CIMNE RESEARCH

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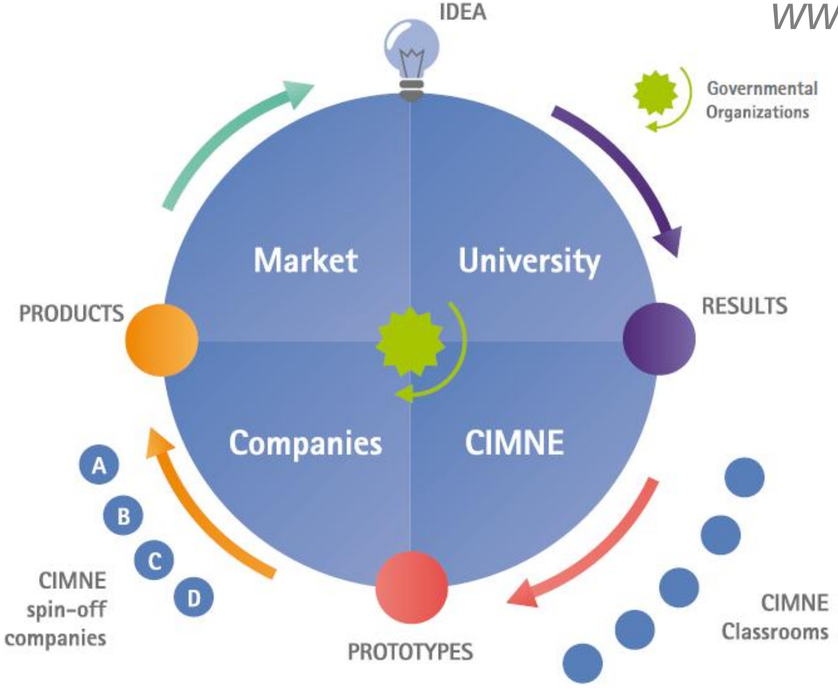
M.Á. Toledo , R. Morán

International Workshop on Overflowing Erosion of Dams and Dikes
PART 1. Embankment dams and Dikes
Aussois, 11th-14th December 2017

What is CIMNE ?

INTERNATIONAL CENTER for NUMERICAL METHODS in ENGINEERING

www.cimne.com



CIMNE: the "I" of international

CIMNE: Numerical Methods in Engineering

The mission of CIMNE is to **solve engineering problems** developing **UNCONVENTIONAL COMPUTATIONAL APPROACHES**

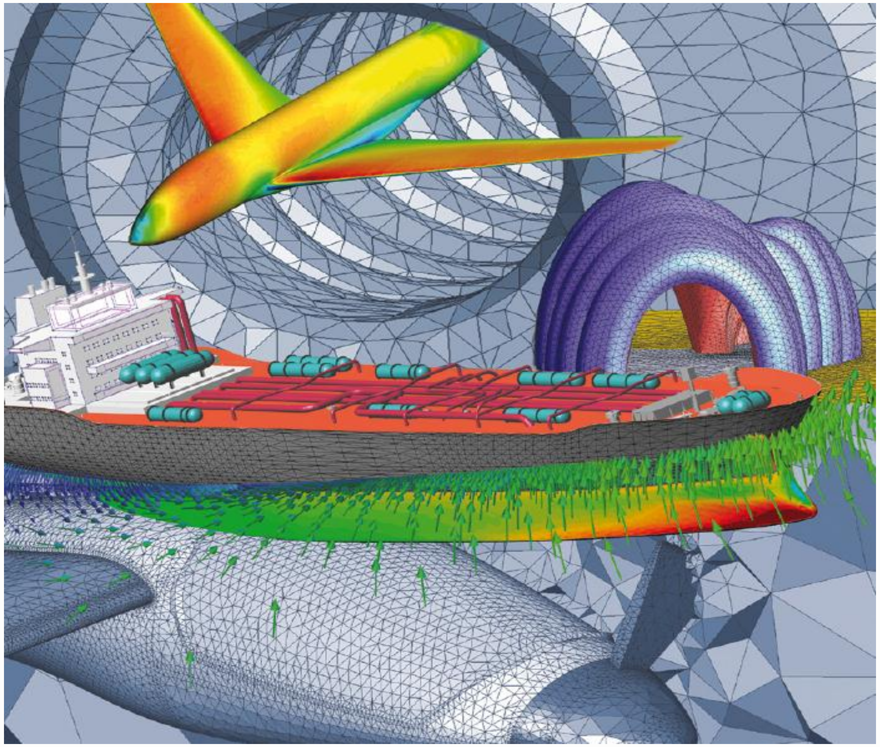
Available COMMERCIAL CODES:

- Provide solution to **conventional** engineering needs (design, construction,…)
- Solve **single physics**
- Verified, validated, user-friendly

CIMNE provides solutions to problems where commercial codes fails

- **Designs** *ah hoc* **solution strategies**
- Combines **different numerical approaches**
- Develops **novel computational techniques**
- Combines **multiple physics**

CIMNE: Numerical Methods in Engineering



CIMNE:

- Works in **several areas of engineering** (civil, maritime, aeronautic, ….)
- Works in **team** with experts on the **physical/engineering problem**

  COUPLING EXPERIMENTAL-NUMERICAL APPROACH

- Develops:
  - Basics formulations
  - Novel techniques
  - Novel computational approaches
  - Wizards (technology transfer)

APPLIED RESEARCH

CIMNE is developing

KRATOS
MULTI-PHYSICS

An opensource platform
to use and develop multi-disciplinary programs

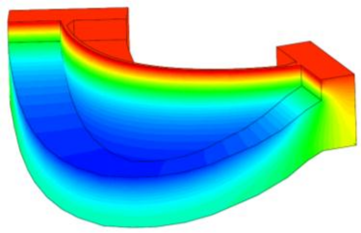
- **MULTI-TECHNIQUE** (Finite Elements, Discrete Elements, Particle methods, …)
- **MULTI-PHYSICS** (Computational Fluid Dynamics, Computational Structural Mechanics, Thermal analysis, …)
- **Natural coupling** of existing applications
- High Performance Computing (**HPC**)

