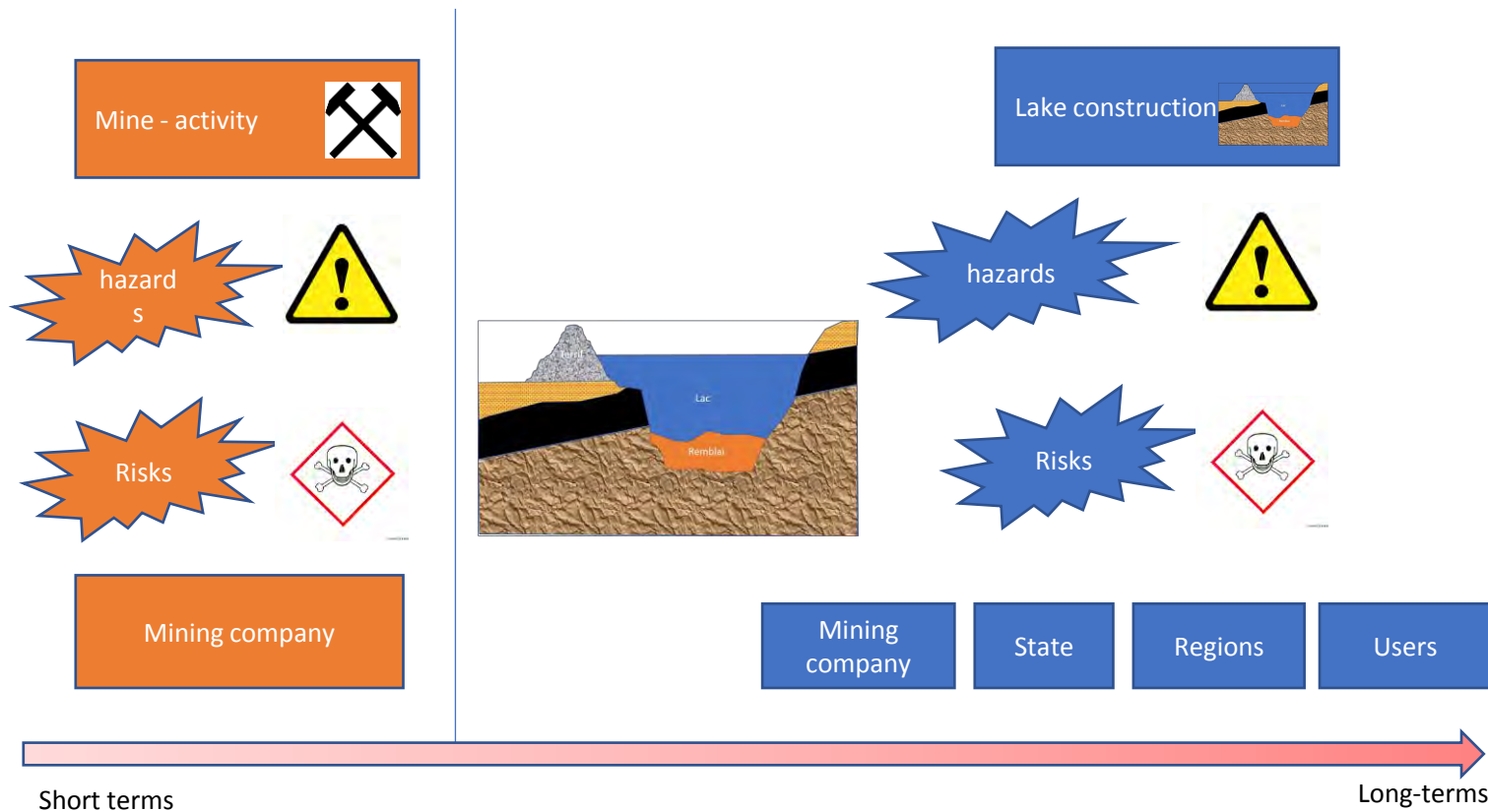
Heavy raining

Water inflow

Fire

Natural hazards

Risk managements before and after pit lake constructions



Scenarios

N°	Effect	Impact
1	Variation of the water level <ul style="list-style-type: none"> - Water equilibrium - Flooding - Temperature - Heavy raining - Snow 	Very important for the stability of the lake – open pit mine Variation + or -, cycling
2	Natural and induce seismicity	Low in European coalmines – accept Greece
3	Saturation and unsaturated	Important – related to 1
4	Erosion <ul style="list-style-type: none"> - Surface - Foot 	Very important + cycling
5	Degradation of the slope – characterisation of the soil	It is function of the time
6	Water quality – chemical impact	It can be studied with effect of the characterisation
7	Mechanical overloading – unloading	Low to medium
8	Excavated the lake – dewatering	Low

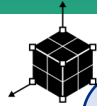
Slope stability - State of flooded open pit mine

Open pit mines are typically steep-sided and barren of vegetation with highwalls composed of highly fractured and blasted bedrock, slope stability is always a major concern.

After a mining pit is flooded, **a large landslide has several potentially** serious consequences:

- possible threat to human health or damage to buildings or roads near the affected pit highwall;
- drowning of individuals or wildlife on the shore of the lake due to “tidal waves”;
