WORKSHOP ON RESILIENT LEVEES

UPC-CIMNE potential contributions

Marcos Arroyo

30 JUNE 2017, UNIVERSITY OF PISA

Outline

- Numerical applications (levee related)
  - Soil atmosphere interaction (railway embankment)
  - Overtopping
  - Site investigation
- Kratos
- Erosion testing channels

Soil-atmosphere interaction

- CODE_BRIGHT (THM FEM)
- Atmospheric boundary condition
  - fluxes of air, water and energy deduced from the atmospheric data and the model state near the boundary.
  - Example: water flux

Water flux at the atmospheric boundary

In general, the flux of water j_w is considered as the sum of precipitation P_r, evaporation j_E, flux of vapour advected by air j_g^w and surface run-off j_{sr}. In this case, the advective flux of vapour j_g^w is neglected and therefore

11. $$j_w = P_r + j_E + j_{sr}$$

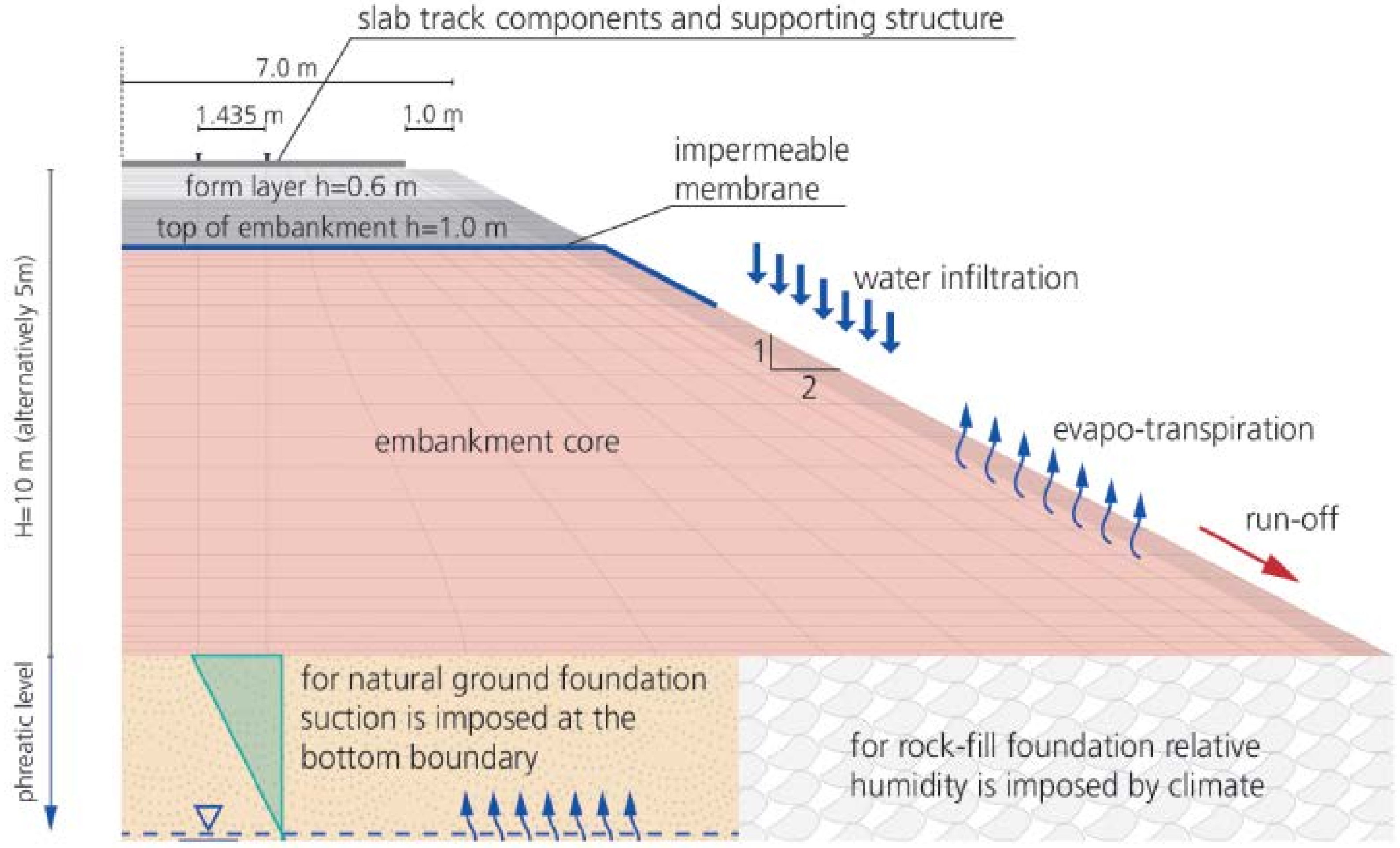
Surface run-off is activated by saturation ($P_l > P_{ga}$) and driven by positive soil water pressure. The evaporative flux j_E is proportional to the difference in atmospheric water vapour density (ρ_{va}^{atm}) and the atmospheric vapour density at the boundary elements (ρ_v) computed from relative humidity data

12. $$j_E = \beta_g(\rho_{va}^{atm} - \rho_v)$$

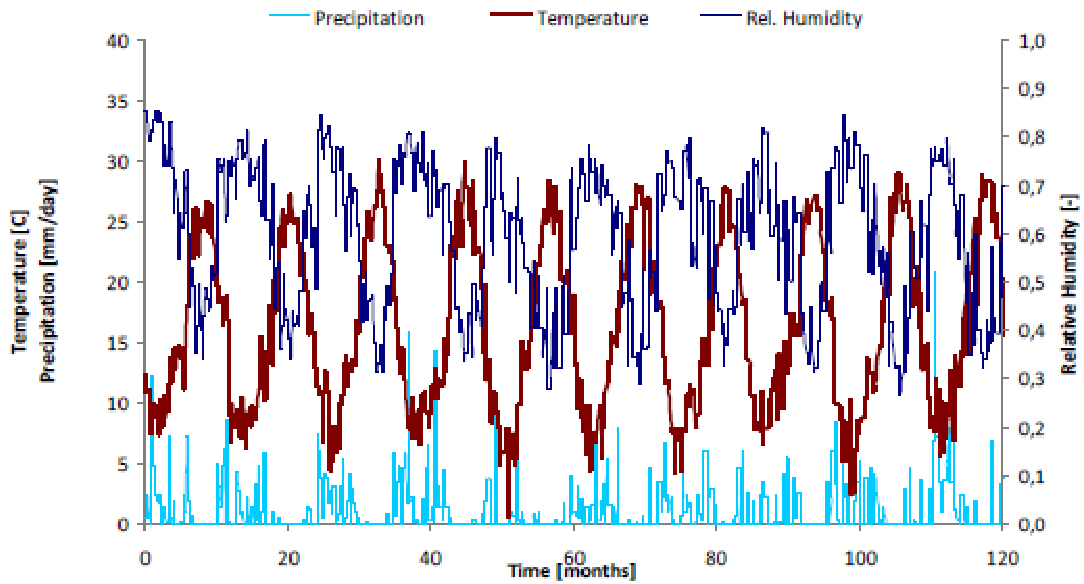
6 where β_g is an aerodynamic diffusion coefficient, a function of the wind velocity v_a, which is von Karman's constant, the roughness length and the height at which v_a and ρ_{va}^{atm} are measured (Louis, 1979). To represent a membrane at a boundary, P_r and j_E are set to 0.

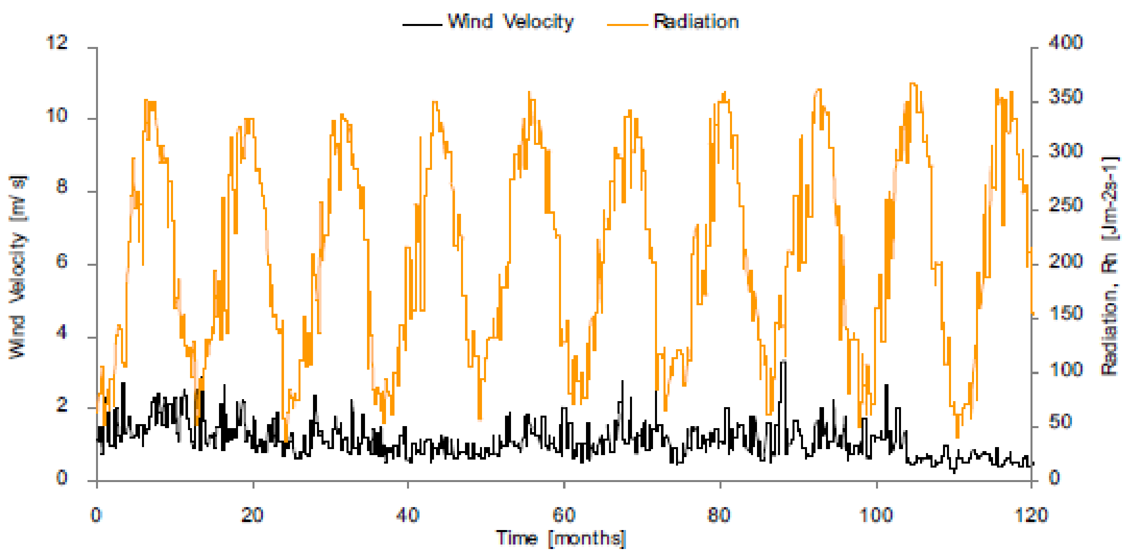
Pérez-Romero et al (2016)

Soil-atmosphere interaction



Andalucia (hot & dry)





A Coruña, 2016

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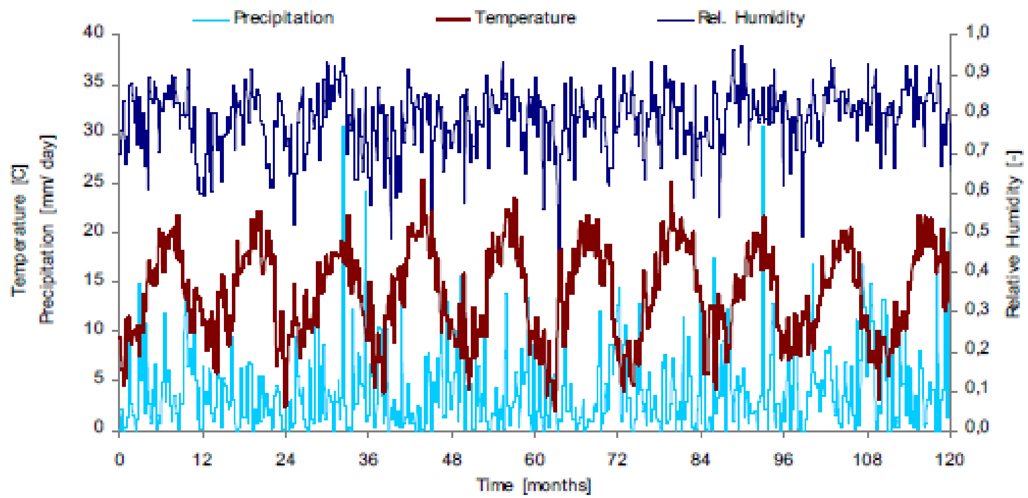
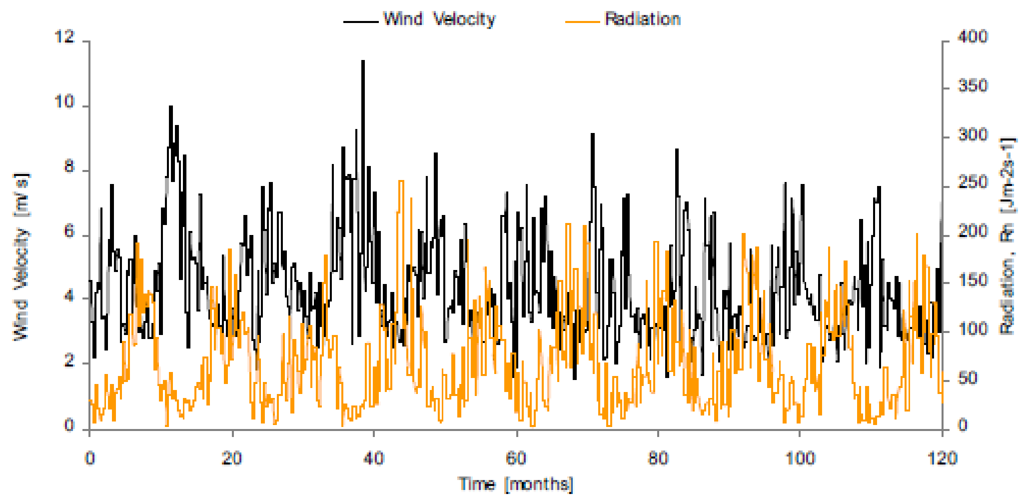
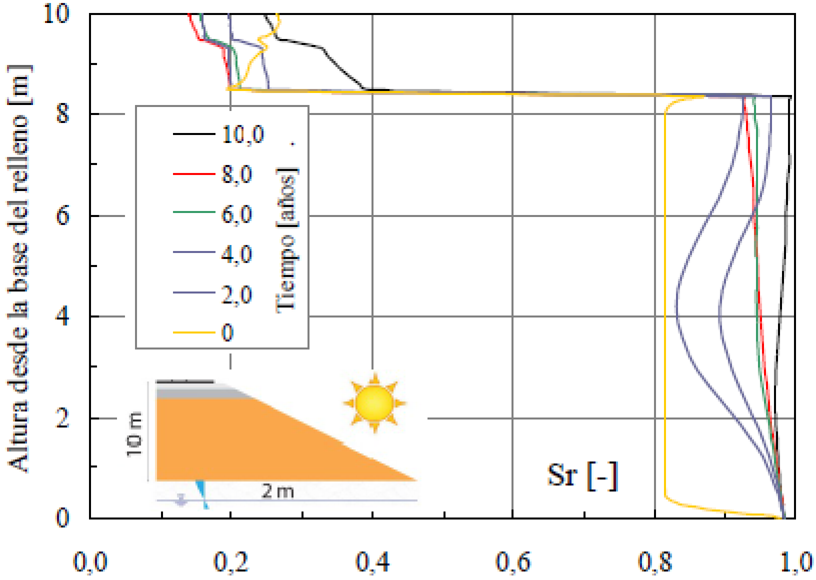
Basque coast (cold & wet)

