



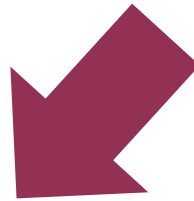
# GEO-HYDROMECHANICAL BEHAVIOUR OF FLOODED OPEN PIT AND PIT WALLS EMPLOYING NUMERICAL MODELS

*International Conference on  
"SUSTAINABILITY, RISK ASSESSMENT AND REVITALIZATION  
OF POST-MINING PITS AND SPOIL DUMPS"*

*RAFF and SUMAD projects' achievements*

*7&8 / 10 / 2022*

Works  
carried out



Stability of pit walls and  
inner dumps bedding  
plane.

Hydrogeological study  
of the final flooding  
particular effects of  
the hydraulic sink.

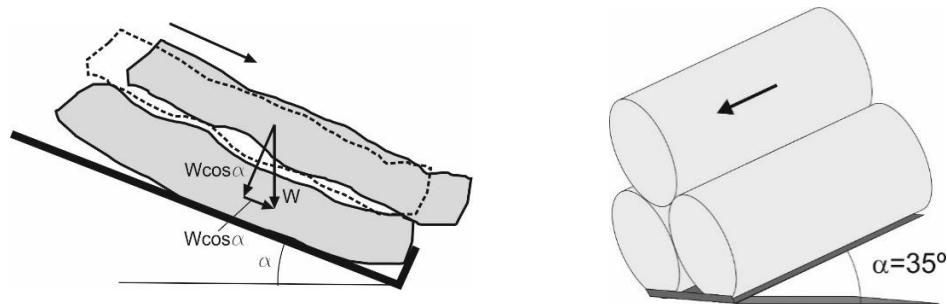
# Stability in pit walls and inner dump

- Effect of the bedding plane on the stability of pit walls.
- Collection of existing data related to the characterisation and classification.
- Coal mining region of El Bierzo, in León, located in the northwest of the Iberian Peninsula.



*Main mine basins in Spain*

- Groups of shales
- Laboratory analyses
  - Tilt tests (characterize discontinuities)
- Slope failure mode



*Tilt test scheme*

- 3 geotechnical scenarios have been analysed:
  - Bedding plane and/or stratification arranged perpendicular to the free face of the slope.
  - Bedding plane and/or stratification arranged in the direction of the free face of the slope (with a tolerance of  $\pm 20^\circ$ ) and dip in the opposite direction to the free face of the slope.
  - Bedding planes and/or stratification arranged in the direction of the free face of the slope (with a tolerance of  $\pm 20^\circ$ ) and dip in the same direction as the free face of the slope.

# Numerical model verification

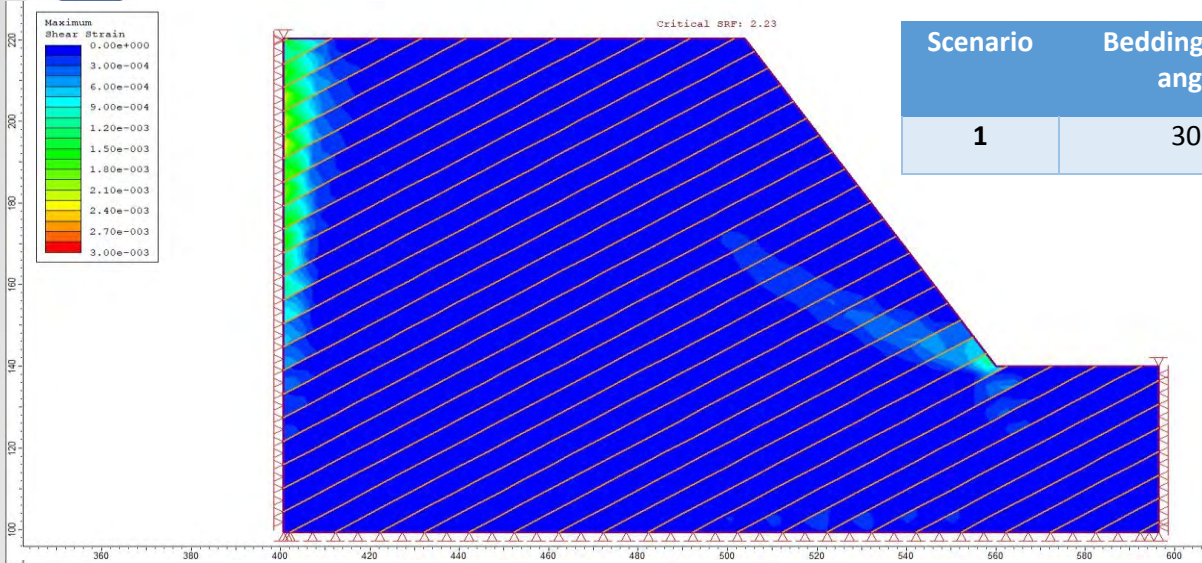
- Different scenarios with different bedding plane angles have been simulated
- 5 base scenarios with known initial conditions
- 80-metre high slope
- Overall slope angle of  $55^\circ$

Scenario	Bedding plane angle
1	$30^\circ$
2	$70^\circ$
3	$90^\circ$
4	$105^\circ$
5	$140^\circ$

*Scenarios configuration*

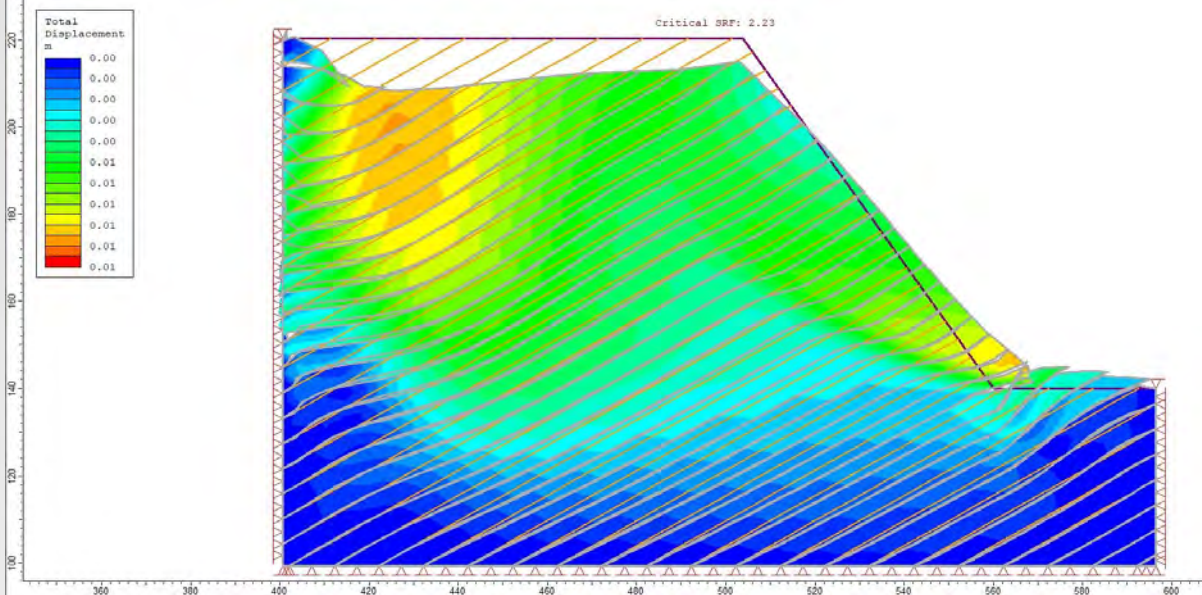


# Scenario 1. 30° bedding plane



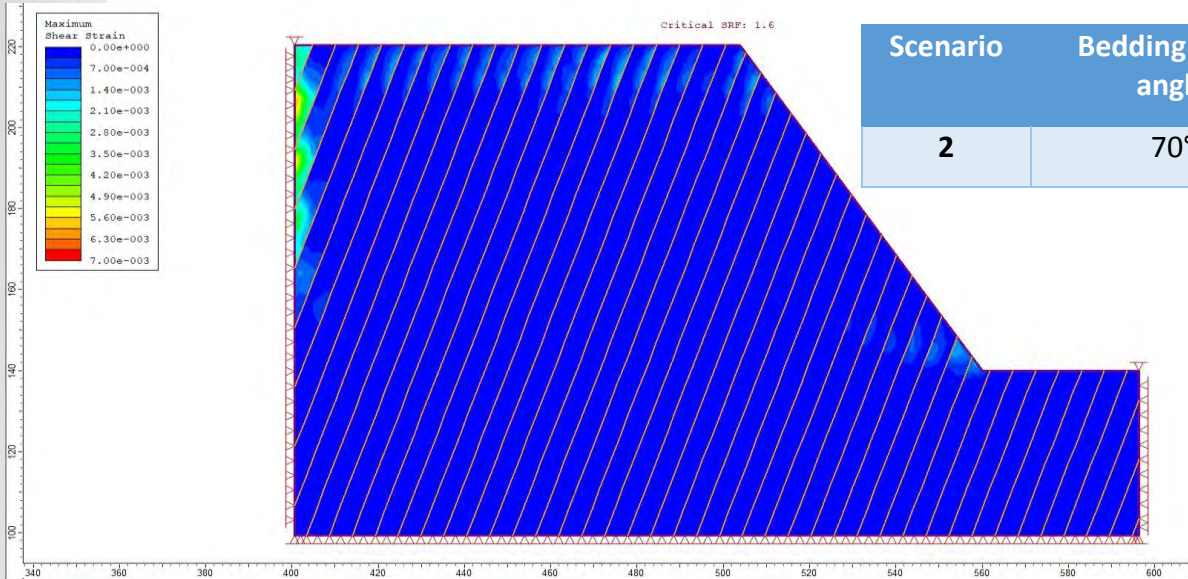
Scenario	Bedding plane angle	Stability Conditions	Safety Factor
1	30°	Stable conditions	2.23

*Scenario 1 maximum shear strength values*



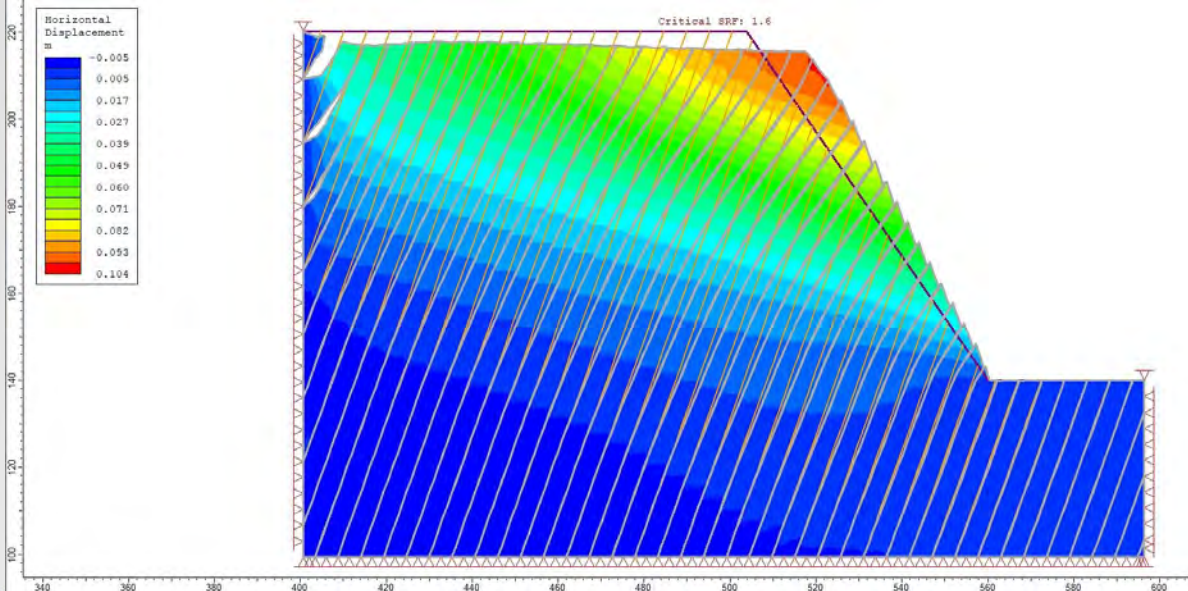
*Scenario 1 calculated displacements*

# Scenario2. 70° bedding plane



Scenario	Bedding plane angle	Stability Conditions	Safety Factor
2	70°	Toppling effect	1.6

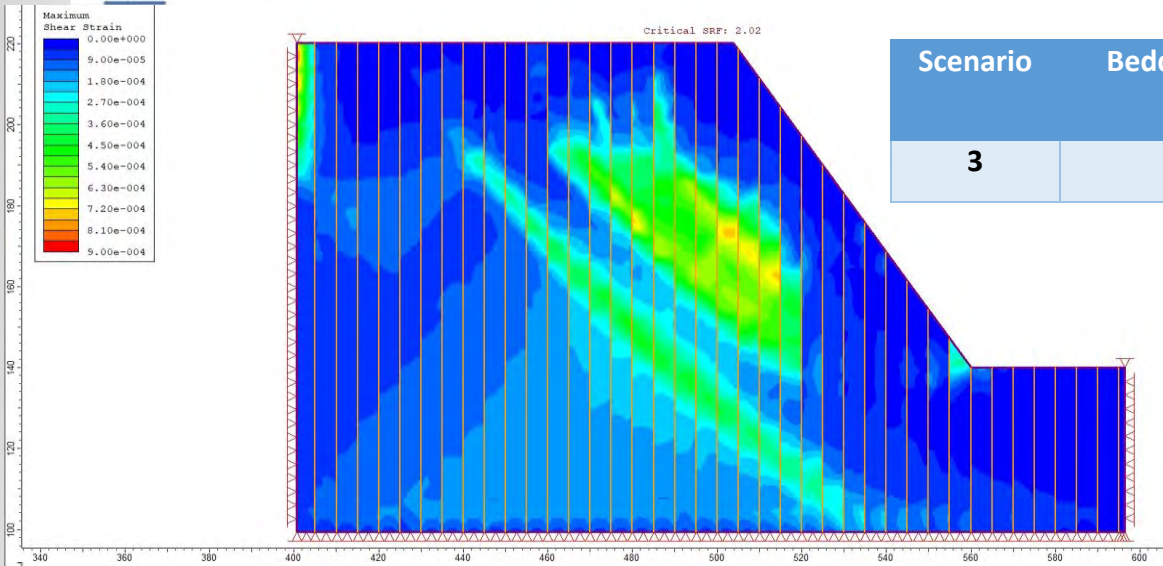
*Scenario 2 maximum shear strength values*