- possible inducement of turnover due to turbulent mixing.

Advance Numerical modelling of abandoned mining lakes



Study the long-term behaviour of flooded open pit mines using a large-scale 3D hydromechanical modelling using FLAC3D (FDM)

Stability assessment of specific geological features, investigation of geotechnical accidents

Numerical modelling



Along with the advent of powerful computers, numerical modelling has become a **prominent approach** to design mines and post-mines structures. Numerical modelling yields to mining engineers a **unique predictive insight in the stability response**, especially in challenging medium and projects dealing with **safety** and **environmental stakes**.



Large scale scanning
For unflooded surface

In Situ
Observations

Large scale bathymetry
survey for unflooded
surface

Geotechnical and
hydromechanical
characterisation

3D Numerical model

Creation of an envelope for finely meshed zones

- ① Create the shifted lake contour with an offset distance of 100 m
- ② Extrude this curve to create the lateral border
- ③ Shift the topography surface 100 m
- ④ ~~Delete~~ and assemble these 3 surfaces together

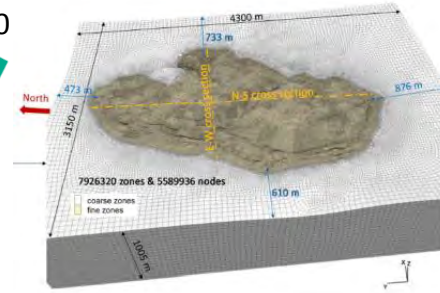
Slope stability of Most lake



Czech Republic: Lake Most.
 The Lake Most is situated in the central part of the Most
The lake catchment area : 1 050 ha
Max. depth of the lake* : 75.0