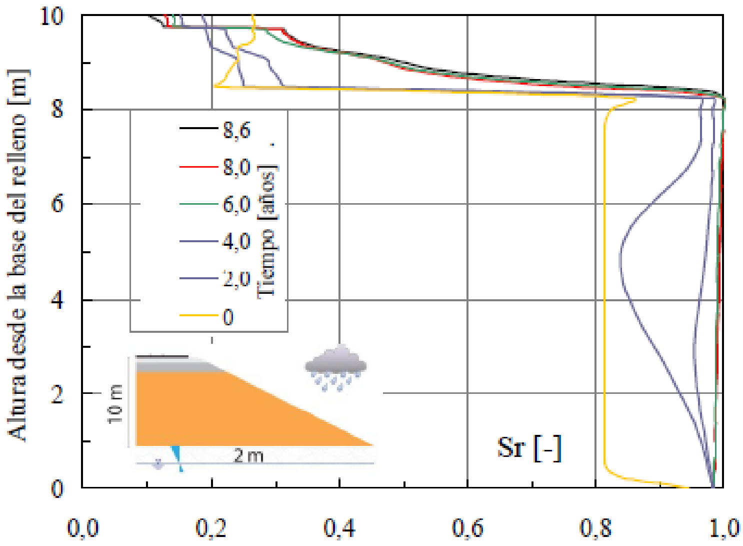




SEMR SEMSIG SPG

Drying within





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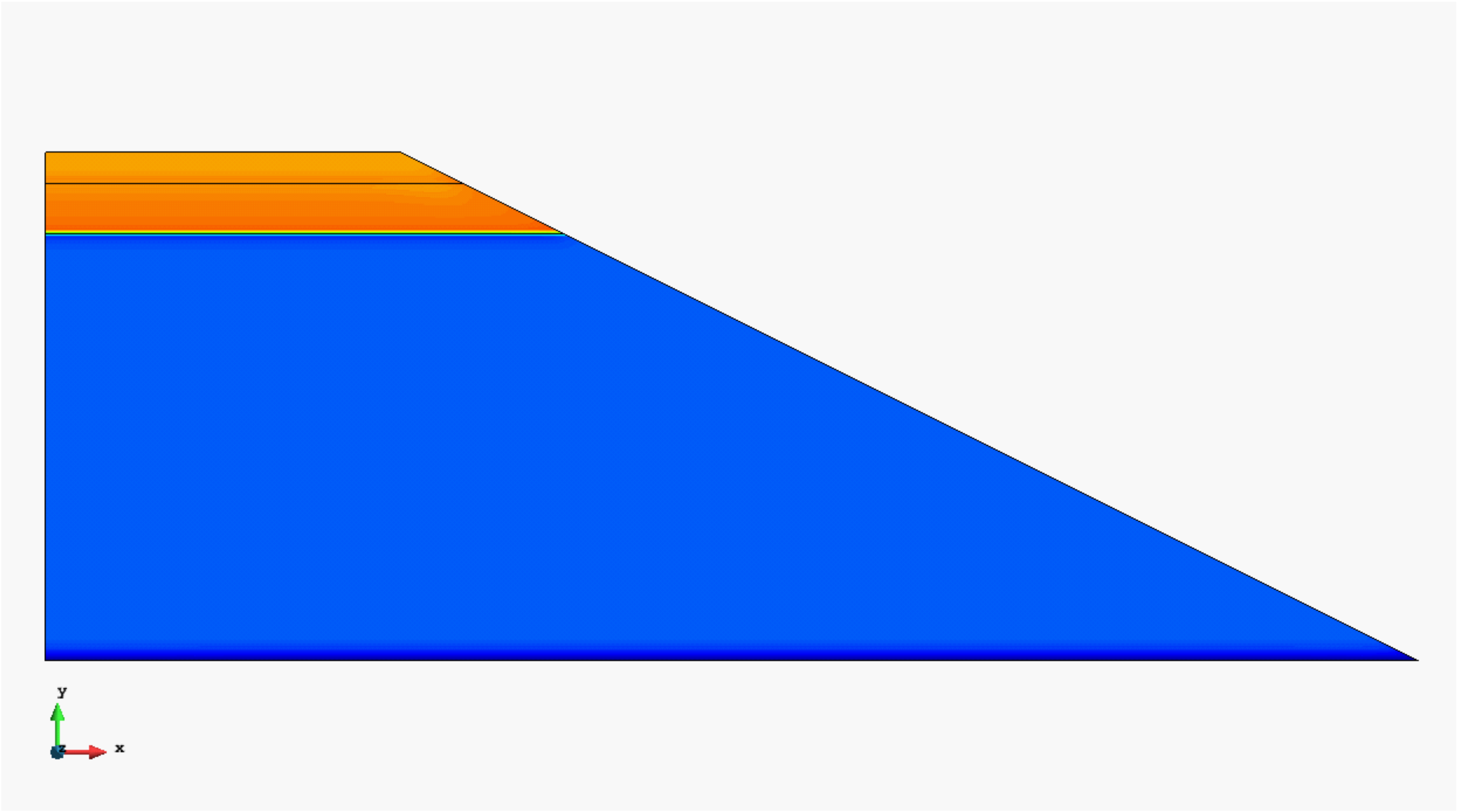
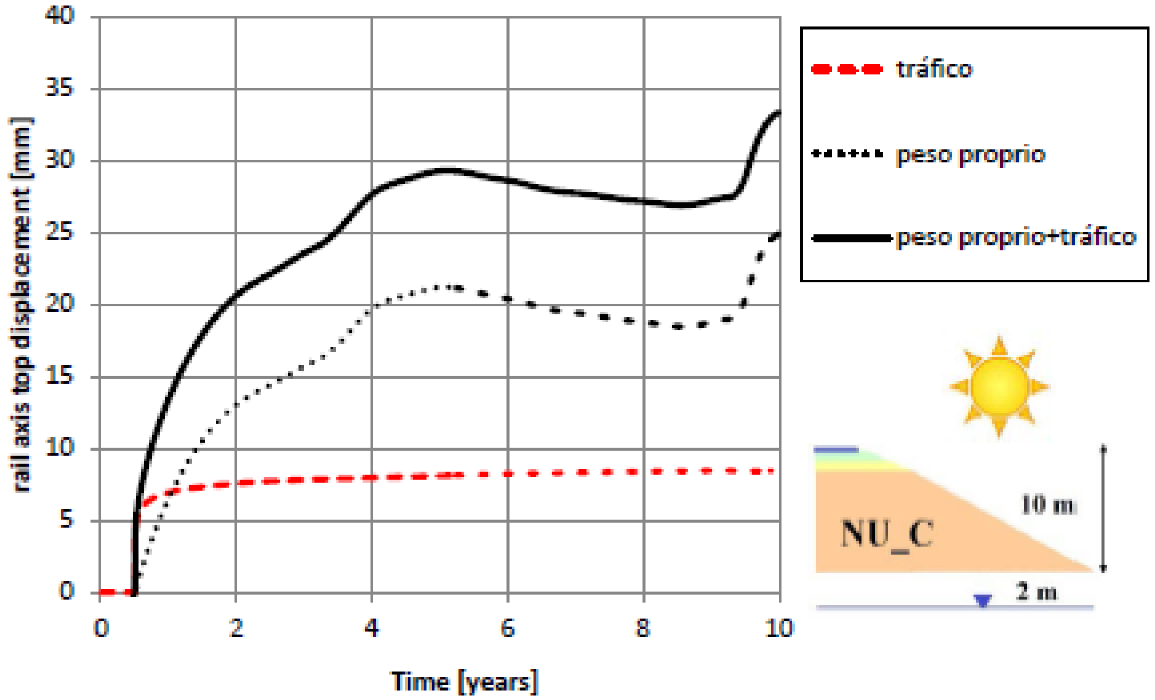
Andalucia nf 2 m 10 years



SEMR SEMSIG SPG

Post-construction settlements



Soil –atmosphere interaction

- Currently working on
  - large scale field test
  - representation of the vegetation effect on ET

Outline

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  - Soil atmosphere interaction (railway embankment)
  - Overtopping
  - Site investigation
- Kratos
- Erosion testing channels

Numerical and Experimental Study of Failure of Rockfill Dams under Extreme Events

Antonia Larese, Riccardo Rossi, Eugenio Oñate,
M.A. Toledo, R. Morán, H. Campos

KRATOS MULTI-PHYSICS

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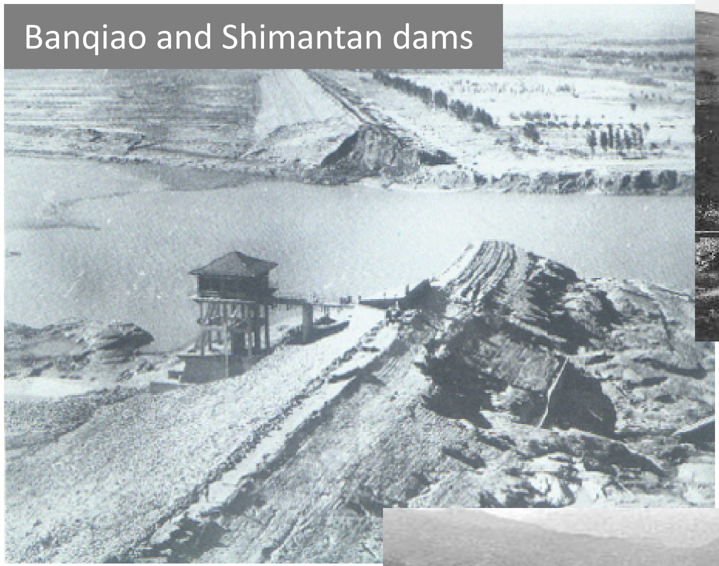
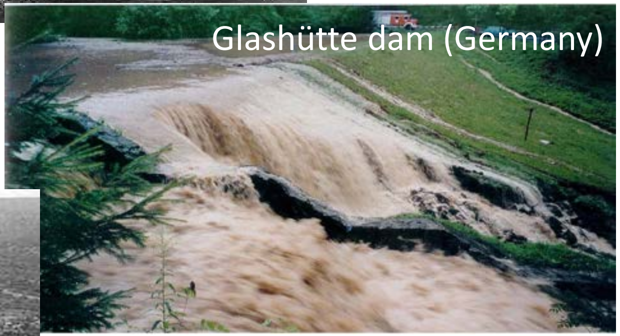
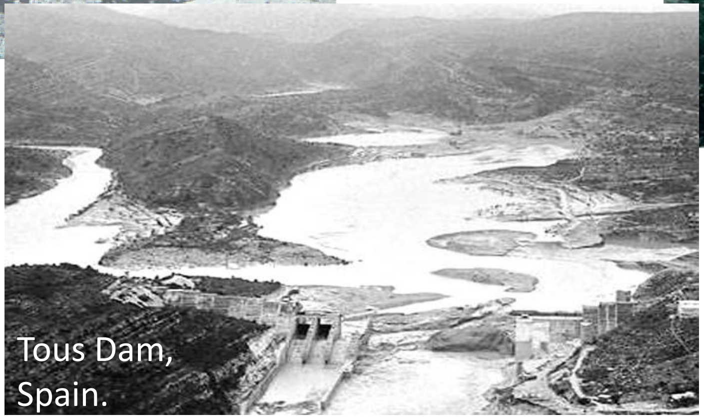
Overtopping in rockfill dams

Overtopping is still one of the principal causes of failure of embankment dams


Banqiao and Shimantan dams


Dale Dyke dam (UK)


Glashütte dam (Germany)


Tous Dam,
Spain.

What does it happen if a rockfill dam is overtopped?