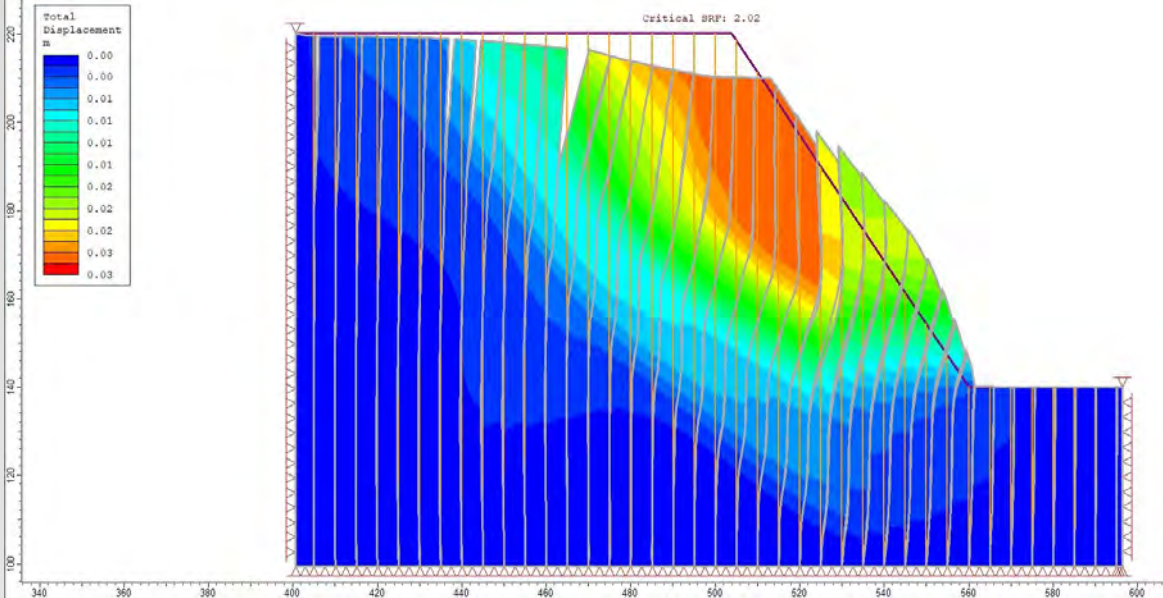
*Scenario 2 calculated displacements*

# Scenario 3. 90° bedding plane

Scenario	Bedding plane angle	Stability Conditions	Safety Factor
<b>3</b>	90°	Buckling effect	2.02



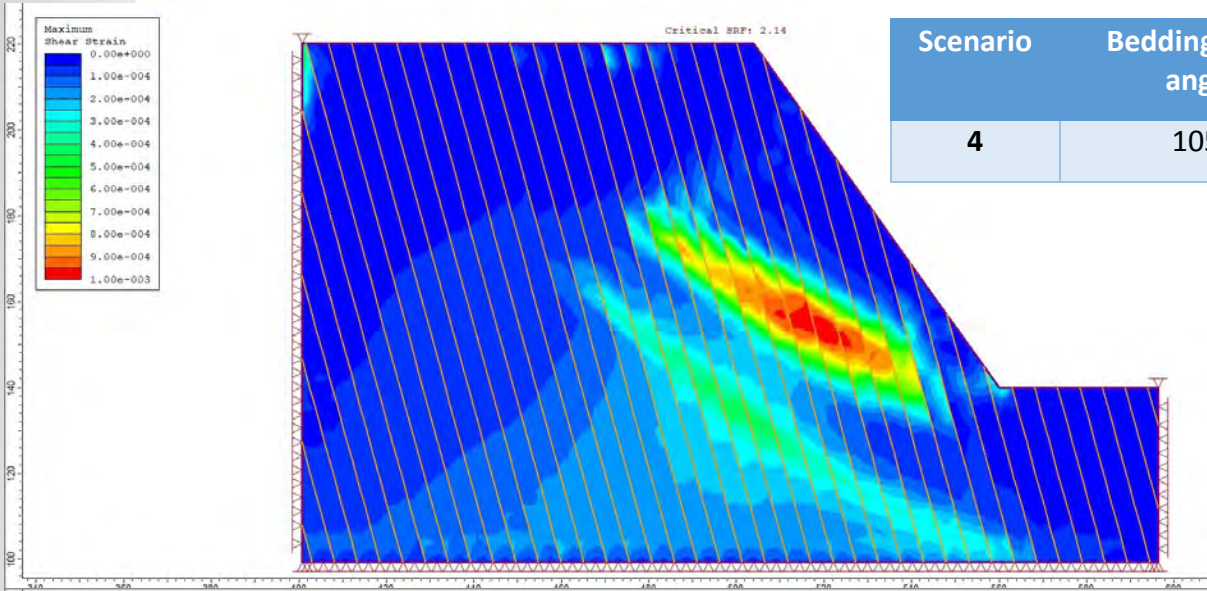
*Scenario 3 maximum shear strength values*



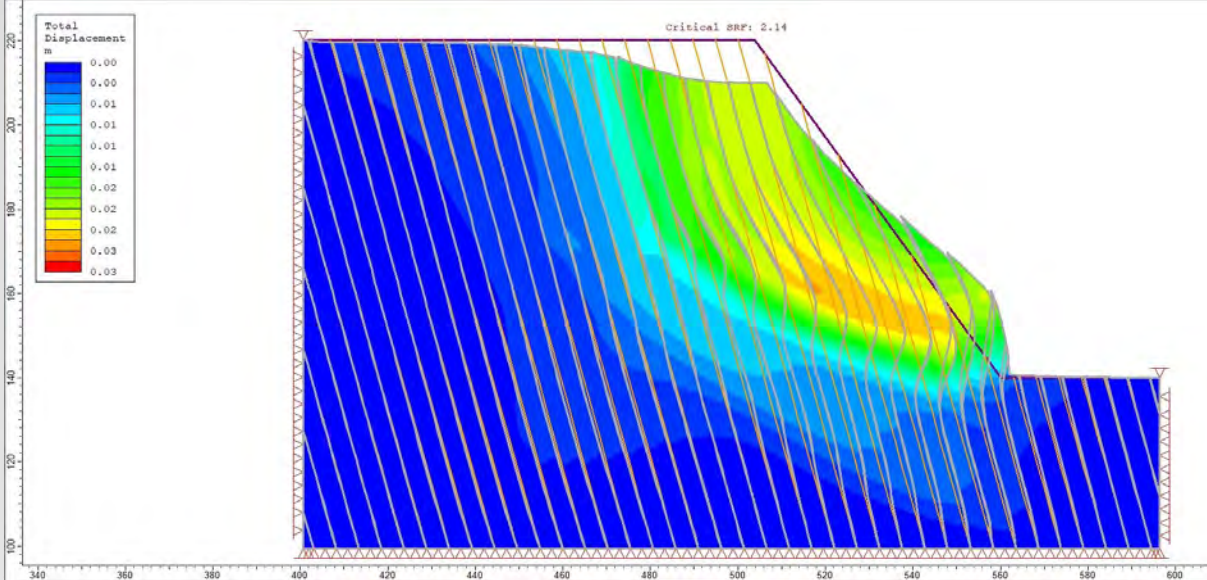
*Scenario 3 calculated displacements*

# Scenario 4. 105° bedding plane

Scenario	Bedding plane angle	Stability Conditions	Safety Factor
4	105°	Stable conditions	2.14

