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Problèmes de mécanique des roches liés à la maintenance et à la modernisation des barrages existants
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Hydromechanical analysis of dam foundations: application issues and case studies

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Outline

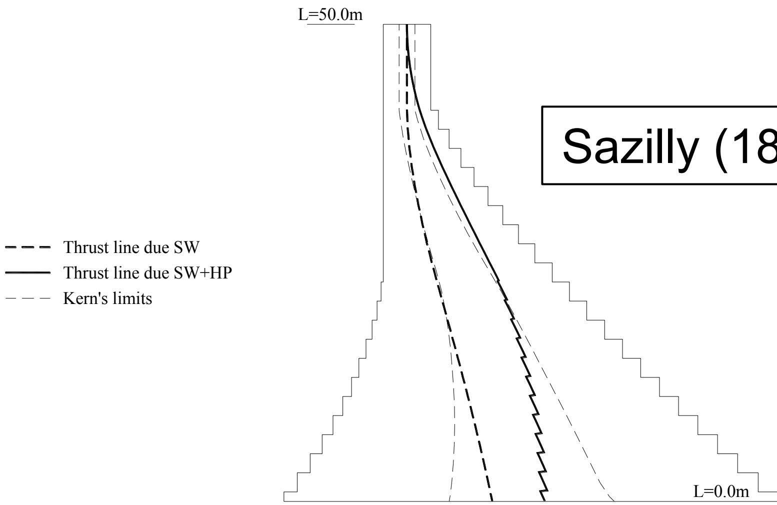
> Hydromechanical behaviour of dam foundations
  - Conceptual models
  - Numerical representation options
  - Models for monitoring analysis and safety assessment
  - Practical issues

> Case 1 – Masonry dam – Rehabilitation study

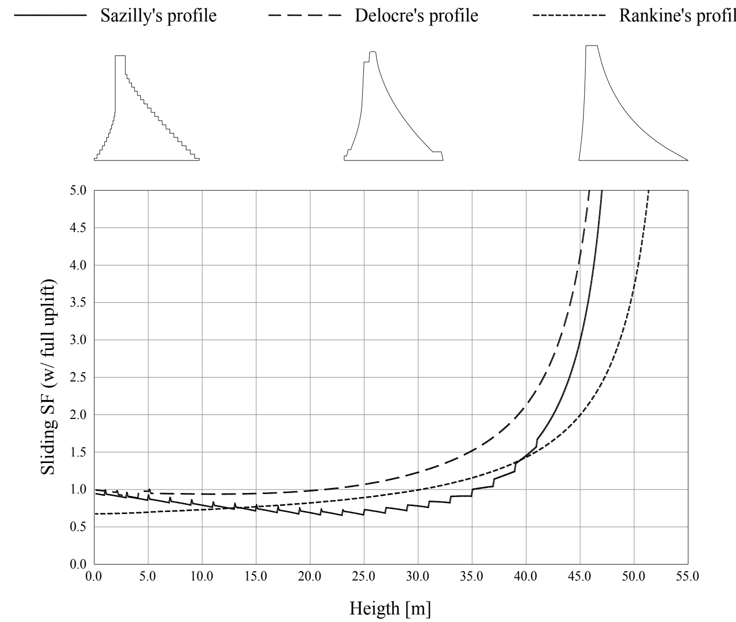
> Case 2 – Alqueva arch dam – Analysis of insitu tests and monitored behaviour

> Concluding remarks

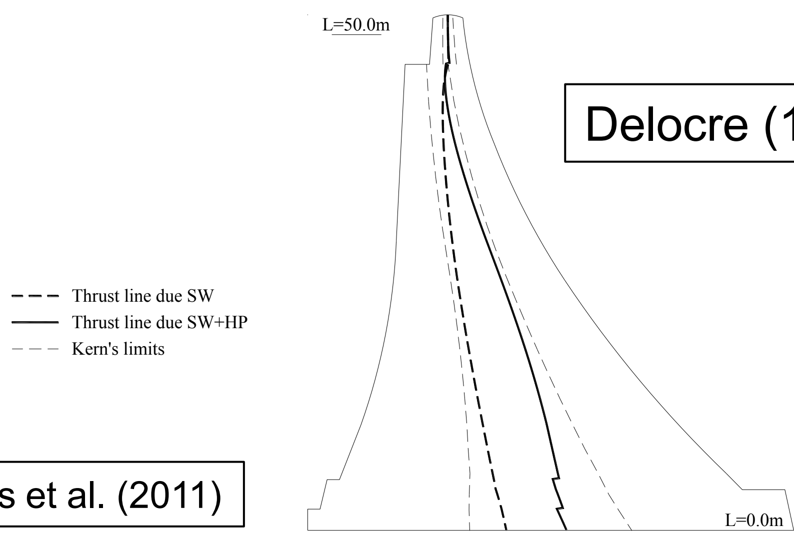
19th century gravity dam profiles
– Design based on masonry total stresses



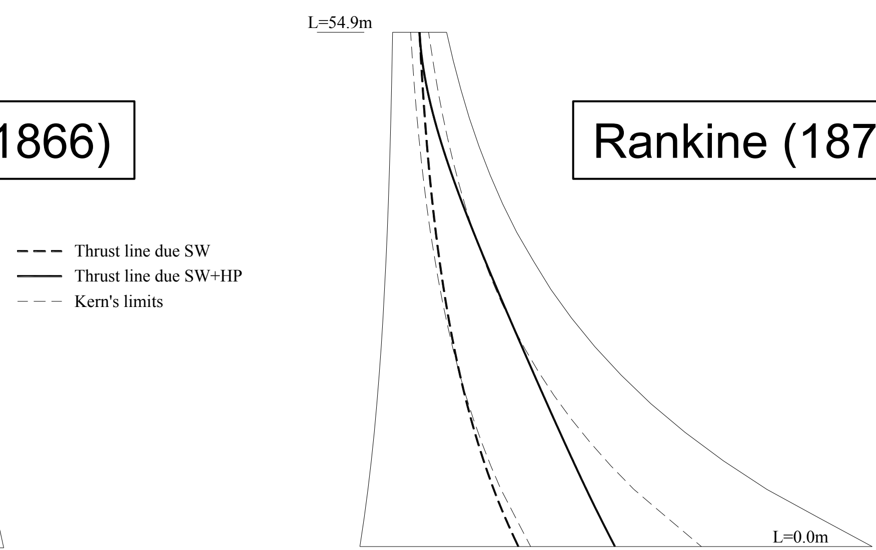
Sazilly (1853)



sliding safety factors (assuming φ=45°)



Delocre (1866)

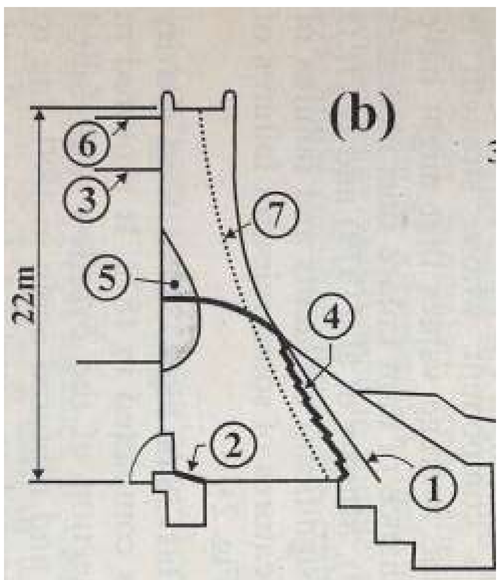


Rankine (1872)

Bretas et al. (2011)

The importance of uplift pressures

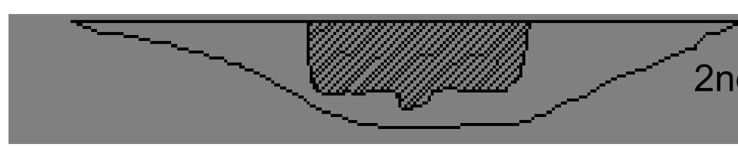
- The importance of the uplift water pressures for dam stability was first recognized by **Lévy (1895)** in his analysis of the accident of Bouzey dam



Léger et al. 1997

Bouzey dam
– 1st failure 1884, 2nd failure 1895

(1) Original profile
(2) 1st failure
(3) Water level at 1st failure
(4) Main rupture, 2nd failure
(5) Tension zone at 2nd failure
(6) Water level at 2nd failure
(7) Line of thrust (excluding internal water pressure)



2nd failure

Conceptual models

> In most rock masses, fluid flow takes place through the discontinuities. Numerical **fracture flow models** are available and are widely used. However, equivalent **continuum modelling** remains a valuable option.

> **Equivalent continuum analysis**

- Darcy's flow law
- Requires less data (permeability zoning)

> **Fracture flow analysis**

- Cubic law of flow in discontinuities
- Requires more data
  - *fracture patterns (DFN, …)*
  - *joint apertures; joint stiffness (flow-stress coupling); in situ state*
- Computationally more demanding (namely in model generation effort)

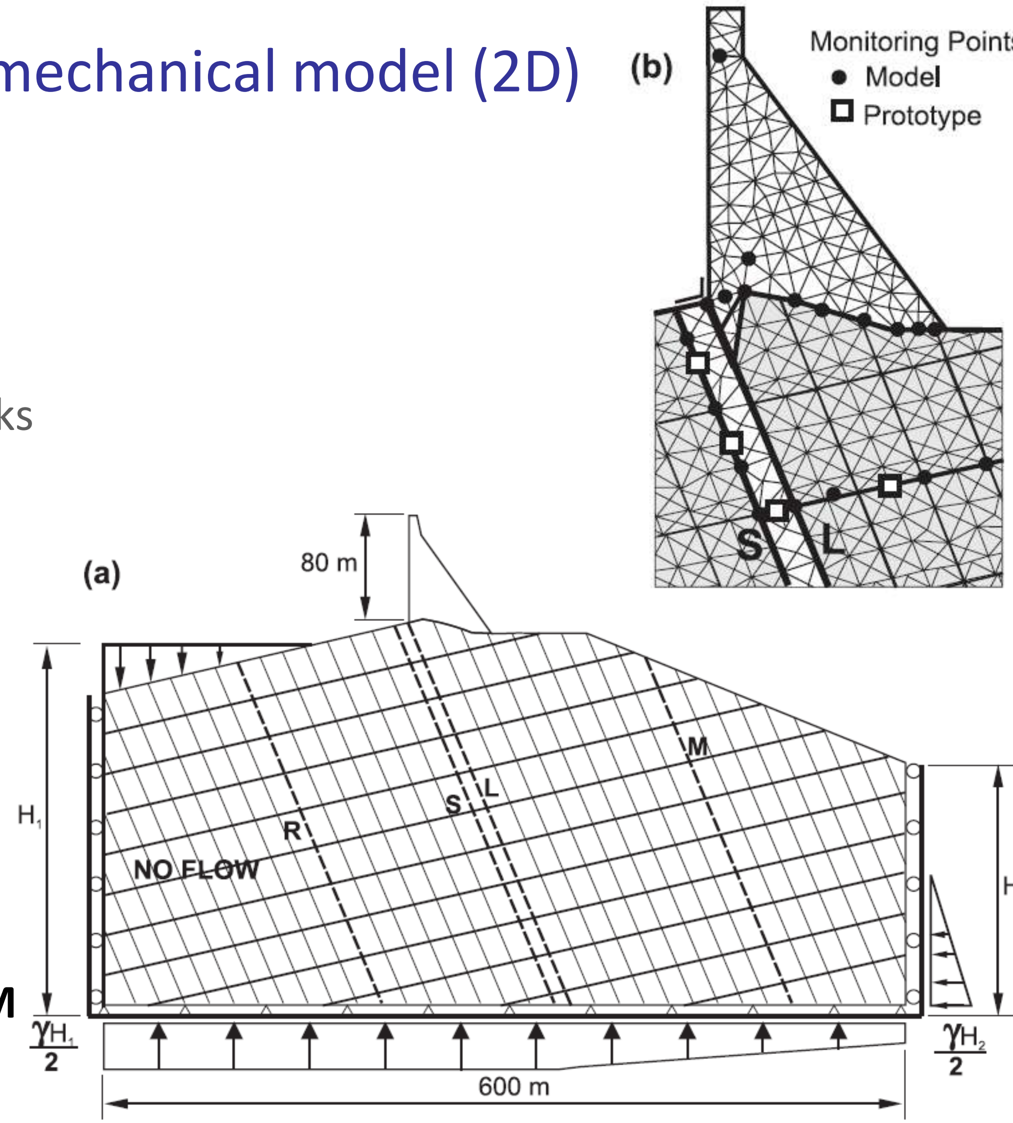
Example: gravity dam hydromechanical model (2D)