- **Seepage** inside the downstream shoulder
- External **erosion** of the downstream toe
- Instability of the downstream shoulder

Possible FAILURE of the downstream rockfill shoulder due to hydrodynamic effects

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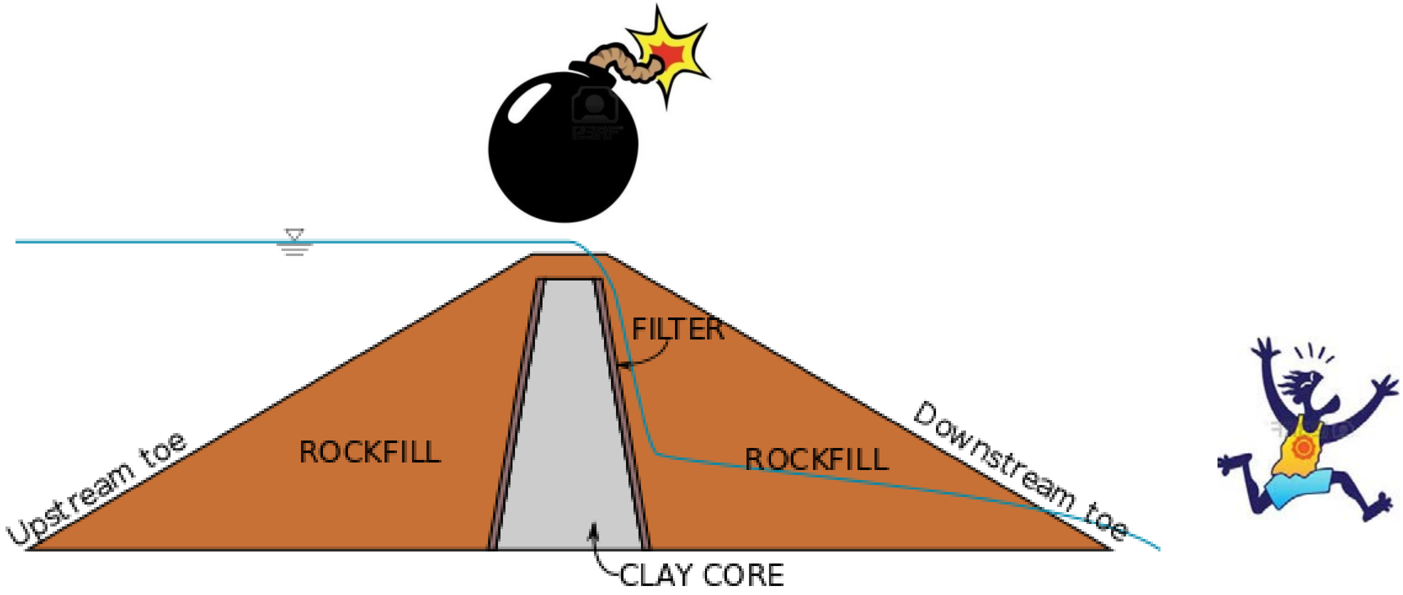
Current regulation considered the dam failed once overtopping begins, once the first drop crosses the crest of the dam



Failure in a rockfill dams IS NOT A SUDDEN PHENOMENON

In order to get to the failure of the dam:

- Overtopping
- TIME

We need a better knowledge of what is going on in the downstream shoulder when overtopping begins in order to reduce the "safety factor" we are now adopting

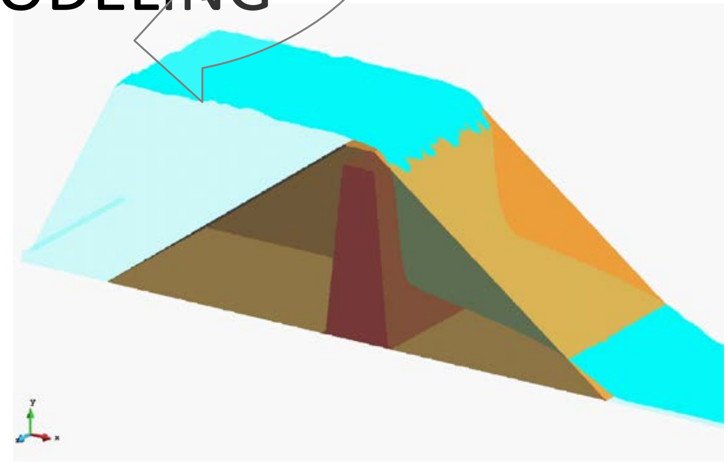
Overtopping: how to study its consequences?

PHYSICAL MODELING

To save time and money
To overcome scale effects

NUMERICAL MODELING

To calibrate the models
To have realistic and valuable results



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PHYSICAL MODELING

ETS de Ingenieros de Caminos Canales y Puertos UPM

Miguel Á. Toledo, Hibber Campos, Ricardo M. Alves, Rafael Morán

CEDEX

Y Centro de Estudios hidrográficos de CEDEX

Ángel Lara and Rafael Cobo

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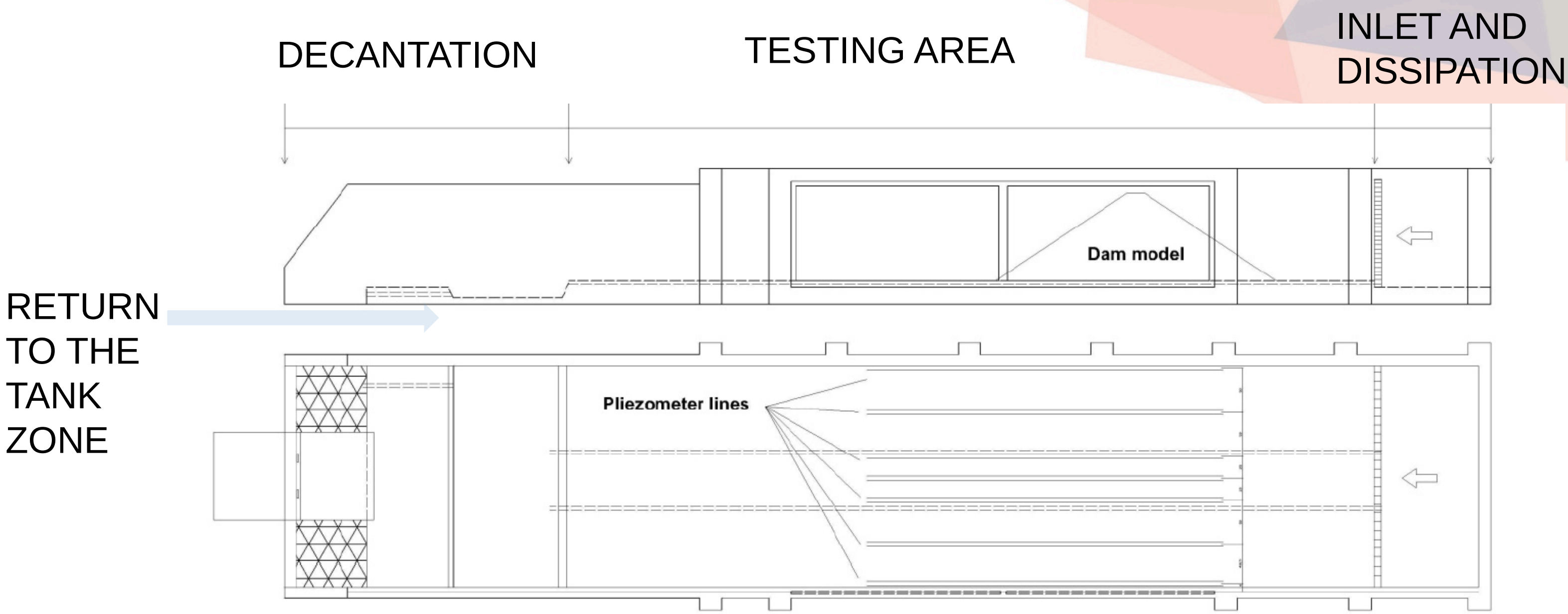
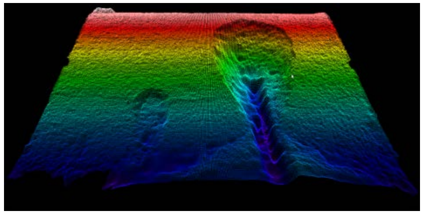


The experimental channel is equipped with:

- 85 hydraulic piezometers
- three ultrasonic limnimeters
- The experimental channel is equipped with a robotized laser profile meter that allows to obtain a Digital Terrain Model (DTM) of the tested rockfill dam at any moment of the failure process



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NUMERICAL MODELING

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Mètodes Numèrics en Enginyeria

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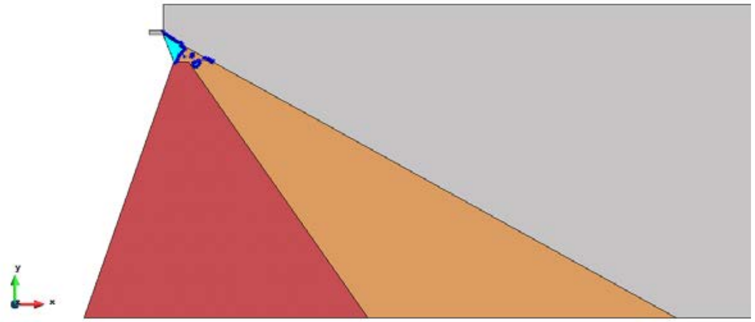
Mathematical modeling

Objective:

- Evaluation the hydrodynamic forces on the rockfill during an overtopping

Basic ingredients:

- Variable incoming conditions
- Flow in porous media (rockfill)
- Free surface flow in the clear fluid region
- Transient regime



n=0.37
D =0,085m

n=0.37
D =0,3m

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Seepage in soils vs seepage in rockfill

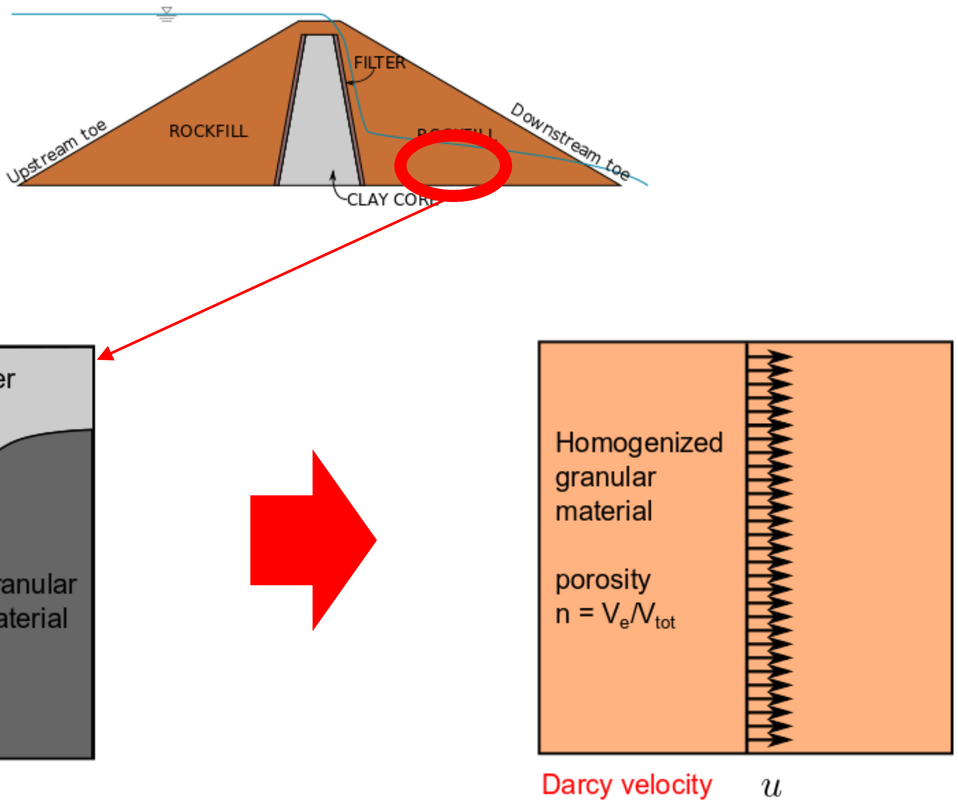
Seepage in soil

- Low permeability
- Pore pressure plays an important role
- Very **slow** phenomenon (order of week, months, years)
- Laminar flow
- Governed by **Darcy law** (linear resistance law)

Seepage in rockfill

- High permeability
- Pores are big and interconnected
- Very **fast** phenomenon (order of minutes, hours)
- Turbulent flow
- Governed by a **non linear resistance law**

Seepage in rockfill



Seepage in rockfill

- “Macro scale” for global overtopping simulation

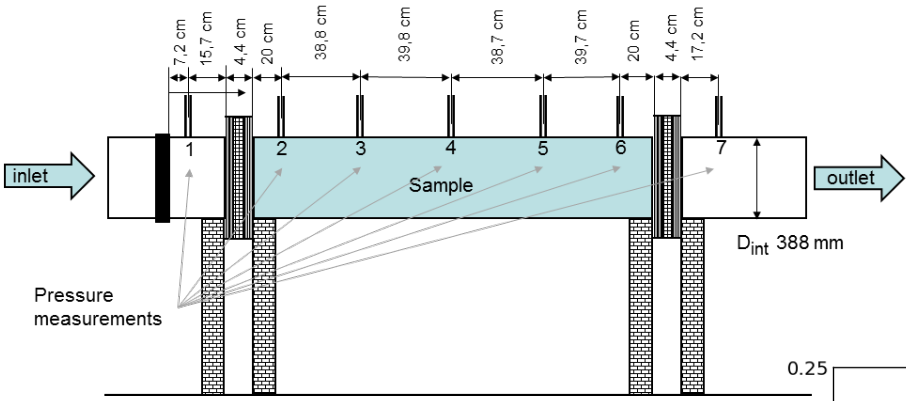
$$\partial_t \mathbf{u} + \overline{\mathbf{u}} \cdot \nabla \mathbf{u} + n\nabla p - 2\nabla \cdot \nu \nabla^s \mathbf{u} \\ -\mathbf{b}n + \alpha \mathbf{u} + \beta \mathbf{u} \cdot \mathbf{u} = 0 \text{ in } \Omega,\ t \in (0,T); \\ \nabla \cdot \mathbf{u} = 0 \text{ in } \Omega,\ t \in (0,T).$$