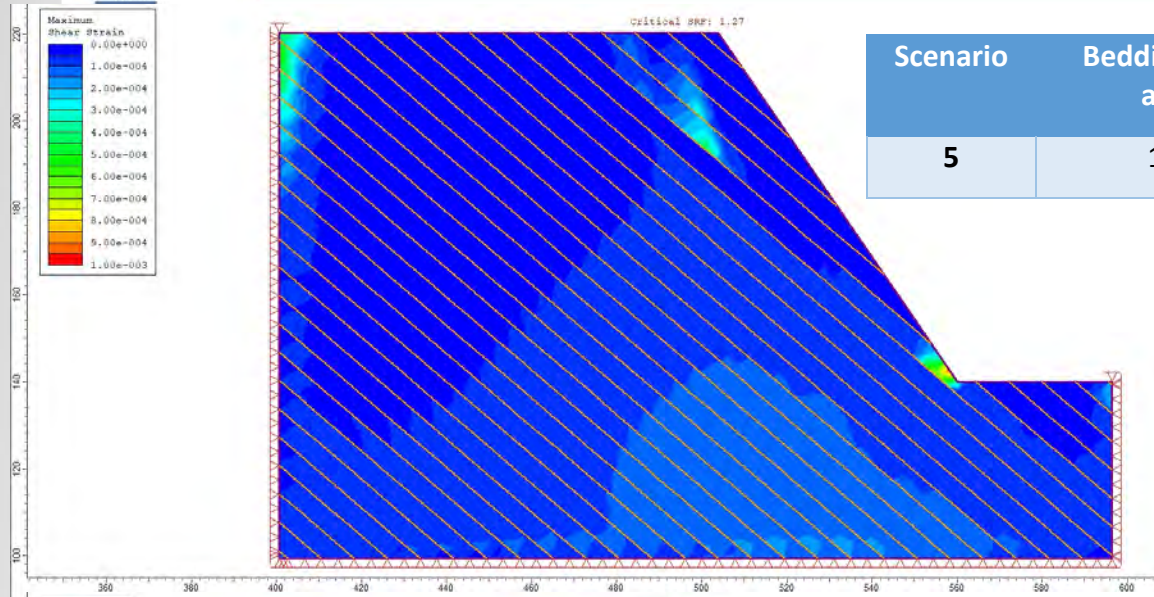


*Scenario 4 maximum shear strength values*



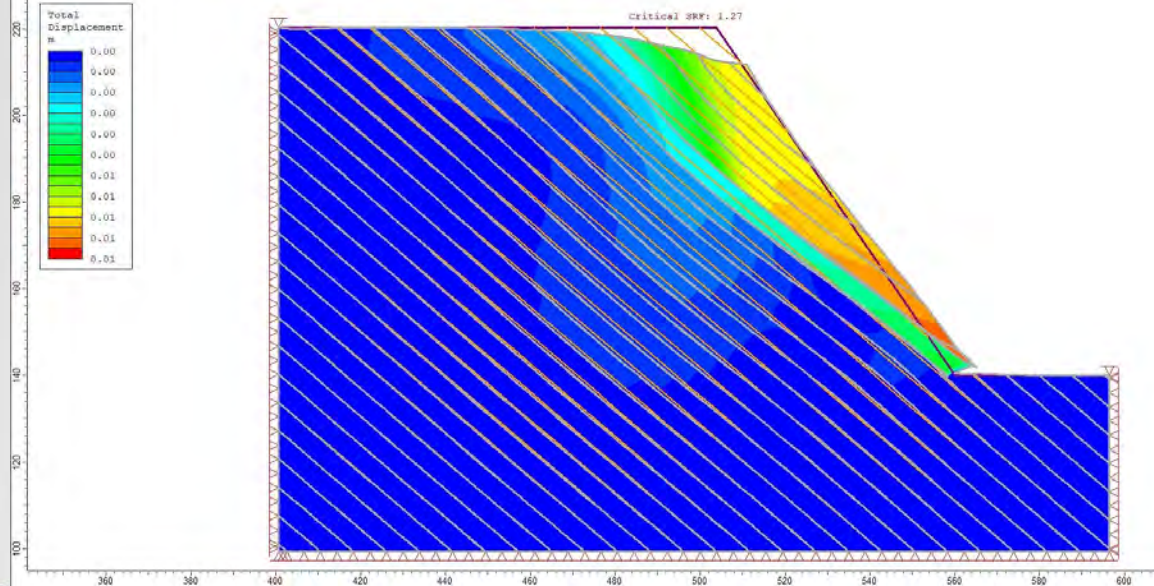
*Scenario 4 calculated displacements*

# Scenario 5. 140° bedding plane



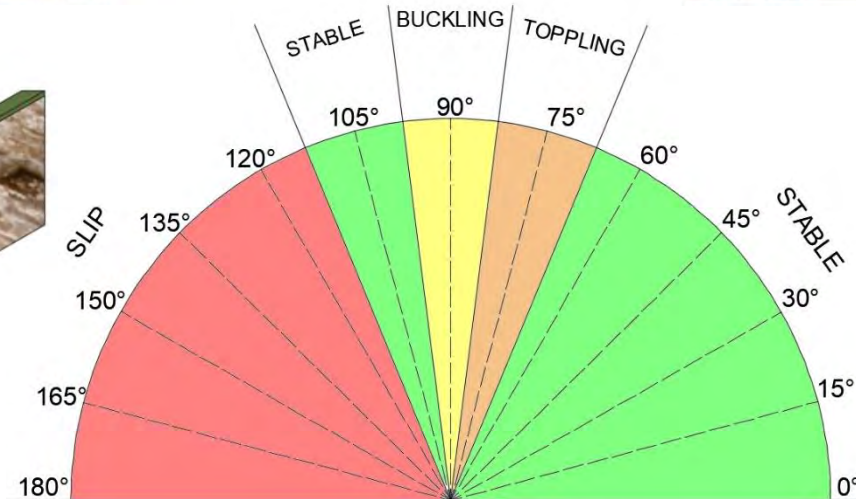
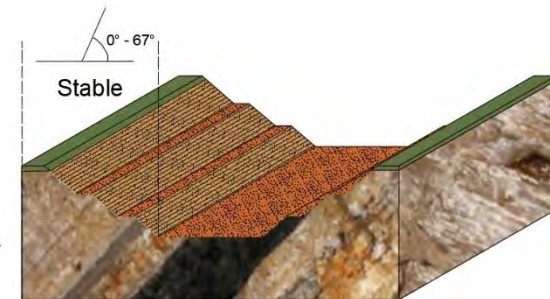
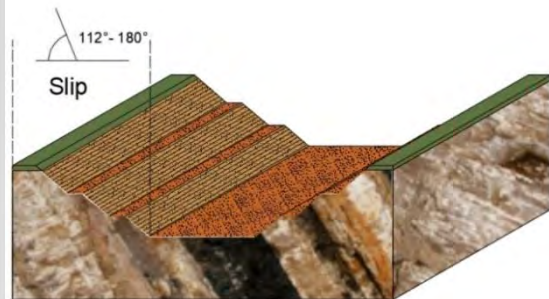
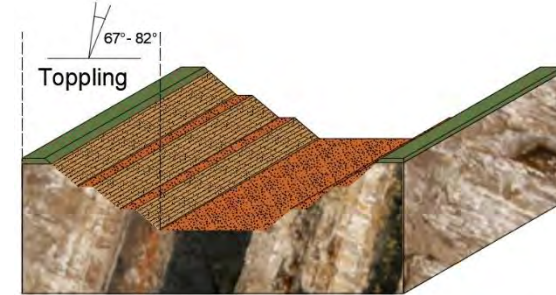
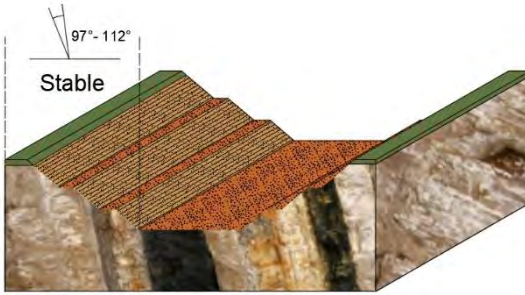
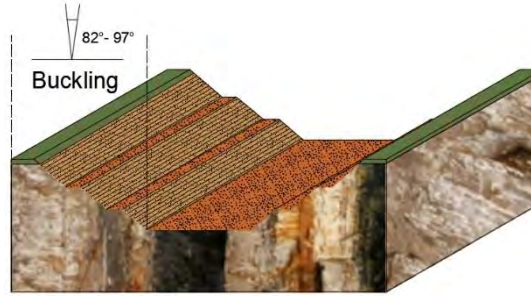
Scenario	Bedding plane angle	Stability Conditions	Safety Factor
5	140°	Slip event	1.27

*Scenario 5 maximum shear strength values*



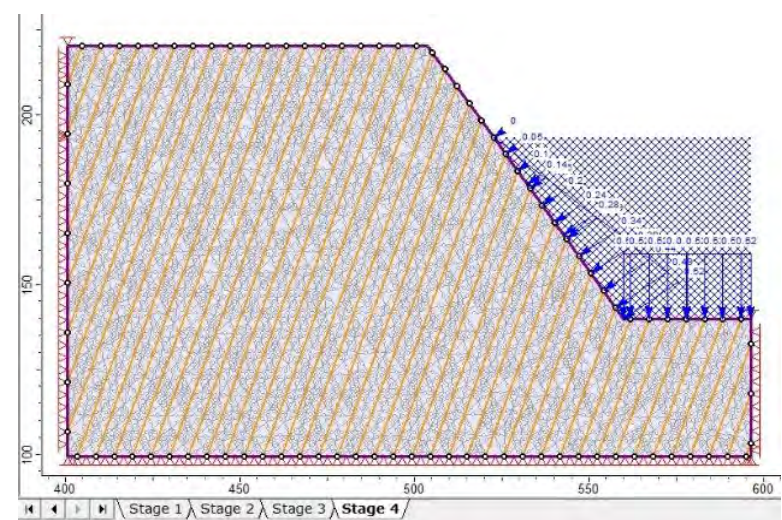
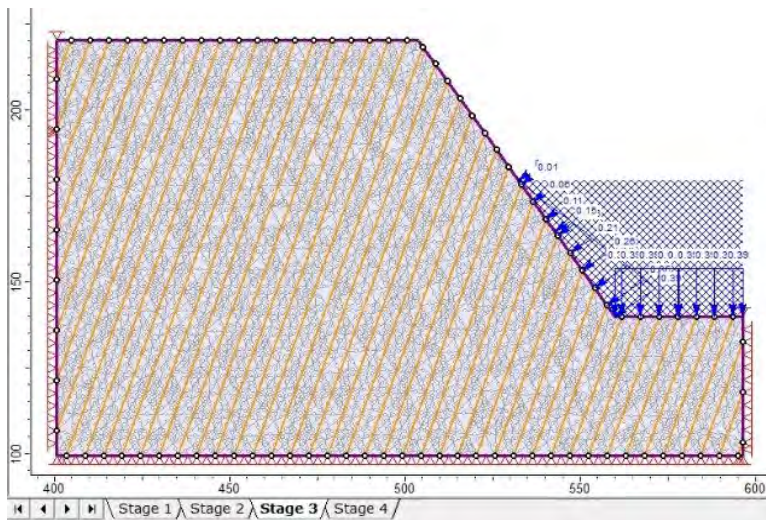
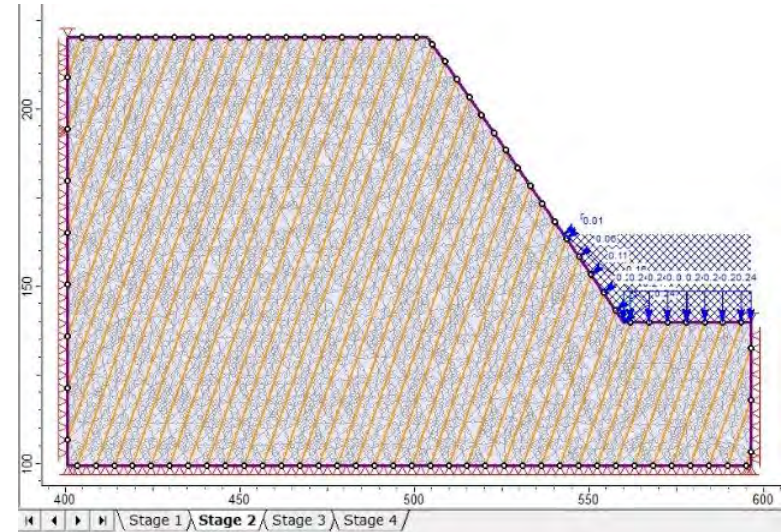
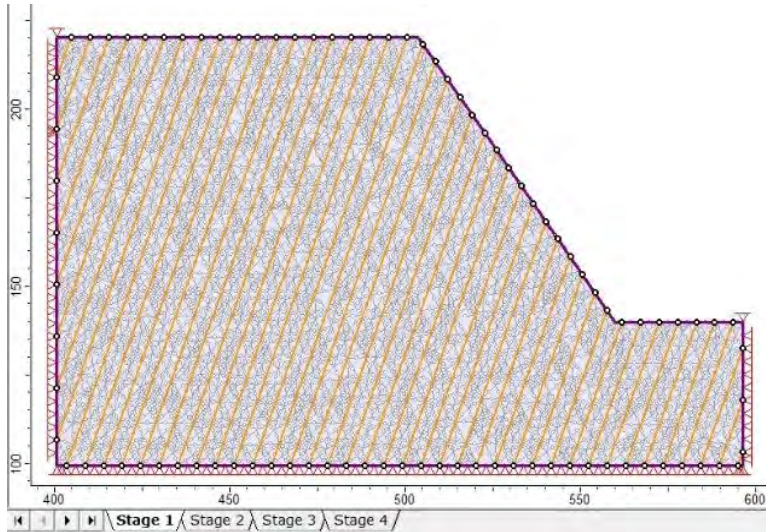
*Scenario 5 calculated displacements*

# Summary of model results



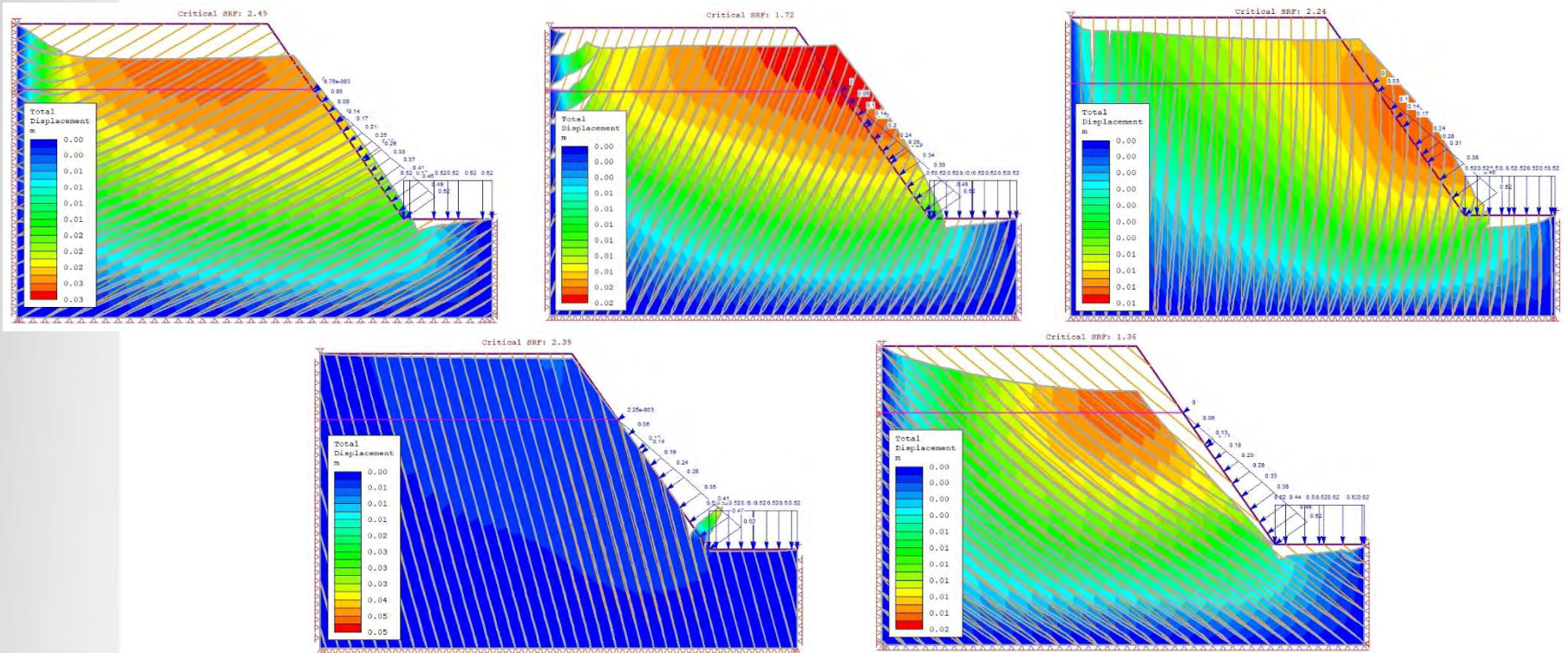
*Type of slope failure as a function of the dip of the bedding plane*

# Open-pit flooding model results



*Stages of open pit flooding in Phase2D*

# Open-pit flooding model results



**Total displacements calculated in the final flooding stage for the 5 scenarios**

Scenario	Bedding plane angle	Stability Conditions	Safety Factor (no flooding)	Safety factor (with flooding)
1	30°	Stable conditions	2.23	2.49
2	70°	Toppling effect	1.6	1.72
3	90°	Buckling effect	2.02	2.24
4	105°	Stable conditions	2.14	2.39
5	140°	Slip event	1.27	1.36

- Conglomerates, shales, sandstones and siltstones.