> UDEC model
- fracture flow
- deformable, impermeable blocks

> Joint pattern is highly idealized

> Analysis concentrates on the behaviour of steep discontinuity upstream (extensive monitoring system, Kovari et al. 1989)

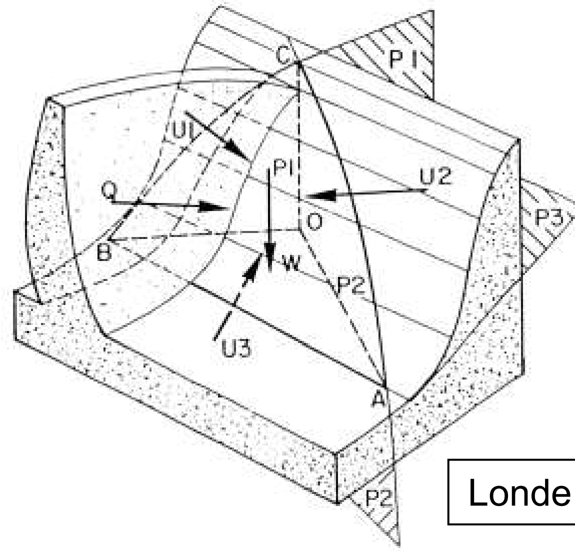
> The main advantage of using a **DEM (block) model** is to perform safety assessment based on **mechanical discontinuum analysis**



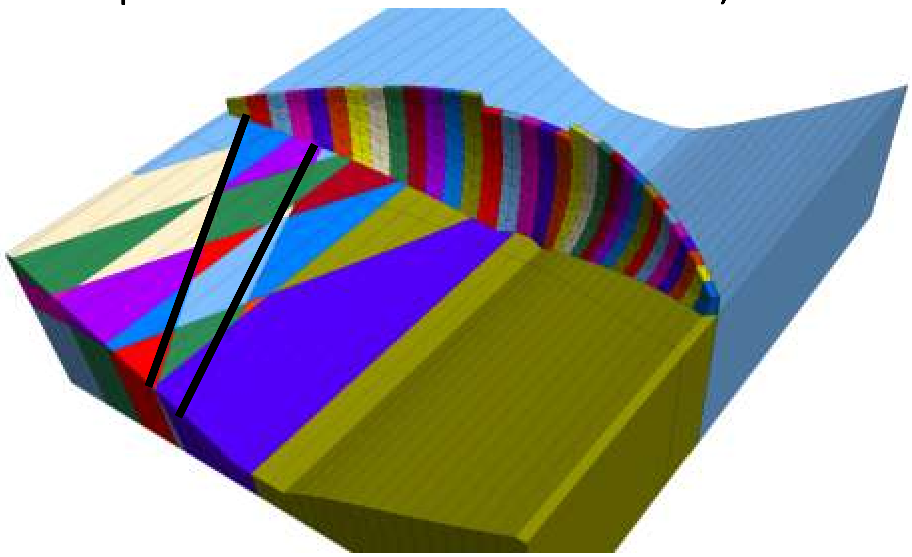
UDEC model of Albigna dam
Gimenes & Fernández (2006)

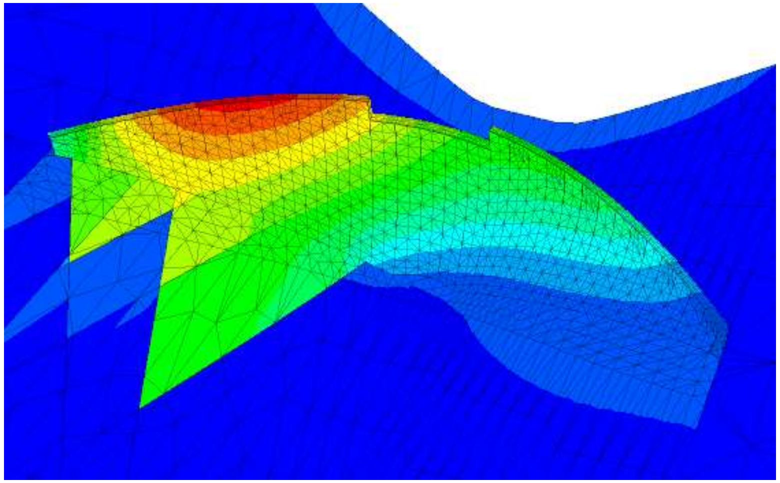
Modelling for safety assessment
- Arch dams

- Fracture patterns for mechanical and hydraulic analysis have different critical issues
  - *Stability analysis – joint persistence*
  - *Flow analysis – network connectivity*
  - *Most DFN research has been directed towards flow analysis*
- For safety assessment, much simpler fracture geometry models are sufficient (but with water pressures on all discontinuities)



Londe (1973)



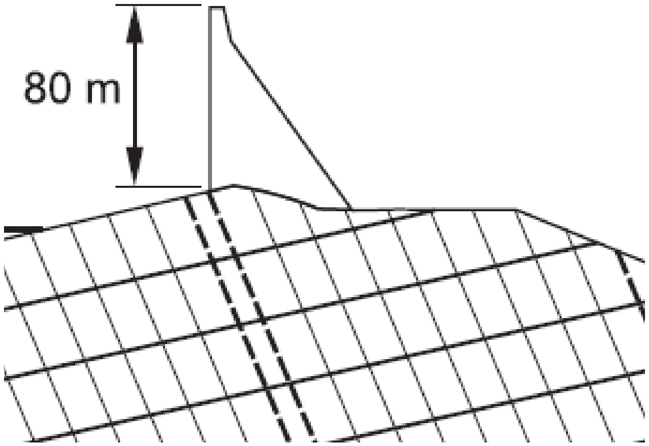


3DEC model of B.Sabor dam

Note: models with simplified joint patterns

> In DEM models, **joint spacing** larger than the real one is often used to save computer run time (or to make a large model feasible)

- In mechanical stability analysis, joint stiffness (kn) is usually not an issue
- Global deformability can always be respected with proper combinations of joint kn and block material E
- In hydro-mechanical analysis, realistic joint stiffnesses have to be used for proper stress-flow coupling in the cubic law
- Simplified representation of a few joints by a single numerical discontinuity is different for mechanical and hydraulic properties



Dam foundations issues

> Modelling issues:

- Grout curtain
- Drainage system
- Flow often takes place at shallow depths (fractured/disturbed zone)

> Model uses:

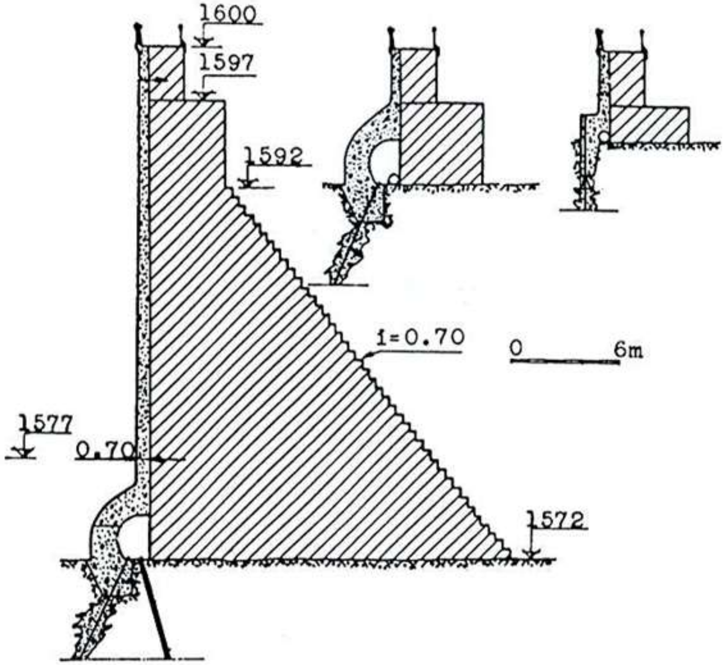
- interpretation of monitoring data under operating conditions
  - *Equivalent continuum model is easier to apply*
- assessment of failure scenarios
  - *Discontinuum model is preferable*
  - *"Hybrid" option:*
    - use discontinuum mechanical model
    - assign water pressure fields to all discontinuities obtained with continuum analysis

Masonry dams – Rehabilitation options

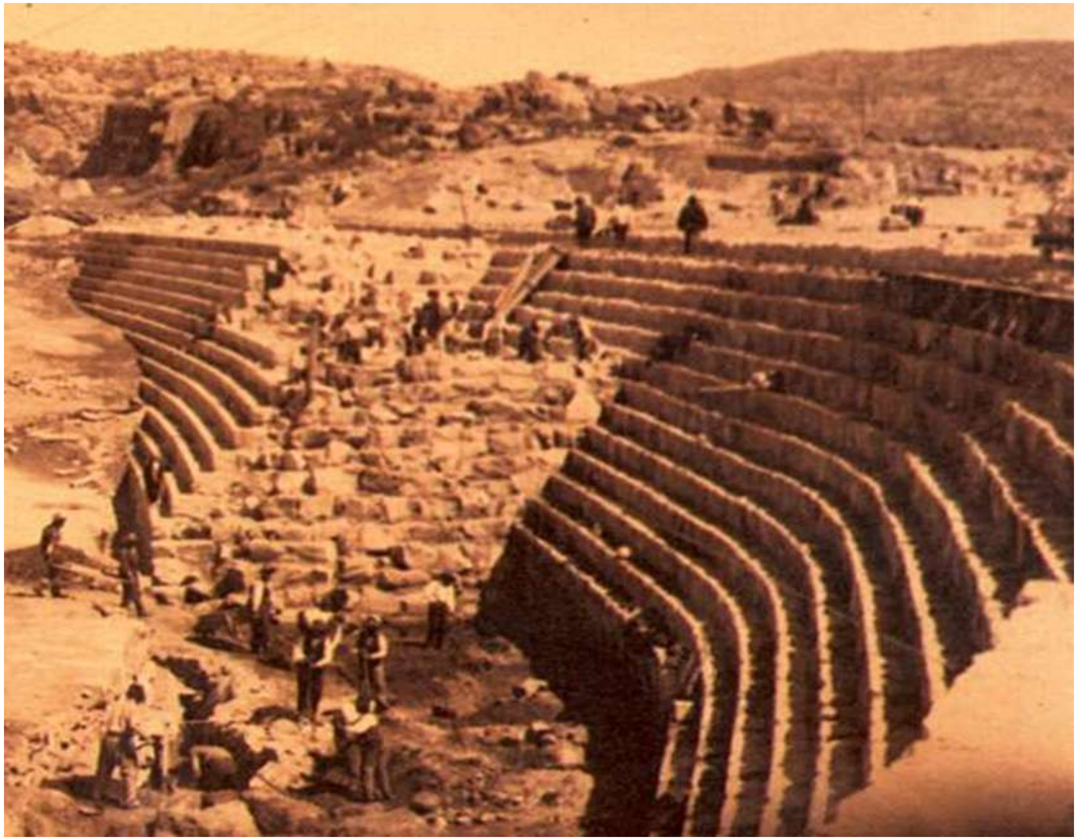
> Old masonry dams

- deterioration processes – flow through dam body and rock mass
- need for rehabilitation
  - *stop deterioration*
  - *guarantee safety*
  - *new regulatory requirements (e.g. seismic loading, …)*
- impermeabilization
  - *concrete facing*
  - *geomembranes*
  - *grouting (masonry and rock)* *--->* *Case study 1 : Póvoa dam*
- drainage
- monitoring improvement (piezometers, drain flows, …)

