Doctoral course, ED353, Aix-en-Provence, France, 24-30 April 2026

Hydro-mechanical behavior of geomaterials for civil engineering structures

Theoretical models, simulations, lab testing and risk analysis

Objectives: How to characterize and model the hydro-mechanical behavior of geomaterials from the microscale to the structure scale?

Friday 24/04/2026	10h30-12h30	**Mechanical behavior of granular materials**	N. Benahmed
Monday 27/04/2026	10h30-12h30	**Mechanical instabilities and failure in granular materials**	A. Wautier
Tuesday 28/04/2026	9h-11h	**Risk assessment of civil engineering structures**	L. Peyras
	11h-13h	**Uncertainty propagation and reliability analysis**	C. Carvajal
	14h-16h	**Practical session on dam failure assessment**	L. Peyras et C. Carvajal
Wednesday 29/04/2026	9h-11h	**Hydraulic actions on soil: erosion, hydro-mechanical instabilities**	P. Philippe
	11h-13h	**The Discrete Element Method (DEM): a numerical modeling approach adapted to geomaterials**	J. Duriez
	14h-16h	**Practice of DEM**	A. Wautier
Thursday 30/04/2026	9h-11h	**Multi-phase Lattice Boltzmann Method (LBM) and its Application to Partially Saturated Granular Soils (Theory and Practice)**	N. Younes
	11h-13h	**Simulating large displacement problems in Continuum Mechanics with the Material Point Method (MPM)**	J. Duriez
	14h-16h	**Mixing properties in granular media**	M. Souzy

Detailed content of the course

1- Mechanical behavior of granular materials (N. Benahmed, 2h)

General concepts: strain, stress-strain relationship, effective stresse

Experimental characterization of geomaterials: different types of tests, drained/undrained behaviors; Volumetric strain behavior (contracting/dilatation), triaxial shear strength, relationship with constitutive soil properties

Instability and failure of geomaterials: instability line, characteristic line, critical state (Mohr-Coulomb criterion)

Examples of instability-related disorders

2- Mechanical instabilities and failure in granular materials (A. Wautier, 2h)

Granular plasticity: interlocking between elasticity and plasticity, plasticity-non-association, incrementally non-linear plasticity

Failure modes: diffuse or localized failure, material or structural softening

Instability criteria: plastic limit surface, localization criterion, second-order work criterion criterion

3- Safety assessment of civil engineering structures (L. Peyras, 2h)

Introduction to operational safety

Functional analysis
System failure mode analysis: overview of the existing methods (APR, APD, AMDE, AMEC, HAZOP)
System failure scenario analysis: overview of the existing methods (event trees, cause-trees, bow-tie)
System safety assessment: probabilistic, semi-probabilistic, expert
Illustrated examples on civil engineering systems

4- Uncertainty propagation and reliability analysis (C. Carvajal, 2h)
Introduction of uncertainties in mechanical modeling
Random variables and random fields
Mechano-fiabilistic coupling: First-Order Reliability Method, response surfaces, Monte-Carlo simulations

5- Practical session: Mechano-fiabilistic computations for the risk assesment of the rupture of a dam (L. Peyras et C. Carvajal, 2h)
Application of courses 9 and 10 on the real case of a dam

6- Hydraulic actions on soil: erosion, hydro-mechanical instabilities (P. Philippe, 2h)
General context: flood risk, protective structures, external and internal erosion
Surface erosion: local law(s), erosion lab tests and interpretation models
Example for piping erosion and contact erosion
Hydro-mechanical instabilities: fluidization, gravity collapse

7- The Discrete Element Method (DEM): a numerical modeling approach adapted to geomaterials (J. Duriez, 2h)
Presentation of the DEM calculation cycle
Contact laws, particle shape, numerical damping, parallel calculation concepts
DEM as a tool for virtual experiments providing continuum stress and strain quantities
Overview of hydro-mechanical couplings

8- Practical session: Implementation of a 1D minimal DEM code and introduction to YADE (A. Wautier, 2h)
This session requires that students have a computer (loan possibilities to be discussed with the teacher) Python (https://www.python.org/) installed, and know how to use classes.
For the YADE part: Ubuntu desktop with sudo apt install permission or any other Operating System with Docker installed.

9- Multi-phase Lattice Boltzmann Method (LBM) and its Application to Partially Saturated Granular Soils (Theory and Practice) (N. Younes, 2h)
Origins, Background, and Theory
Benchmarks (Real-time Tutorial)
Coupling with the Discrete Element Method (DEM) for simulating partially saturated granular assemblies at the Representative Elementary Volume (REV)
Modeling Partially Saturated Granular Assemblies: Investigating various aspects at the REV scale, including suction, capillary stress, and more.

10- Simulating large displacement problems in Continuum Mechanics with the Material Point Method (MPM) and CB-Geo MPM – PyCBG softwares (J. Duriez, 2h30)
Overview of the MPM formulation for solving linear momentum balance equation in continua : capabilities and limitations of MPM
Hands-on activity on MPM simulations with the CB-Geo MPM code and its PyCBG interface

Ubuntu desktop with sudo apt install permission or any other Operating System with Docker installed

11- Mixing properties in granular media (M. Souzy, 2h)
General concepts: mixing, dispersion, molecular diffusion, stretching laws
Mixing in dry granular media, segregation, rotating drum, fluidized bed, vibrations
Mixing of particle suspensions, interstitial flow, lamellar approach, Diffusive Strip Method, coalescence
Mixing in porous media, experimental characterization of stretching laws, 3D velocity fields in porous medium, anomalous dispersion
Example of particle suspension flow in a constriction: risk of clogging and intermittent flow

Practical information

The course will be held at INRAE Aix-en-Provence (France) from Friday April 24th to Thursday April 30th in the lecture room "Salle Cézanne". The address is 3275 route Cézanne, 13100 Aix-en-Provence.

From Aix-en-Provence, to reach the premises, take bus 13 (or bus 110) to Le Tholonet (stop at Ferrageon).

There will be no registration fee for the course. Registration can be made here :
https://evento.renater.fr/survey/doctoral-school-registration-hydro-mechanical-behavior-of-geomaterials-for-civil-engineering-structures-9igj0ew0

Lunches will be taken at the collective restaurant close to the lab. Rates for visitors are around 10-15 € per meal. Alternatively, it is possible to bring your lunch box.

For any question, please feel free to contact Antoine Wautier (antoine.wautier@inrae.fr).