*Core extraction process*



*Core samples*

# Sample testing and saturation process

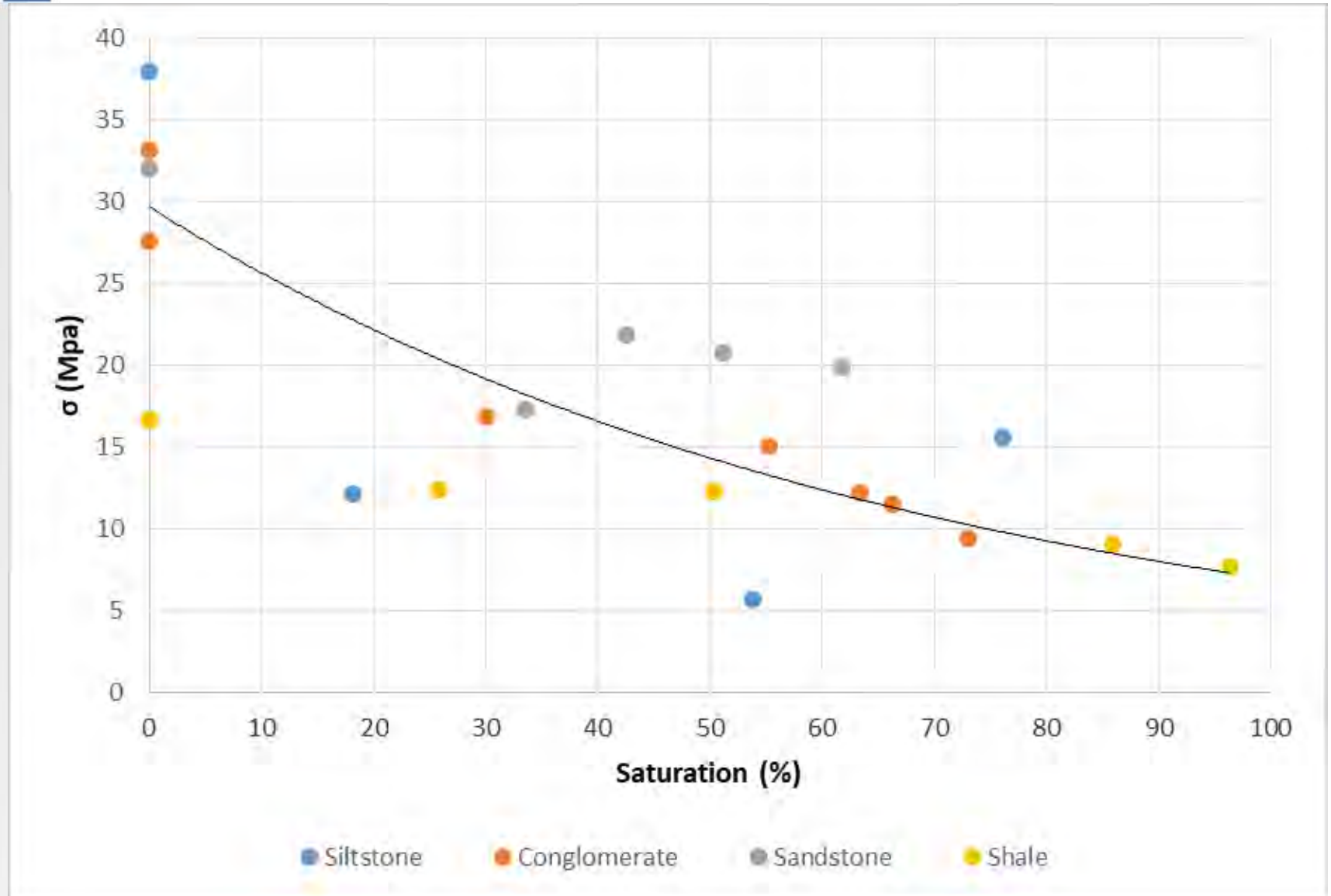
- ⦿ 5 siltstone samples (open pit).  
Between fine and very fine size
- ⦿ 7 conglomerate samples (open pit). Clasts with very varied size, the bigger ones over 35 mm.
- ⦿ 6 sandstone samples (open pit).  
Coarse and very coarse grain size. Some grains over 2 mm.
- ⦿ 5 shale samples (dump block).  
Black shales with high coal content and vegetal fossils.



SATURACIÓN DE MUESTRA EN CÉLULA DE TRIAXIAL

*Core sample saturation process in triaxial cell*

# Saturation vs strength results

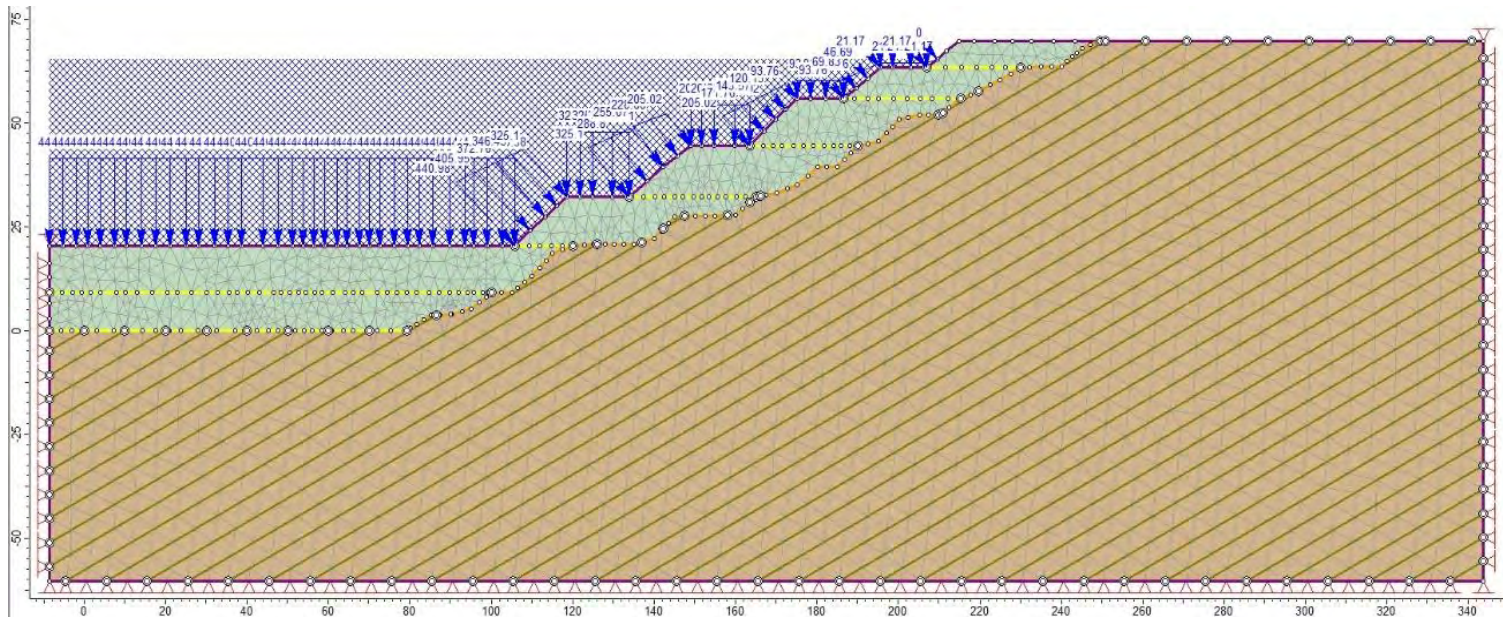


# Saturation vs strength results

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- ◉ **Extraction process**
  - Fast
  - Large number of cores
  - Difficult process
  
- ◉ **Saturation process**
  - Novel methodology
  - Accuracy on the final saturation percentage
  - Excessively long periods of time in some samples
  
- ◉ **Strength values**
  - Considerable decrease in early stages of saturation
  - Measure for the calibration of the stability numerical models

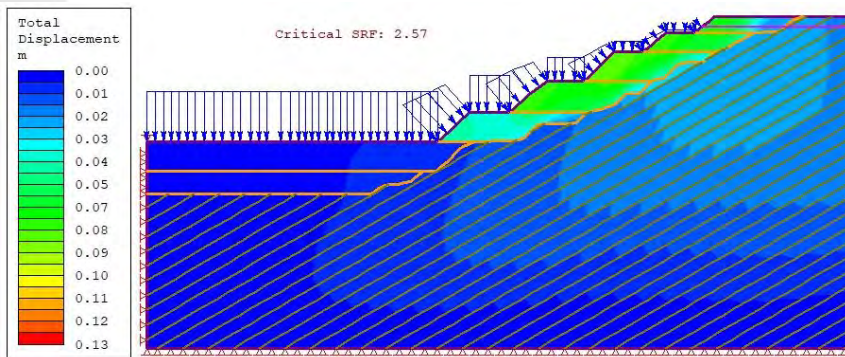
- Stability of the inner dump in the process of flooding the cut at the end of its useful life.
- Overall angle of the original slope: 22.3°.
- Height 70 metres.
- Overall slope of the inner dump: 24.3°.
- Joint network: different scenarios with overall angles of 30°, 90°, 105° and 165° in comparison with the free face of the slope.



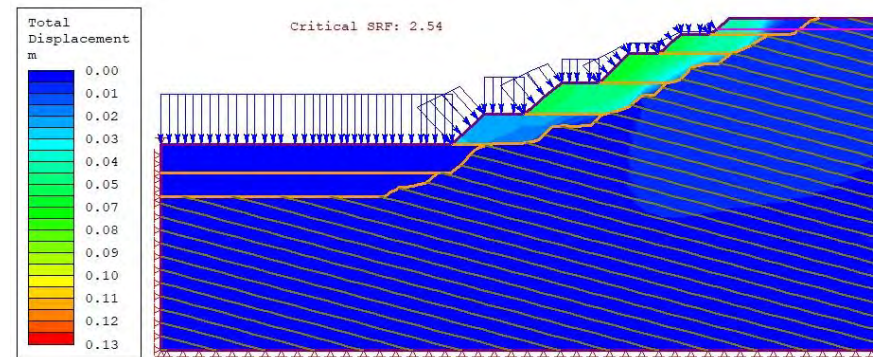
*Model geometry in the final flooding stage*

# Bedding plane impact on inner dump stability. Model results.

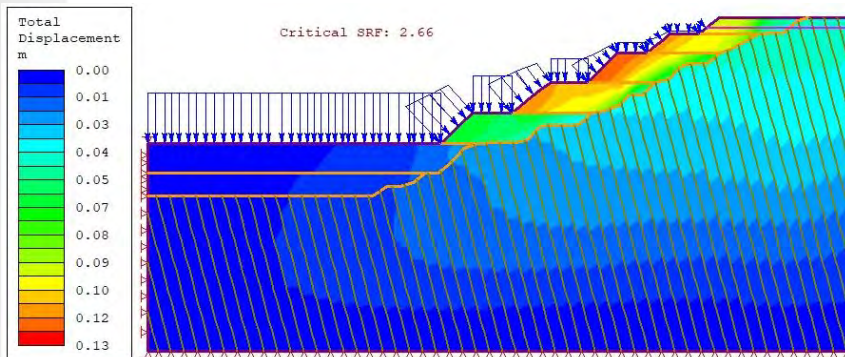
Scenario	Bedding plane angle	Safety Factor
<b>1</b>	30°	2.57



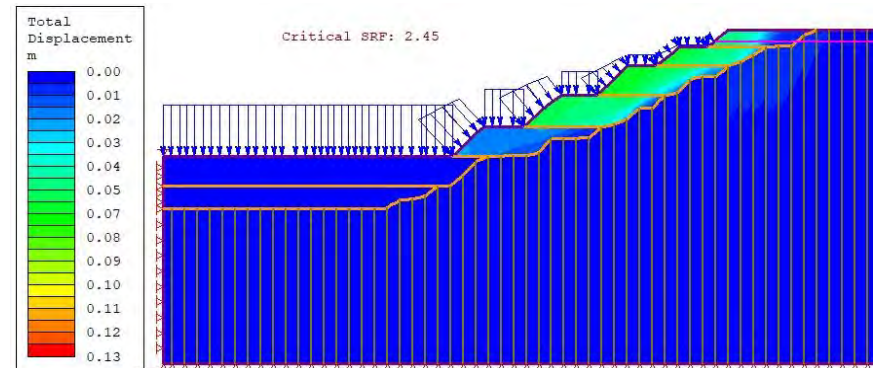
Scenario	Bedding plane angle	Safety Factor
<b>2</b>	165°	2.54



Scenario	Bedding plane angle	Safety Factor
<b>3</b>	105°	2.66



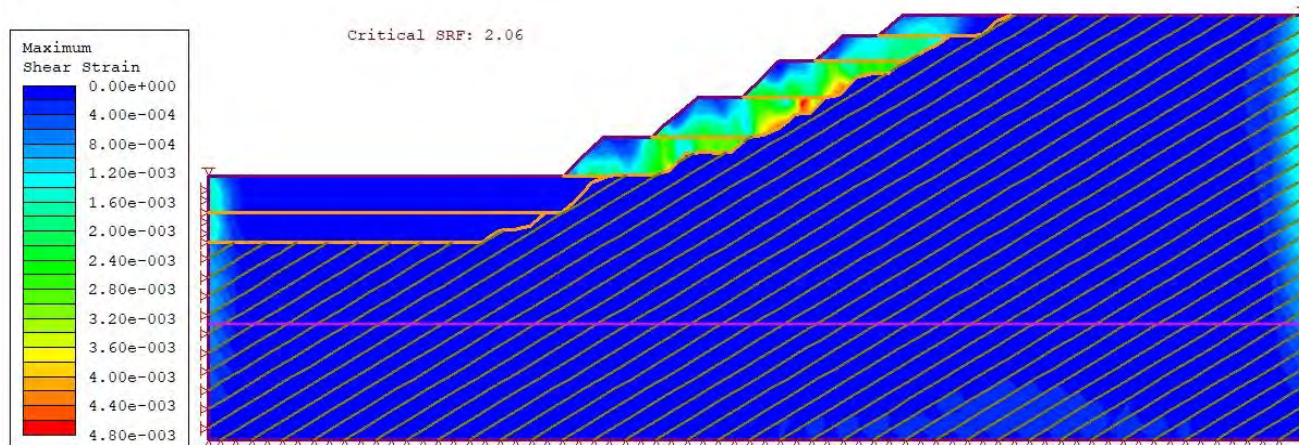
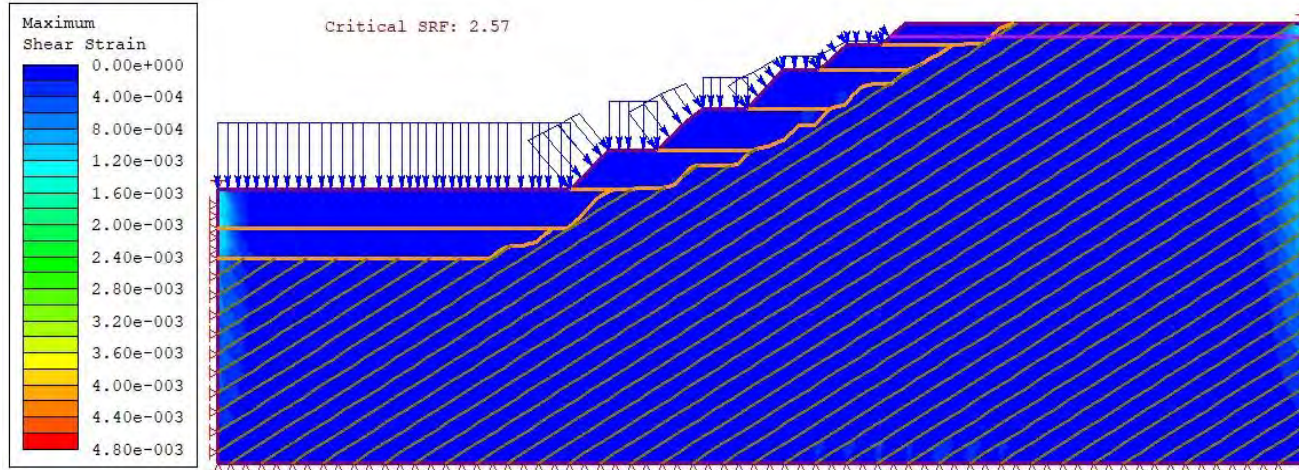
Scenario	Bedding plane angle	Safety Factor
<b>4</b>	90°	2.42



*Total displacements calculated for the different scenarios.*

# Bedding plane impact on inner dump stability. Model results.

## Flooding scenario vs. Non-flooding scenario



*Safety factor increase due to open-pit flooding (upper image) vs. without flooding (lower image)*

# Conclusions

- Effect of the bedding plane on the pit walls and the inner dump of an open-pit before and after the flooding process was studied.
- Laboratory studies, with the aim of precisely establish the geomechanical properties.
- Different numerical models have been proposed to demonstrate the theoretical scenarios described.
- The stability conditions are strongly influenced by the global orientation of the bedding plane.
- Overall, it has been observed that the different configurations of the bedding plane angle of the rock mass do not represent a specific stability issue to the inner dump as a whole.
- The stability of the inner dump itself will be conditioned by the possible failure events specific to the rock mass.
- The flooding process of the open-pit has a general positive effect on slope stability, increasing the value of the global safety factor due to the hydrostatic pressure.