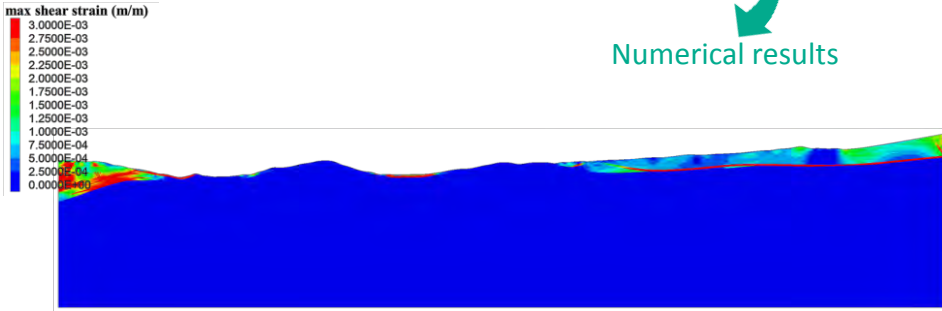
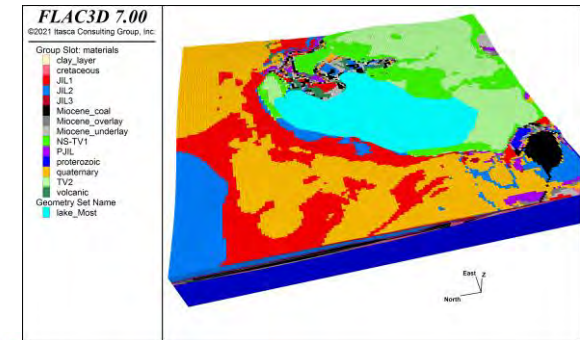
Globale and locale
 safety factor
 Failure probability
 Reliability index



3D Simulation

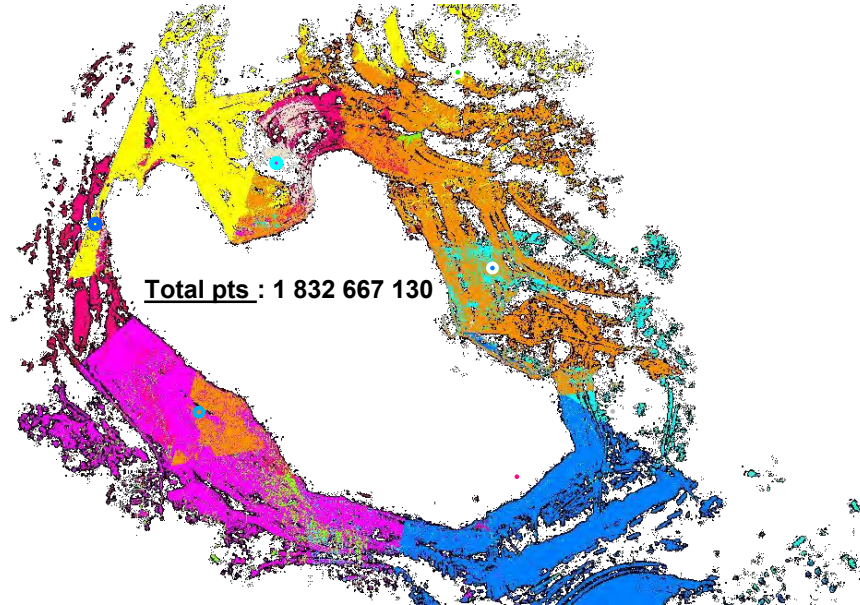
3D Modelisation

Numerical results



Survey of bottom and slopes of flooded artificial reservoirs

In-situ measurement of lake Most geometry has been performed with a long-range scan laser. Digital elevation models (DEM) of the reservoir slopes will be obtained for 3D modelling of slopes (to be used for later local scale stability assessment).



Geotechnical data: initial distribution

geotechnical parameters

Depth	Geology	Layer	Description	Thickness	Permeability
From the surface	quaternary	Overlayers (JUIL2, JIL3, PJIL, TV1, TV2, shear zone/contact layer, TT)	Clay - sand	max = 140 m	10^{-4} m/s to 10^{-9} m/s* see section, text mention 10^{-6}
	Miocene	Coal seam (UB)	Coal with clay layers	2-3 m, max = 5 m	10^{-5} to 10^{-6} m/s
		Coal seam (MB)		18-20 m	
		Coal seam (LB)		5 m	
		Ground coal (C)	Coal with clay layer	$\mu = 7$ m, max. 16.2 m	
	Cenozoïc	Tertiary ()	Clay and sands	0 to 20 m	????may be close 10^{-7} to 10^{-11} m/s
		Volcanic formation (TUF)	Weathered basalt, Tuff, tuffites	Tens of meters	
	Mesozoïc, cretaceous	Upper cretaceous sediments	Marls, clayey marl and limestone	Tens of meters	
Proterozoic	Crystalline Complex	Deeper rock			