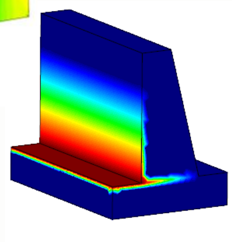
www.cimne.com/kratos

CIMNE

KRATOS MULTI-PHYSICS in dam engineering

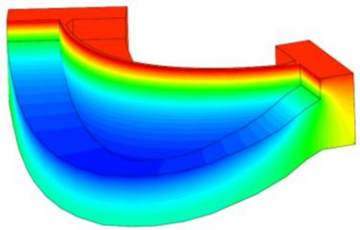
Thermo mechanical analysis

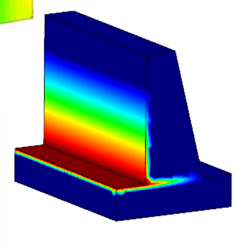


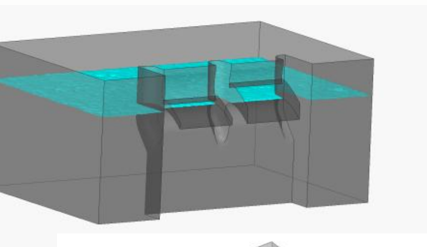


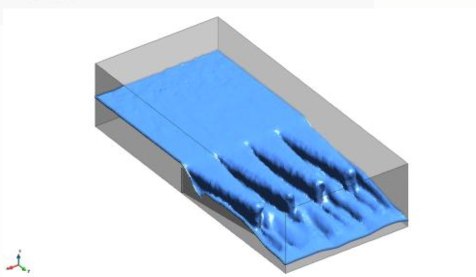
KRATOS in dam engineering

Thermo mechanical analysis





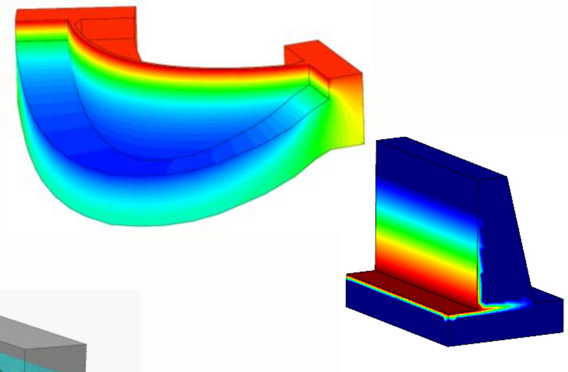


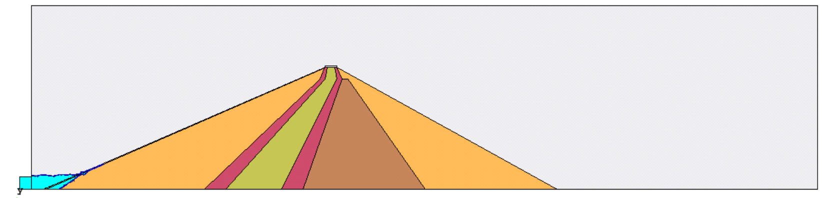


Spillways hydraulic performance

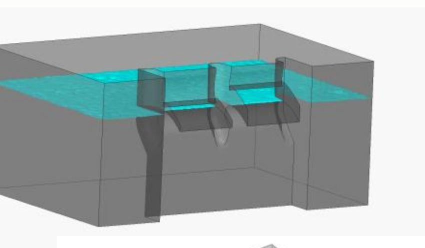
KRATOS in dam engineering

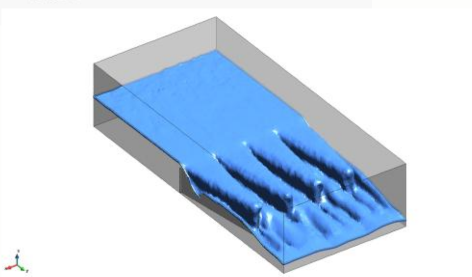
Thermo mechanical analysis





Zoned rockfill dams

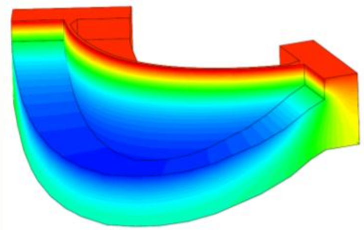


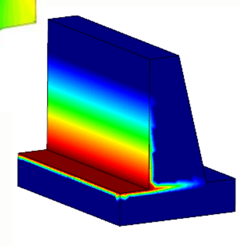


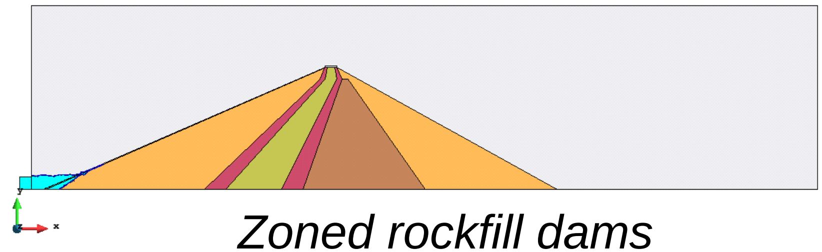
Spillways hydraulic performance

KRATOS MULTI-PHYSICS in dam engineering

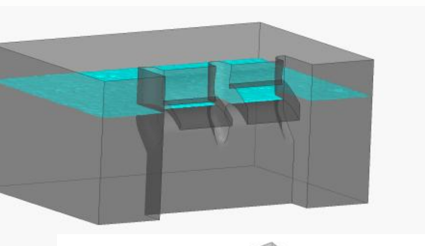
Thermo mechanical analysis

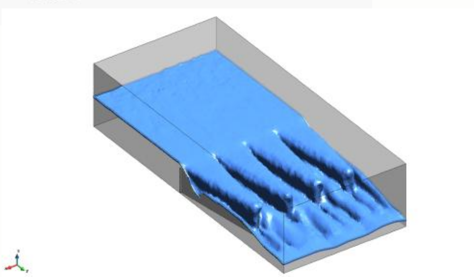




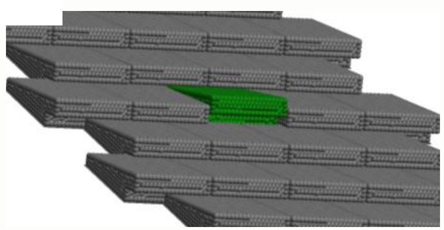


Zoned rockfill dams





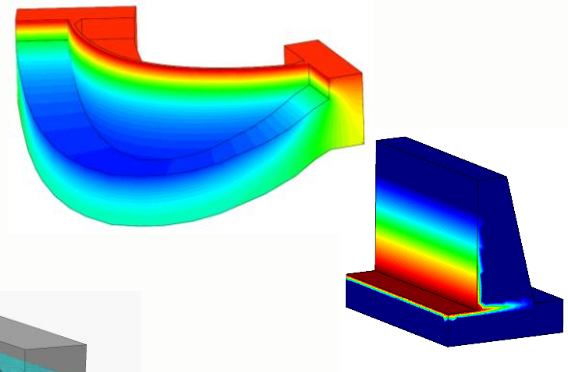
Spillways hydraulic performance

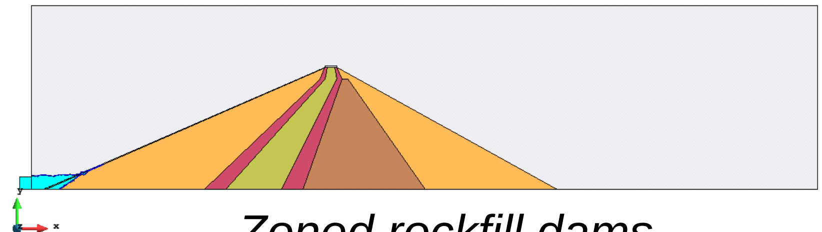


Stability analysis

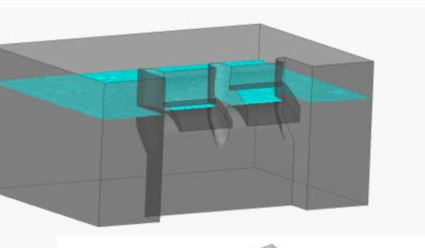
KRATOS Multi-Physics in dam engineering

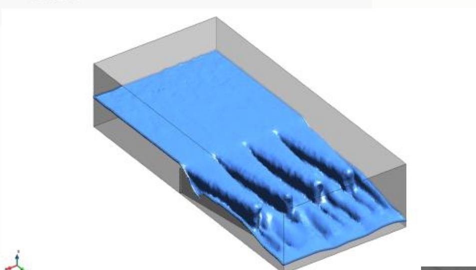
Thermo mechanical analysis





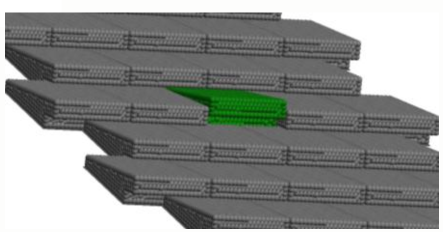
Zoned rockfill dams



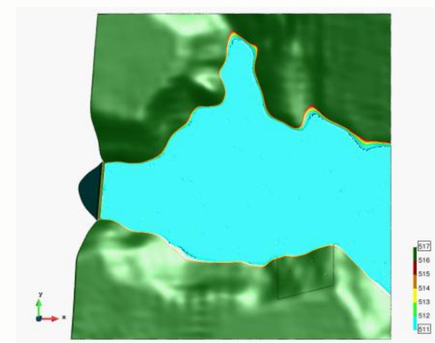


Spillways hydraulic performance

KRATOS Multi-Physics



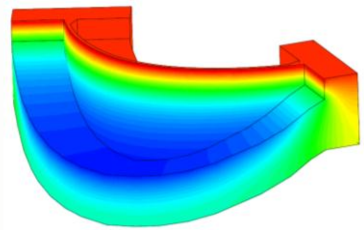
Stability analysis

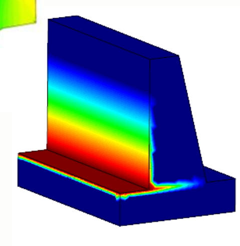


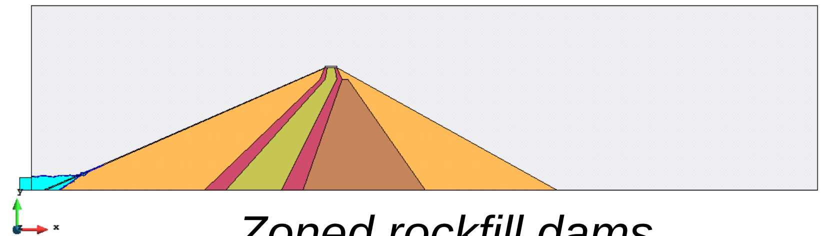
Wave generated by landslide into reservoir

KRATOS in dam engineering

Thermo mechanical analysis

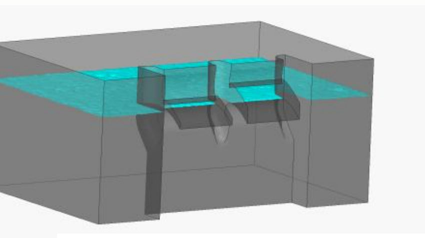


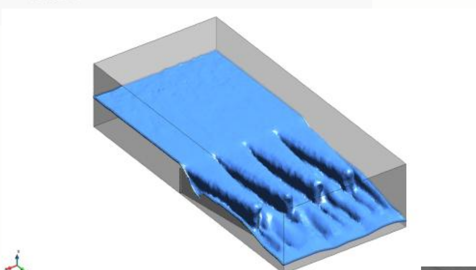




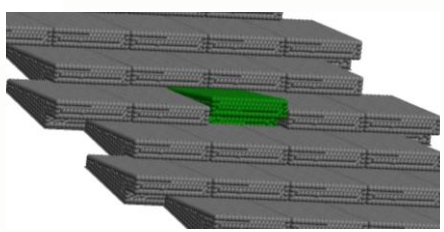
Zoned rockfill dams

DAM SAFETY



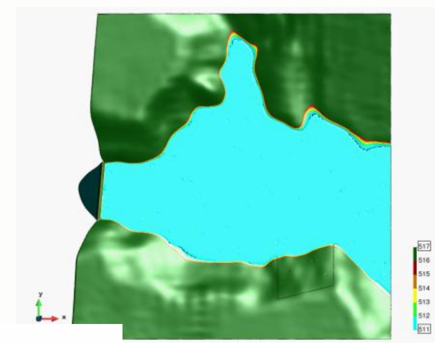


Spillways hydraulic performance

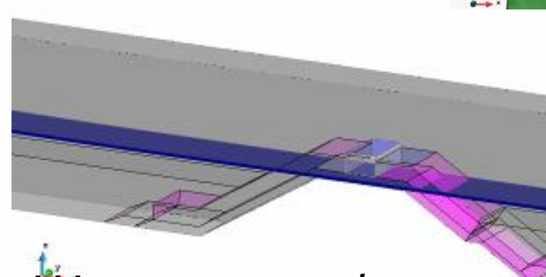


Stability analysis

DAM SECURITY



Wave generated by landslide into reservoir

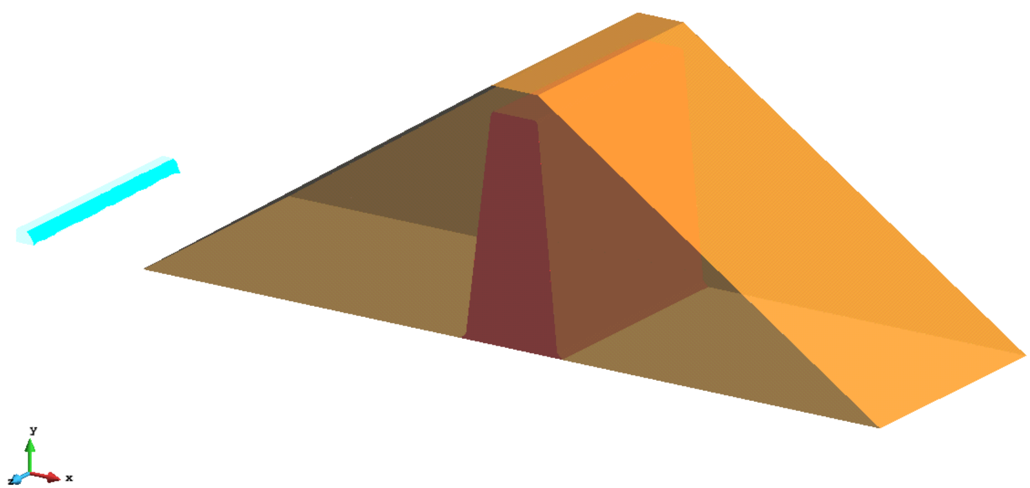


Wave overtopping

DAM SAFETY

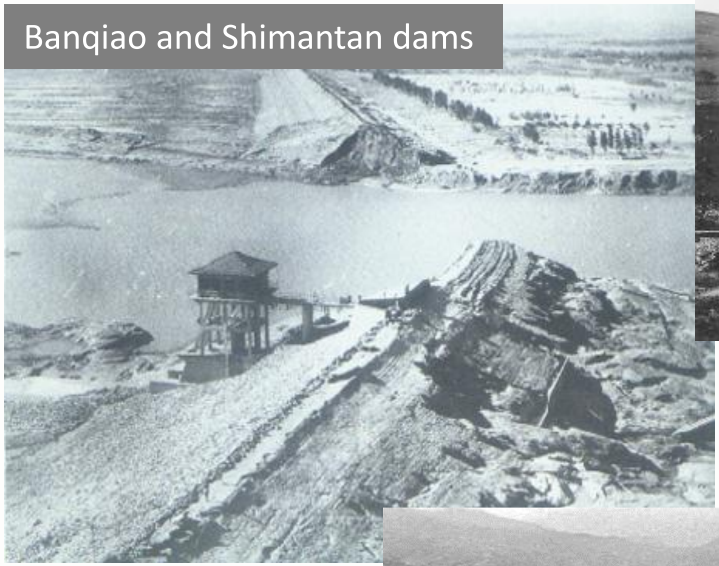
OVERTOPPING IN ZONED ROCKFILL DAMS

1. ROCKFILL
   - Seepage
   - Failure
2. CLAY CORE mechanical failure



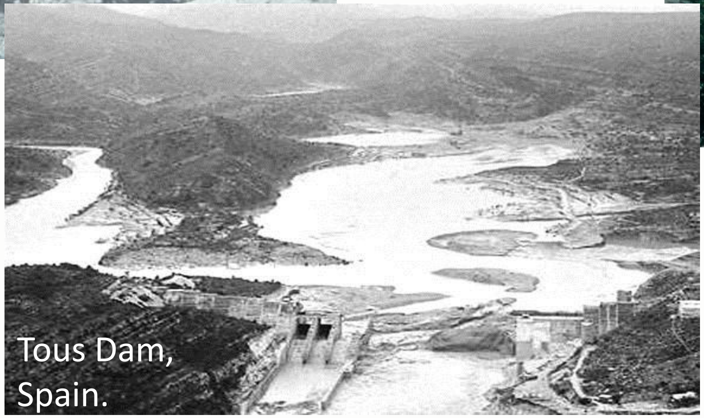
Overtopping

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.