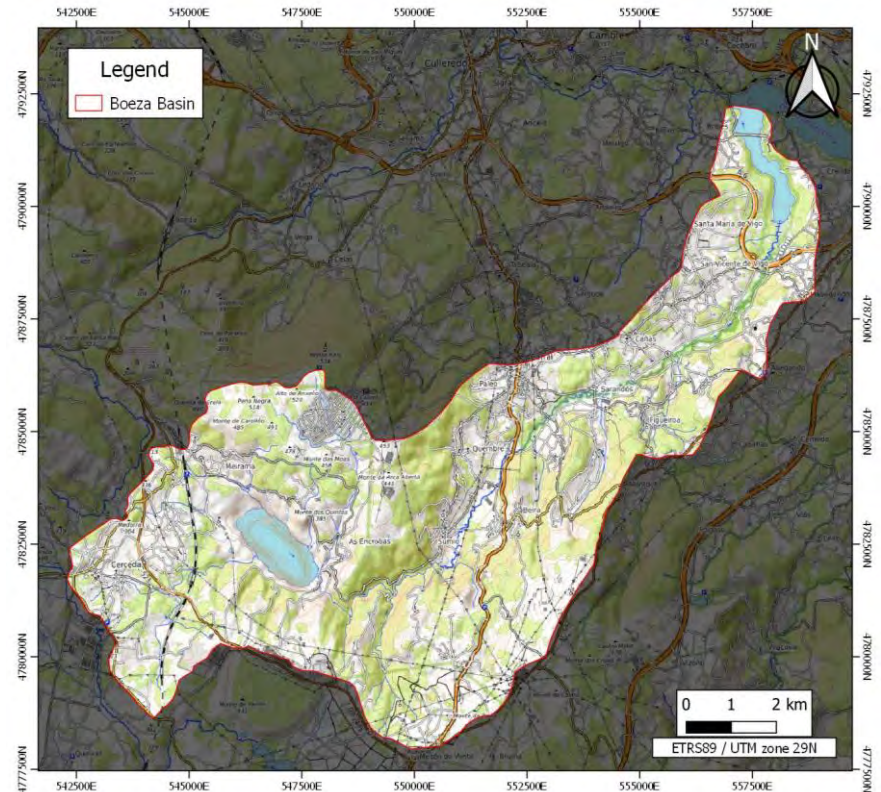
- Simulation of the flooding of the Meirama coal open-pit mine
- Northwest of the Iberian Peninsula



*Meirama open-pit during mining activity (left) and nowadays (right)*

# Introduction and objectives

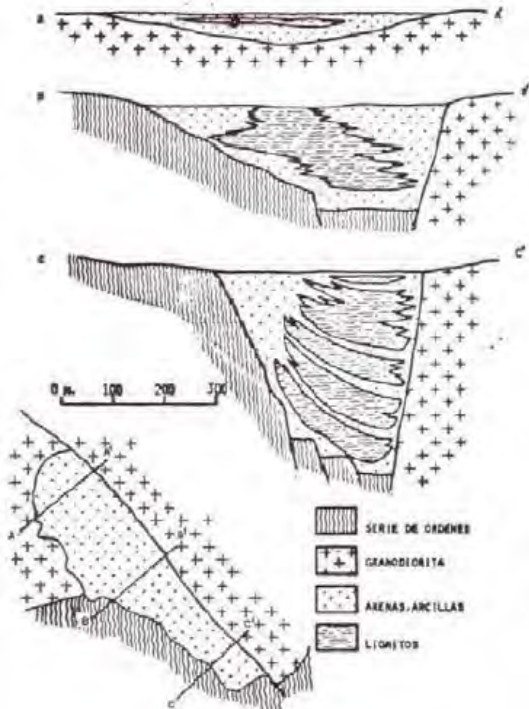
- Effect of the hydraulic sink in flooding operations.
  - Quantify and analyze the spatial effects of surface-water and groundwater fluxes on water balance dynamics.
  - Develop a numerical model in transient regime.
- 
- Barcés river basin (90 km<sup>2</sup>).
  - The flow regime of the Barcés River was modified once the flooding of the open-pit mine.
  - Cecebre reservoir, the main source of drinking water for A Coruña.



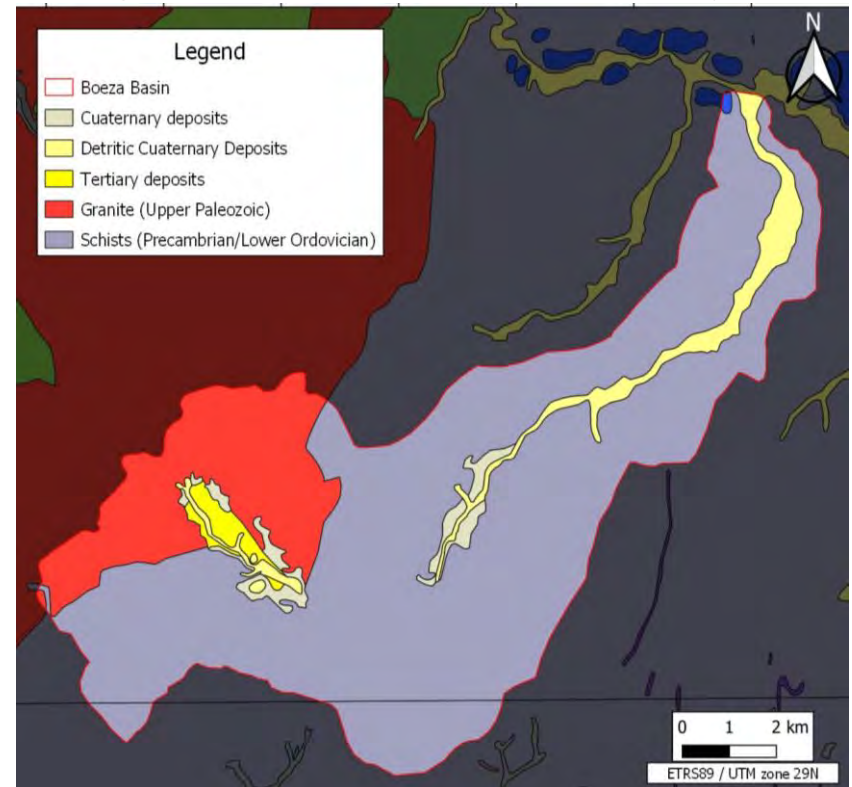
*Boeza's hydrogeological Basin*

# Geological context

- Materials: granodiorites and schists
- Terrace deposits, identifying up to two terrace levels
- Surface alteration strengths of less than 40 meters in the granitic massifs and less than 15 meters in the schists
- Tertiary sedimentary basin is formed, rich in lignite, on a substratum of mainly granodiorites and schists

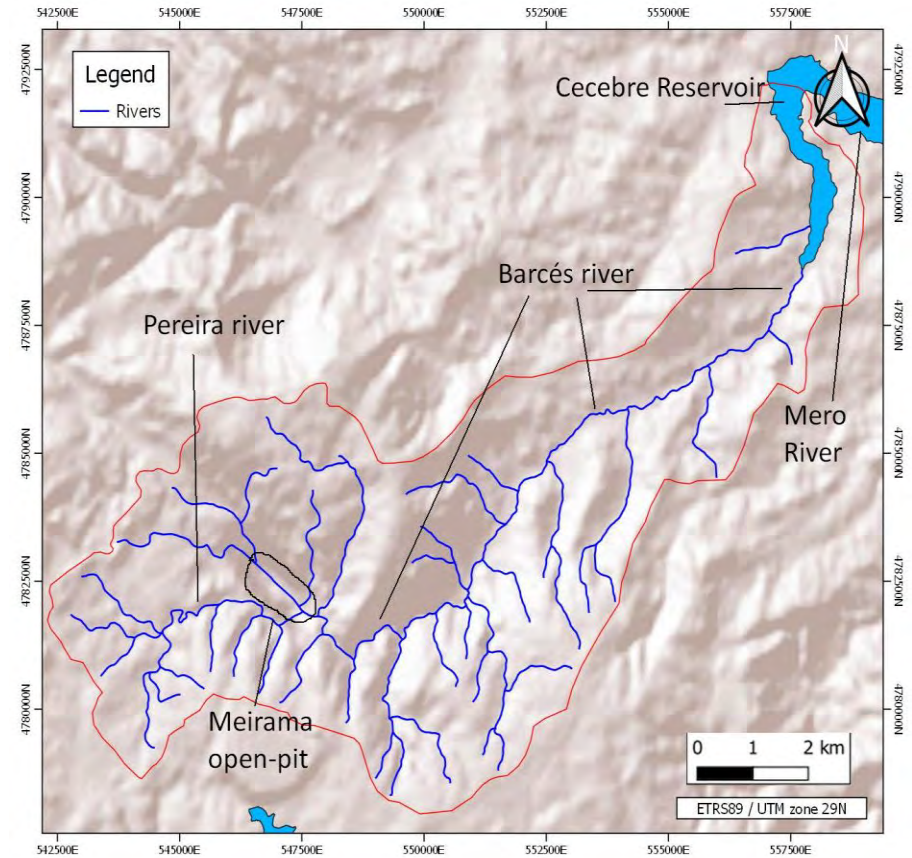


[www.subterra-ing.com](http://www.subterra-ing.com) Typical cross sections of Meirama's Basin



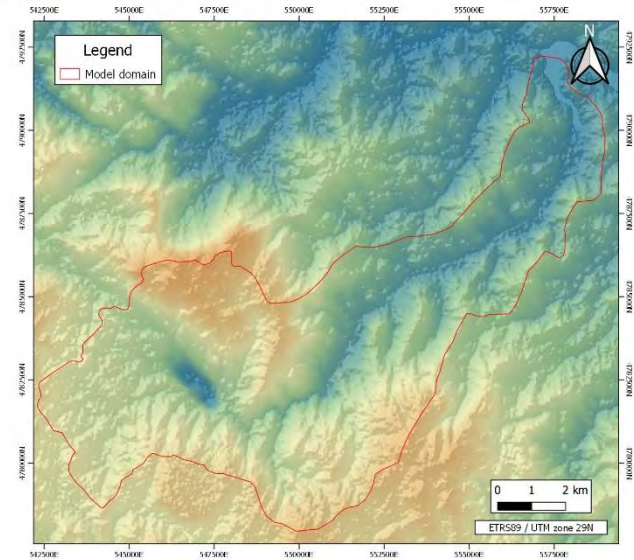
Boeza's Basin regional geology

- Granitic massif and the schists present are materials with low hydraulic conductivity and low porosity.
- Granitic massif is highly altered and in turn fractured in the vicinity of the northwest edge of the Meirama open-pit.
- hydrogeology is considered significant in the first 50 metres below the present topography.

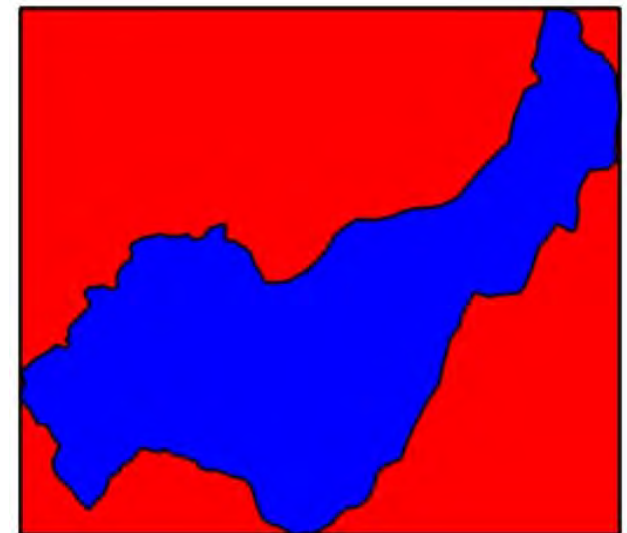


**Actual Boeza's basin hydrography (after open-pit flooding)**

- MODFLOW 2005 with the ModelMuse GUI.
- Three-dimensional (3D) model was defined.
- Horizontal model boundaries are defined by taking into account the hydrological basin extension of
- Barcés River.
- First 50-metre depth layer (groundwater flows).
- Second layer representing the impermeable substratum.