- Modified form of the Navier Stokes equation to take into account the presence of porous material
- Non linear resistance law inserted in the governing equations (Forchheimer type)

$$\mathbf{i} = \alpha \mathbf{u} + \beta \mathbf{u}^2;$$

- α and β can be arbitrary chosen by the users

Validation: Permeameter



Material	Porosity	Diameter D50
Mat1	0.4133	35mm
Mat2	0.4074	10mm
Mat3	0.3983	20mm

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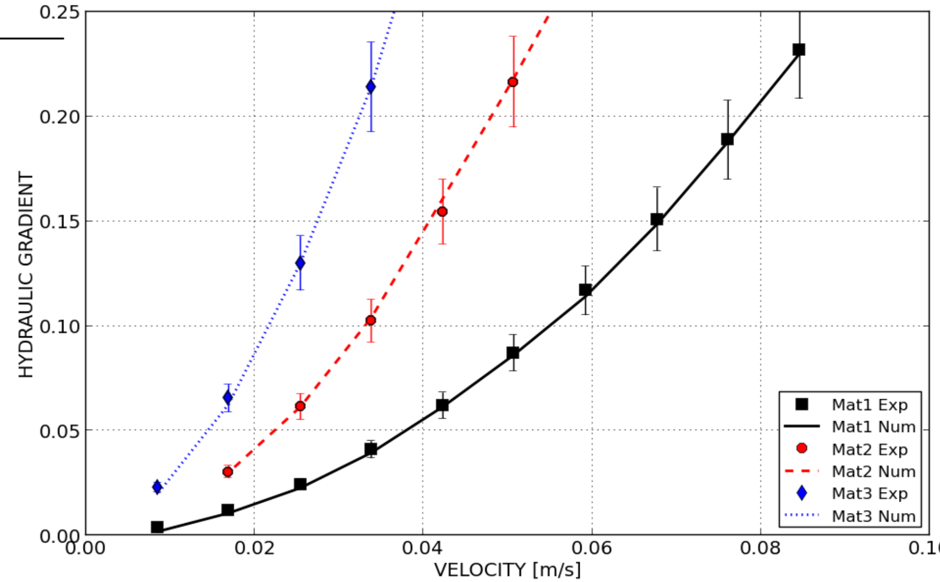
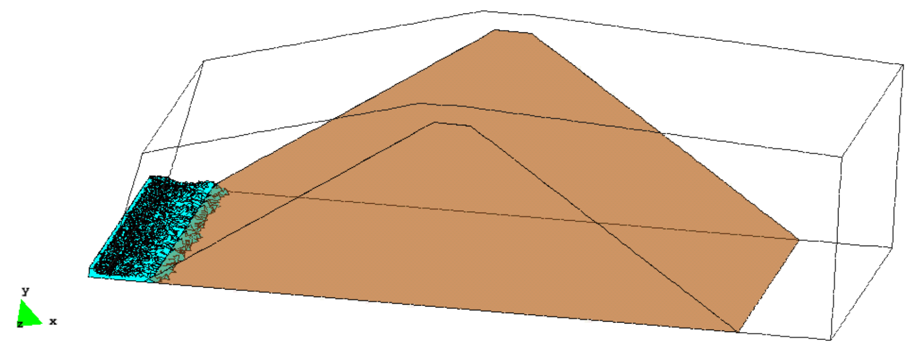
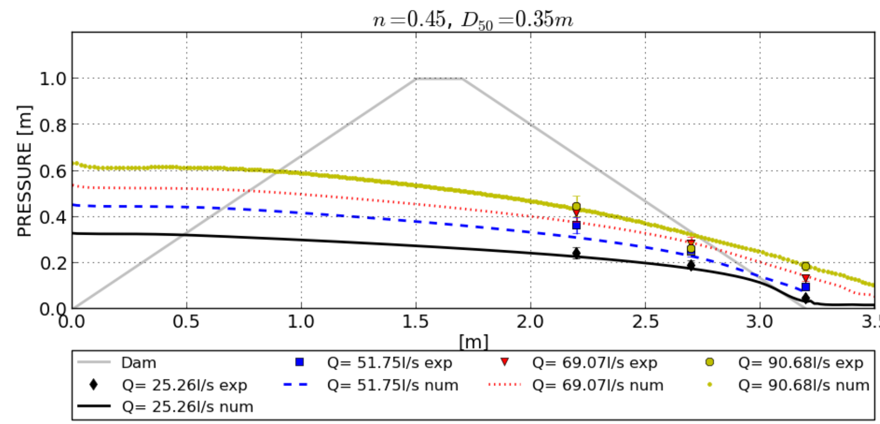


Validation: small scale dams





- Larese, A.; Rossi, R.; Oñate, E.; Toledo, M.A.; Moran, R., Campos, H., *Numerical and experimental study of overtopping and failure of rockfill dams*. International Journal of Geomechanics (ASCE) (2013) ISSN 1532-3641.

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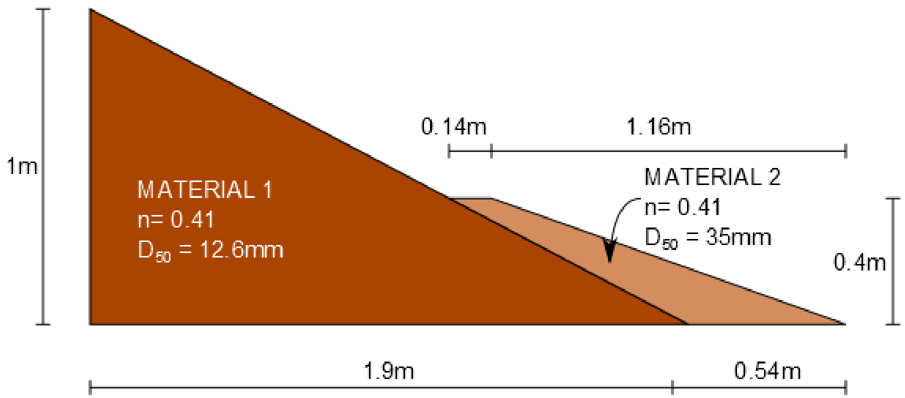
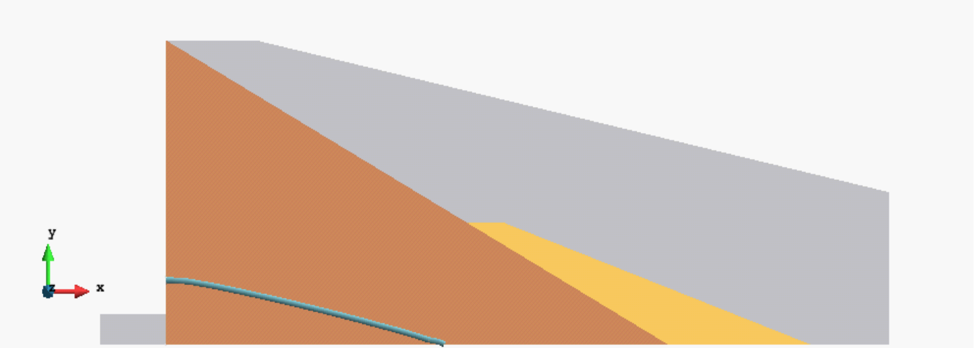
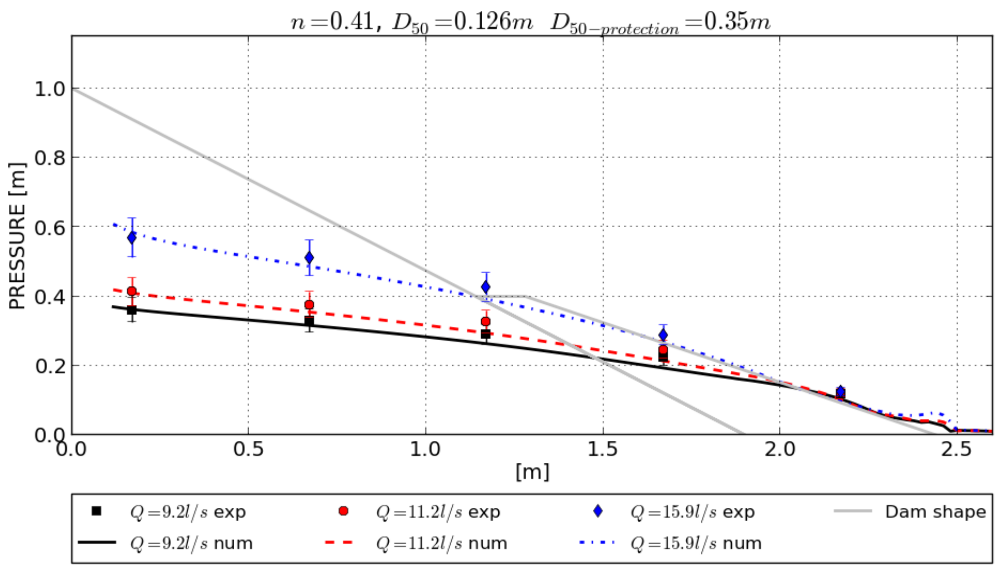
Validation: small scale dams







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Evaluation of the dam breaching

The CFD code can be coupled with *ANY structural code* for the calculation of the structural response

- The material is rigid until reaching the yield stress
- No recoverable deformation (no elastic behavior)
- After reaching yield stress, it flows like a fluid
- No need of tracking historical variables
- Large deformations occur

Non-Newtonian constitutive model

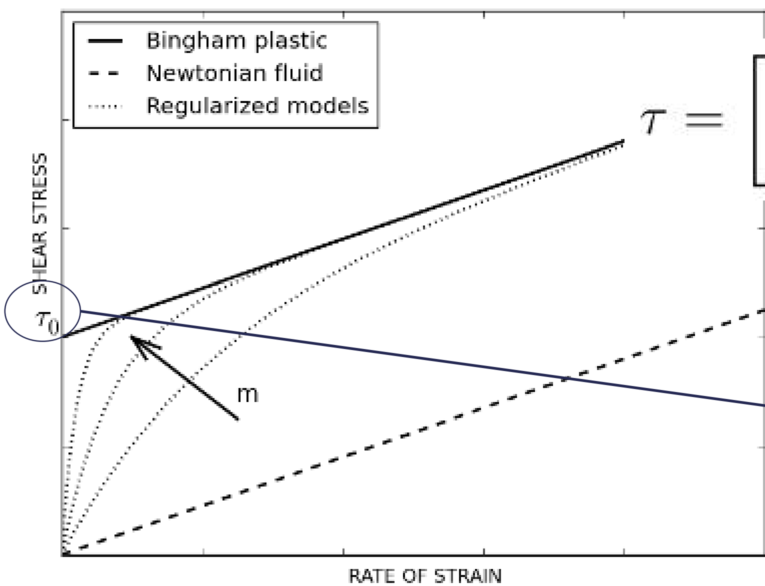
The Particle Finite Element Method (PFEM) is employed to naturally follow the large deformation of the material

- Larese, A.; Rossi, R.; Idelsohn, S.R.; Oñate, E.A coupled PFEM-Eulerian approach for the solution of porous FSI problems. Computational mechanics.50 - 6,pp. 805 - 819. (2012). ISSN 0178-7675
- Larese, A. A coupled Eulerian-PFEM model for the simulation of overtopping in rockfill dams Phd thesis: Universitat Politècnica de Catalunya (UPC BarcelonaTech), Barcelona, Spain, 2012

CONSTITUTIVE MODEL

VISCO-RIGID CONSTITUTIVE LAW FOR THE ROCKFILL SLOPE

BINGHAM MODEL / *REGULARIZED BINGHAM MODEL*

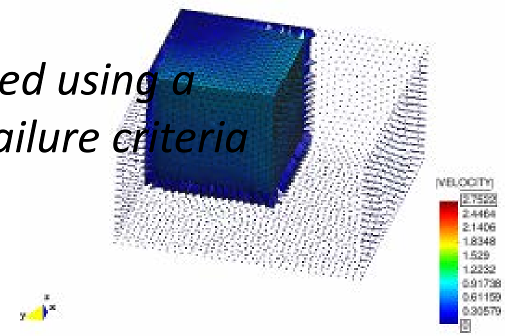


$$\dot{\gamma} = 0 \qquad if \quad \tau < \tau_0$$

$$\tau = \left[\mu + \frac{\tau_0}{\dot{\gamma}}\left(1 - e^{-m\dot{\gamma}}\right)\right]\dot{\gamma} \qquad if \quad \tau \geq \tau_0$$

Yield stress defined using a *Mohr Coulomb* *failure criteria*

$\tau_0 = p_s' tg\, \phi$



VARIABLE YIELD MODEL

$$\tau = \left[\mu + \frac{p_s' tg(\phi)}{\dot{\gamma}}\left(1 - e^{-m\dot{\gamma}}\right)\right]\dot{\gamma}$$