OVERTOPPING IN ZONED ROCKFILL DAMS

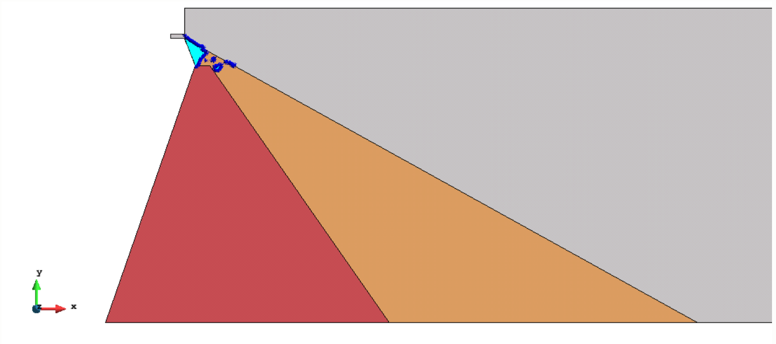
1. Rockfill. Seepage

Objective:

- Evaluation the hydrodynamic forces on the rockfill during an overtopping

Basic ingredients:

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



n=0.37
D =0,085m

n=0.37
D =0,3m

OVERTOPPING IN ZONED ROCKFILL DAMS

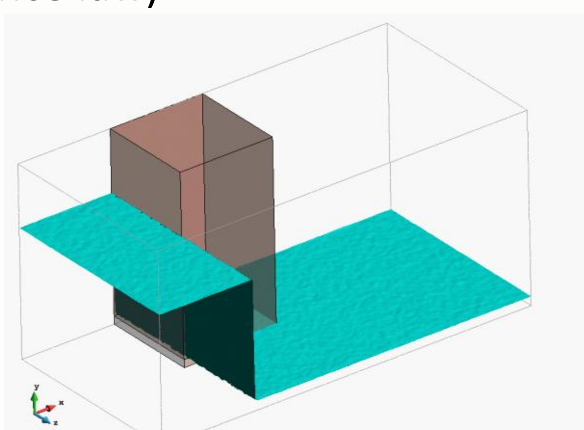
1. Rockfill. Seepage

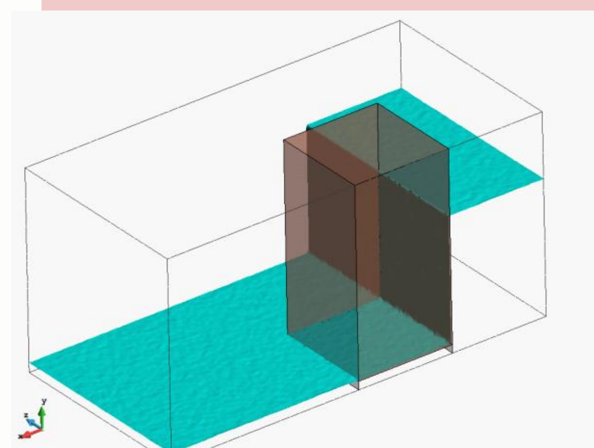
SEEPAGE IN SOIL (earthfill)

- 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

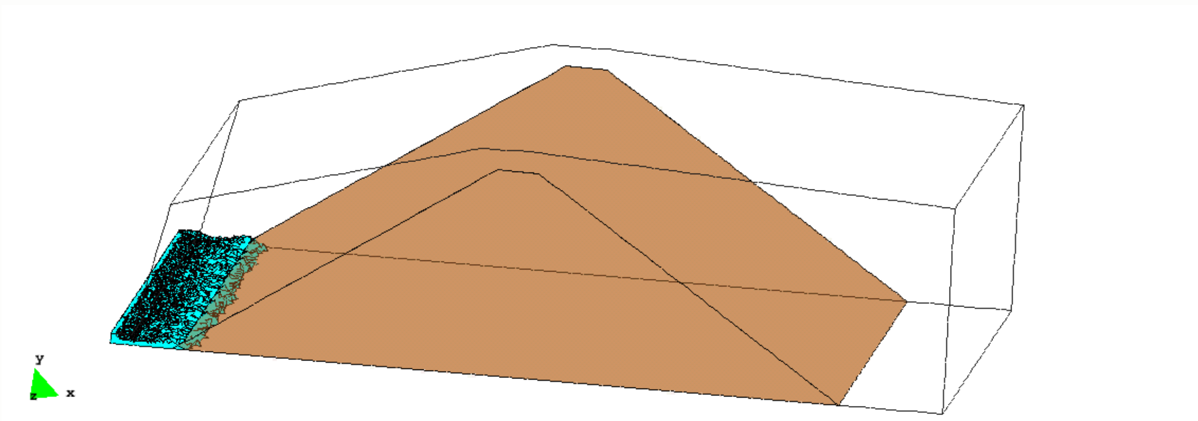
- High permeability
- Pores are big and interconnected
- Very **fast** phenomenon (order of minutes, hours)
- Turbulent flow
- Governed by a **non linear resistance law**





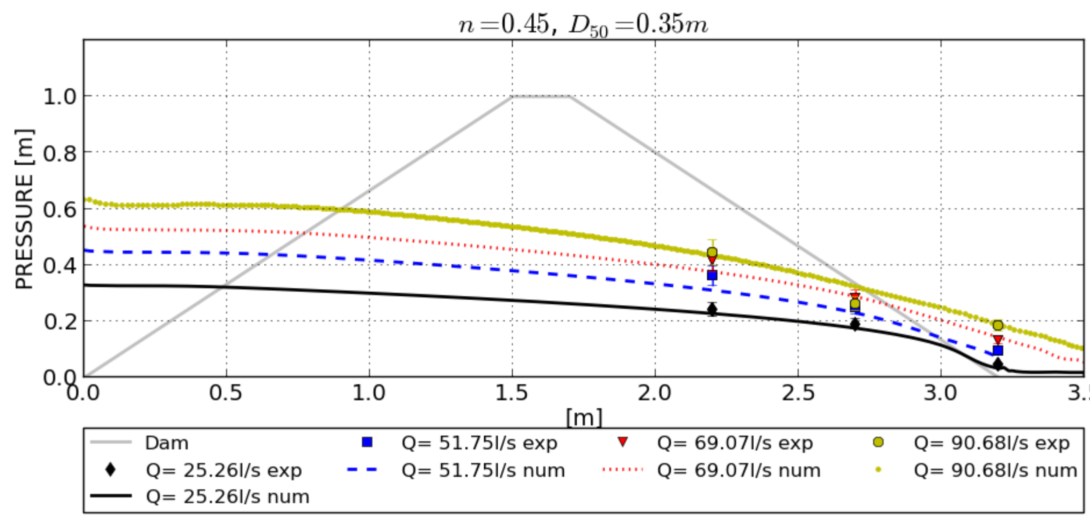
OVERTOPPING IN ZONED ROCKFILL DAMS

1. Rockfill. Seepage



2D and 3D SIMULATIONS

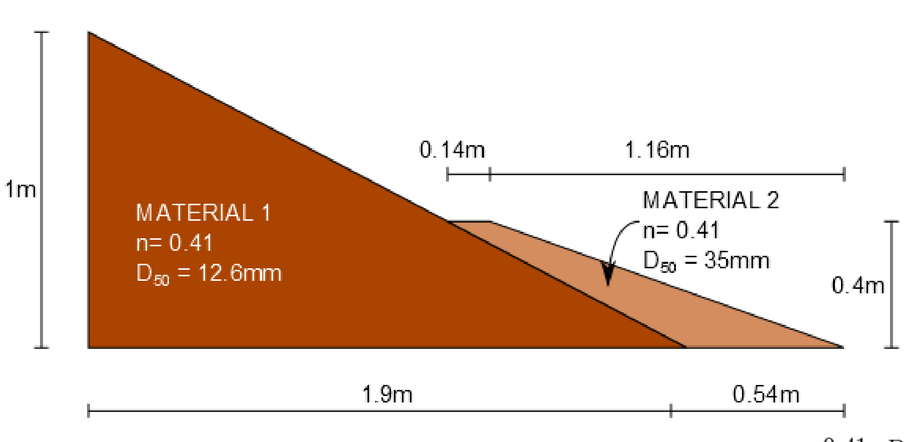
Validation on small scale dams experiments performed at the UPM.