Lagoa Comprida dam
- Concrete facing

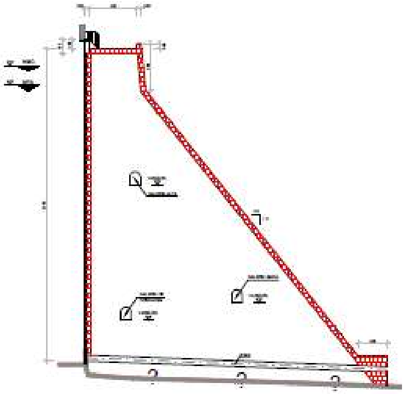


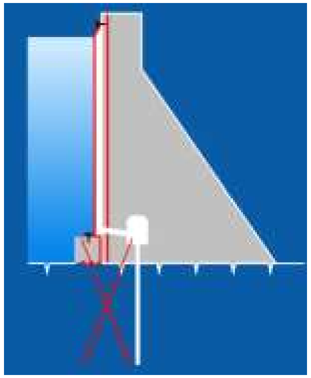
Lagoa Comprida dam
Owner: EDP
H = 28 m
built 1914, heightened 1934,
rehabilitation 1966



Covão do Ferro dam
- Geomembrane

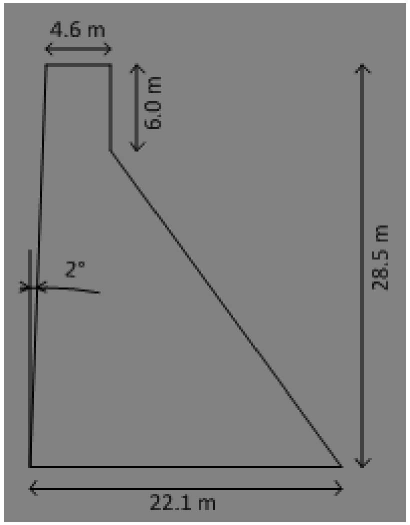
Scuero et al. 2007





Covão do Ferro dam
Owner: Pebble Hydro
H = 33 m
built 1935-56
rehabilitation 2006

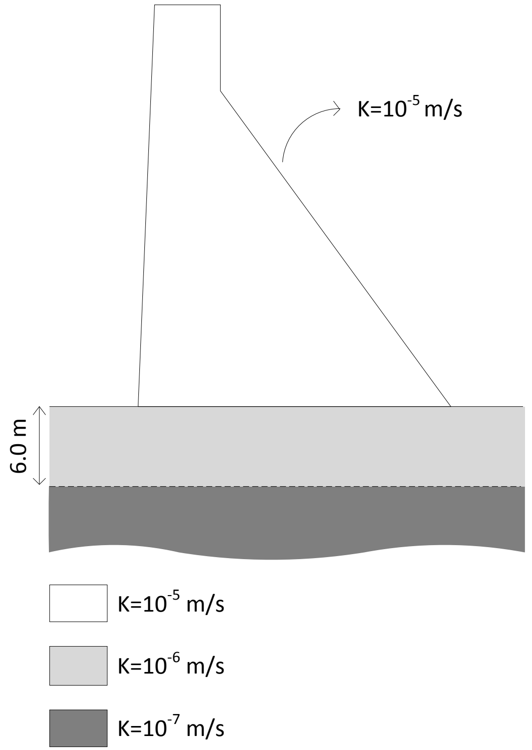
Póvoa dam



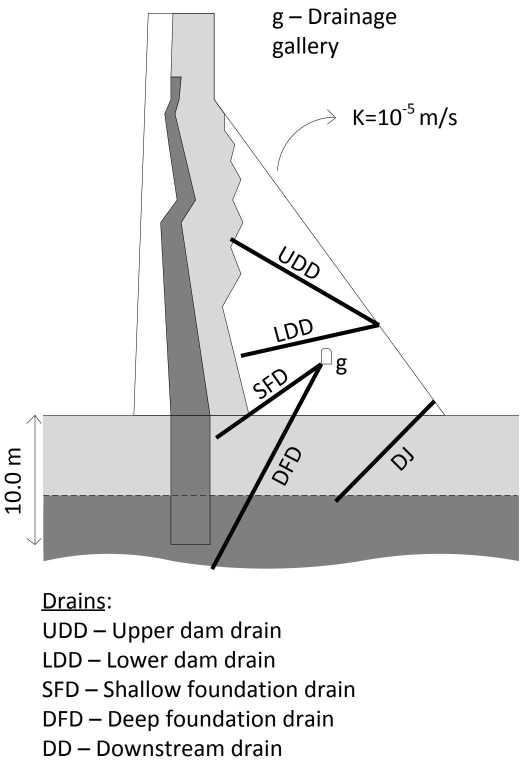
Póvoa dam
Owner: EDP
built 1927
H = 28 m

Rehabilitation project for Póvoa dam: grouting of dam and foundation

- Extensive flow through **dam body** and **rock mass**
- Concern about masonry integrity and sliding failure on foundation
- Exploration with limited reservoir level
- Foundation
  - granitic rock mass
  - good quality below 10m
  - top layer very fractured and permeable



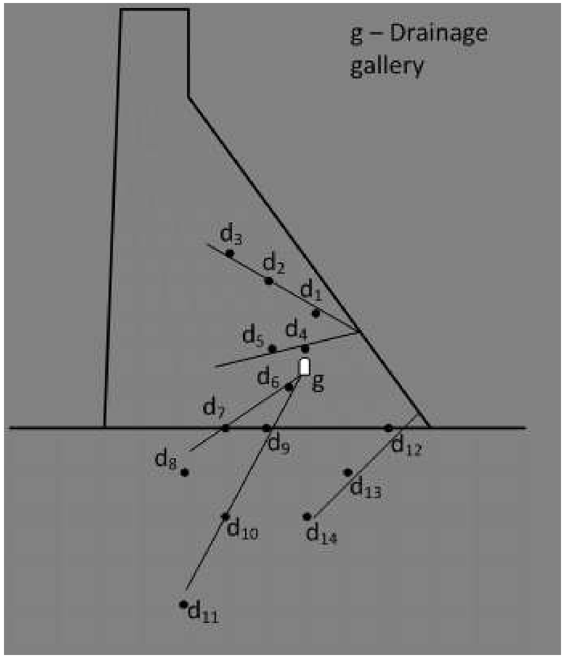
(a) Permeability properties before rehabilitation



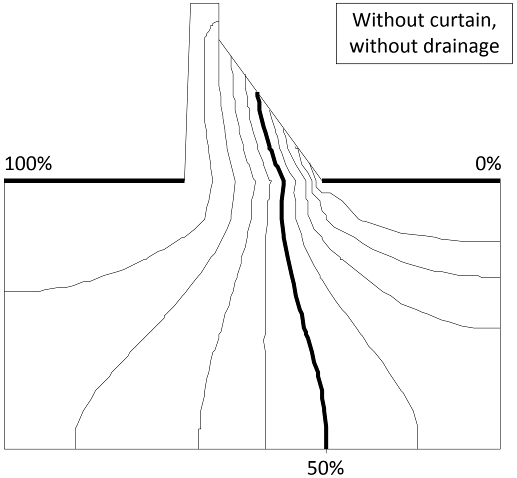
(b) Permeability properties and drainage system after rehabilitation

DEM block model for hydromechanical analysis

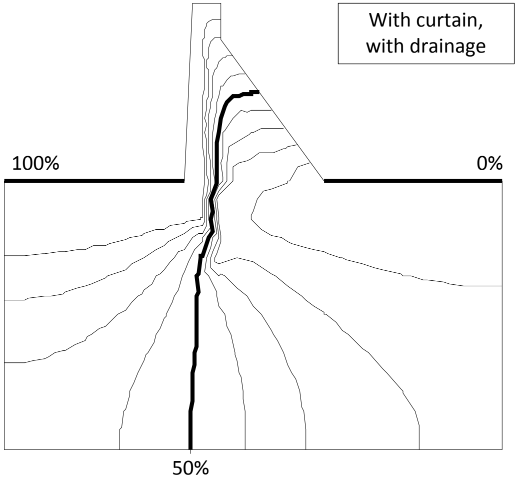
(E.M. Bretas, thesis, 2012)



- Simplified blocky structure
  - *horizontal flow paths (and sliding planes)*
  - *vertical cross-joints*
- Blocks
  - Deformable
  - Impermeable
- Flow in joints
- Joint apertures calibrated for continuum permeability
- Analysis of sliding failure
  - *dam body*
  - *dam-rock interface*



(a) Equipotential lines before rehabilitation works

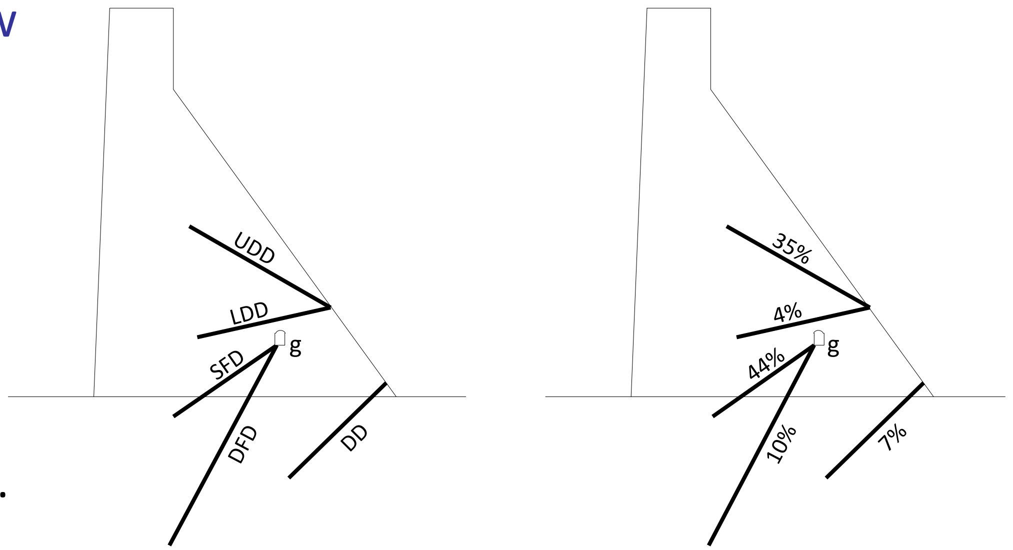


(b) Equipotential lines after rehabilitation works

Analysis of the distribution of flow into the drainage system

> Analysis of drainage alternatives, e.g.

