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 $P$, 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

$$j_w = P + j_E + j_{sr}$$

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

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

where $\beta_g$ 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 $\rho_{va}^{atm}$ are measured (Louis, 1979). To represent a membrane at a boundary, $P$, and $j_E$ are set to 0.

Pérez-Romero et al (2016)
Soil-atmosphere interaction
Andalucía (hot & dry)
Basque coast (cold & wet)
Drying within
Andalucia nf 2 m 10 years
Post-construction settlements
Soil –atmosphere interaction

• Currently working on
  – large scale field test
  – representation of the vegetation effect on ET
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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
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
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
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
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
NUMERICAL MODELING
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

\[ n = 0.37 \]
\[ D = 0.085 \text{m} \]
\[ n = 0.37 \]
\[ D = 0.3 \text{m} \]
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

Homogenized granular material

porosity

\[ n = \frac{V_v}{V_{\text{tot}}} \]

Darcy velocity

\[ u \]
Seepage in rockfill

- “Macro scale” for global overtopping simulation

\[
\frac{\partial u}{\partial t} + \overline{u} \cdot \nabla u + n \nabla p - 2 \nabla \cdot \nu \nabla^2 u = -bn + \alpha u + \beta \mathbf{u} \cdot \mathbf{u} = 0 \text{ in } \Omega, \quad t \in (0, T); \\
\nabla \cdot \mathbf{u} = 0 \text{ in } \Omega, \quad t \in (0, T).
\]

- 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)

\[
i = \alpha u + \beta u^2;
\]

- \( \alpha \) and \( \beta \) can be arbitrary chosen by the users
Validation: Permeameter

<table>
<thead>
<tr>
<th>Material</th>
<th>Porosity</th>
<th>Diameter (D50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mat1</td>
<td>0.4133</td>
<td>35mm</td>
</tr>
<tr>
<td>Mat2</td>
<td>0.4074</td>
<td>10mm</td>
</tr>
<tr>
<td>Mat3</td>
<td>0.3983</td>
<td>20mm</td>
</tr>
</tbody>
</table>

![Diagram of permeameter setup]

![Graph showing hydraulic gradient vs. velocity]
Validation: small scale dams

Validation: small scale dams

MATERIAL 1
n = 0.41
D_{50} = 12.6 mm

MATERIAL 2
n = 0.41
D_{50} = 35 mm

n = 0.41, D_{50} = 0.126 m, D_{50,\text{protection}} = 0.35 m
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

Yield stress defined using a Mohr Coulomb failure criteria

\[ \tau_0 = p_s \cdot t g \phi \]

\[ \tau = \left[ \mu + \frac{p_s}{\gamma} \cdot t g(\phi) \left( 1 - e^{-m \gamma} \right) \right] \dot{\gamma} \]
Coupled model

Porosity = 0.4052;
Pore index = 0.68;
Apparent specific weight = 2.50 gr/cm³
Dry density = 1.49 gr/cm³
Saturated density = 1.91 gr/cm³
$D_{50} = 35.04\text{mm}$.
A node is considered MOVED if DISPLACEMENT > 30mm
Homogeneous dam.

Advance of failure

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

<table>
<thead>
<tr>
<th>Q [l/s]</th>
<th>Bexp</th>
<th>Bnum</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.75</td>
<td>0.71</td>
<td>0.68</td>
<td>4.2%</td>
</tr>
<tr>
<td>69.07</td>
<td>1.08</td>
<td>1.04</td>
<td>3.7%</td>
</tr>
<tr>
<td>90.68</td>
<td>1.56</td>
<td>1.58</td>
<td>1.3%</td>
</tr>
</tbody>
</table>

Plant view of the downstream slope deformation process
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
References

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● Erosion testing channels
Penetration tests in siliceous sand

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

- Parameter calibration: Fontainebleau sand

Triaxial tests

Oedometer test
Penetration tests in siliceous sand

- Modelling the penetration test

Diagram showing the setup of a penetration test in siliceous sand, including details such as force gauge, pile instruments' output, and stress sensors' output.
Effect of crushing
Arching around the shaft
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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.

www.cimne.com/kratos
**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

- Fluid Dynamic Application
- Solid Mechanics Application
- FSI Application
- Particle Mechanics Application (MPM)
- DEM Application
- Thermo-Mechanics Applications

COUPLED or DERIVED APPLICATION
- High reusability
- Flexibility
- Reduced conflicts
KRATOS
www.cimne.com/kratos

\[ \int d\Omega \] \quad \rightarrow \quad \text{Test} \quad \rightarrow \quad \text{R&D} \quad \rightarrow \quad \text{Ind.}

[Image of evolutionary sequence and Kratos logo]
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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

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