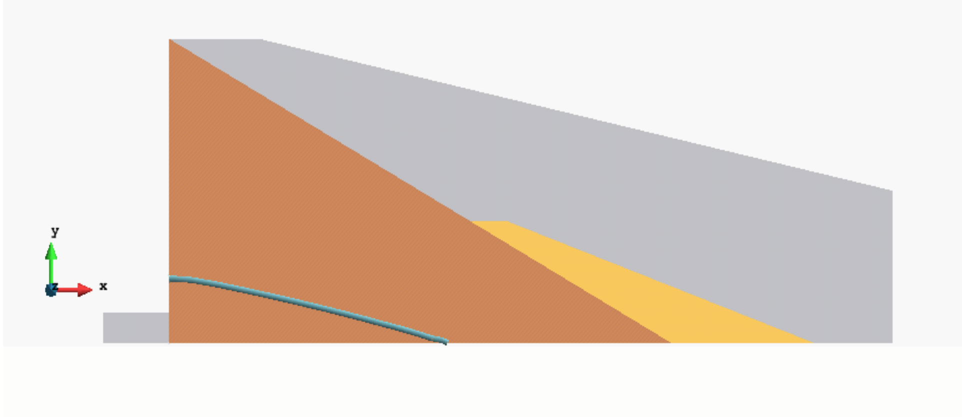


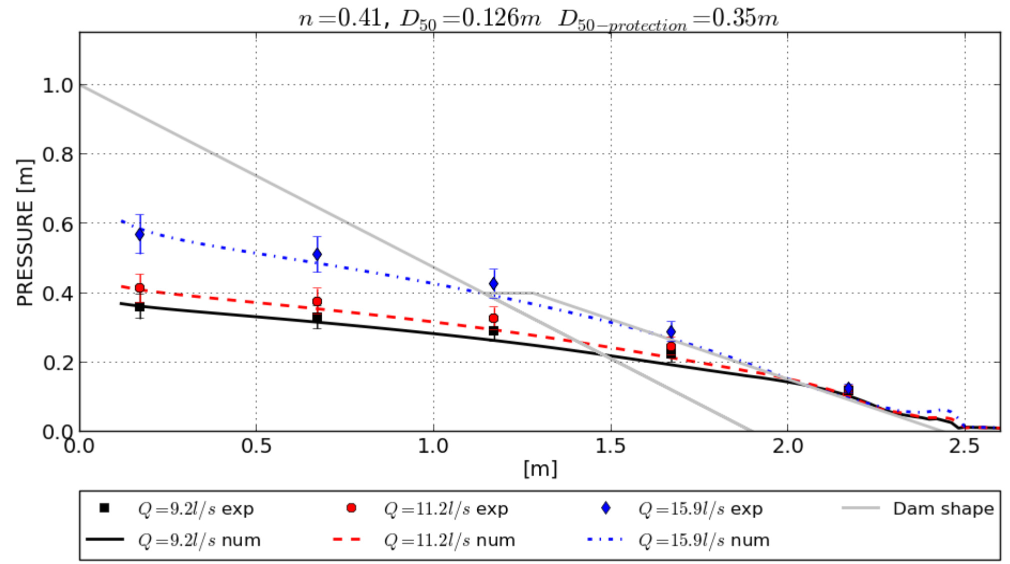
- Larese, A.; Rossi, R.; Oñate, E.; Toledo, M.A.; Moran, R., Campos, H., *Numerical and experimental study of overtopping and failure of rockfill dams*. International Journal of Geomechanics (ASCE) (2013) ISSN 1532-3641.

OVERTOPPING IN ZONED ROCKFILL DAMS

1. Rockfill. Seepage







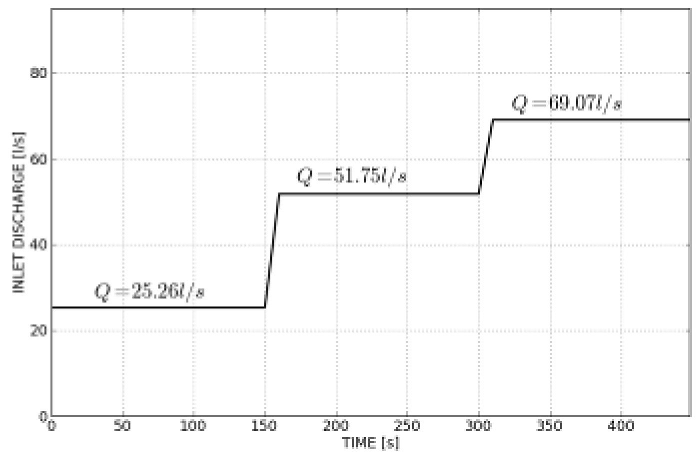
LAYERS OF DIFFERENT **POROUS MATERIAL** CAN BE SIMULATED

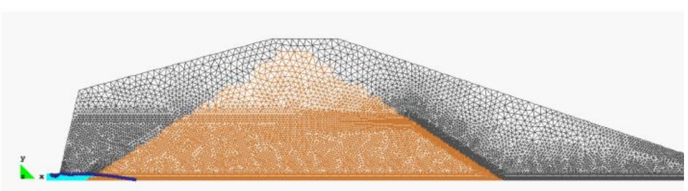
Curtesy of Dr. Morán.
Source. Dr. Morán PhD Thesis

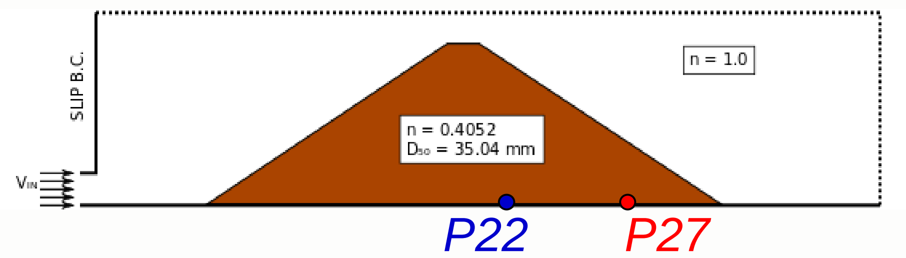
OVERTOPPING IN ZONED ROCKFILL DAMS

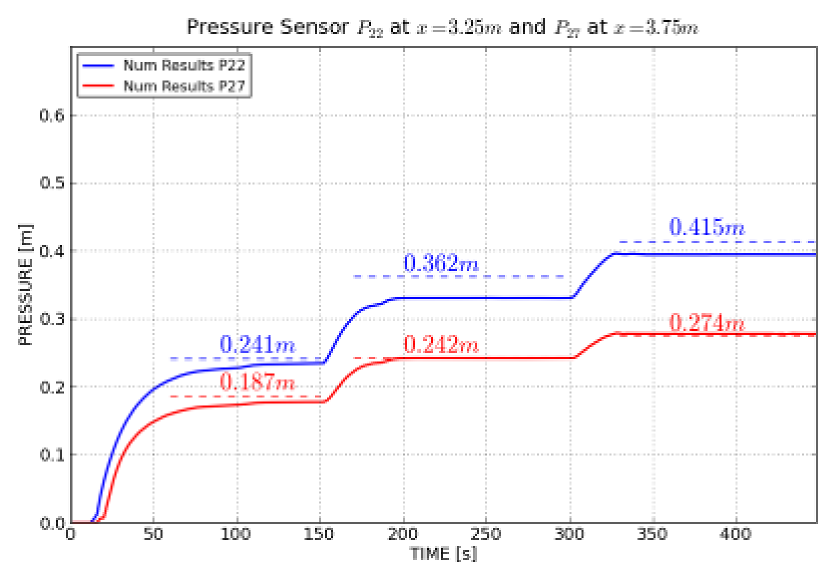
1.Rockfill. Seepage

- **TRANSIENT** REGIME
- **HYDROGRAMS** AS INFLOW CONDITIONS



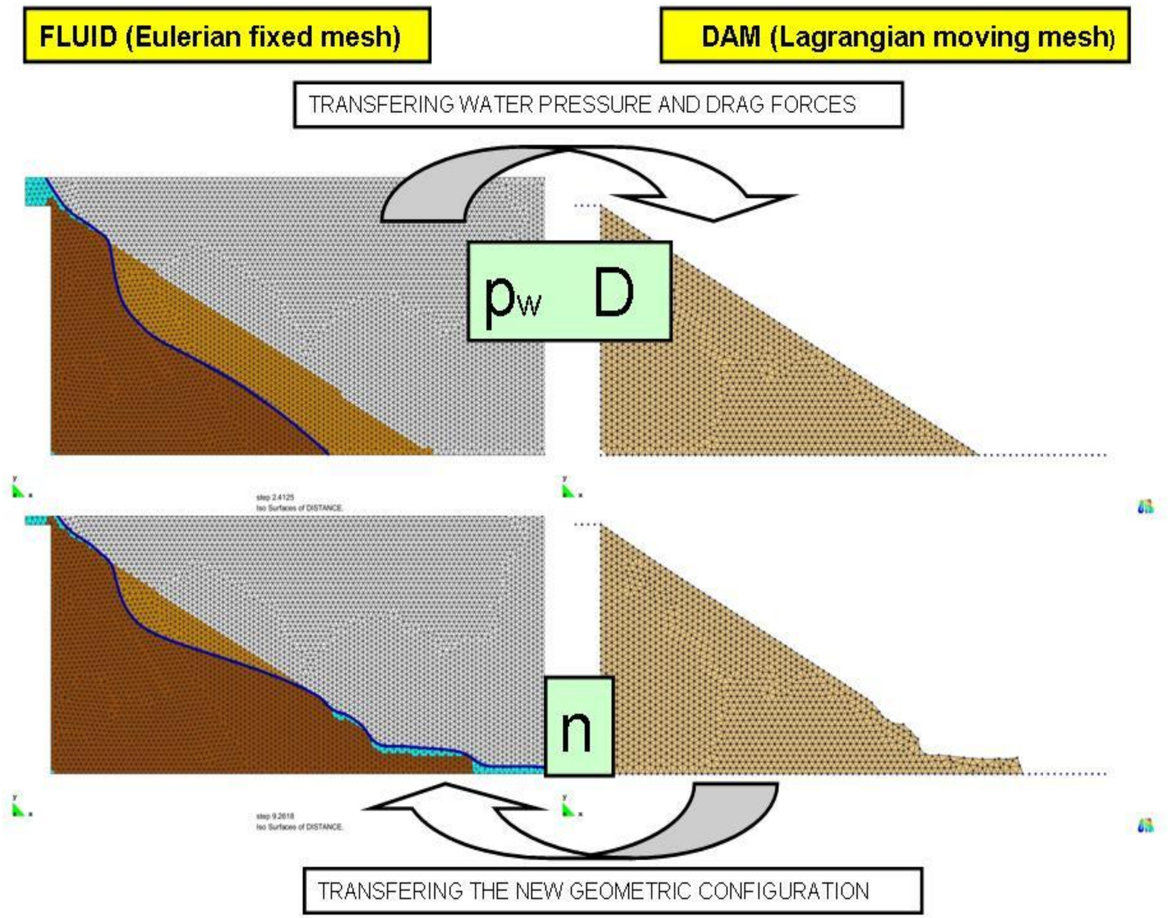






OVERTOPPING IN ZONED ROCKFILL DAMS

1.Rockfill. Failure



- *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.; 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).