- suppression of LDD (4%)
  - *flow goes into UDD and SFD*
- suppression of DD (7%)
  - *flow goes to downstream face*

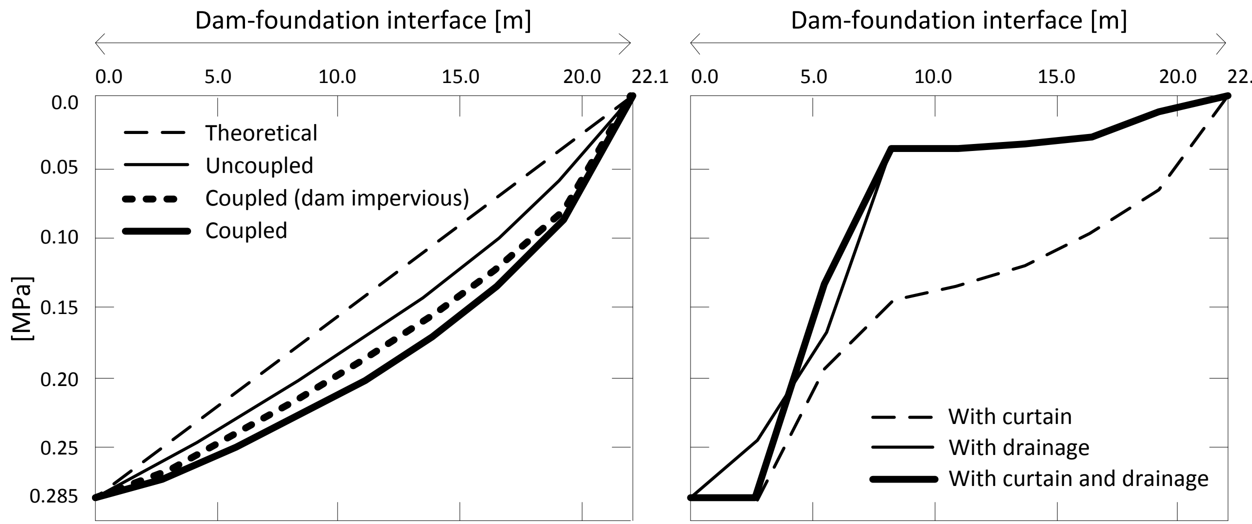


(a) Drains identification

(b) Distribution of the flow rates to the drainage system

	Before rehabilitation	With curtain	With drainage	With curtain and drainage
Total flow rate (l/min)	2150	496	3070	592
Input – Upstream foundation	0 %	1 %	2 %	2 %
Input – Upstream face	100 %	99 %	98 %	98 %
Output – Downstream foundation	1 %	2 %	0 %	0 %
Output – Downstream face	99 %	98 %	36 %	15 %
Output – Drainage system	-	-	64 %	85 %

> Uplift pressures on dam-rock interface

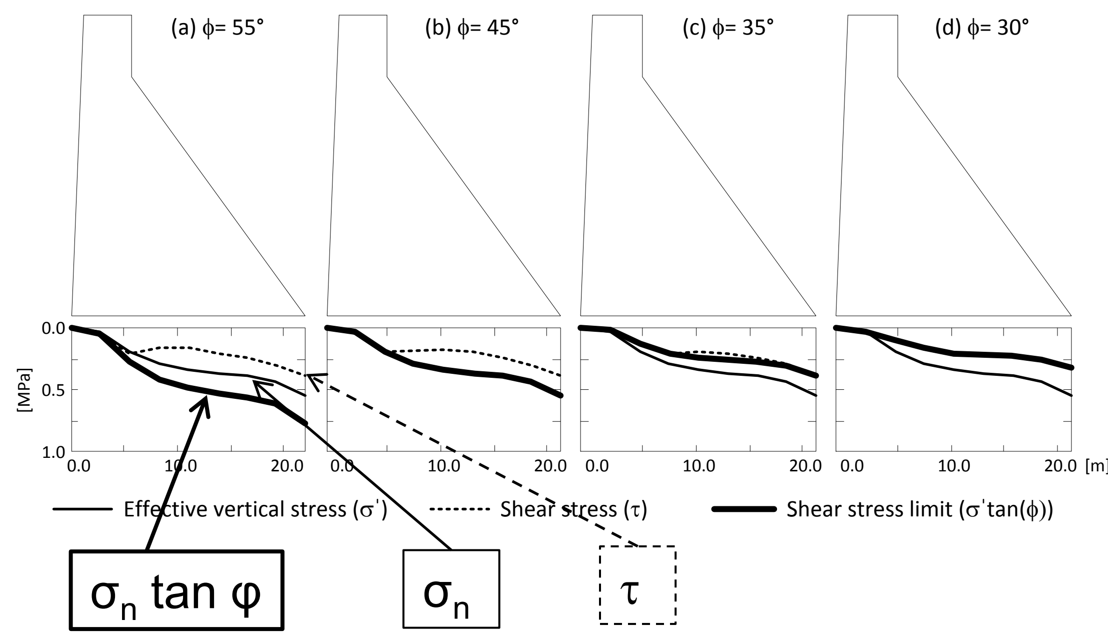


(a) Uplift diagrams for the initial conditions, before rehabilitation

(b) Uplift diagrams for the final conditions, after rehabilitation

> Sliding failure mechanism on dam-rock interface

- assumed c=0, φ=45°
- safety factor
  - *before: SF=1.0*
  - *with grout/drainage: SF=1.5*



Alqueva arch dam

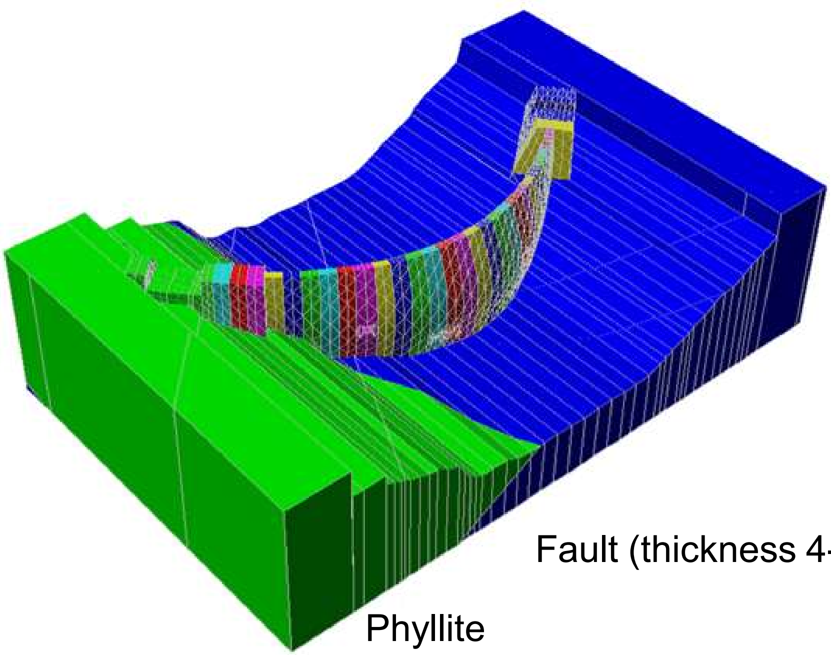
Double curvature arch dam:

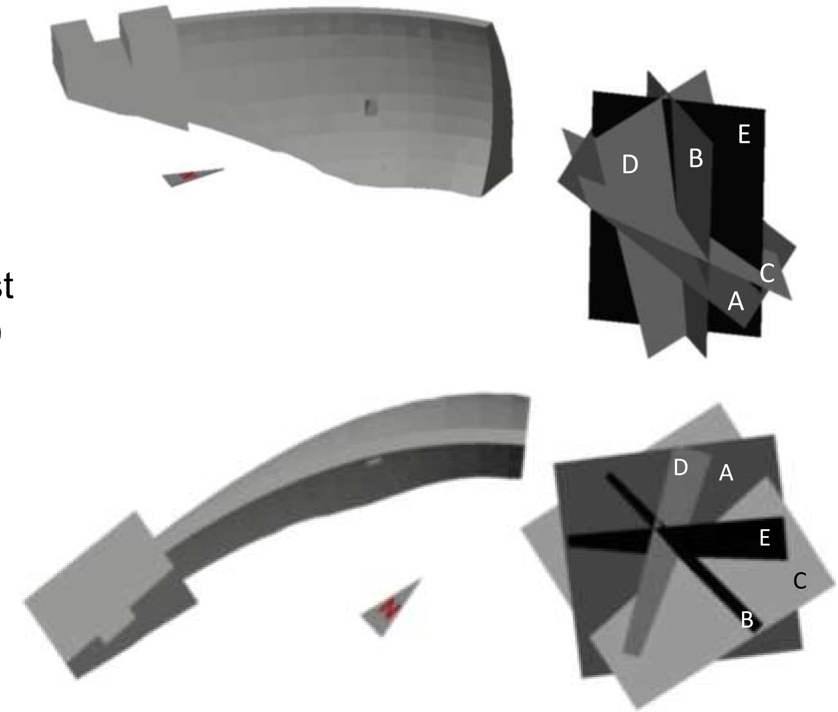
Height	96 m
Crest length	348 m
Central cantilever thickness	7-30 m
Reservoir volume	4150 hm3

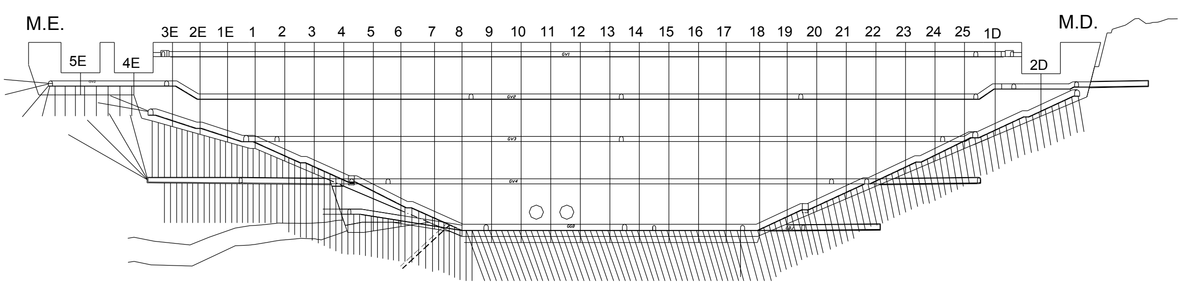
Built : 2003

Owner : EDIA

Research project on hydromechanical behaviour
L.B. Farinha, thesis, 2011



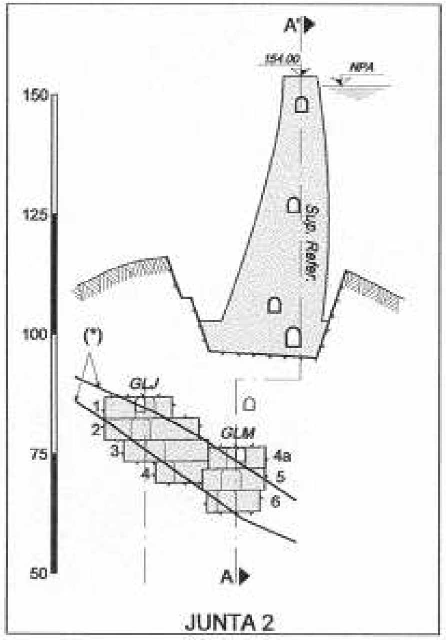


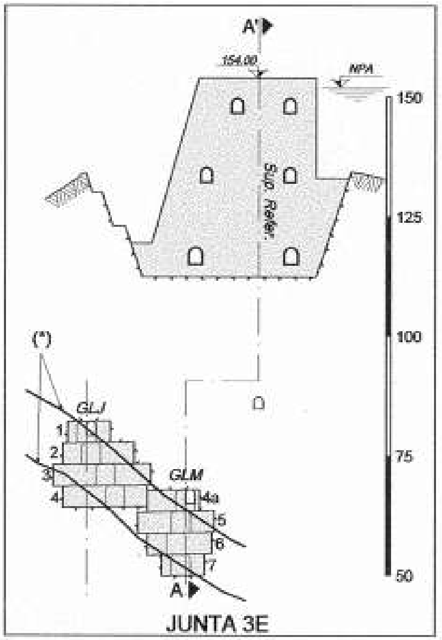


Drainage system

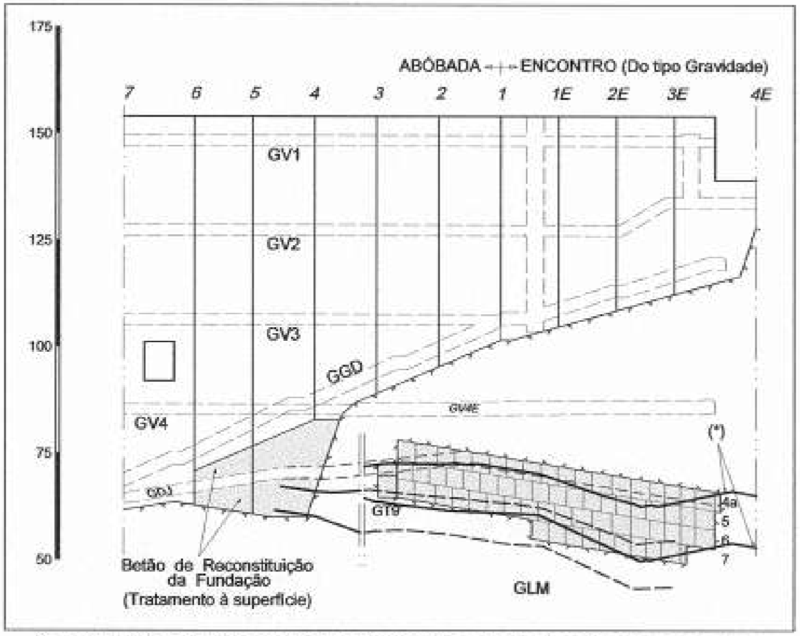
Discontinuities		Cohesion (MPa)	Friction angle (˚)
Green schist	Along schistosity	0.10	24
	making an angle < 15° with schistosity	0.17	38
	making an angle > 15° with schistosity	0.18	43
Phyllite	Along schistosity	0.11	22
	Subvertical and subhorizontal	0.13	29
	Between subvertical and subhorizontal	0.13	36