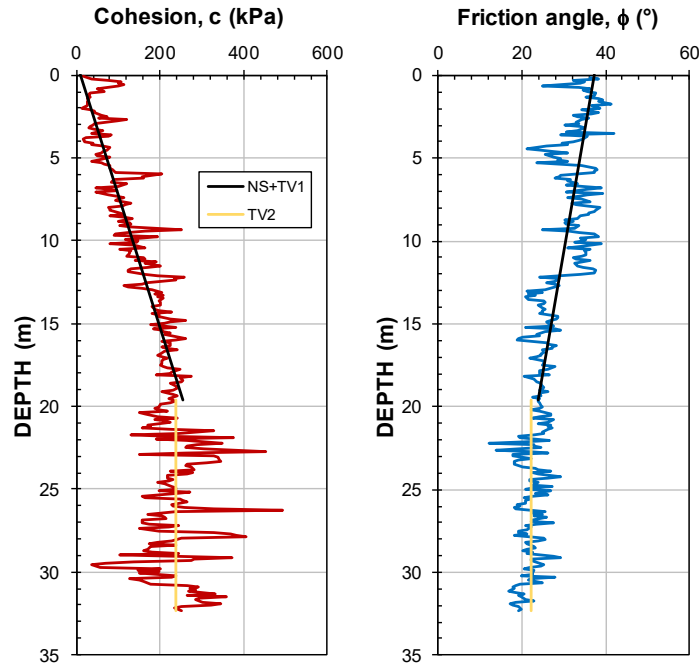
Geotechnical data: initial distribution

geotechnical parameters

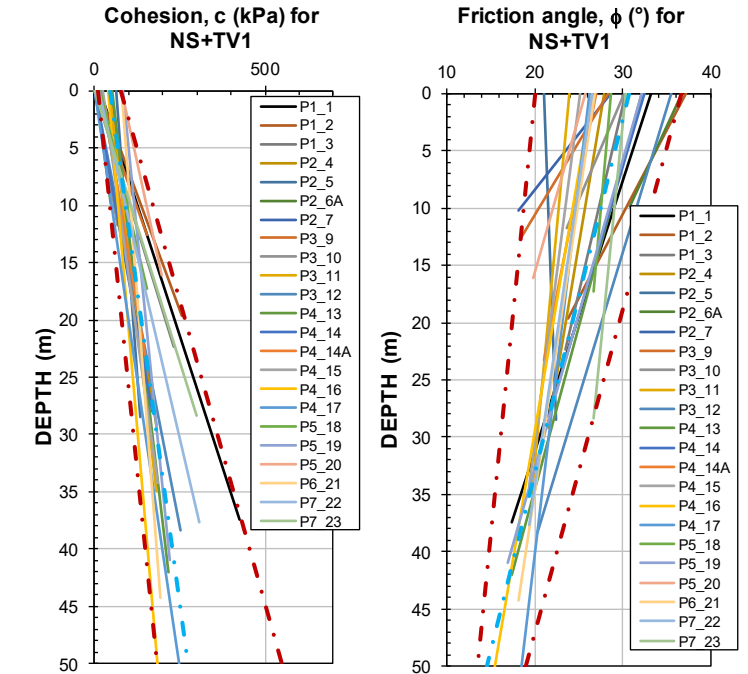
Geotechnical parameters		Plastic clays JIL2	Plastic clays JIL3	Sandy clays PJL	Coal	Shear zone	Consolidated dump TV1	Dump (weak) TV2
Soil unit weight above phreatic level γ_{unsat}	[kN/m ³]	20	17	18	15	17	17	17
Soil unit weight below phreatic level γ_{sat}	[kN/m ³]	22	18	20	18	20	20	20
Cohesion c'	[kN/m ²]	93	72	15	50	8	25	18
Friction angle ϕ'	[°]	17	13.6	30	35	9.5	20	20
Young's modulus E'	MPa	70	60	100	120	70	70	80
Poisson's ratio ν'	-	0.35	0.35	0.35	0.30	0.30	0.35	0.35
Permeability k	[m/sec]	1E-9	1E-7	2E-7	1E-5	1E-5	1.47E-6	1.32E-8
Thickness	[m]	?	?	?	?	?	?	?