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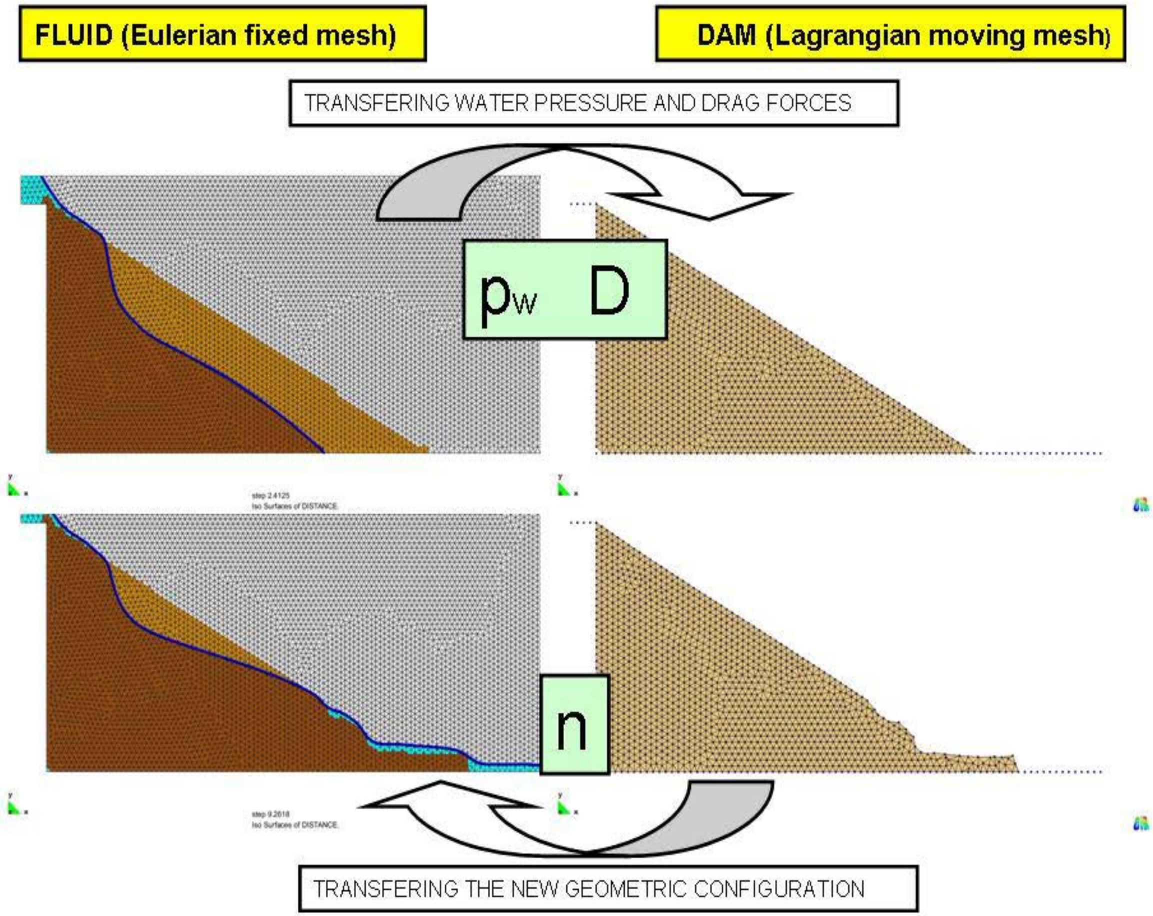
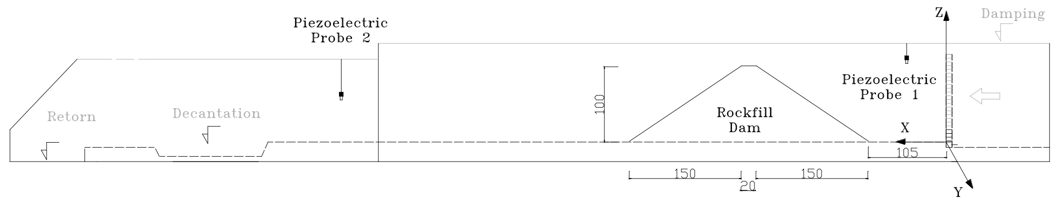
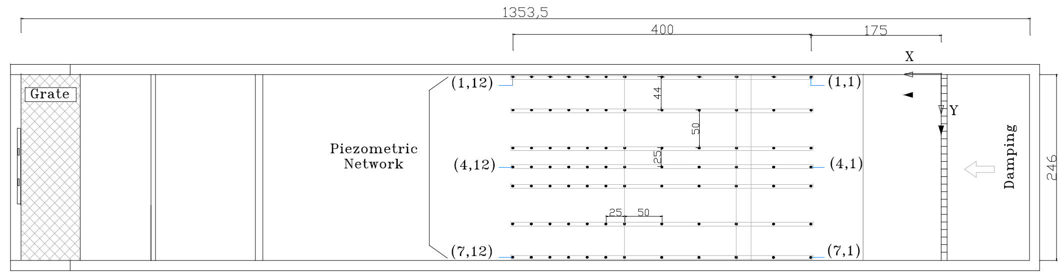
Coupled model



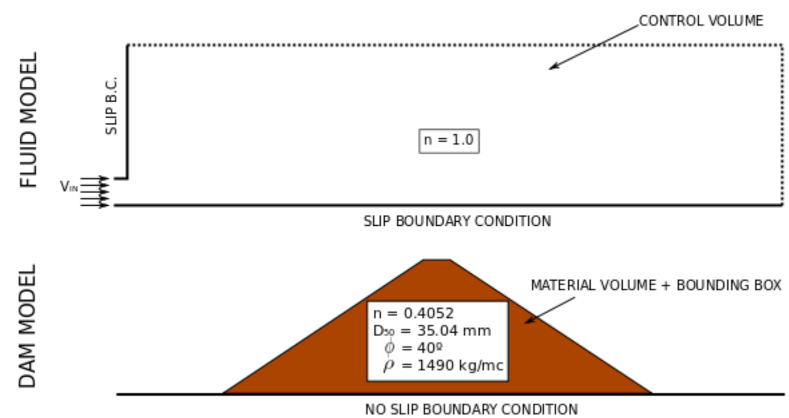
- Larese, A.; Rossi, R.; Oñate, E. *Coupling Eulerian and Lagrangian models to simulate seepage and evolution of failure in prototype rockfill dams* . Proceedings of the XI ICOLD Benchmark Workshop on Numerical Analysis of Dams..ISBN 978-84-695-1816-8, Valencia, Spain (2011).

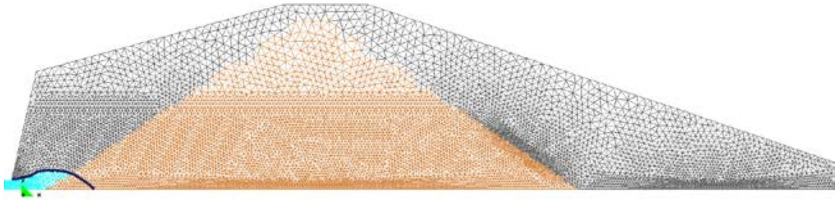
Validation: coupled problem



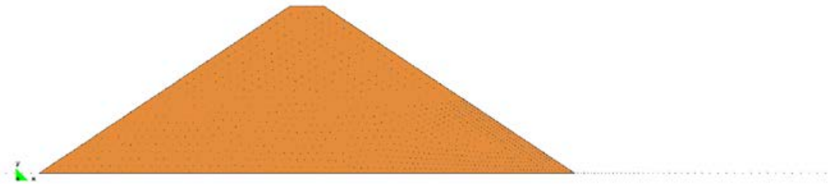


- Porosity = 0.4052;
- Pore index = 0.68;
- Apparent specific weight = 2.50 gr/cm^3
- Dry density = 1.49 gr/cm^3
- Saturated density = 1.91 gr/cm^3
- D_{50} = 35.04mm.



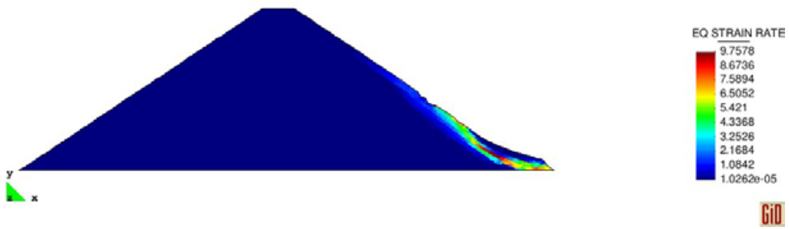


WATER (Eulerian)

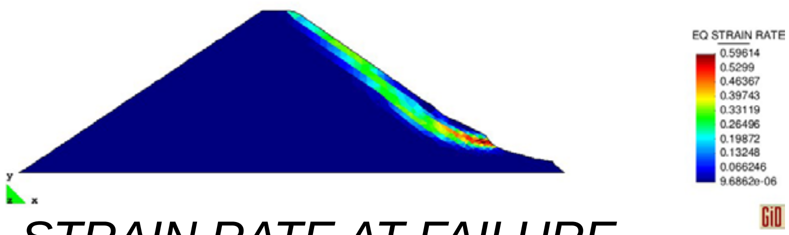


STRUCTURE (PFEM)

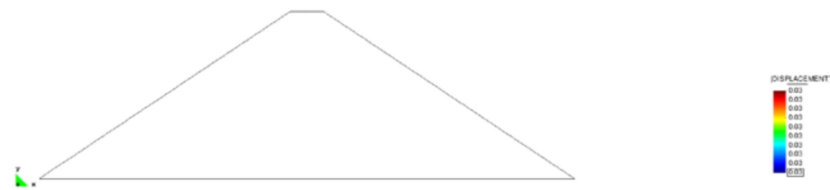
1st FAILURE



2nd FAILURE



STRAIN RATE AT FAILURE
STRUCTURE



DISPLACEMENT
STRUCTURE

A node is considered MOVED if DISPLACEMENT > 30mm

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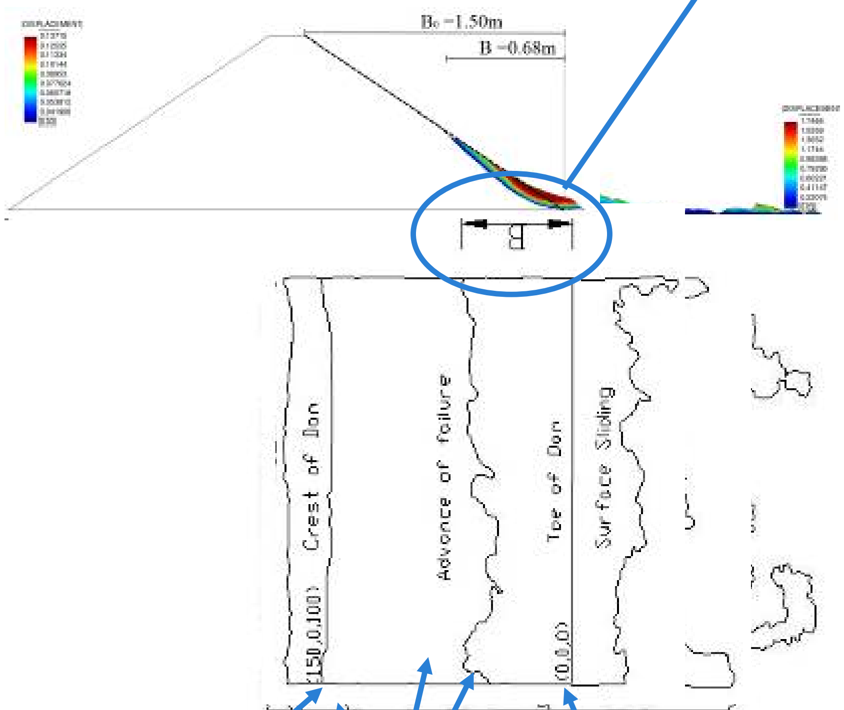
Homogeneous dam.