Fault treatment: replacement with concrete





(*) - TECTO E MURO DA FALHA (MODELO TRIDIMENSIONAL INTERPRETATIVO - PREVISÃO DE PROJECTO)



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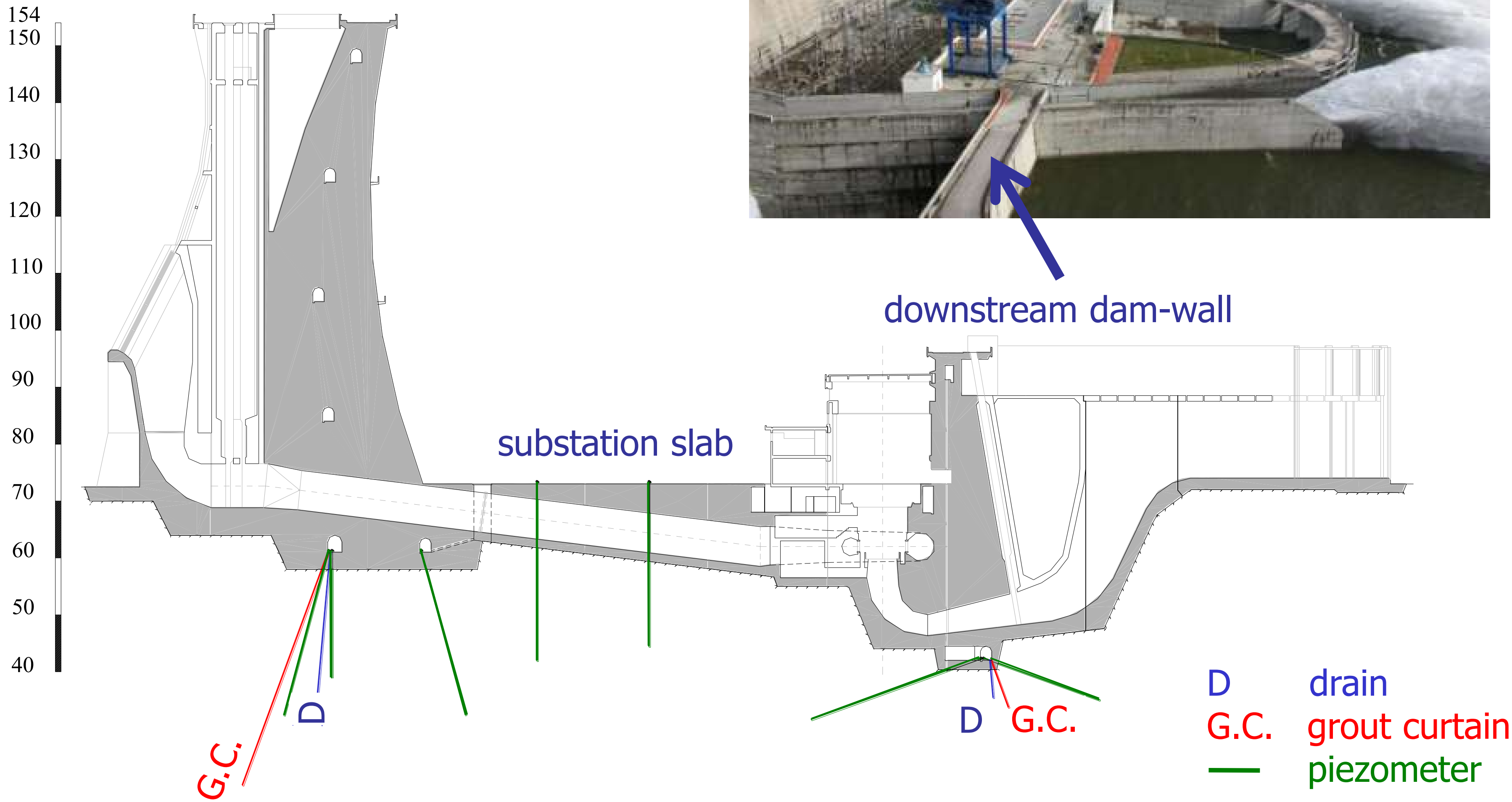
Alqueva dam

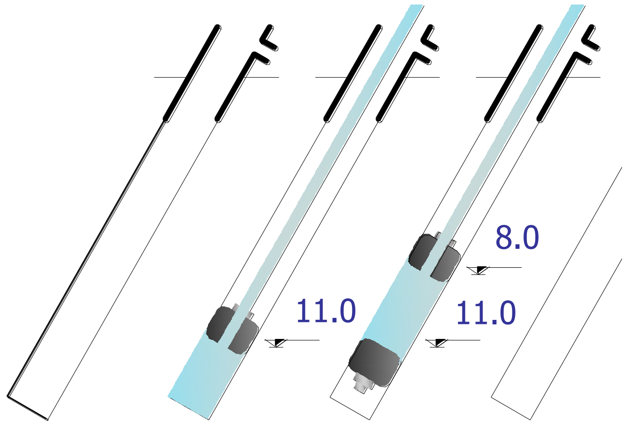


(m)
154
150
140
130
120
110
100
90
80
70
60
50
40
downstream dam-wall
substation slab
G.C.
D
D
G.C.
D drain
G.C. grout curtain
piezometer

Water inflow tests and water electrical conductivity analysis

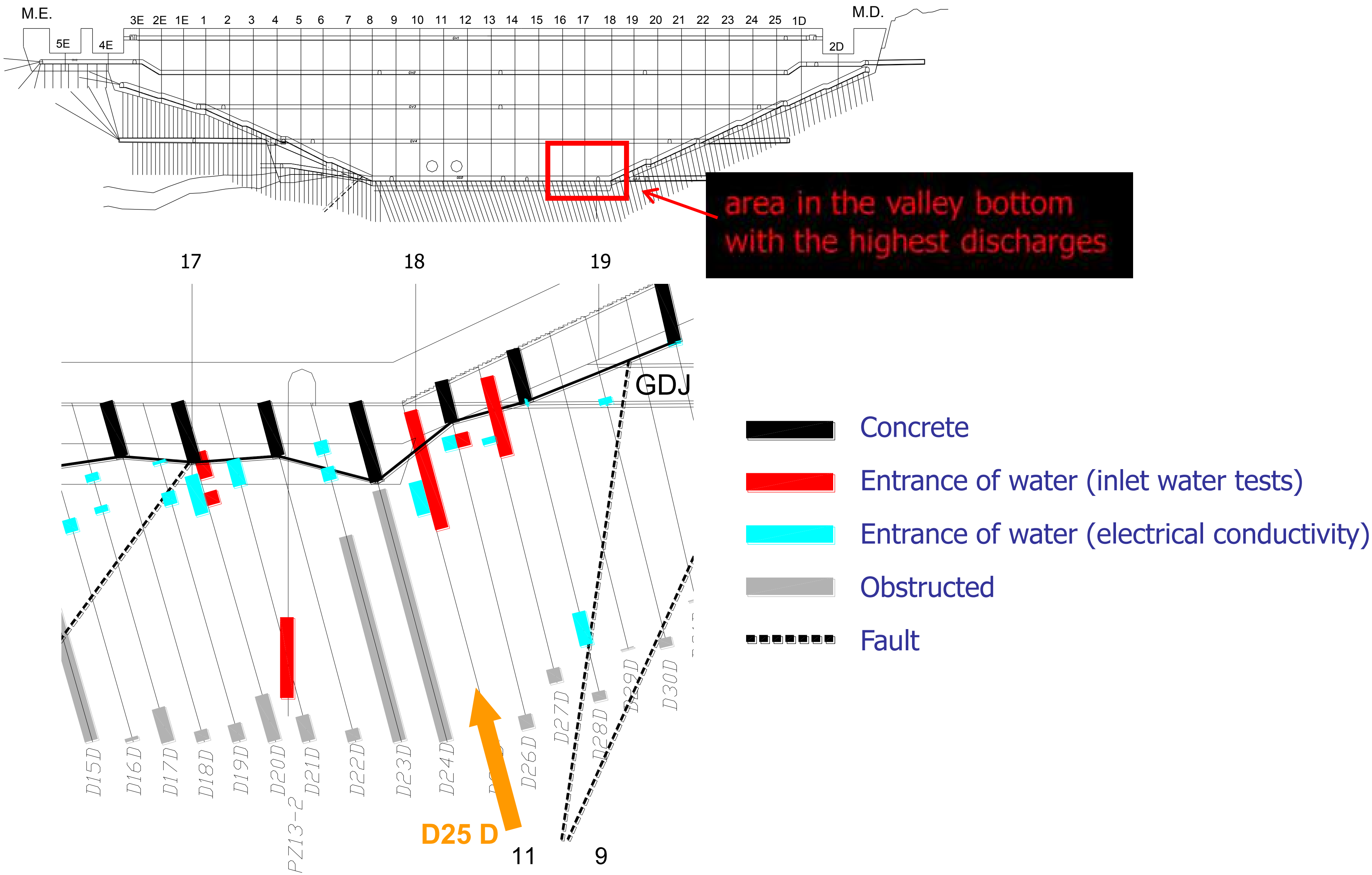
Tests provide information about:

- the depth at which the main seepage paths cross the drains
- the distribution of discharges and water pressures along the boreholes
- the existence of seepage paths linking different boreholes



packer tests to measure water inflow into borehole segments

Inflow of water into each borehole

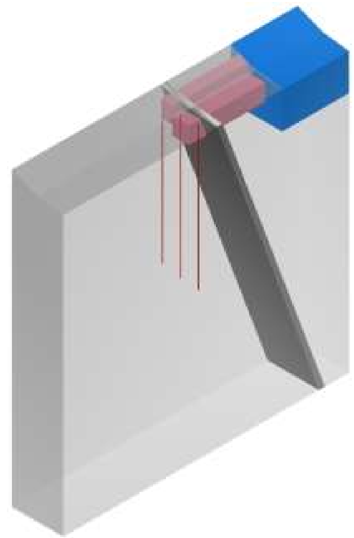


Local analyis of flow in the vicinity of drain D25D

> Consider slice containing 3 drains

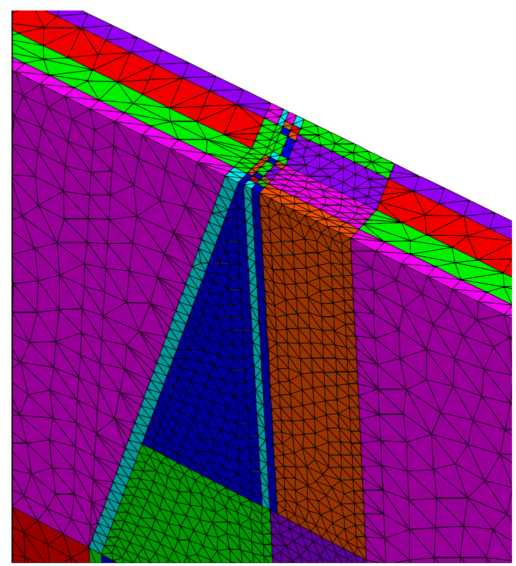
> Local model

- Assume uncoupled continuum flow
- Identify average permeabilities of higher conductivity regions