Placement depth (m) in clays	0–25	25–40	40–70	>70
Cohesion (kPa)	40	88	162	253
Friction angle (°)	17	18.6	18.6	17.5

Geotechnical data of the Most lake (CZ) – 2020 data and analysis



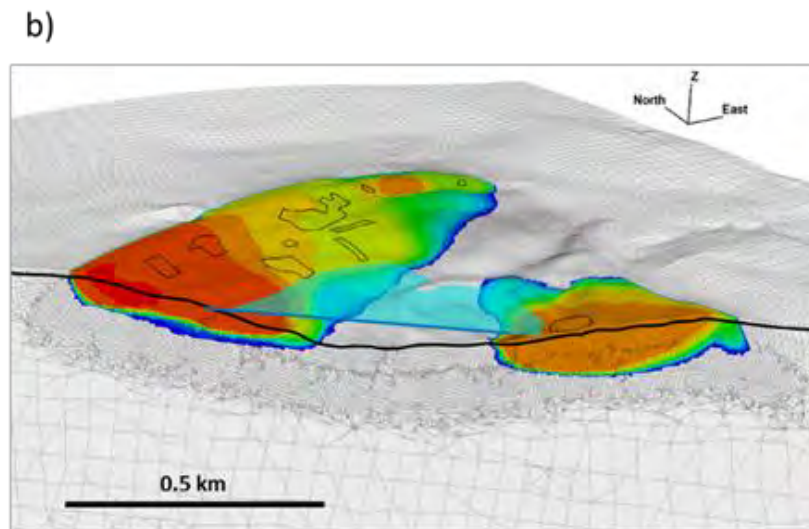
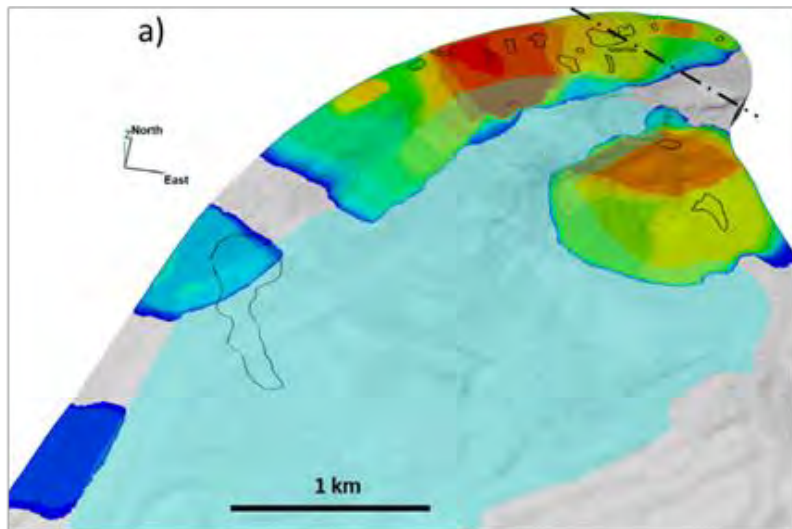
(a)



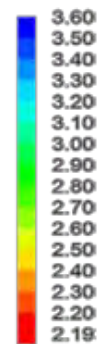
(b)