Advance of failure

B: ADVANCE OF FAILURE horizontal distance of the highest point that moved from the undeformed toe

NUMERICAL

EXPERIMENTAL



Advance of failure [m]

Q [l/s]	*Bexp*	*Bnum*	*E*
51.75	*0.71*	*0.68*	*4.2%*
69.07	*1.08*	*1.04*	*3.7%*
90.68	*1.56*	*1.58*	*1.3%*

Plant view of the downstream slope deformation process

CREST OF THE DAM

UNDEFORMED DOWNSTREAM TOE OF THE DAM

MAXIMUM ADVANCE OF THE FAILURE LINE FOR A GIVEN DISCHARCE

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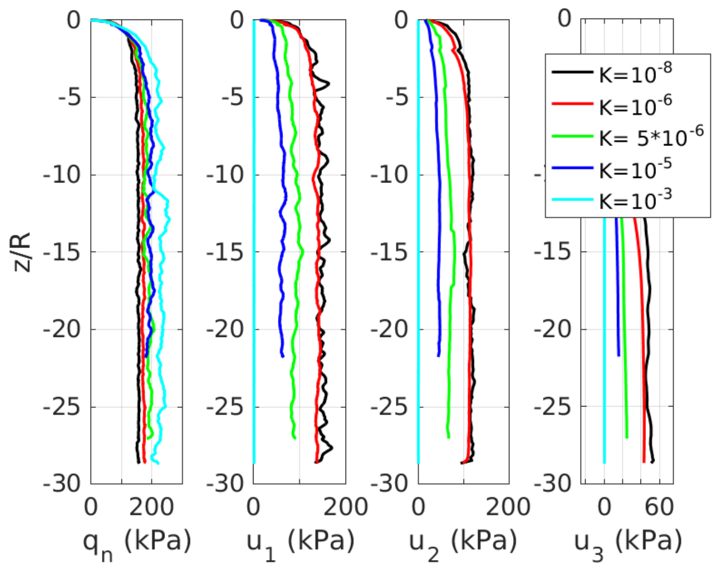
PFEM is evolving towards soils

- Cam-Clay, MC and other models being implemented
- Applications to In situ test but also levees



Cone penetration test. Net cone resistance and water pressure at the three measurement positions in terms of the normalized penetration depth. Selection of the smooth cases with Ko = 0.5

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References

Antonia Larese
antoldt@cimne.upc.edu

- Larese, A.; Rossi, R.; Idelsohn, S.R.; Oñate, E. A coupled PFEM-Eulerian approach for the solution of porous FSI problems. Computational mechanics.50 - 6,pp. 805 - 819. (2012). ISSN 0178-7675.
- Rossi, R.; Larese, A.; Dadvand, P.; Oñate, E. An efficient edge-based level set finite element method for free surface flow problems. International journal for numerical methods in fluids. 71-6, pp.687-716 (2012). Larese, A.; Rossi, R.; Oñate, E.; Toledo, M.A.; Moran, R., Campos, H., Numerical and experimental study of overtopping and failure of rockfill dams. International Journal of Geomechanics (ASCE) 15 (4)
- Larese, A., Rossi, R., Oñate, E., Finite Element Modeling of free surface flow in variable porosity media. Archives for Numerical Methods in Engineering DOI: 10.1007/s11831-014-9140-x.
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- Larese, A.; Rossi, R.; Oñate, E., Toledo, M.; Physical and numerical modelization of the behaviour of rockfill dams during overtopping scenarios. Dam Maintenance and Rehabilitation II. pp. 479 - 487.CRC Press, 2010. ISBN 978-0415616485 (2011)
- Larese, A.; Rossi, R.; Oñate, E. , Simulation of the beginning of failure in rockfill dams caused by overtopping . Dam Protection against Overtopping and Accidental Leakage, Eds. Toledo, Moran & Oñate Taylor & Francis group London ISBN 978-1-138-02808-1, pp. 111-118, (2015).

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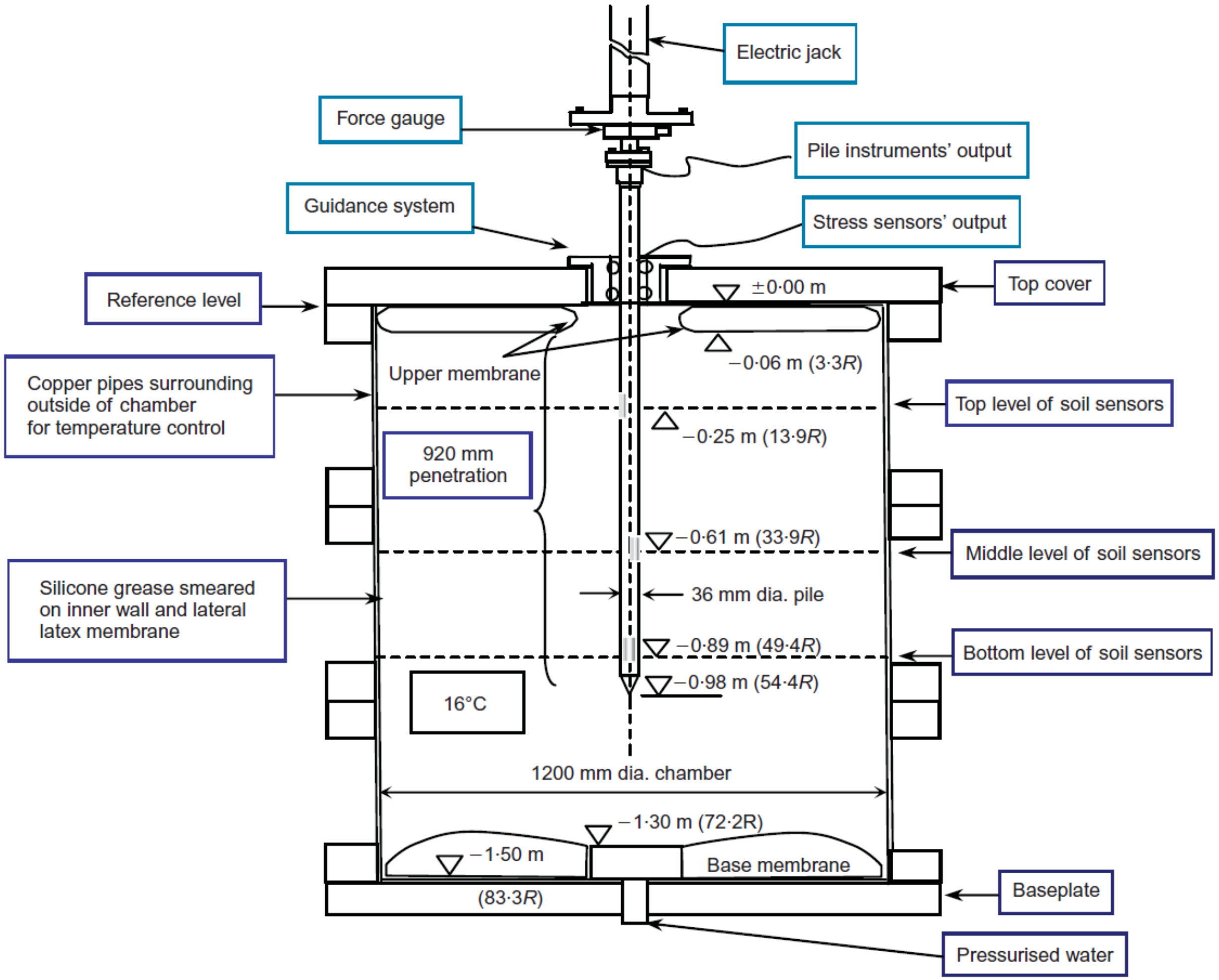
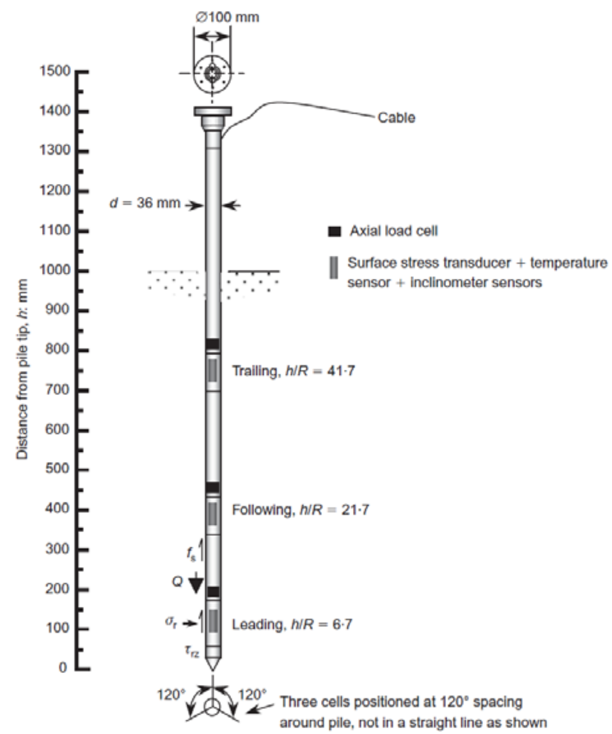
Penetration tests in siliceous sand

- Tests in instrumented INPG calibration chamber (Jardine et al., 2013, Yang et al. 2013)
  - Fontainebleau NE34 sand (siliceous)

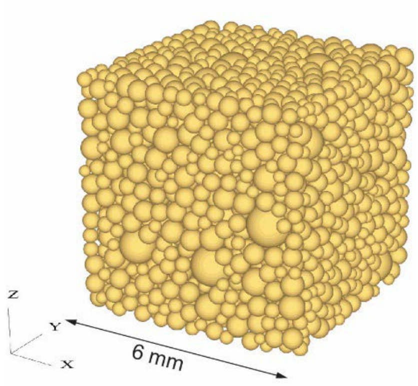


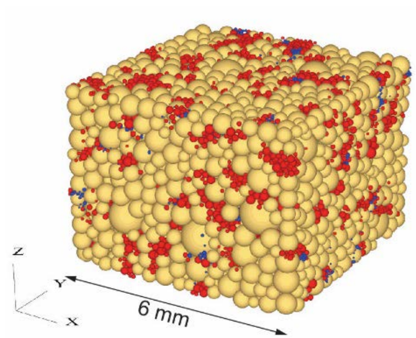


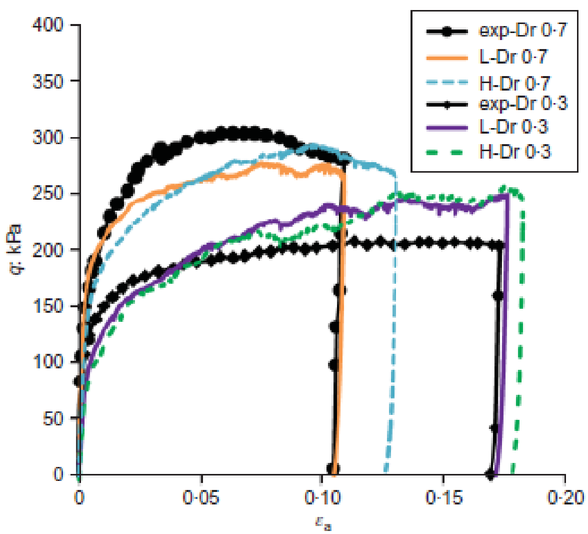
Mini-ICP pile (36 mm dia.)