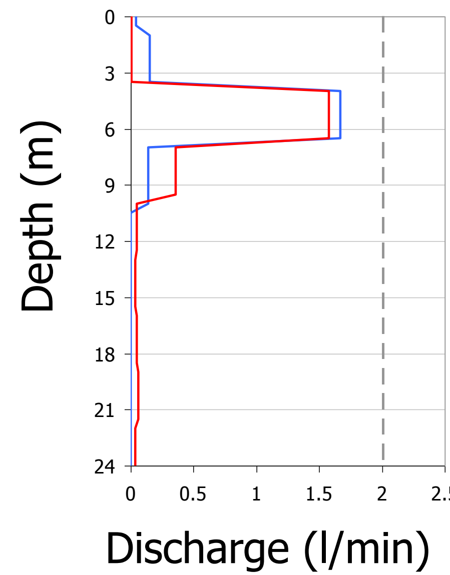


> 3DEC used in local model

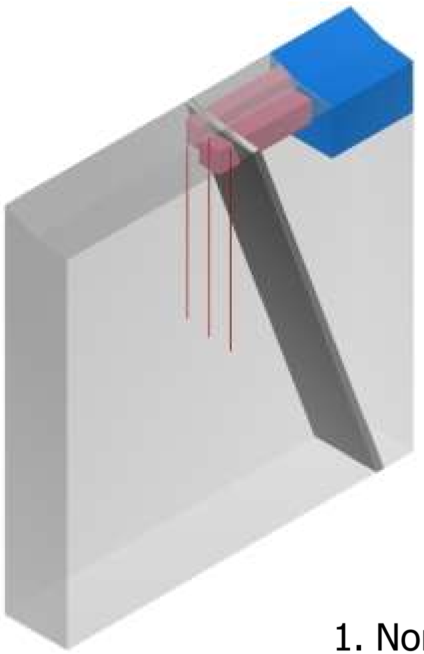
- not an obvious choice for continuum analysis...
- flow analysis using tetrahedral meshes of deformable blocks
- ultimate aim was arch dam mechanical analysis



Volume of water inflow into each test interval



3D model of the vicinity of drain D25 D



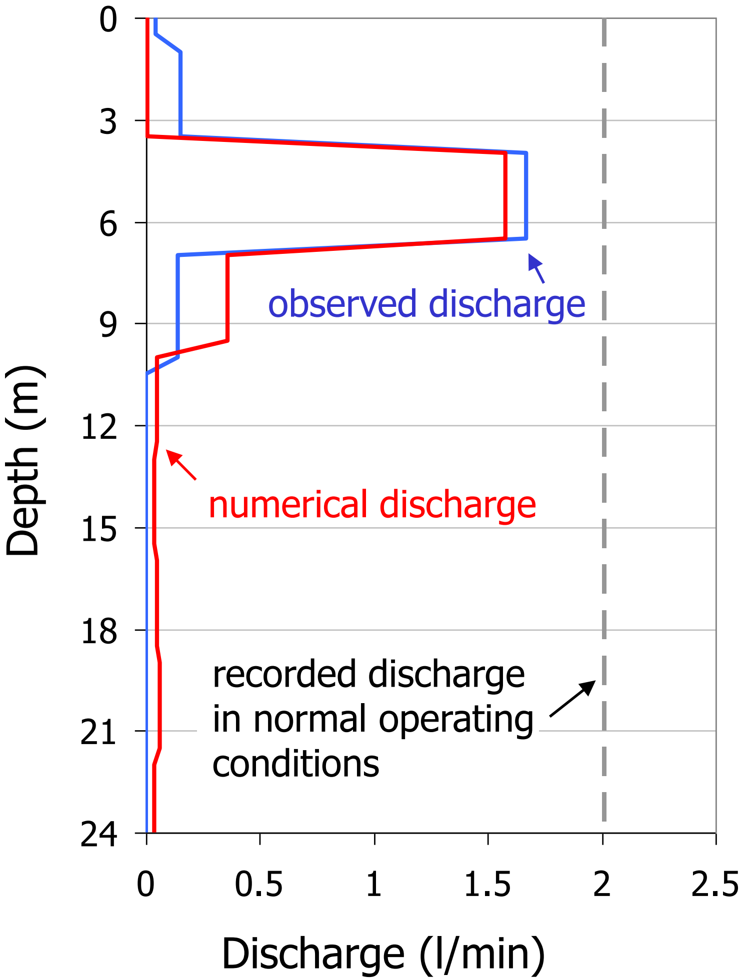
		k (× 10^{-7} m/s)
Rock mass	(grey)	0.10
Grout curtain	(dark grey)	0.01
Near-surface area upstream from the dam	(blue)	10.0
Layer of higher permeability upstream from the drains	(pink)	5.0

1. Normal operating conditions

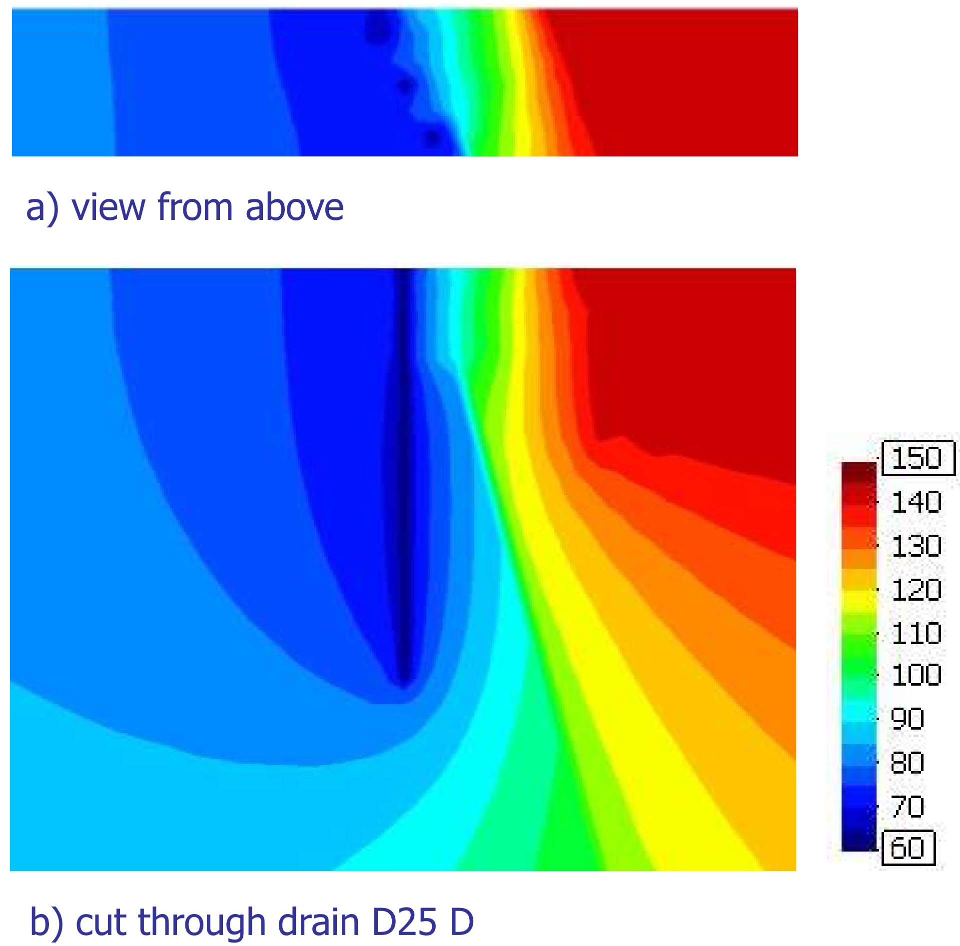
2. Drain D25 D closed

Date	$H_{upstream}$ (m)	Discharge (l/min)				Discharge (l/min)			Water pressure (bar)	Percentage of hydraulic head
		D24 D	D25 D	D26 D		D24 D	D25 D	D26 D	D25 D	D25 D
Oct. 2006	143.58	0.04	2.01	1.03	(measured)	0.04	-	1.29	4.825	58.6 %
		0.07	**2.18**	**0.82**	**(numerical)**	**0.15**	**-**	**1.81**	**4.18**	**50.7 %**
Mar. 2007	150.08	drops	2.18	1.23		drops	-	1.53	5.250	59.1 %
		0.07	**2.35**	**0.88**		**0.16**	**-**	**1.96**	**4.50**	**50.6 %**

Tests results / numerical modelling

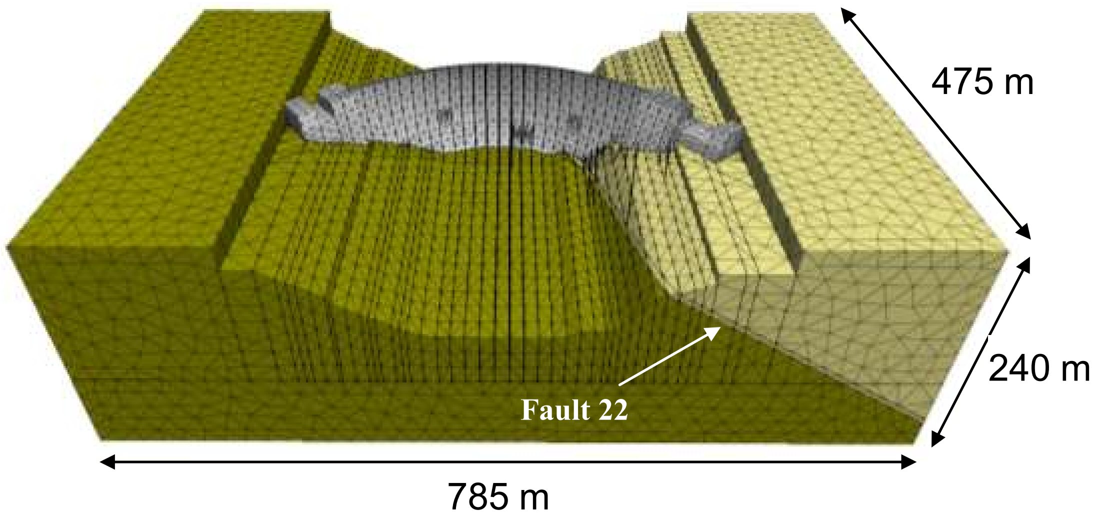


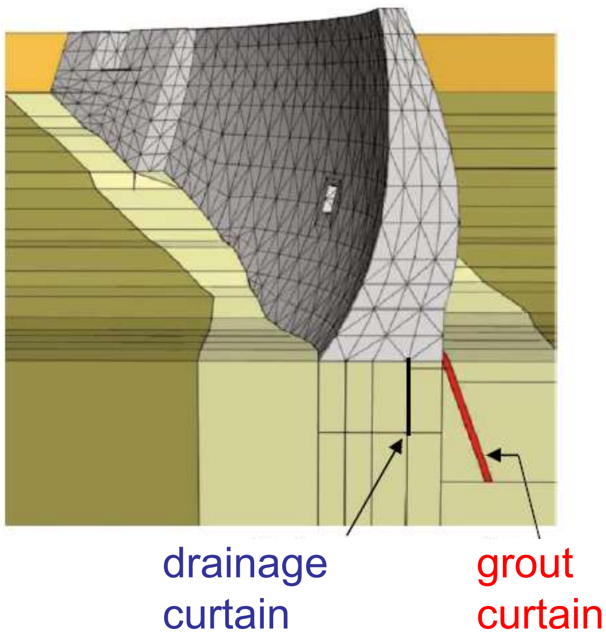
Volume of water entering each test interval