Geotechnical data

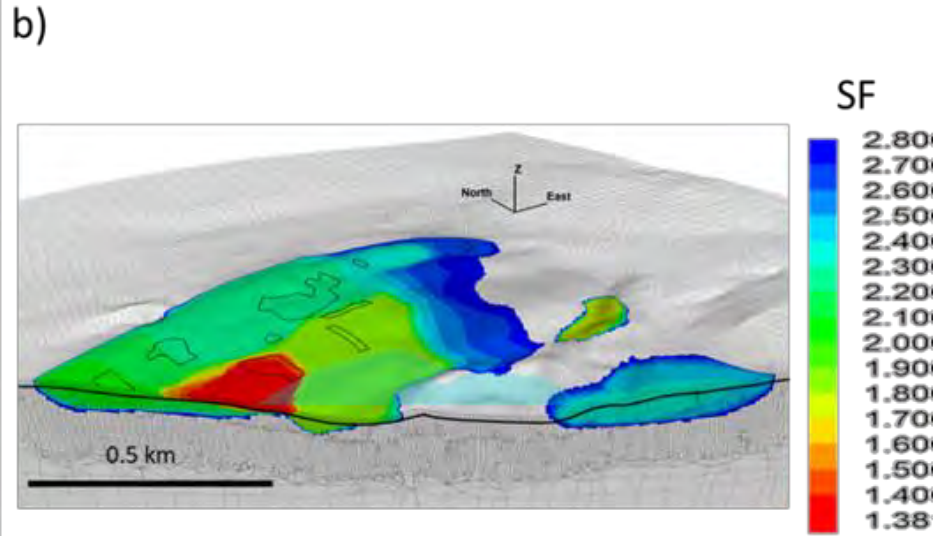
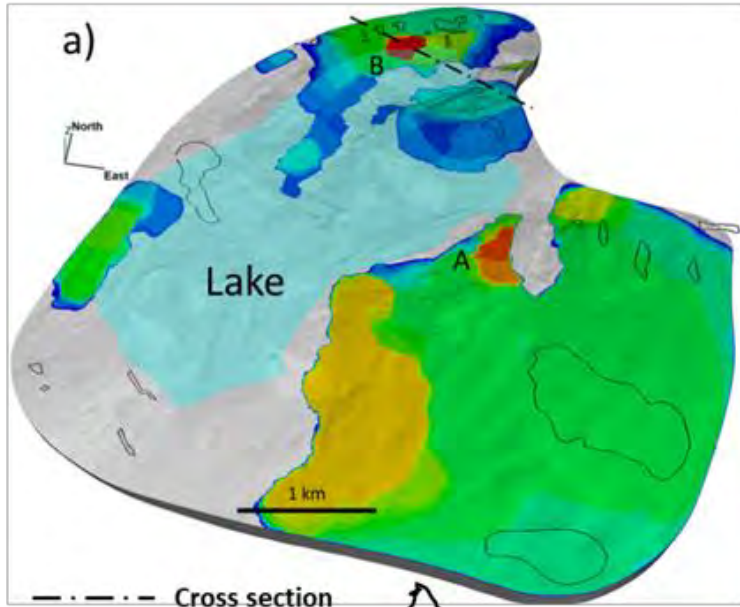
dump unit / Property	NS + TV1	TV2	Contact Layer
cohesion: c (kPa)	mean : 4.59 d+46.15 min : 3.5 d+10 LN dist [0.6 , 650]: $\mu_{LN}=0.0324$ d+4.034 $s_{LN}=-0.0063$ d+0.598	mean : 247.4 min : 4 d-60 LN dist [6 , 1098]: $\mu_{LN}=5.31$ & $s_{LN}=0.626$	6.0
Friction angle: ϕ (°)	mean : -0.323 d+30.69 min : -0.13 d+20 LN dist [7 , 44]: $\mu_{LN}=-0.241$ d+28.73 $s_{LN}=-0.071$ d+6.074	mean : 22.7 min : 16.8 BS dist [8.2 , 38.6]: $b=22.019$ & $g=0.244$	6.0
Young's modulus: E (MPa)	mean : 3.67 d+18.51 min : 2.96 d+5 LN dist [1 , 354]: $\mu_{LN}=0.037$ d+3.577 $s_{LN}=-0.004$ d+0.377	mean : 193.9 min : 3.6 d-52 LN dist [29.6 , 636.5]: $\mu_{LN}=3.855$ d+32.046 $s_{LN}=0.6195$ d+28.295	70
saturated density: ρ (t/m ³)	mean : 0.0124 d+1.739 (d≤12.5 m) 0.0035 d+1.869 (d>12.5 m) min : 0.0035 d+2.0 N dist [1.3 , 2.2]: $\mu=0.0053$ d+1.813 $s=-0.0008$ d+0.0919	mean : 2.023 min : 0.0017 d+2.079 N dist [1.55 , 2.285]: $\mu=2.023$ & $s=0.098$	2.0