OVERTOPPING IN ZONED ROCKFILL DAMS

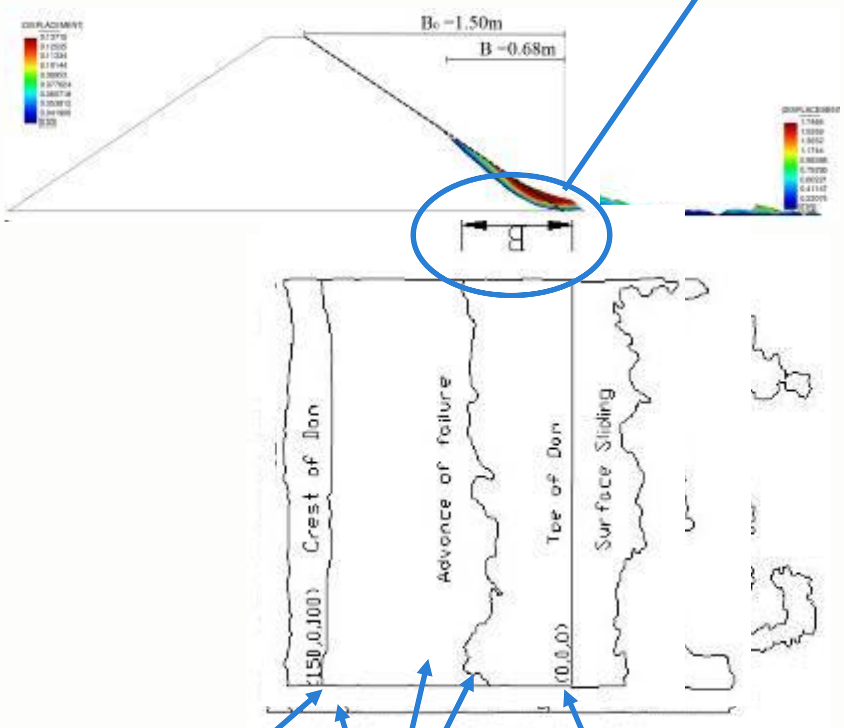
1.Rockfill. Failure

B: ADVANCE OF FAILURE horizontal projection of the highest point that moved

90.68l/s

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

OVERTOPPING IN ZONED ROCKFILL DAMS

1.Rockfill. Failure

CONCLUSIONS

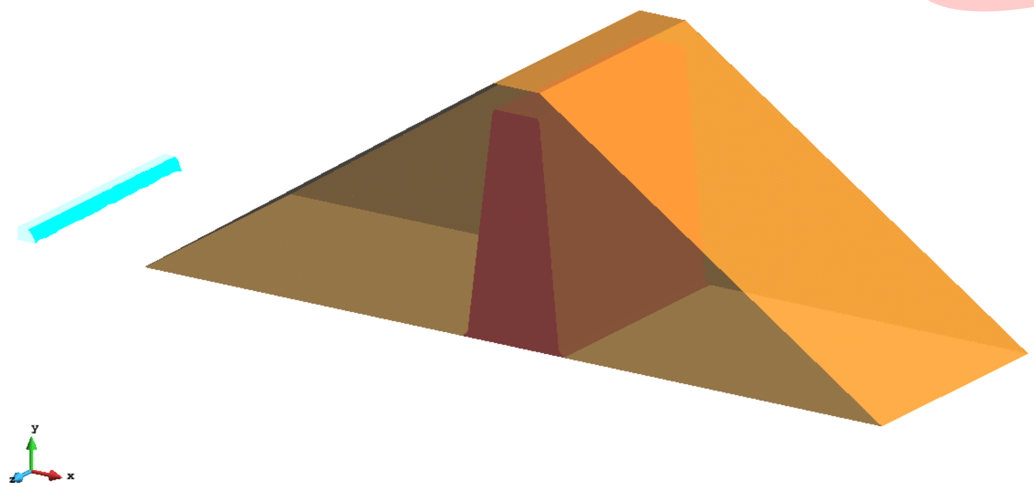
1. Seepage and free surface tool
   - **Precise, robust, efficient, validated**
   - *Ongoing*: user friendly **interface** (free and downloadable in 2018)
   - *Ambition:* assess of performance on **real cases**.
2. Structural model
   - Good performance of PFEM technique in 2D but not optimal in 3D
   - *Future work:* assess an alternative Lagrangian technique (MPM) now available in Kratos
   - *Ambition:* extend the validation on **real cases**

DAM SAFETY

OVERTOPPING IN ZONED ROCKFILL DAMS

Clay core mechanical failure

ONGOING RESEARCH



OVERTOPPING IN ZONED ROCKFILL DAMS

2.Clay core. Failure

HIRMA (Ref. RTC – 2016-4967-5)

Project funded by the Spanish ministry MINECO

Development and validation of a software to determine the failure hydrograph of embankment dams based on the particular geo-mechanical configuration.

ONGOING RESEARCH

http://blogs.upm.es/serpa/what-we-do/rdi-projects/hirma/

INCLAM Ingeniería del Agua

UNIVERSIDAD POLITECNICA MADRID

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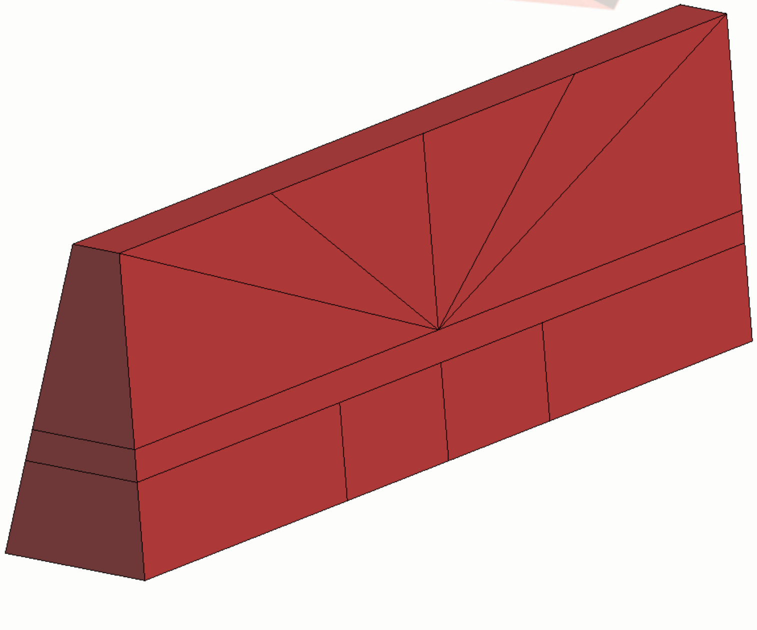
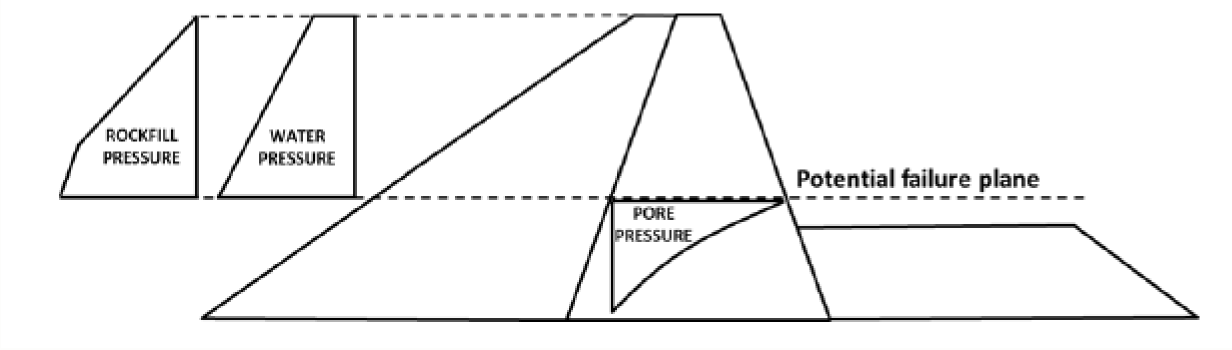
Computational Approach

- **1st stage.** Damage models to identify the behavior of the clay core studying the influence of
  - the downstream shape of the failed downstream rockfill shoulder
  - the clay material
  - the clay core geometry (height/width ratio)
  - the force boundary condition (hydrodynamic, subpressure, water pressure, rockfill pressure)
- **2nd stage.** Elasto-plastic models handling large deformation of the clay core (using MPM and other particle techniques) to reproduce the failure process
- **3rd stage.** Definition of *ad hoc* constitutive models and calibration.

OVERTOPPING IN ZONED ROCKFILL DAMS

2.Clay core. Failure



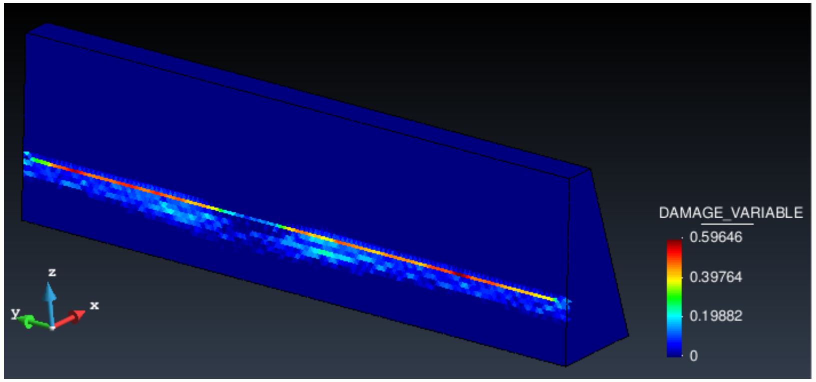


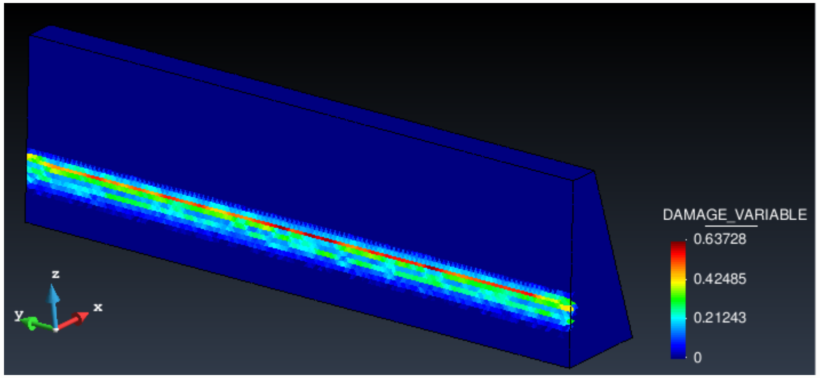
A Model for the Analysis of the Structural Failure of the Clay Core in Rockfill Dams Due to Overtopping
L.F. Ricoy, M.Á. Toledo and R. Morán Protections 2016

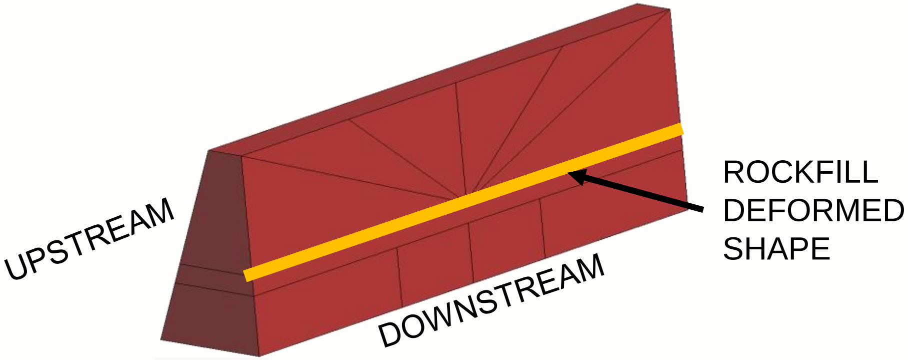
OVERTOPPING IN ZONED ROCKFILL DAMS

2.Clay core. Failure

M.A. Toledo, R.M. Alves, R Morán Structural failure of the clay core or the upstream face of rockfill dams in overtopping scenario. 1st International Seminar on Dam Protections against Overtopping and Accidental Leakage (2014)