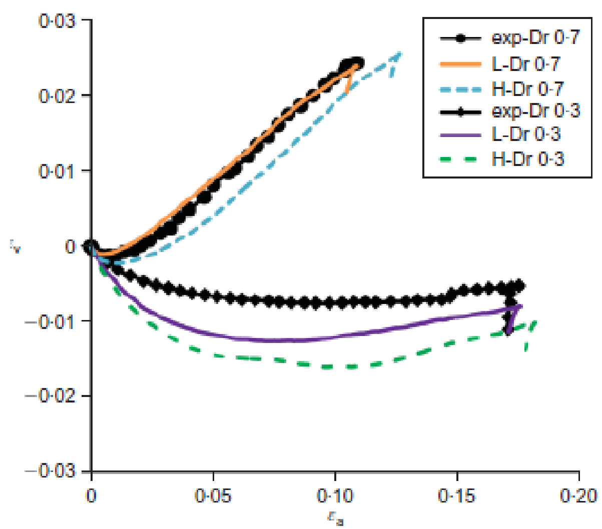
Penetration tests in siliceous sand

❑ Parameter calibration: Fontainebleau sand

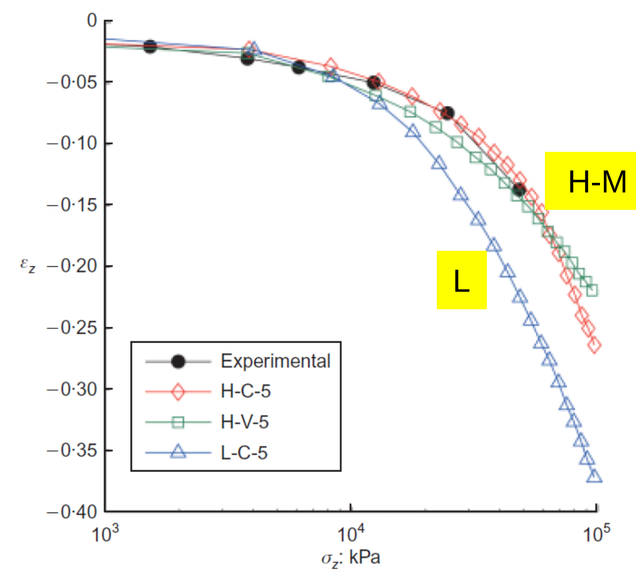








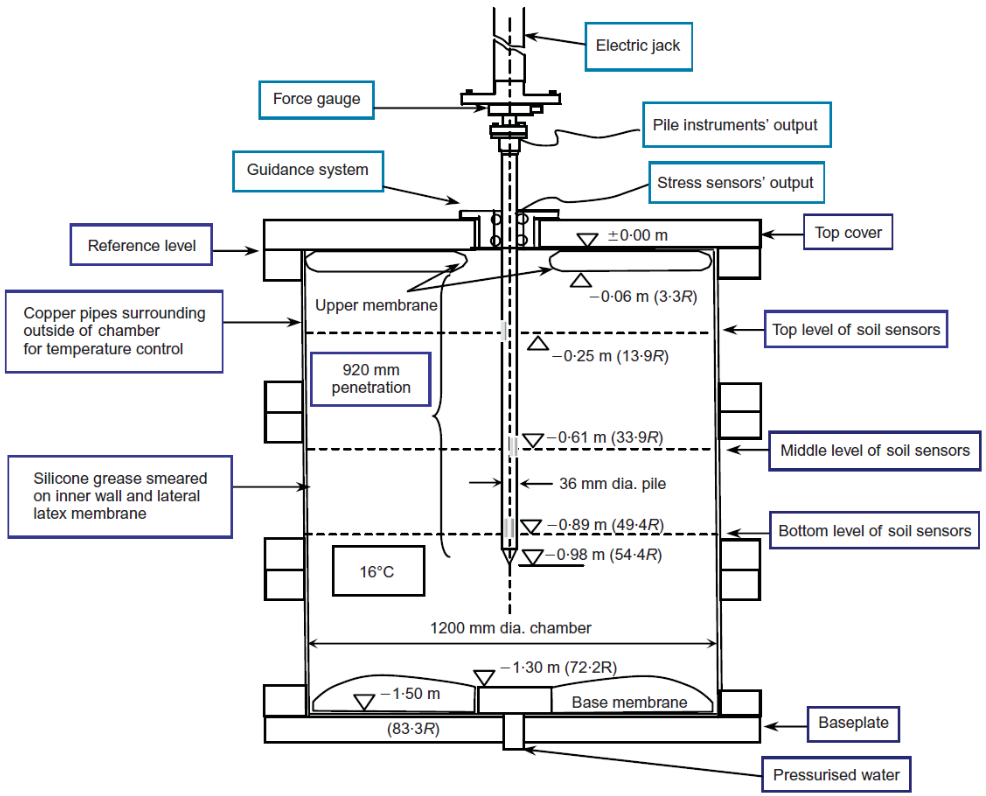
Triaxial tests

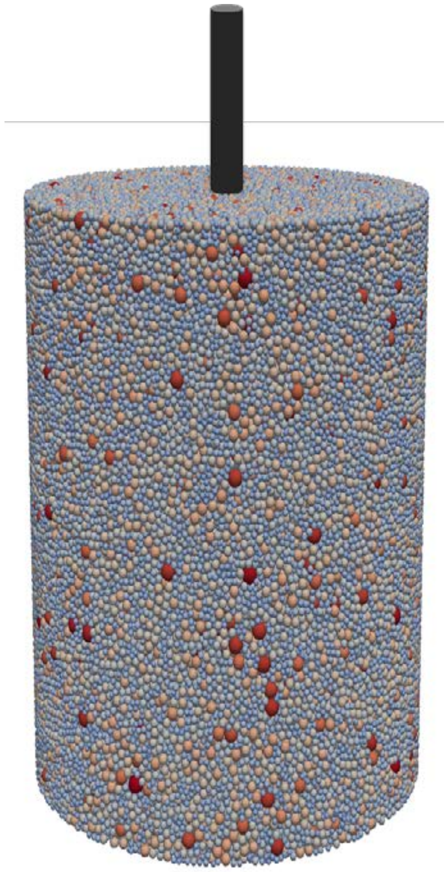


Oedometer test

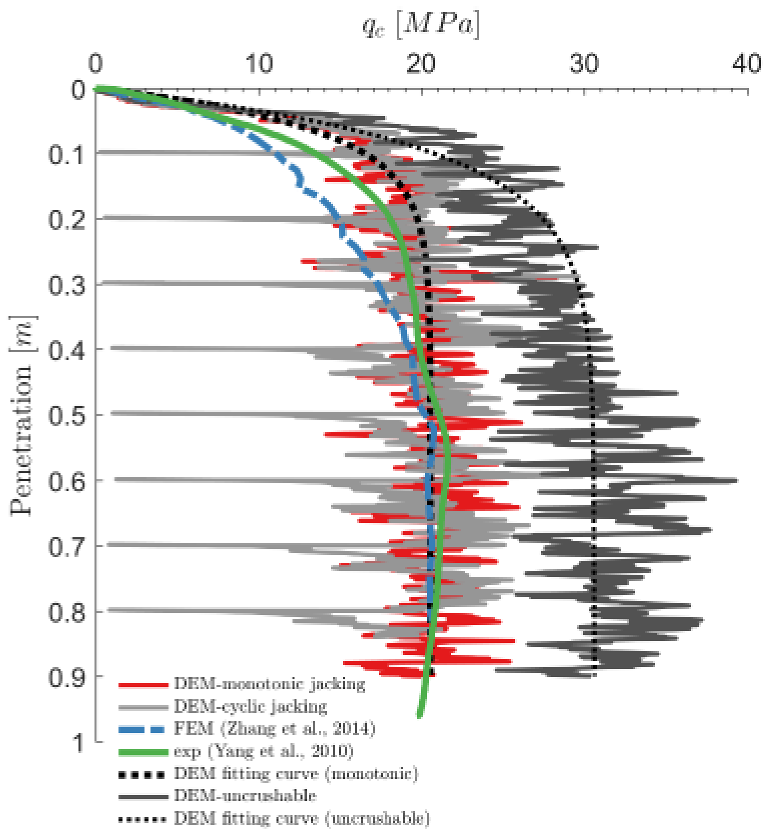
Penetration tests in siliceous sand

❑ Modelling the penetration test

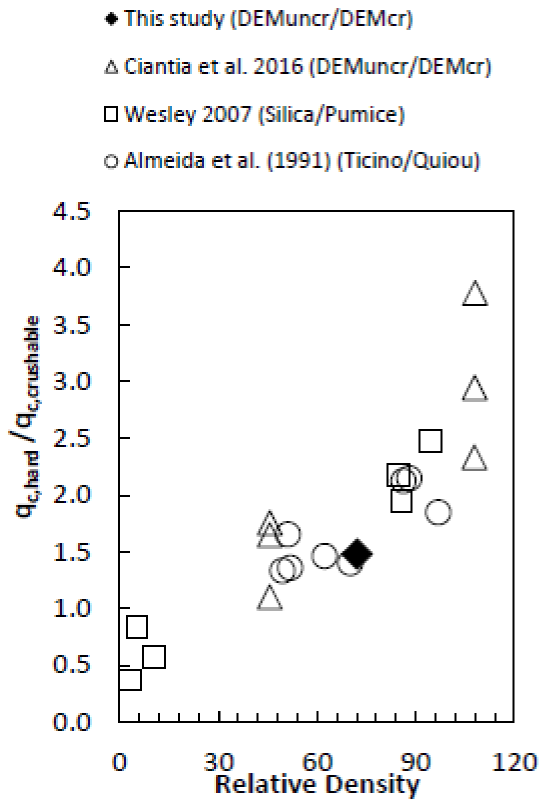




Effect of crushing

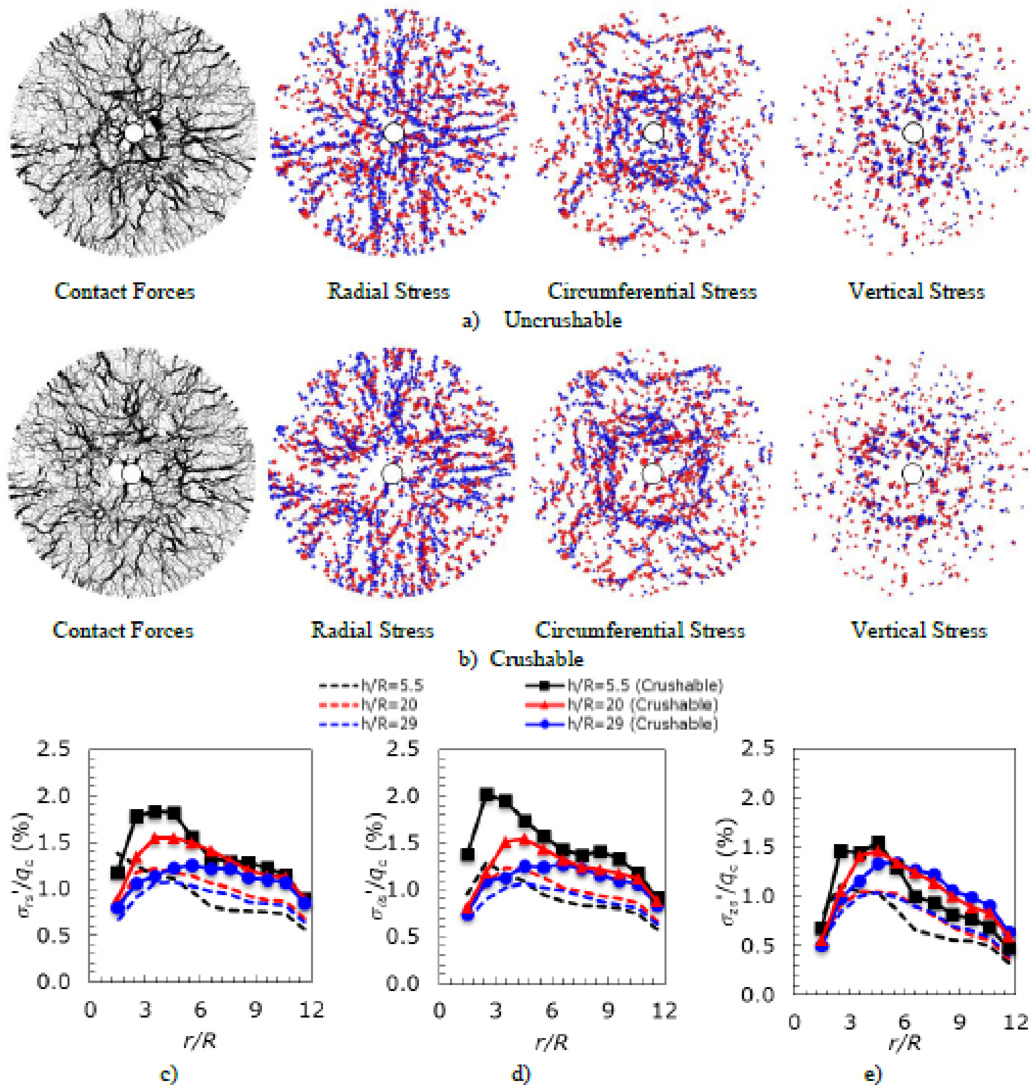


a)



b)

Arching around the shaft



Outline

- Numerical applications (levee related)
  - Soil atmosphere interaction (railway embankment)
  - Overtopping
  - Site investigation
- Kratos
- Erosion testing channels

KRATOS MULTI-PHYSICS

Kratos is a framework for building multi-disciplinary (MULTI-PHYSICS) finite element programs. It provides several tools for fast implementation of finite element applications. CFD, CSD, Thermally Coupled Problems, Particles, ...

OPEN SOURCE

The dynamic nature of KRATOS itself is the principal reason of the continued evolution.

PARALLEL HPC

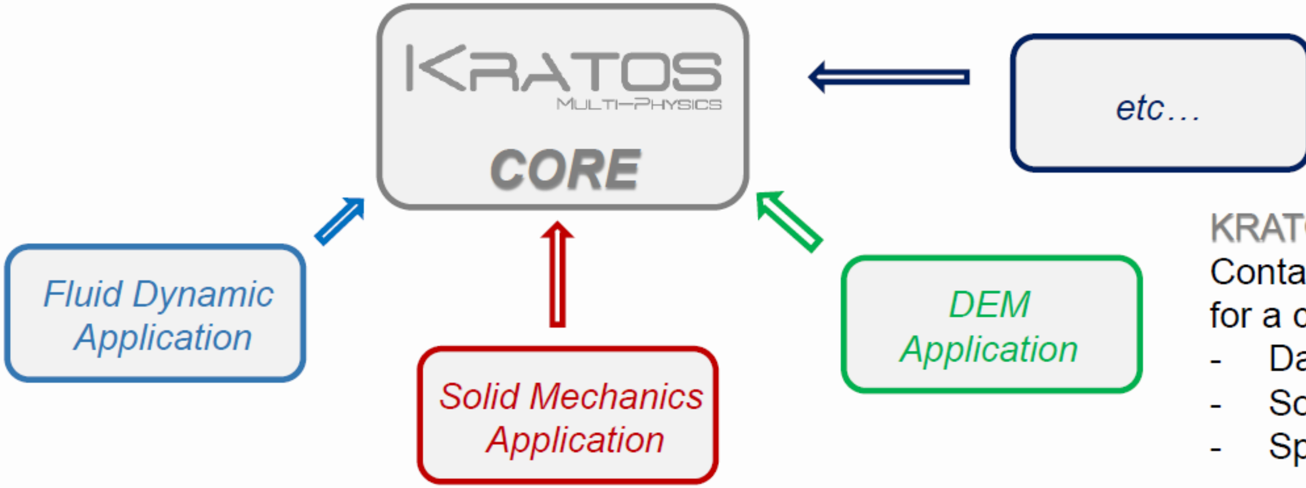
High performance computing in an OpenMP/MPI - based software.