SF



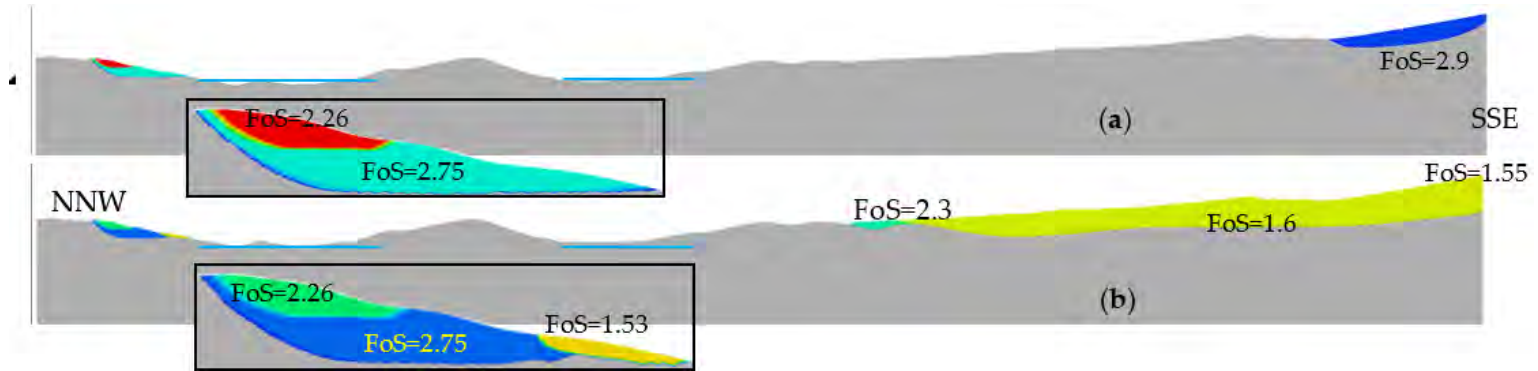
SF contour without contact layer. a) 3D view; b) cross section



SF contour with contact layer. a) 3D view; b) cross section

2D numerical modelling result – Factor of safety (FoS)

Contact layer role: FoS contours for a critical cross section, (a) without contact layer. (b) with contact layer



The hypothesis of the presence of a very weak contact layer (at the bottom of dump bodies), capable of questioning the stability of the slopes of the site (Most Lake).

It should be noted that the contact layer was not detected from the CPT campaign measurements. But neither the absence nor the presence of the contact layer can be confirmed because only 2 profiles are deeper than the dump units on an area to be investigated of more than 8 km².

Conclusion

Mine lakes are a sustainable solution for abandoned open pit mines

Risk assessment should be carried out to insure LT safety and security

A large-scale numerical modelling and collecting data are very useful to assess Slope stability

Application on lake Most,

The results highlighted

- the reliability of the methodology to combine the geometric, geological and hydraulic models to create a large-scale numerical model, and to identify local potentially instable zones.
- the role of the weak layer (contact layer) on the stability