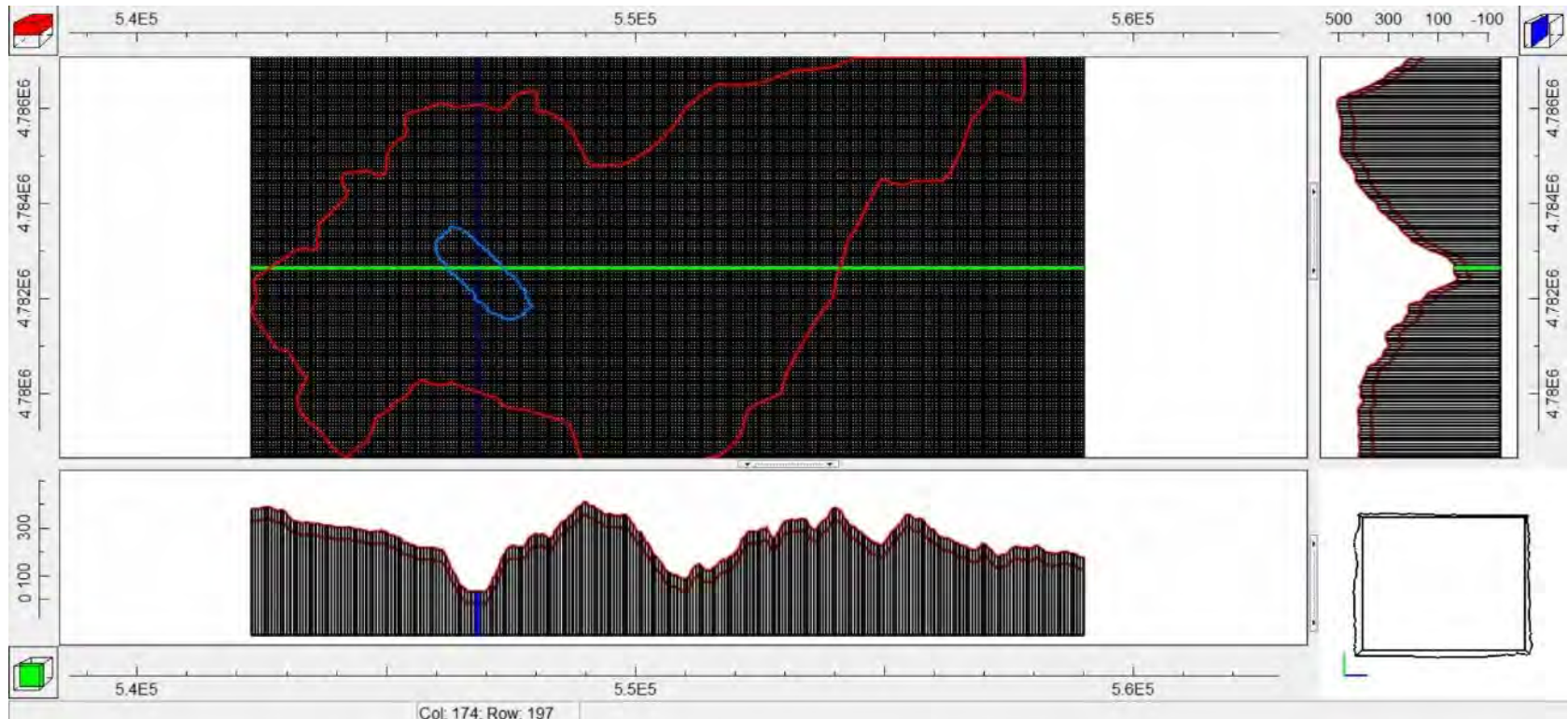


*Model domain and DEM.*



*Model domain*

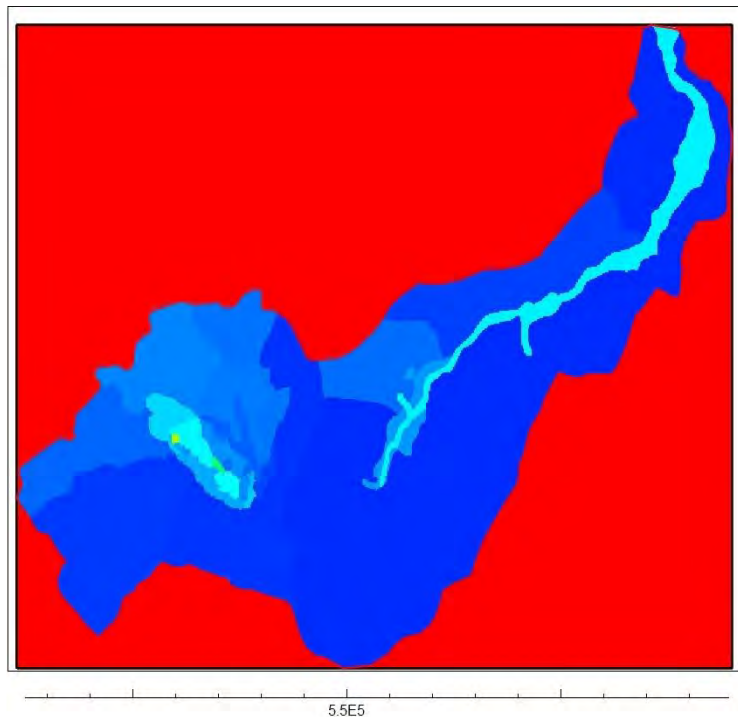
- 2 numerical layers, based on the hydrostratigraphical information described.
- 265,132 cells per layer.
- 30x30m cell size.



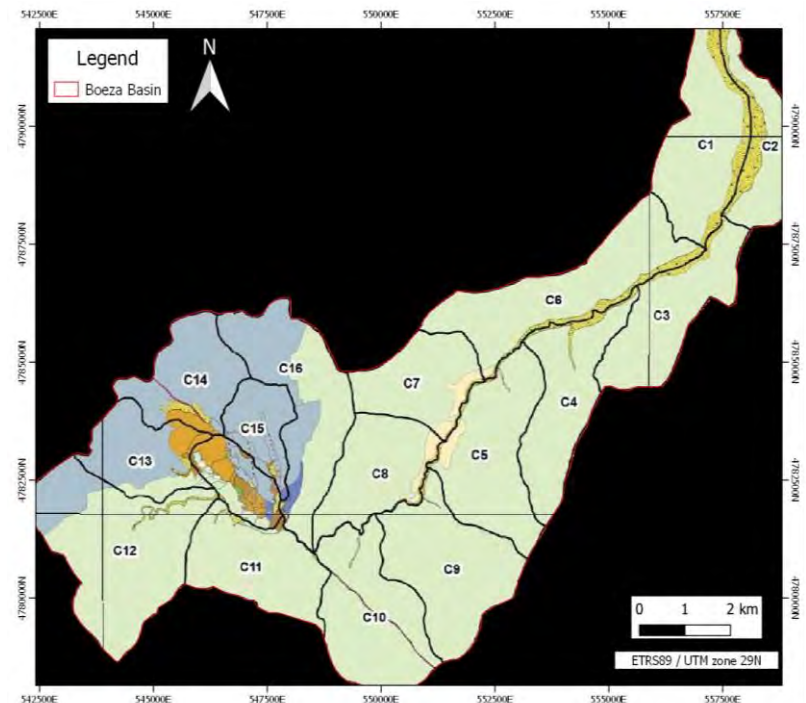
*Representation in ModelMuse of the mesh and vertical discretization: 2 numerical layers.*

# Hydraulic parameters

- Sub-basin differentiation
- $K_x$  between  $1.62E-5$  and  $2.78E-7$  m/s.
- Impervious bottom layer  $K_x=1E-12$  m/s.



*Initial Hydraulic conductivity*

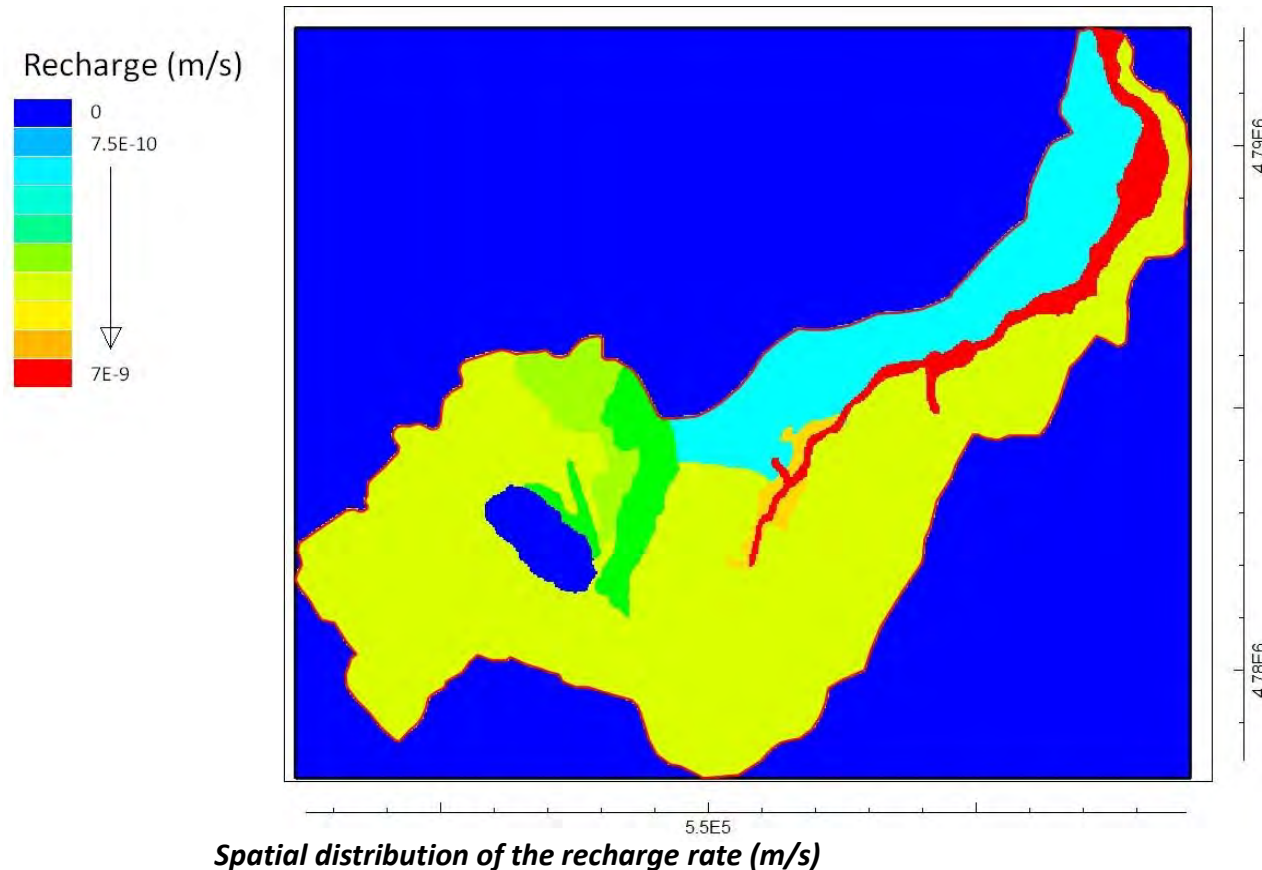


*Sub-basins selected and geological materials*

- ⦿ In the transient state model, the first time step is simulated in a steady-state regime.
- ⦿ 8 time steps have been simulated, representing the different pumping episodes (8 years in total, to attempt to be in line with the real flooding period).

## Recharge

- Visual Balan Software
- From  $7E-9$  m/s to  $7.5E-10$  m/s.



# Boundary conditions

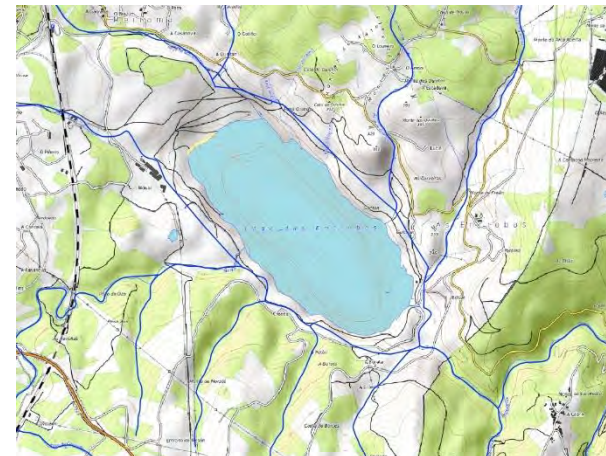
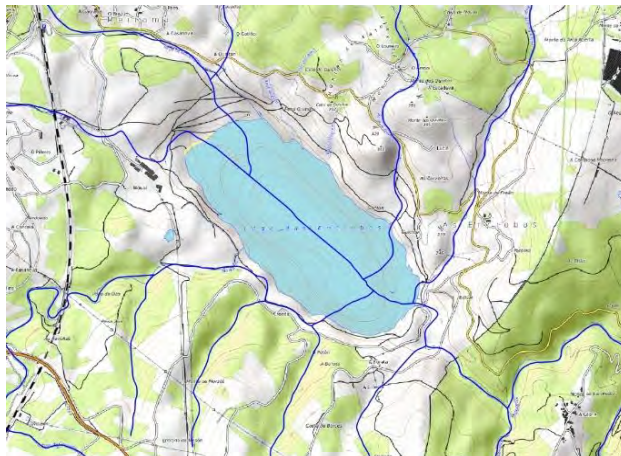
## ⊙ Groundwater abstractions

- Water abstracted from pumping wells.
- Amount of water extracted calculated based on piezometric data in the open-pit area.