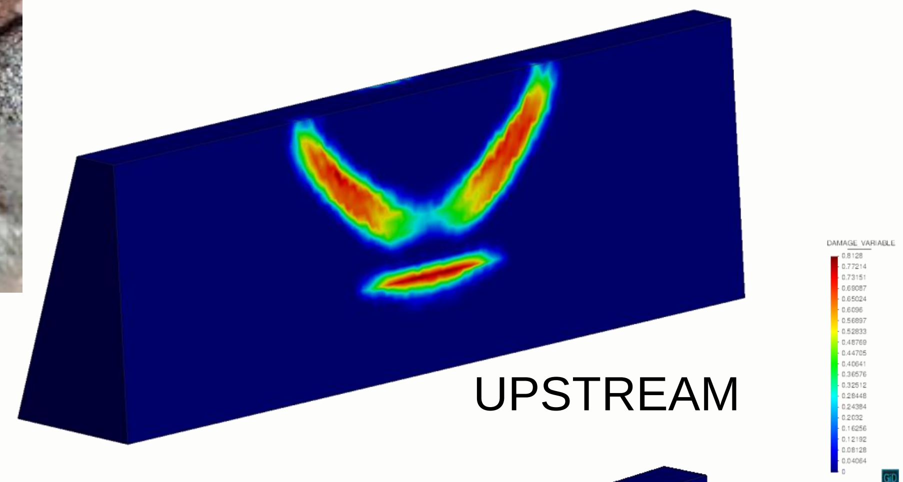


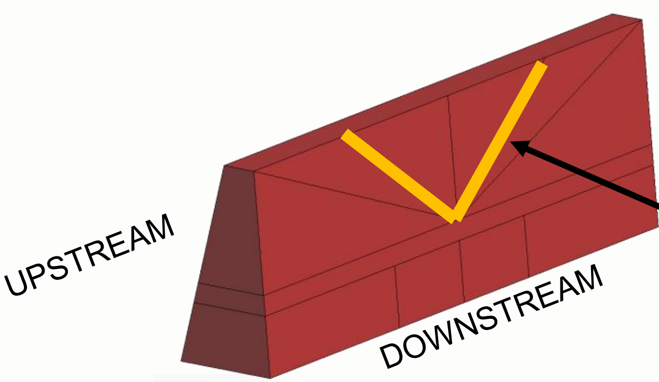


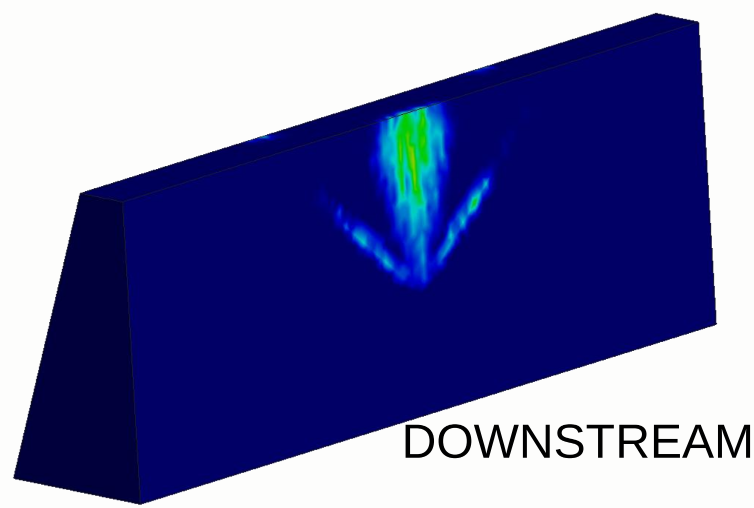
OVERTOPPING IN ZONED ROCKFILL DAMS

2.Clay core. Failure

M.A. Toledo, R.M. Alves, R Morán Structural failure of the clay core or the upstream face of rockfill dams in overtopping scenario. 1st International Seminar on Dam Protections against Overtopping and Accidental Leakage (2014)







OVERTOPPING IN ZONED ROCKFILL DAMS

2.Clay core. Failure

CONCLUSIONS (damage quasi static model)

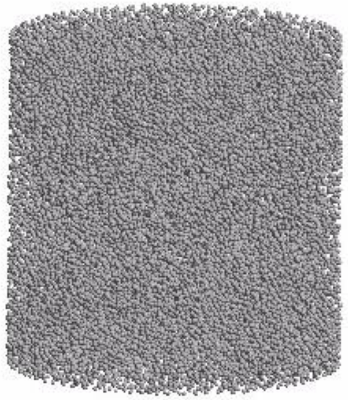
- Failure mode is mostly affected by the rockfill downstream shoulder deformed shape
- Width/height of the core influenced the level of damage but not the failure mechanism
- The subpressure is increasing the damage level

- **3D Dynamic analysis** will now be performed using a particle method based on the continuum mechanics framework (MPM).

OVERTOPPING IN ZONED ROCKFILL DAMS

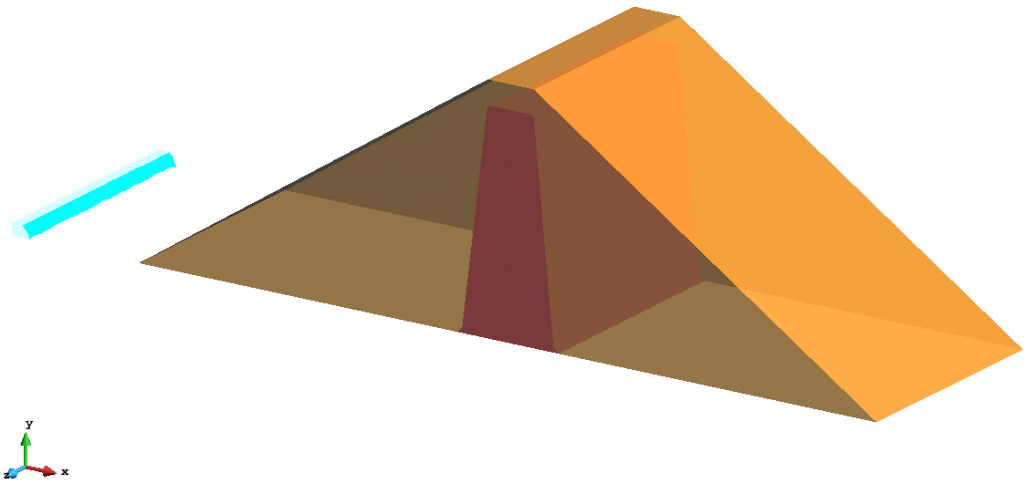
2.Clay core. Failure

- Formulation handling large displacements and deformation
- Based on CONTINUUM mechanics (constitutive law)
- Parallel technique (no need to remesh)
- Suitable for granular material (cohesive or not, drained or saturated)



DAM SAFETY

EARTHQUAKES IN ZONED ROCKFILL DAMS



EARTHQUAKES IN ZONED ROCKFILL DAMS

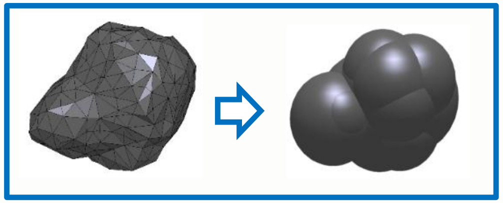
DEMpack KRATOS MULTI-PHYSICS

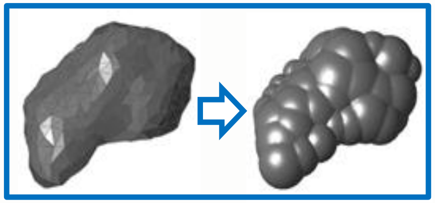
http://www.cimne.com/dempack/

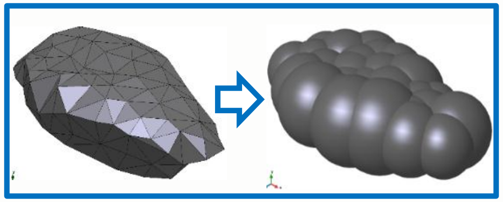
Preliminary study of the potential of discrete elements in the simulation of rockfill slopes using clusters

Vincens, Eric, Jean-Patrick Plassiard, and Jean-Jacques Fry. Dry Stone Retaining Structures: DEM Modeling. Elsevier, 2016