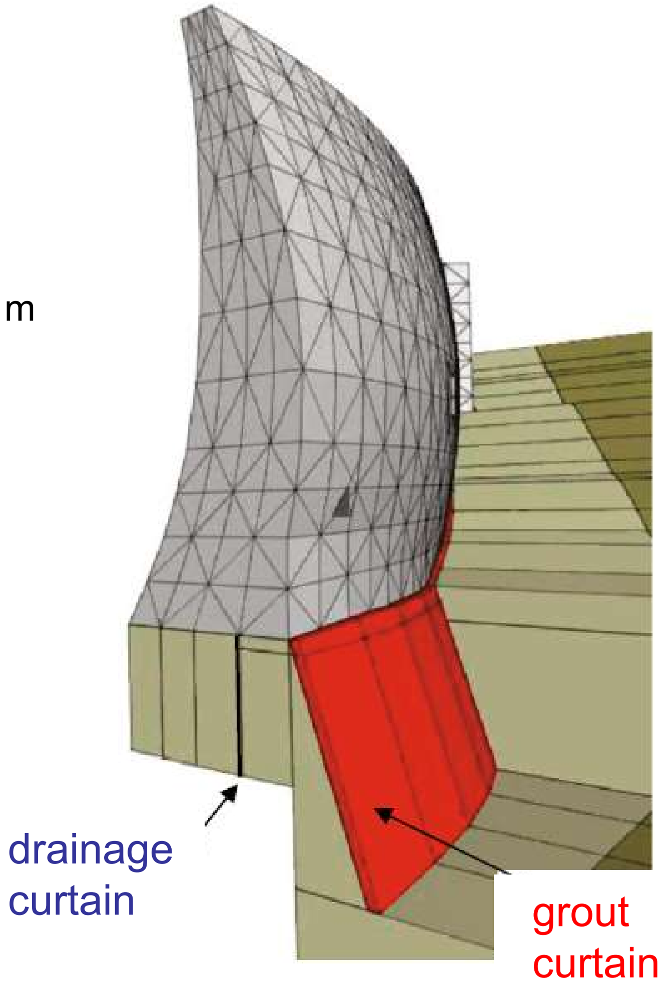


Hydraulic head contours

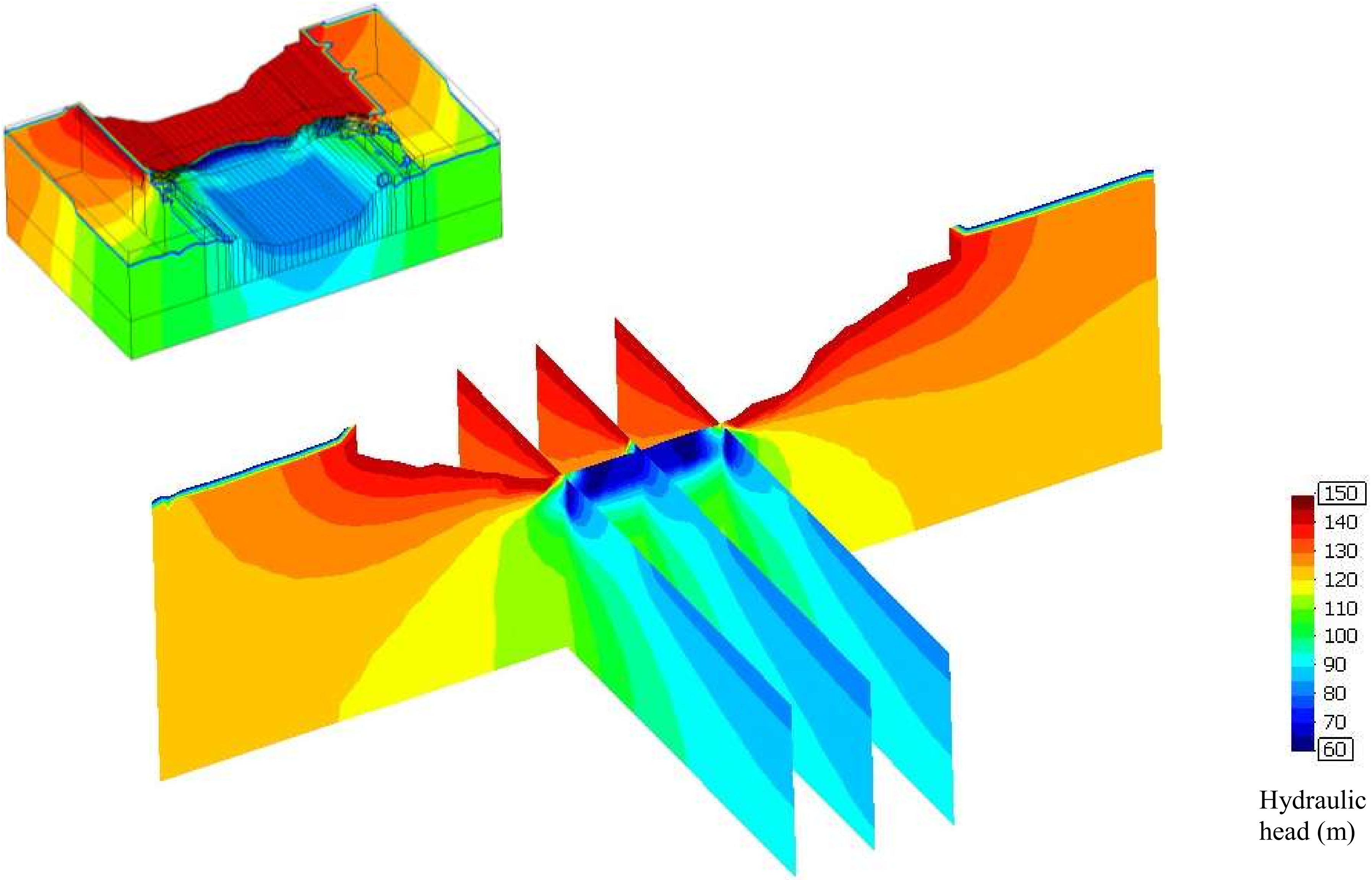
Global model of the dam foundation for hydraulic analysis
- 3dec continuum model (zone permeabilities calibrated by tests/monitoring)



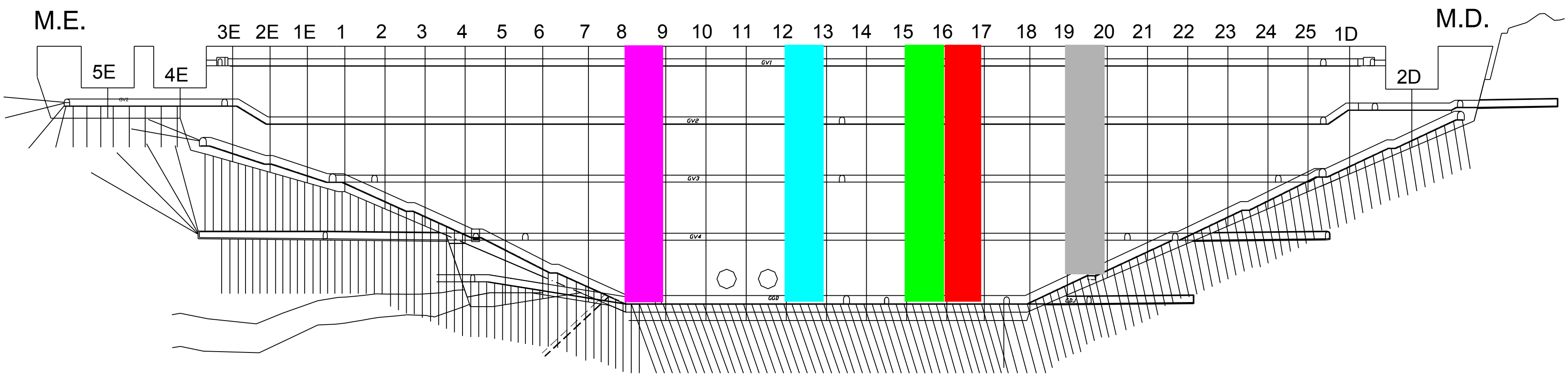


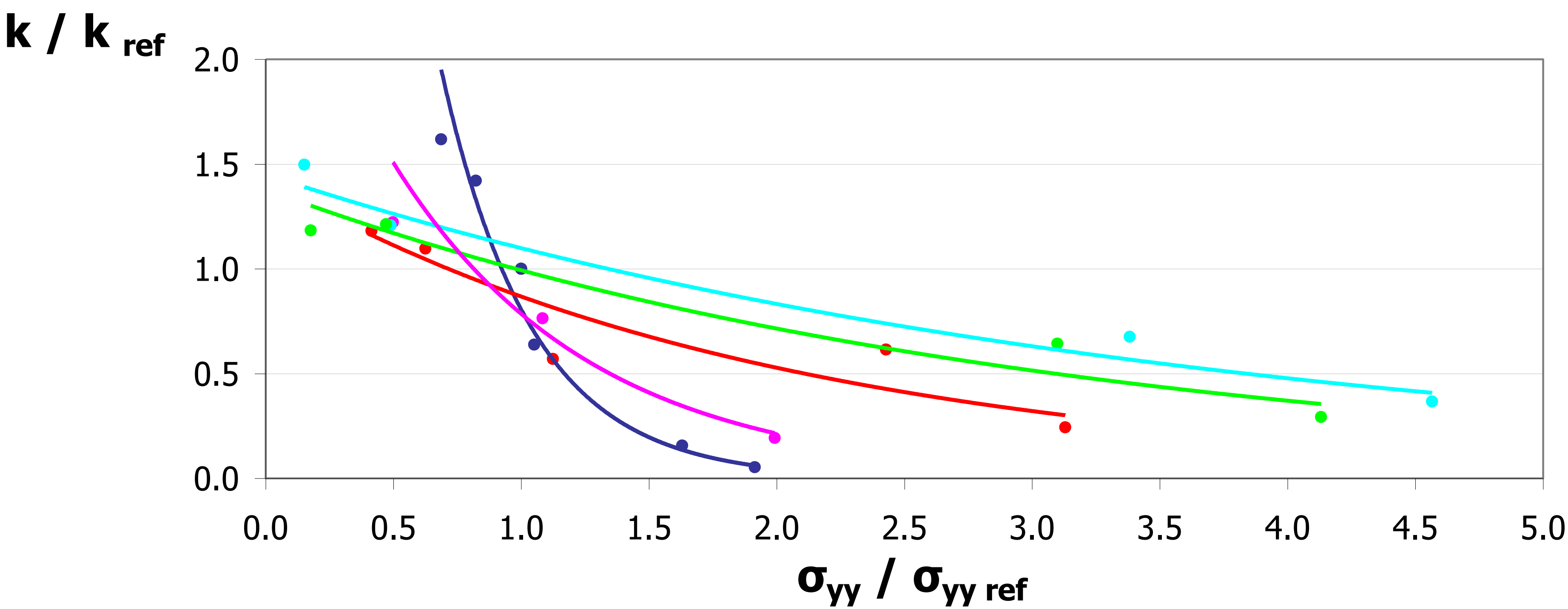


Global 3D hydraulic model (hydraulic head contours)



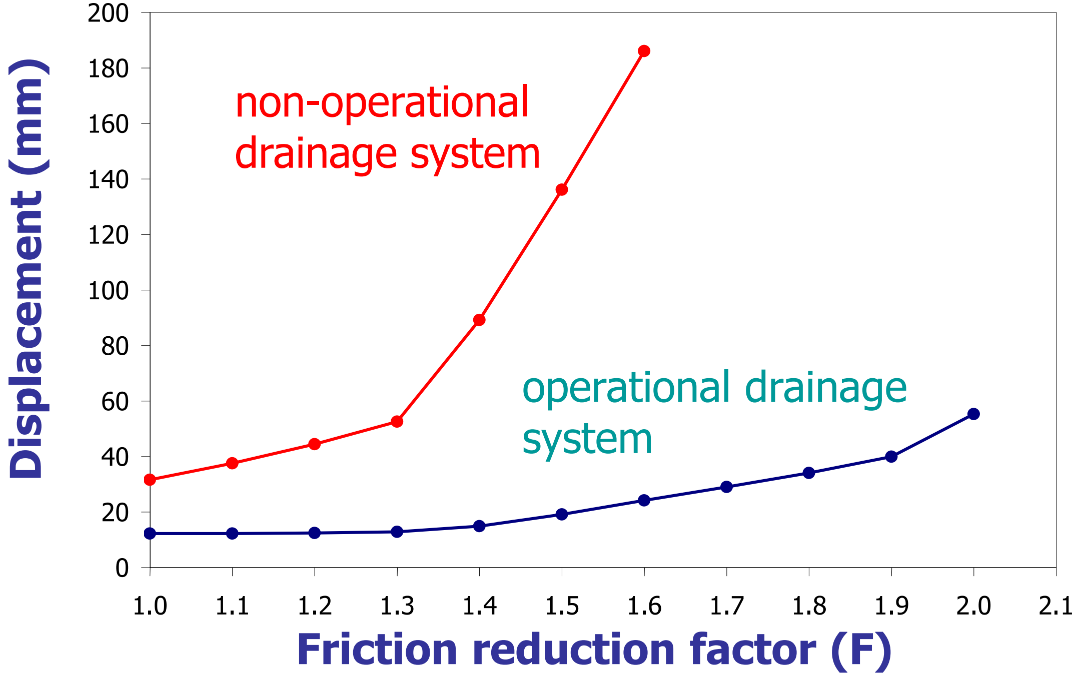
Stress-permeability relations at various locations