## ⊙ Surface water

- Rivers
- Channel diversions during mining activity
- Cecebre's reservoir

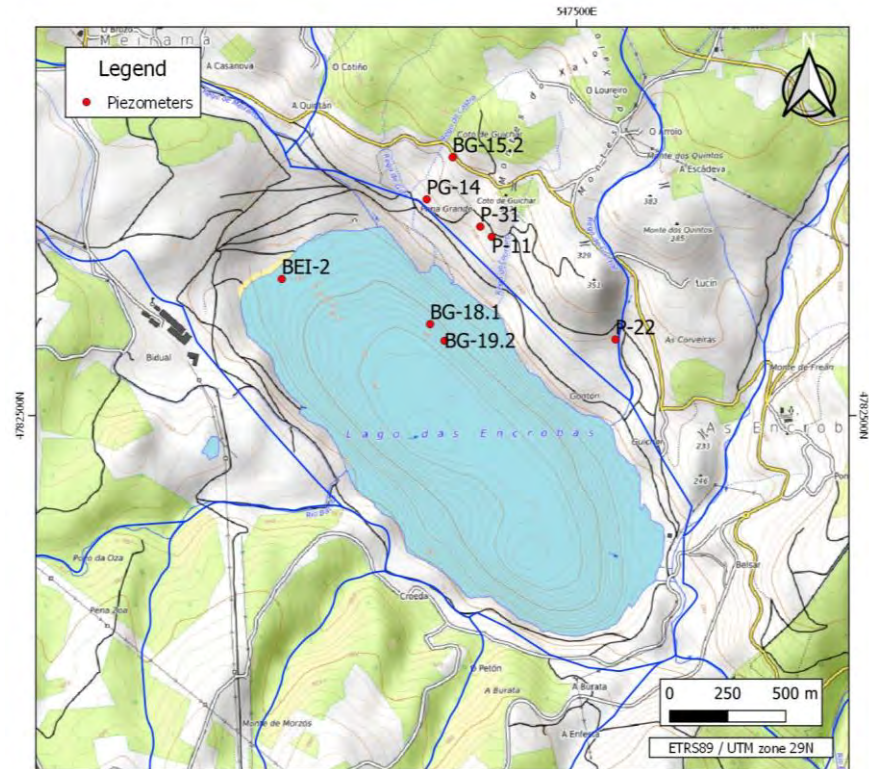
Period	Pumping rate (m <sup>3</sup> /s)
Year 1	-0.00043
Year 2	-0.0002
Year 3	-0.00016
Year 4	-0.00013
Year 5	-0.00011
Year 6	-0.00009
Year 7	-0.00002
Year 8	0



*Rivers near the open pit before (left) and after water course diversion (right).*

# Model calibration

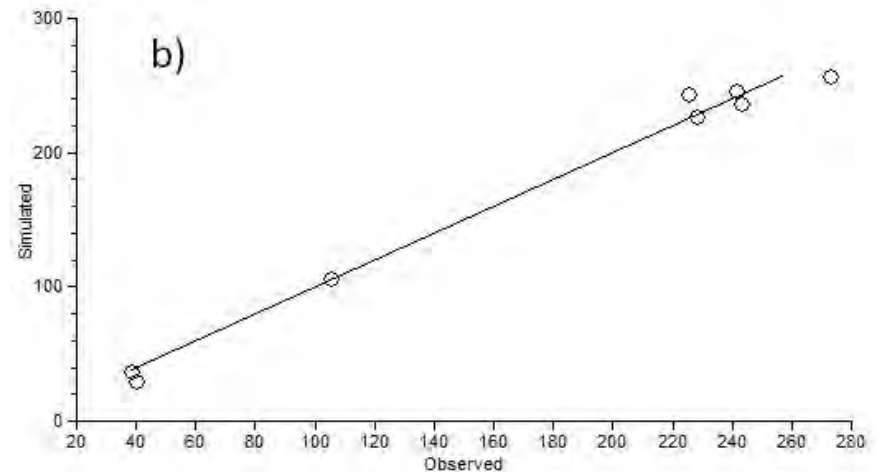
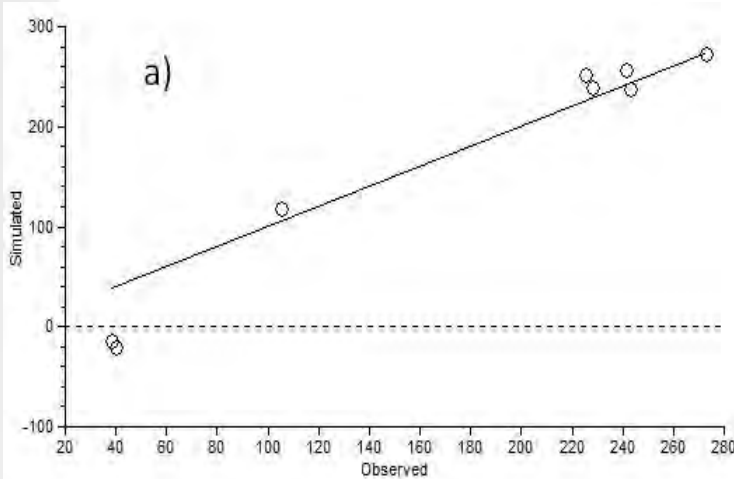
- 8 piezometers with groundwater level data are available in the study area.
- Calibration has been carried out for the period prior to the flooding of the open pit (data available just after the end of the mining operation).
- Parameter modification:
  - Hydraulic conductivity of each hydrostratigraphical unit (local refinement).
  - Pumping regime inside the open pit
  - River conductance



*Location of the piezometers near de open pit*

# Model calibration

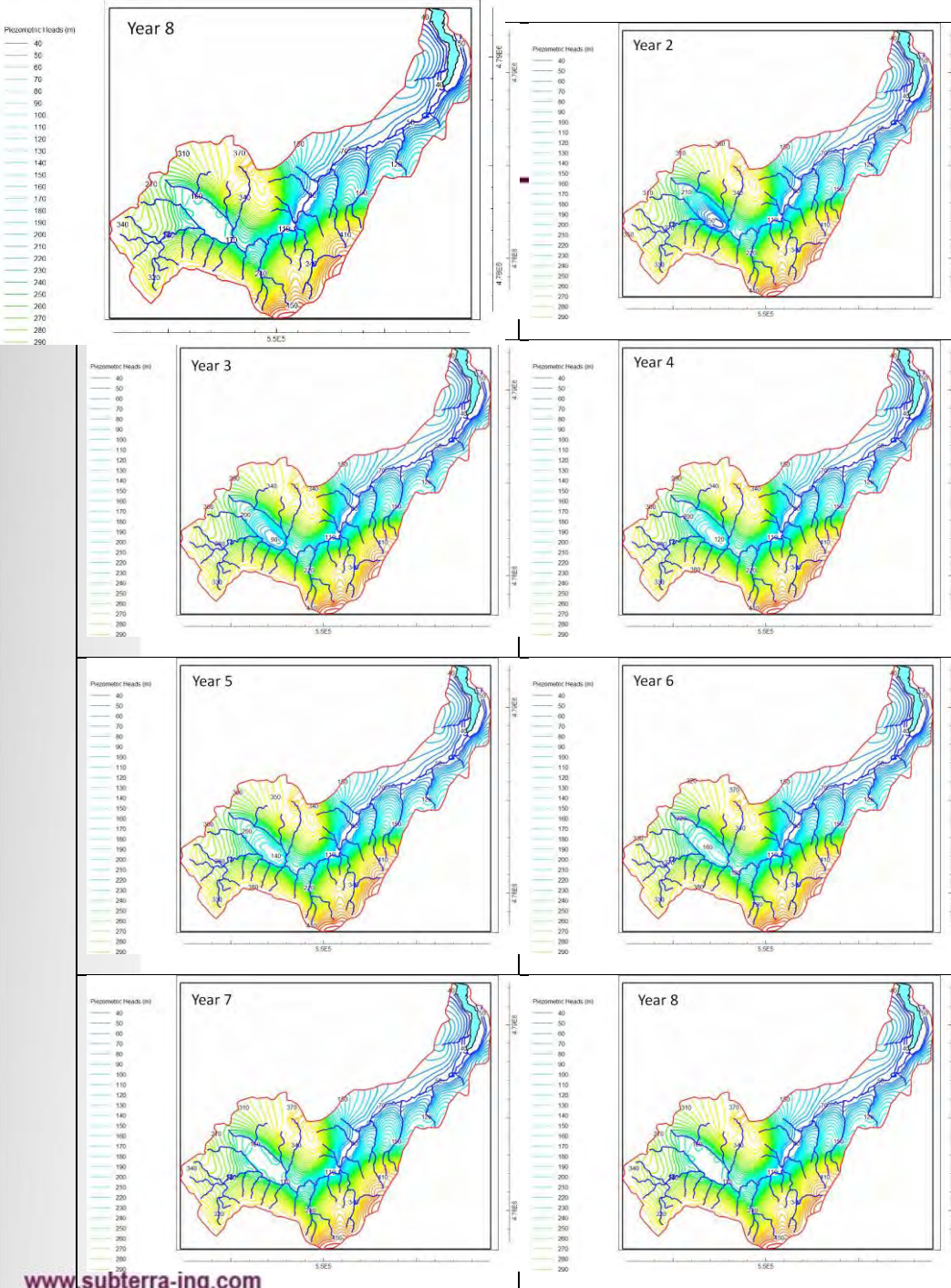
- Root mean square (RMS) statistics of residuals was applied.
- Initial runs RMS=31.25 m.
- Final simulation=10.00 m.
- Dispersion of the positive and negative residuals was more uniformly distributed.



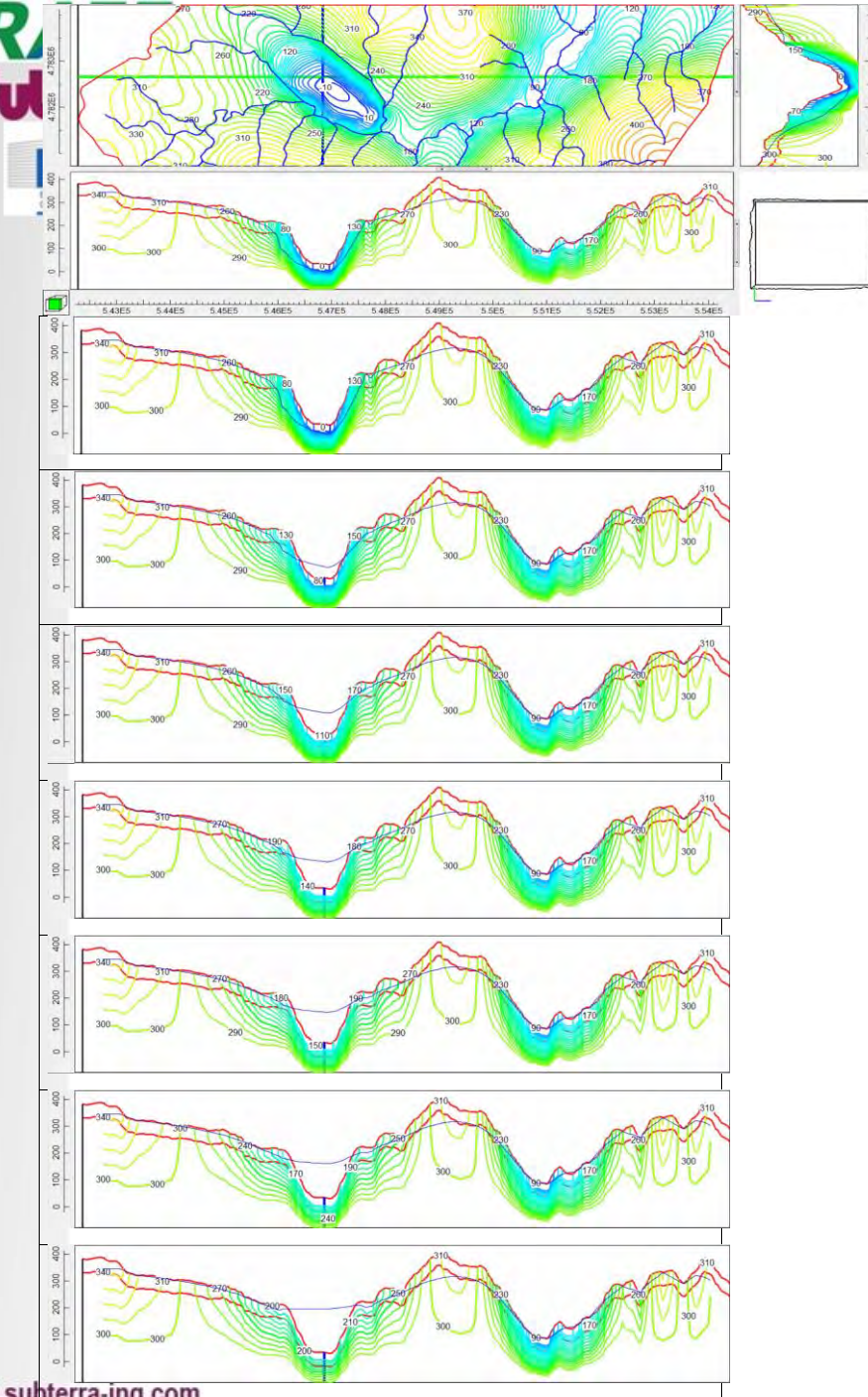
*Residuals a) before and b) after calibration process*

# Model results

- Simulated groundwater level for the surficial aquifer.
- Each image shows the level for each of the years since the pumping stops and therefore the flooding of the open-pit begins.