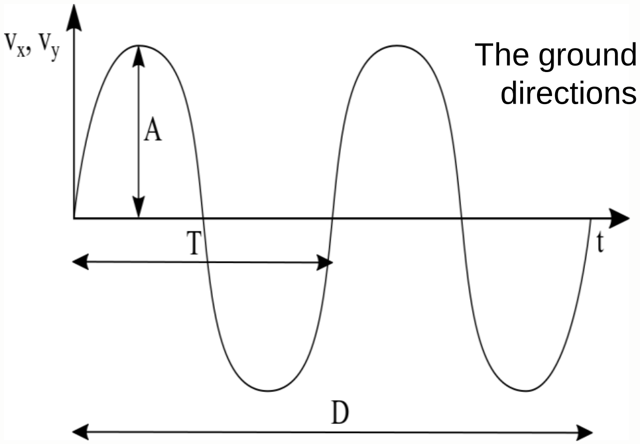
- 3D
- DEM
- Clusters not spheres

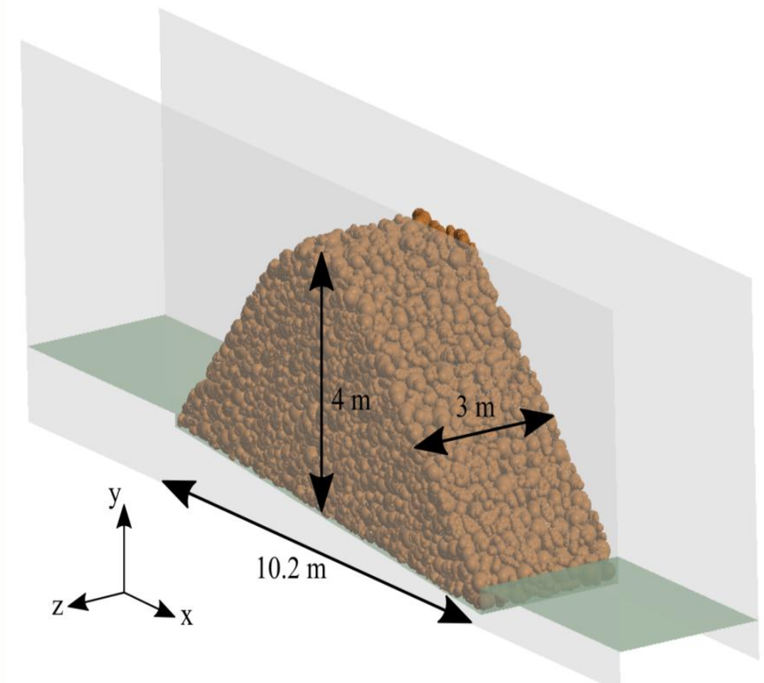




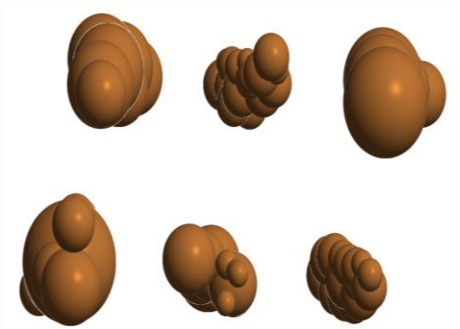


EARTHQUAKES IN ZONED ROCKFILL DAMS





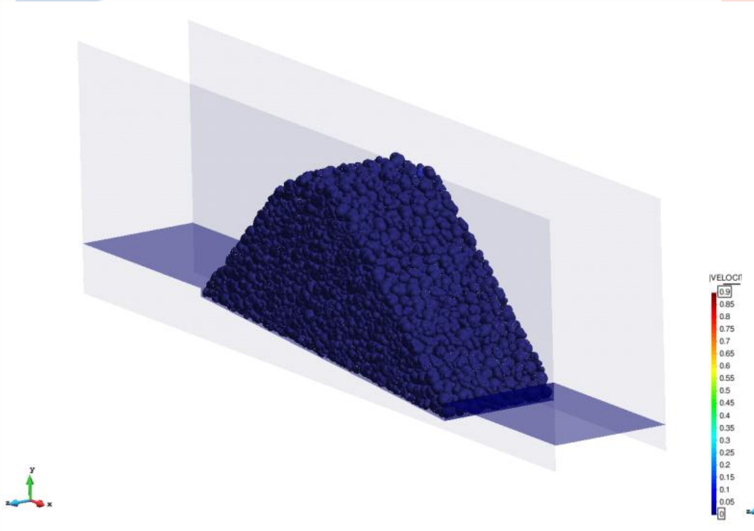
Friction coefficient between stones = 1
Friction coefficient stones / floor = 1
Friction coefficient stones / lateral walls = 0



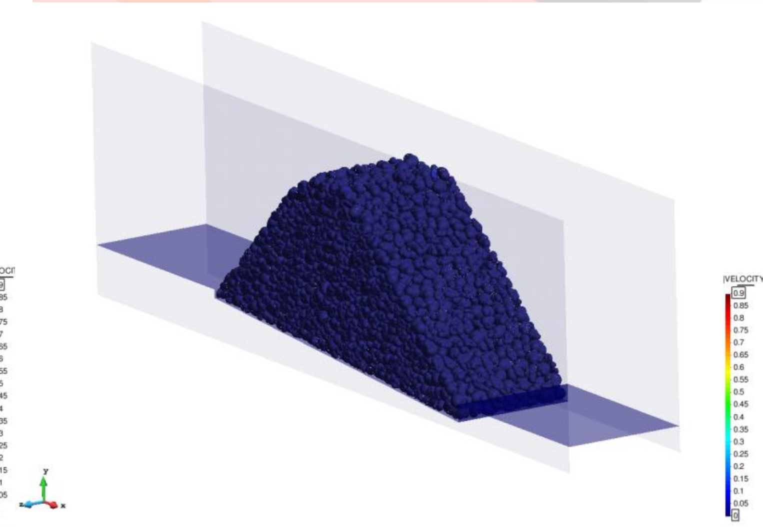
Granulometry	
0.15 m	0 %
0.40 m	60 %
0.50 m	100 %

A (m/s)	0.1 / 0.25 / 0.5
T (s)	1.0 / 0.5 / 0.25
D (s)	1.0 / 2.0 / 4.0

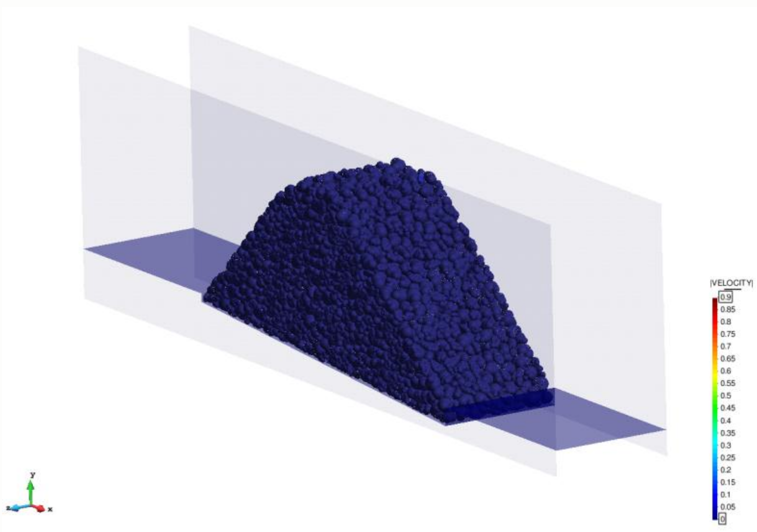
A = 0.1 m/s, T = 0.5 s , D = 4.0 s



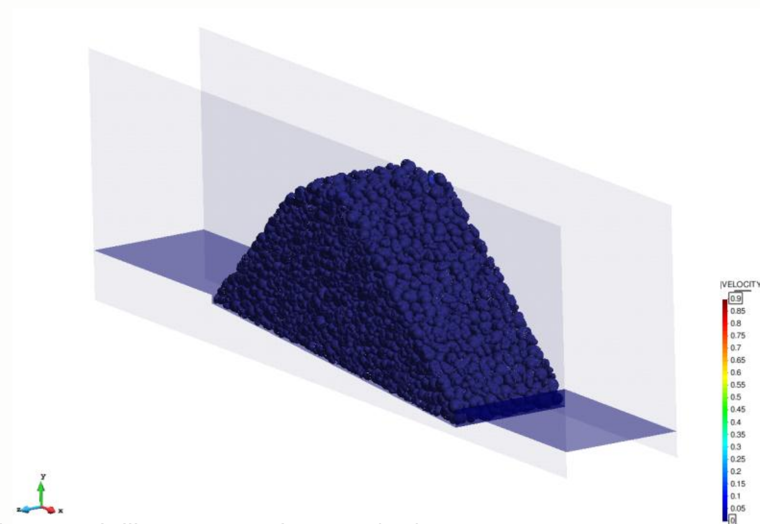
A = 0.1 m/s, T = 0.25 s , D = 2.0 s



A = 0.25 m/s, T = 1.0 s , D = 1.0 s

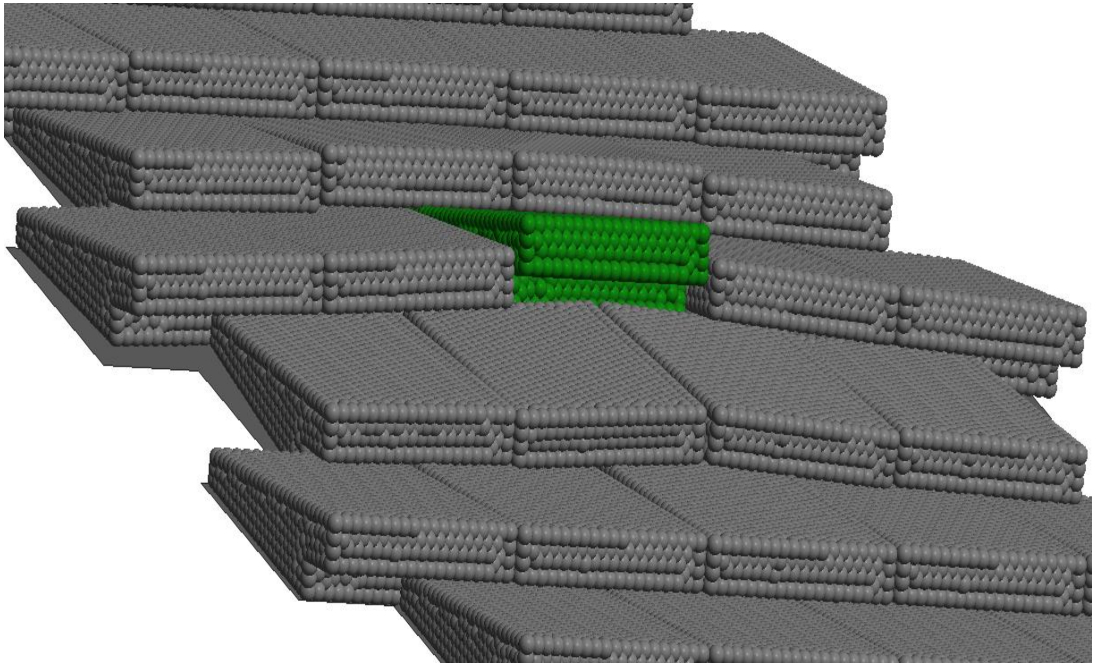


A = 0.5 m/s, T = 1.0 s , D = 2.0 s



DAM SECURITY

STABILITY OF WEDGE-SAHPED BLOCK



STABILITY OF WSBs IN FRONT OF VANDALISM

WSB spillway

Barriga Dam, Spain

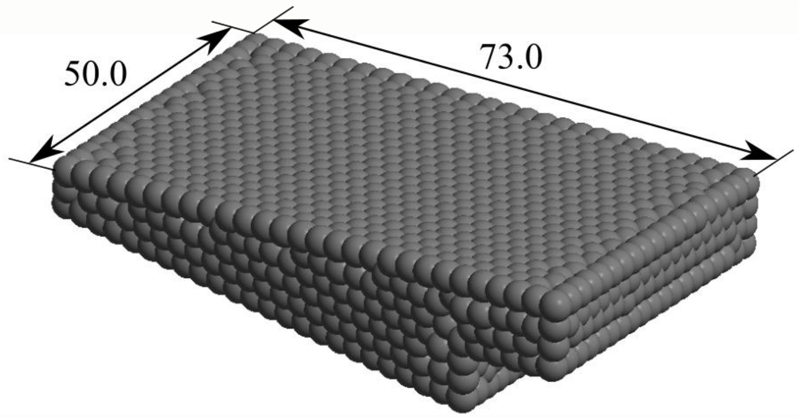
- The threat of vandalism or removal of blocks must be considered for determining the size of the blocks.
- Objective calculate numerically:
  - The force to remove a block
  - The relation force/block weight

STABILITY OF WSBs IN FRONT OF VANDALISM

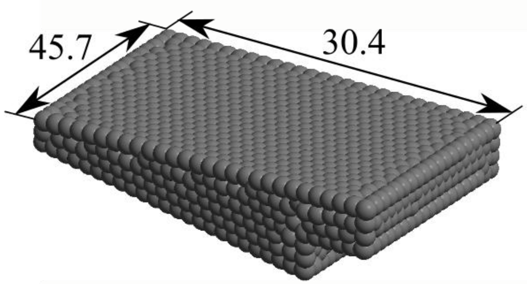
2 blocks were considered:

- *Cluster 1: that employed in Barriga Dam.*
- *Cluster 2: similar to the standard Armorwedge™ block (homothetic to cluster 1).*

Dimensions (cm)



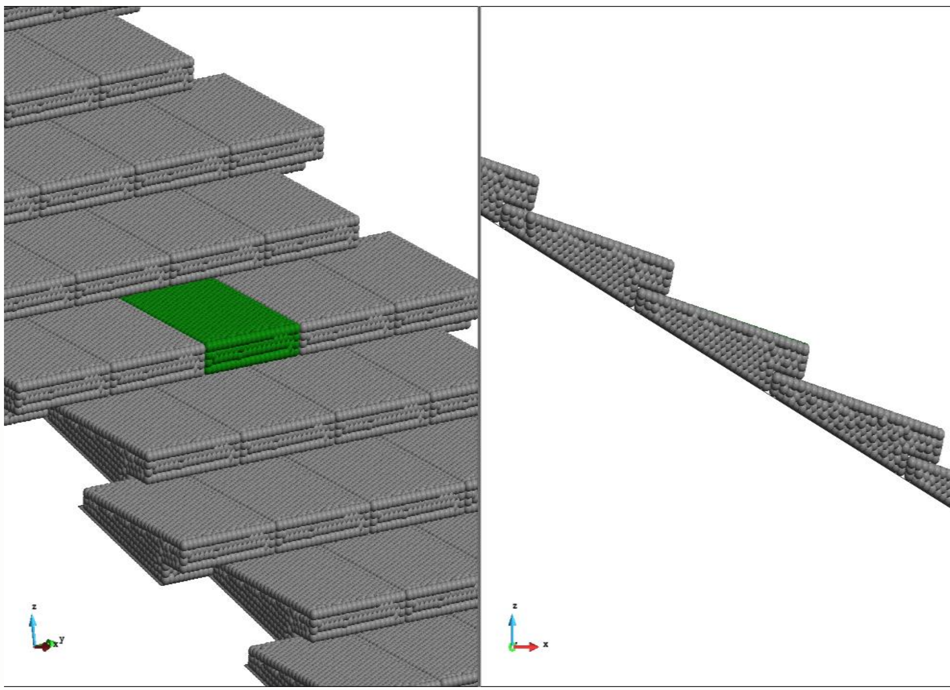
Cluster 1 (1.09 kN)



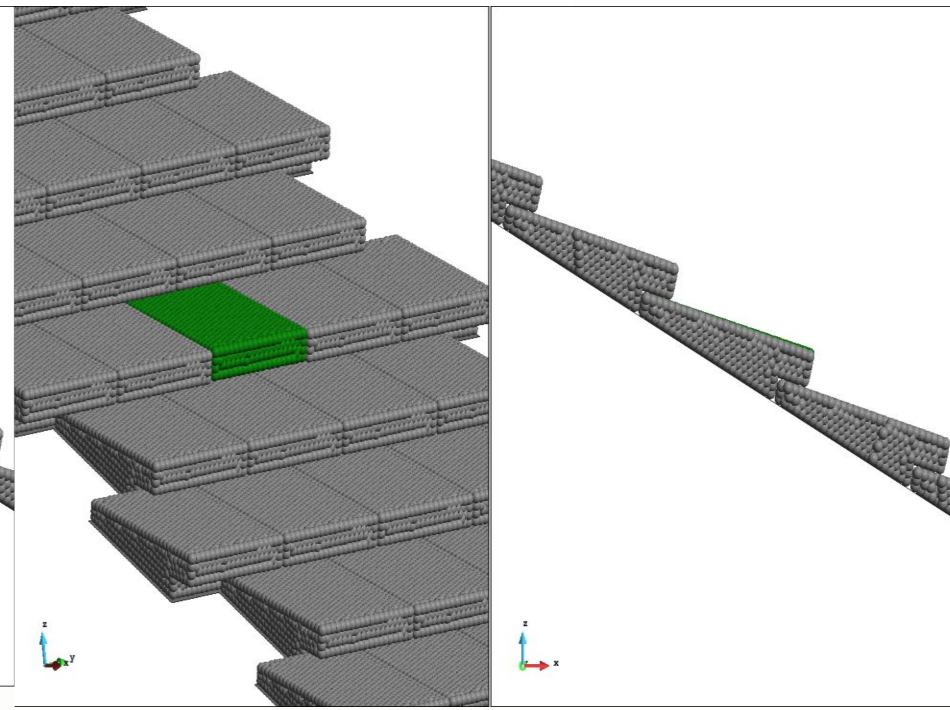
Cluster 2 (0.22 kN)

STABILITY OF WSBs IN FRONT OF VANDALISM

Friction Block-Boundary 0º
Friction Block-Block 33º



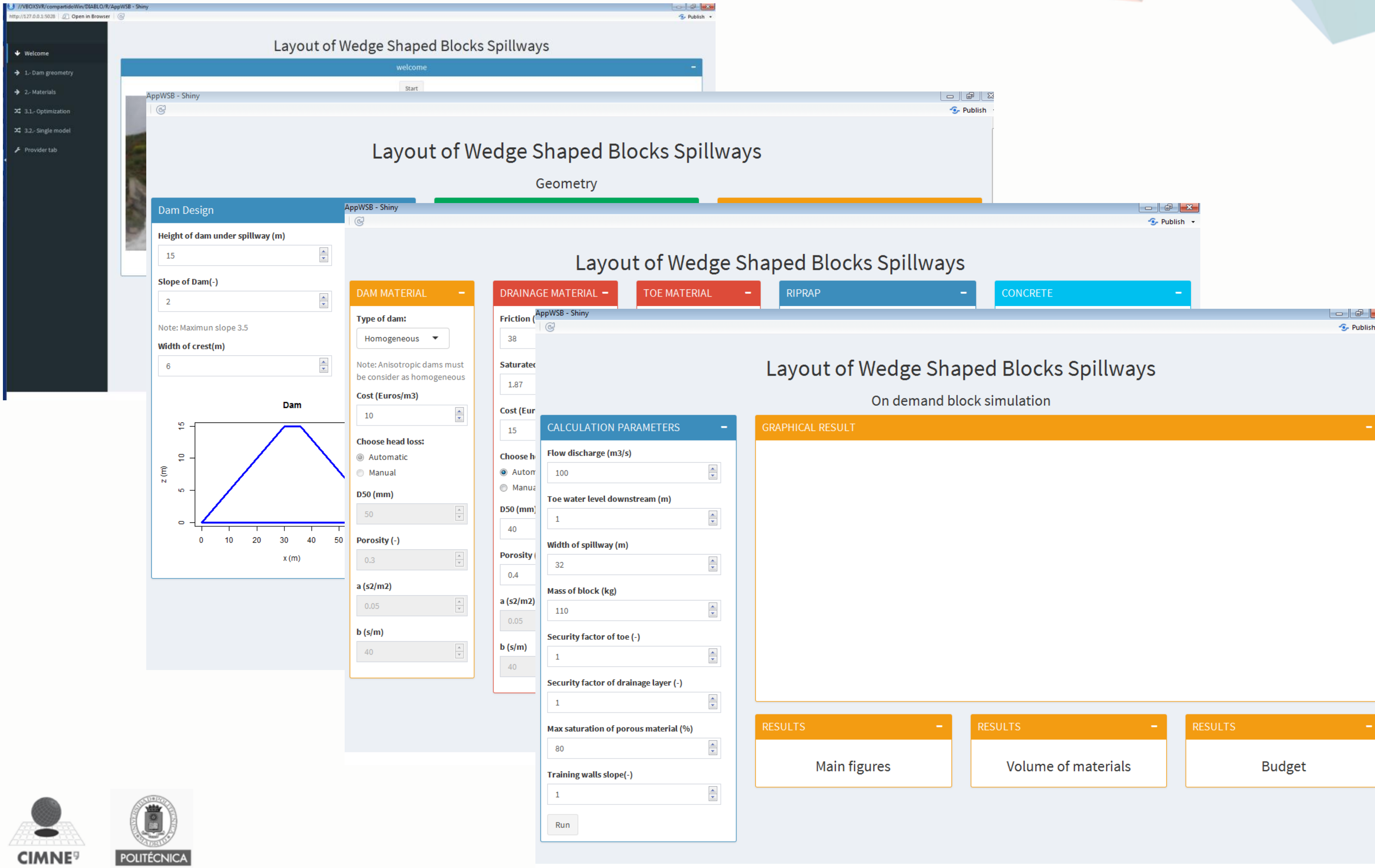
Friction Block-Boundary 33º
Friction Block-Block 33º



DAM DESIGN

WIZARD FOR THE DESIGN OF WEDGE SHAPED BLOCKS SPILLWAYS

WIZARD FOR WSBs DESIGN



CIMNE

POLITÉCNICA

Some research projects related to dams

INTERNATIONAL

- TCAiNMaND - Tri Continental Alliance in Numerical Methods applied to Natural Disasters FP7-PEOPLE-2013-IRSES, Ref.: FP7- 612607, 2014-2017
- FLOODSAFE - Assessment and Initial Steps for the Exploitation of a Simulation Software for the Study and Mitigation of the Effect of Floods on Constructions and Landscape REC Ref:ERC-PoC-2014 AdG n: 267521, 2015-2016
- SAFECON - New Computational Methods for Predicting the security of constructions to Water Hazards accounting for fluid-soil-structure interactions. REC Ref: FP7 – Ideas (Advanced Grant) - Grant Agreement nº: 267521, 2011-2015.

Spanish projects

- HIRMA – Development and validation of a tool for defining the failure hydrogram in embankment dams considering the specific geomechanics MINECO – Ref. RTC – 2016-4967-5, 01/09/2016- 31/08/2019
- ACOMBO - Development of a computational code for the analysis of thermo-mechanical behaviour of arch dams MINECO, Ref: RTC-2015-3794-5, 01/09/2015 31/08/2018
- DIABLO - Development of an optimized code for the design of spillways with wedge-shaped blocks MINECO, Ref: RTC-2014-2081-5, 2014 - 2017
- VOLADAPT – New efficient and effective blasting process, in the sense of use of resources and raw materials, by predictive and adaptive techniques minimizing emission MINECO, Ref: RTC-2014-2237-5, 2014 - 2016
- EDAMS – Métodos numéricos y experimentales para la evaluación de la seguridad y protección de las presas de materiales sueltos en situación de sobrevertido Ref: BIA2010-21350-C03-01, 2010-2013
- XPRES – Desarrollo de un método para el estudio del proceso de rotura de presas de escollera por sobrevertido combinando técnicas de elementos finitos y partículas. MEC, Ref: BIA2007-68120-C03-01,2007-2010

CONCLUSIONS

WHAT DO YOU NEED?

Thank you for your attention!

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