FLEXIBILITY

Kratos can be used with research purposes or by engineers looking for a solution to complex industrial problems

KRATOS – Core-Application approach

www.cimne.com/kratos

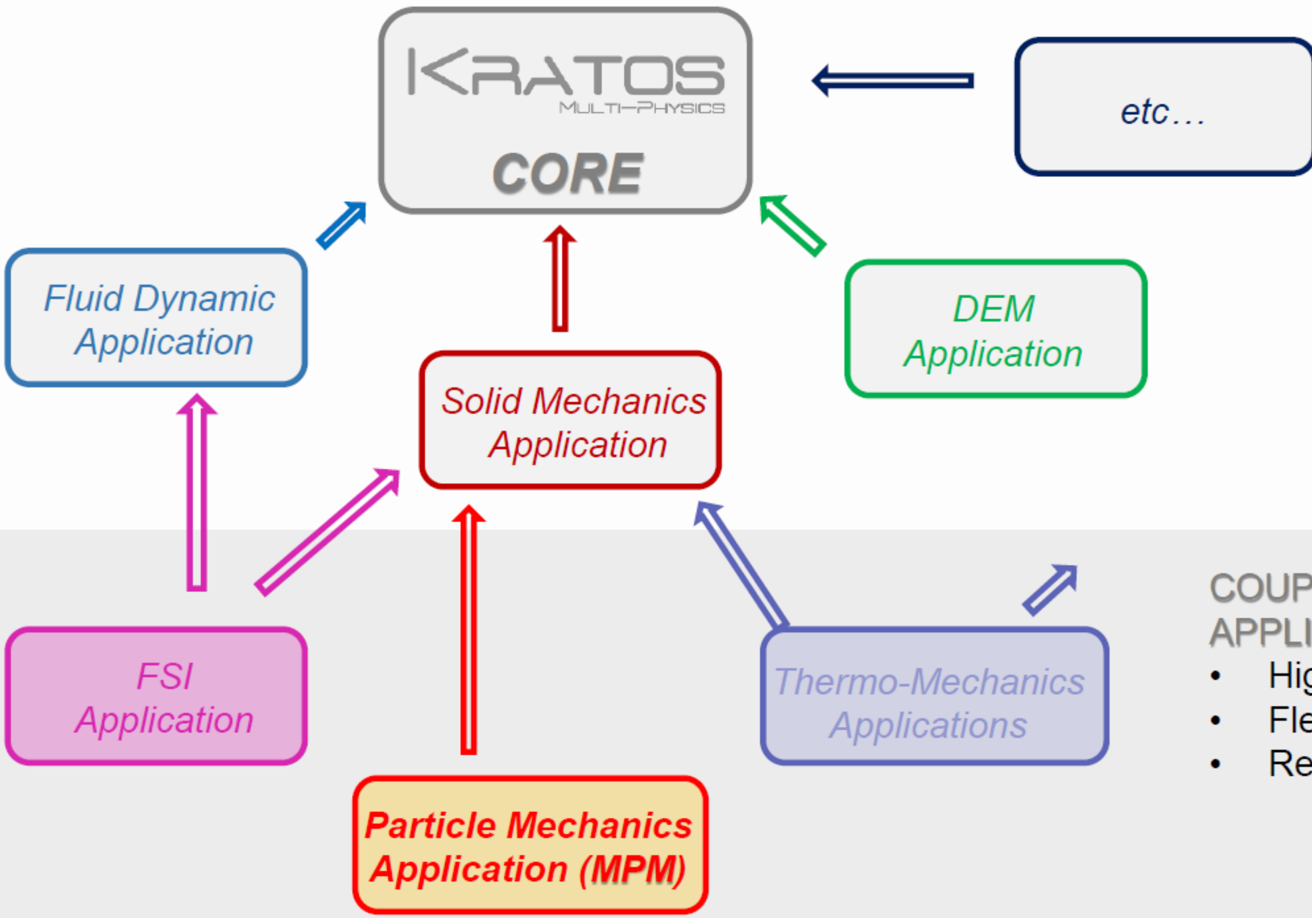


KRATOS CORE:
Contains the basic/common tools for a computational code
- Data structure
- Solvers
- Spatial containers
- ….

KRATOS APPLICATIONS:
Contains the physics

KRATOS – Core-Application approach

www.cimne.com/kratos

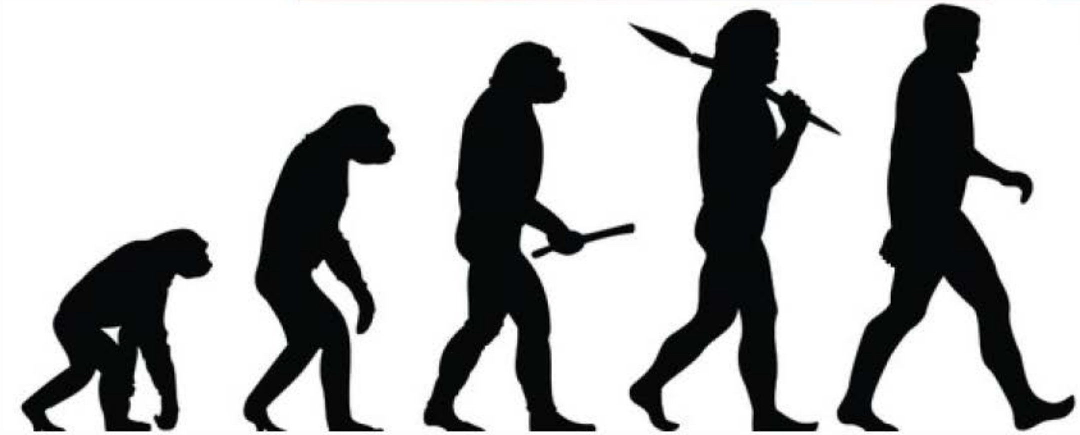


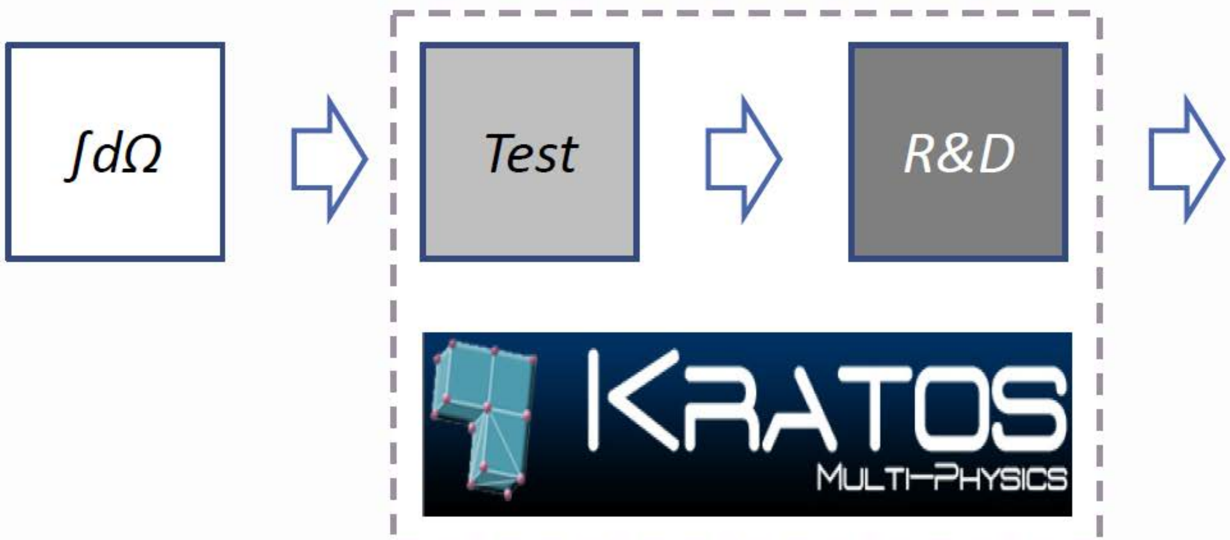
COUPLED or DERIVED APPLICATION

- High reusability
- Flexibility
- Reduced conflicts

KRATOS

www.cimne.com/kratos





Outline

- Numerical applications (levee related)
  - Soil atmosphere interaction (railway embankment)
  - Overtopping
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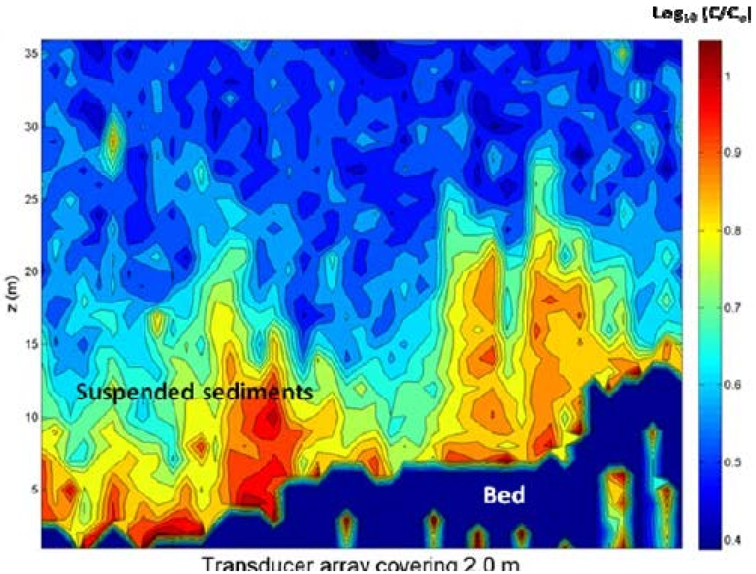
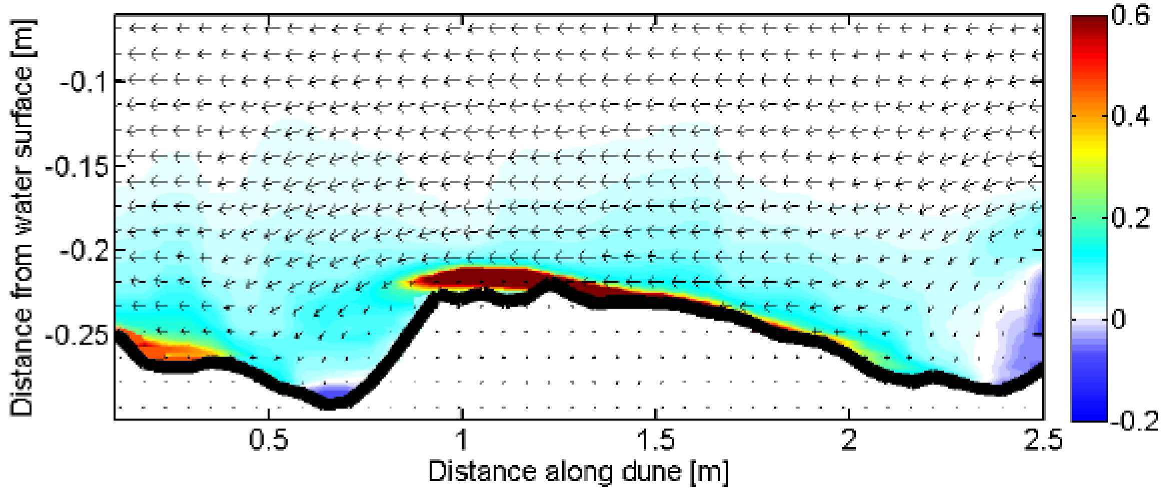
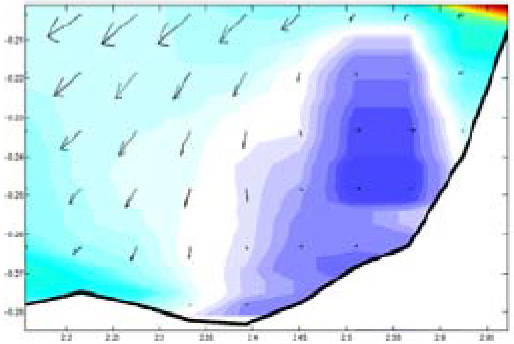
Laboratory (LIM)

- Channel for erosion studies
- Applied for coastal engineering but also overtopping
- 100m long, 3m wide and 5m deep
- Advanced sensorization

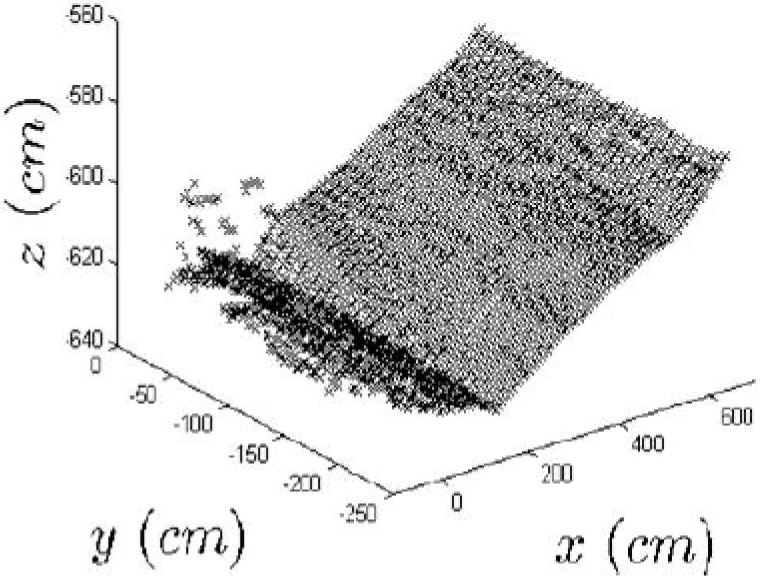


Sonar sediment erosion and water velocity profiling





Optical bed profiling



And a collaborator

- The end....

A collaborator...

THE USE OF INSAR IN LANDSLIDE MONITORING

Josep Raventós*, Marcos Arroyo[†]

* TRE ALTAMIRA, Carrer Còrsega 381-387. 08037 BARCELONA, SPAIN. josep.raventos@tre-altamira.com
[†] DECA- UPC, BARCELONA, SPAIN