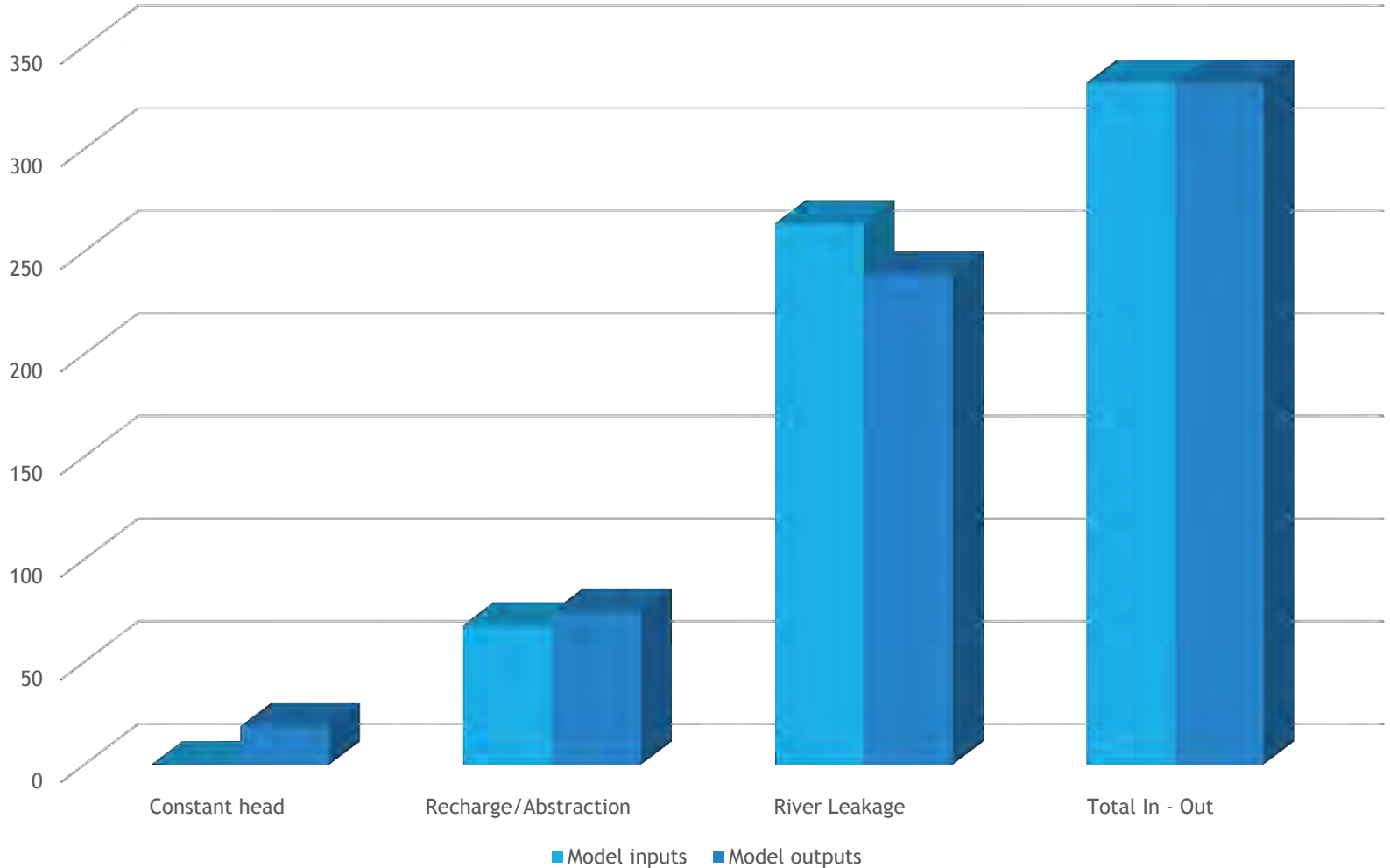
# Model results



- Piezometric heads as well as the groundwater table in the middle zone of the open pit during the flooding period

# Model results

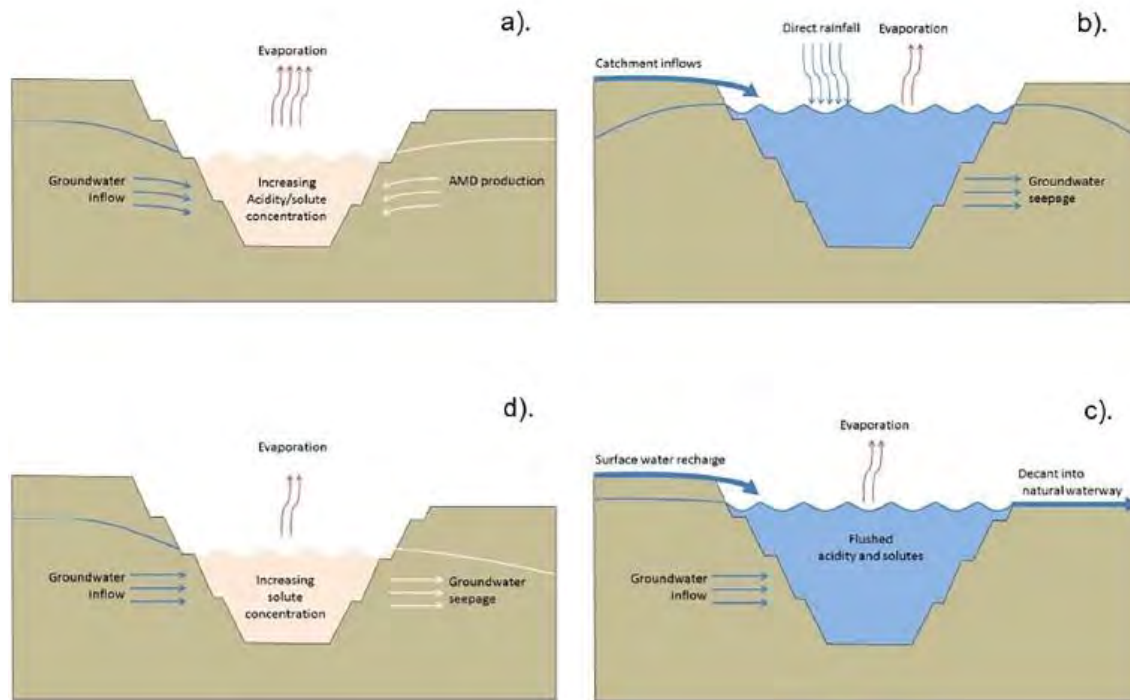
Water Balance (Mm<sup>3</sup>)



**Model groundwater budget. Input and output**

# Hydraulic sink effect analysis

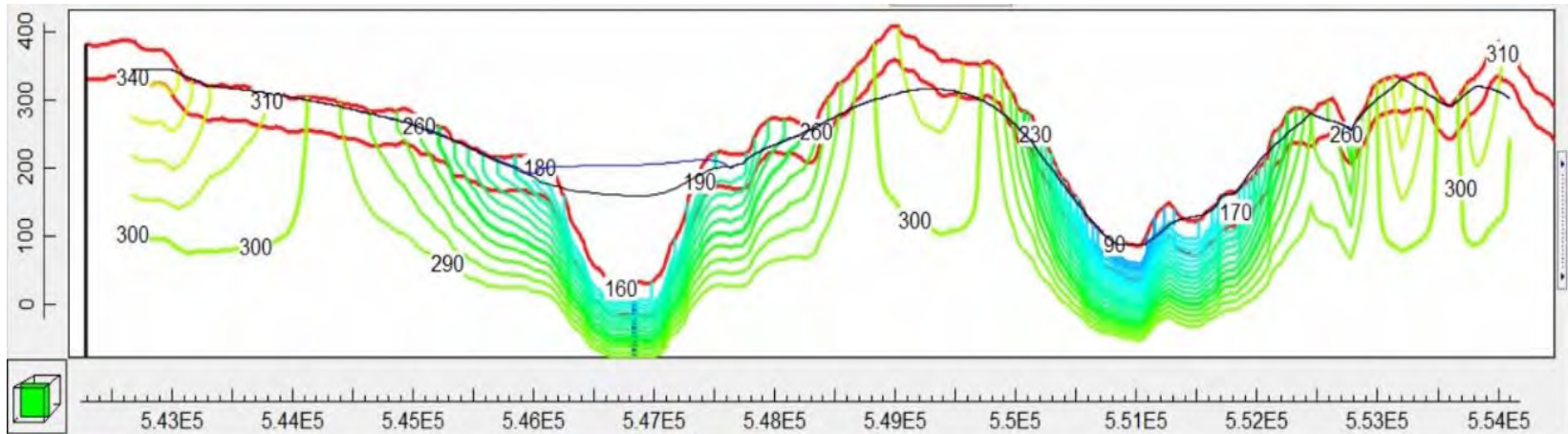
- During the mining operation period, the pumping of water generated for proper drainage works prevents the mobilisation of pollutants into the aquifer.
- If the pit-lake becomes a hydraulic sink due to the regional groundwater flux, it is likely to increase the acidification of artificial lake itself.



*Hydrogeological regimes for pit lakes. a) Evaporative terminal sink, b) surcharged lake, c) surface water flow-through, and d) groundwater through-flow (source McCullough et al. 2018).*

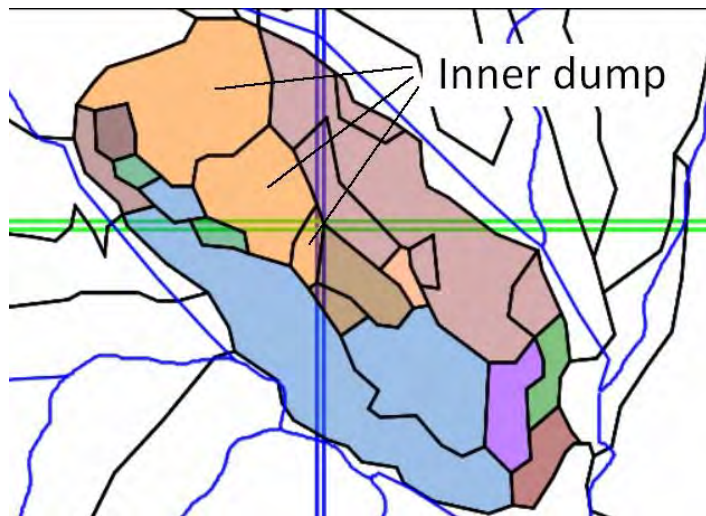
# Hydraulic sink effect analysis

- In order to prevent groundwater flow through the open pit and thus contact with the pyritic materials that cause AMD, it is necessary to generate the hypothesis.
- Hydraulic sink must be generated in such a way that the groundwater flow avoids this contact



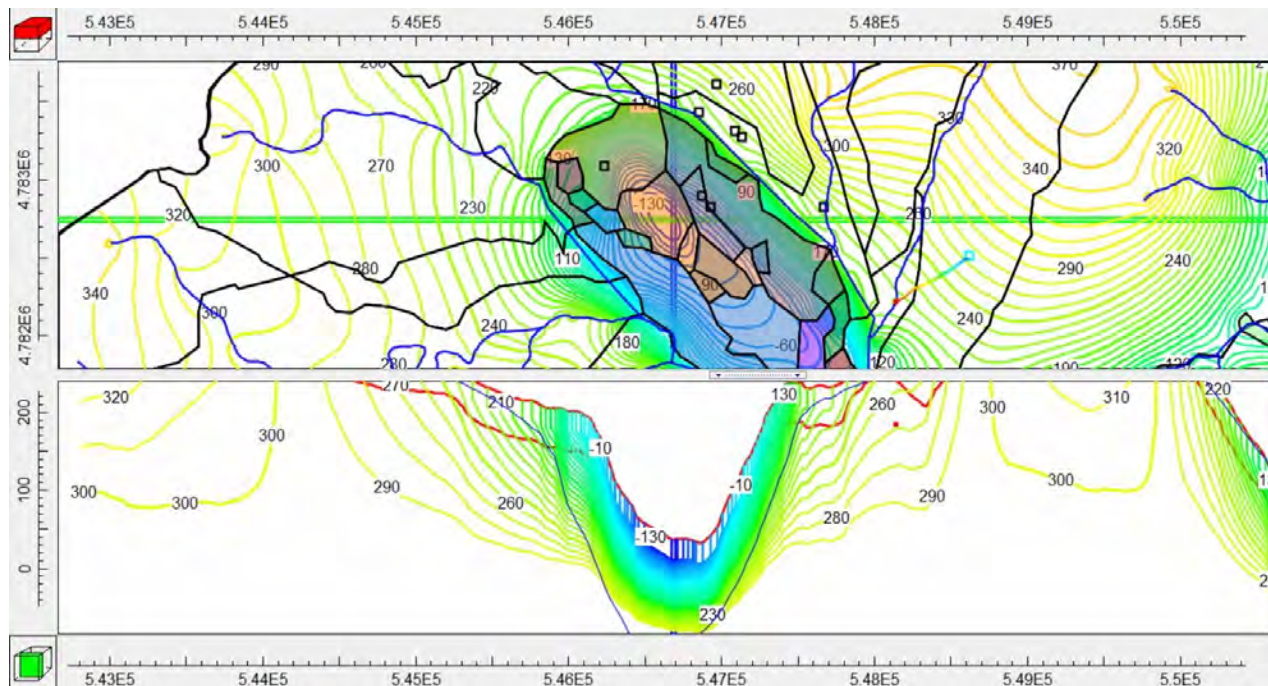
*Comparison between water table in last stage (blue line) and artificial hydraulic sink generation (black line).*

- Modification of the hydraulic conductivity of the materials that constitute the inner dump of the open-pit.



- Increasing  $K_x$  value, as it is a relatively large area, the model is greatly affected as materials became very permeable in comparison with the surrounding, so the simulation does not converge.

- If the hydraulic conductivity is reduced by an order of magnitude ( $K_x=2.3E-6$ ), it can be observed that for the same pumping rate values, an accentuated piezometric depression is generated in comparison with the values of the initial calibrated model.



*Groundwater table reducing hydraulic conductivity ( $K_x$ ) values for the inner dump in the initial step.*

# Conclusions

- Hydrogeological modelling works of flooding an open-pit after the end of mining activity.
- Assess the impact of the cessation of pumping on the regional aquifer, in order to analyse the possible polluting effects of water in contact with the materials associated with coal extraction.
- Effect of the hydraulic sink produced by the mining activity has been studied, as well as the theoretical values needed to generate this process artificially in the final flooding period in order to minimise groundwater contamination.
- Importance of trying to maintain an open-pit lake level lower than the original one, in order to avoid the mobilisation of pollutants into the aquifer.
- Level of importance of the hydraulic properties of the inner dump. With different values of hydraulic conductivity, pumping rates can be very variable.
- The model is more sensitive to high increases in pumping rates than to high decreases.
- The model does not show much sensitivity in areas far from the open-pit.