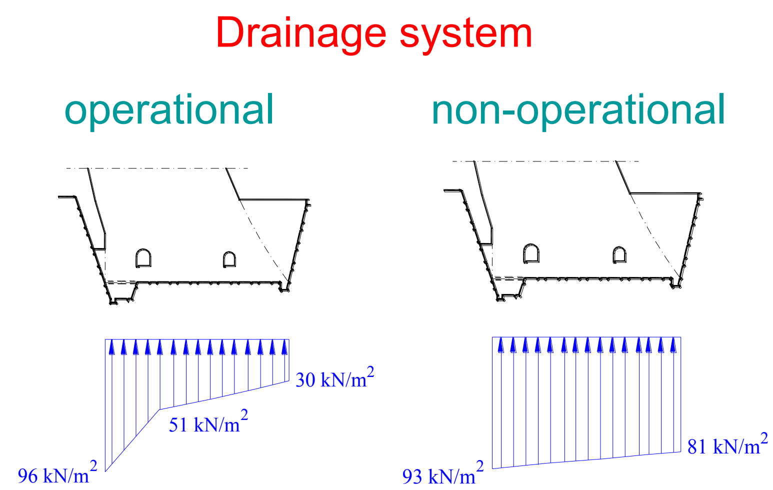




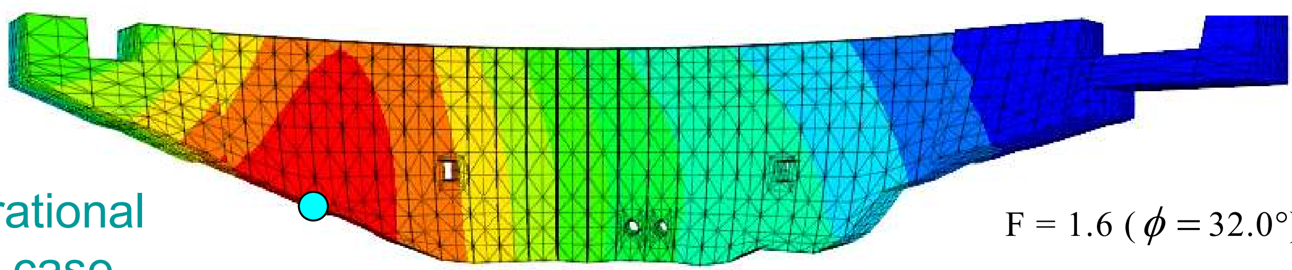
Analysis of failure along dam-rock interface

Safety assessment procedure : progressive reduction of shear strength (friction only) on foundation joint (factor F)





non-operational drainage case



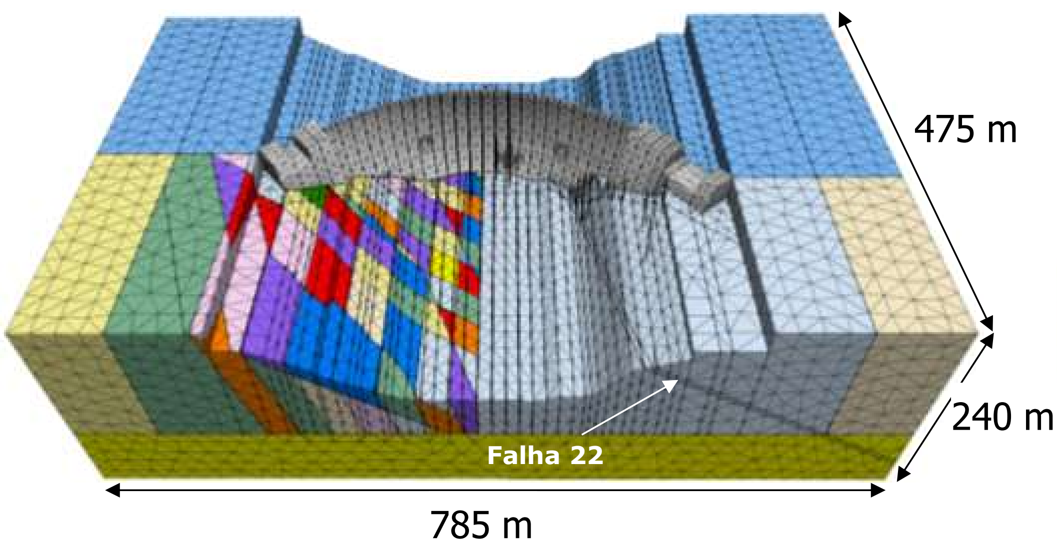
Dam displacement contours

$F = 1.6$ ($\phi = 32.0°$)

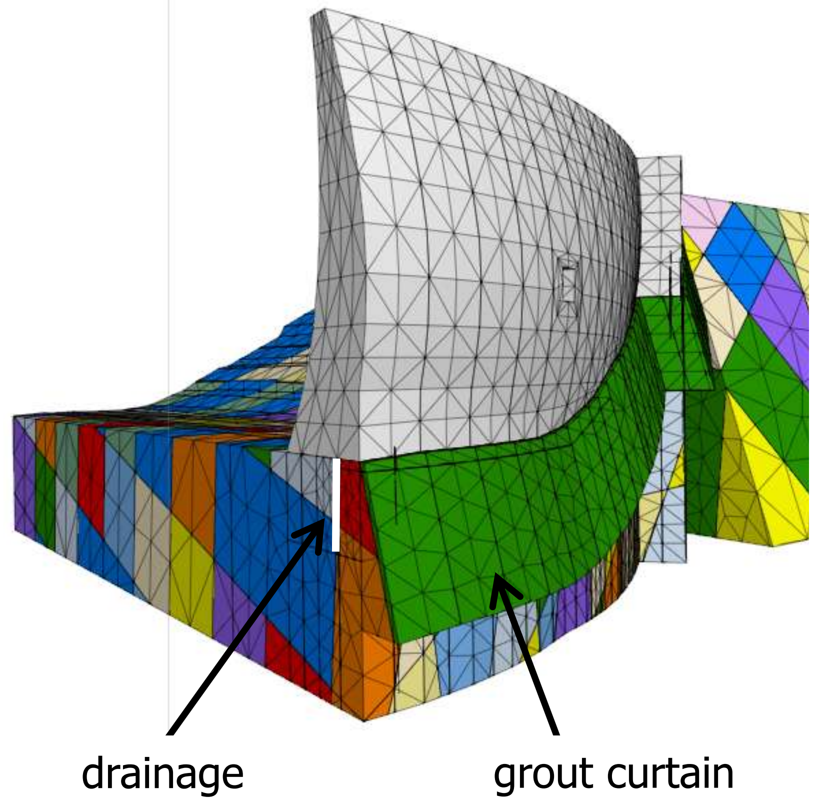
max displ = 196.3

Global block model
– Assessment of modes of failure through rock mass

- Flow analysis performed assuming equivalent continuum
  - uncoupled; with calibrated zone permeabilities; joints have no effect on flow
  - uses internal mesh of deformable blocks
- Joint water pressures transferred to mechanical model for failure mechanism verification



3dec model for right bank failure
Farinha et al. (2012)



Global block model results

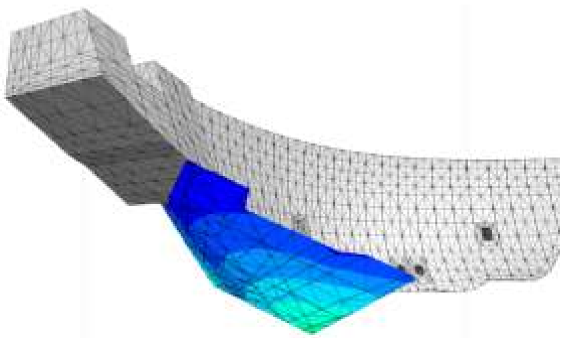
- Given the orientations of the joint sets, the global model results showed a **large safety factor** (as in previous studies)

> Comparison of cases with and without drainage assuming a reduction factor of 5 for (tan ϕ) on the discontinuities

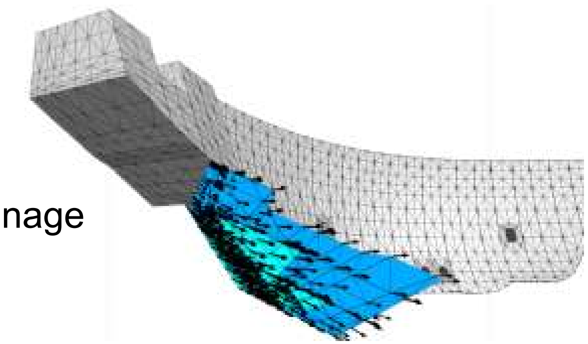
Water pressures at the base of the rock wedge

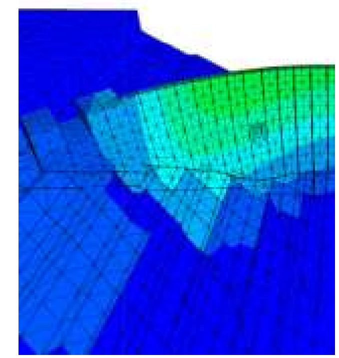
Rock wedge displacements

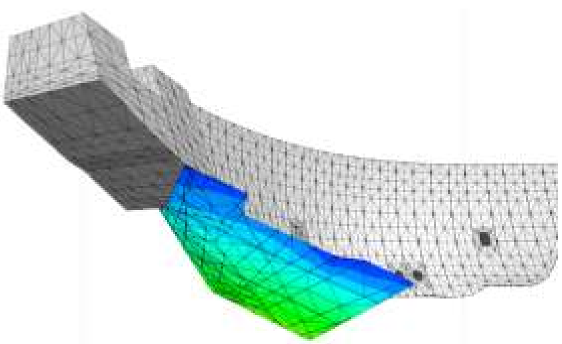
Displacement field



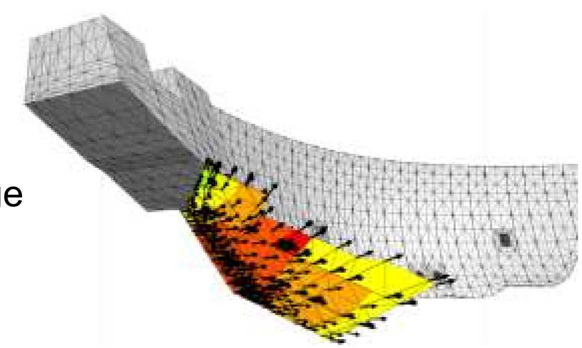
with drainage

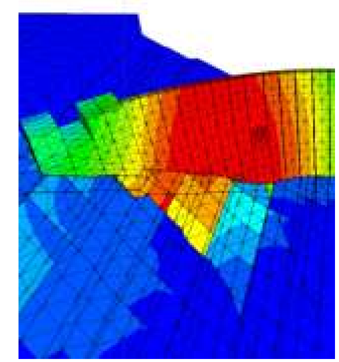






no drainage





Concluding remarks

> There is a choice between fracture flow models and equivalent continuum flow models for dam foundations:

- Both types of representation have their usefulness
- Data availability is often the critical issue
- DFN generation needs to be made easier to use

> Specific issues in dam foundation analysis

- Representation of grout curtain, drainage, local conditions
- Model calibration may require more data than standard monitoring provides

> Failure modelling

- DEM block models are a very appropriate tool
- Water pressures in the discontinuities may be obtained by various methods