CHARTING THE PATH
TOWARD THE FUTURE
6 INTERNATIONAL CONFERENCE
Geotechnical Engineering **Education**

New challenges in rock mechanics: Building new skills in engineering education

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Rock Mechanics and Rock Engineering applications

Wide range of applications of rock mechanics

Civil engineering

- ✓ Underground construction
- ✓ Rock slopes
- ✓ Rock Foundations

Energy related geomechanics

- ✓ Oil and gas engineering
- ✓ Mining
- ✓ Geothermal systems
- ✓ Underground storage/sequestration (waste, CO_2, H_2..)
- ✓ Reservoir geomechanics

Engineering geology

- ✓ Mechanisms of Folding, Faulting, Fracturing
- ✓ Site investigations
- ✓ Hydrogeological investigations
- ✓ Rocks and rock mass properties
- ✓ Mass movement/Subsidence
- ✓ Prevention, protection, stabilisation

Seismology

- ✓ Fault and earthquakes mechanics
- ✓ Rock dynamics
- ✓ Wave propagation

Geophysics

- ✓ Geophysical investigations
- ✓ In situ stress
- ✓ Rock physics

A wide range of skills

Training of engineers and researchers

Various frameworks

- ✓ Undergraduate/Graduate/Doctoral studies
- ✓ Continuing education, Workshops, Short courses
- ✓ Practice

Large range of different skills

- ✓ Technical/scientific expertise
- ✓ Scientific reporting
- ✓ Addressing complexity
- ✓ Account for uncertainties
- ✓ Interdisciplinary and Multidisciplinary problems
- ✓ Decision making
- ✓ Interact with skate holders

Wide range of scientific disciplines

- ✓ Rock Mechanics, Engineering Geology, Geophysics, Seismology
- ✓ Mathematics, Numerical methods, Probability, Statistics, Computing and Data science
- ✓ Laboratory and field testing

Other disciplines

- ✓ Management
- ✓ Legal and administrative aspects of project management
- ✓ Know-how on crisis management
- ✓ Communication to the general public/to the media

Basic training in rock mechanics

Basic training in Rock Mechanics (undergraduate)

Strength and deformability of rocks and discontinuities

- ✓ Linear elasticity
- ✓ Mohr-Coulomb/Hoek-Brown strength criterion
- ✓ Rock joints and discontinuities
- ✓ Rock testing

Rock mass classifications

- ✓ Classifications systems (RMR, GSI, Q-System,…)
- ✓ Rock mass mechanical properties

Rock slopes

- ✓ Failure modes
- ✓ Limit equilibrium model

Rock foundation

Underground construction

- ✓ Ground characterization
- ✓ Excavation methods
- ✓ Rock support design

La Clapière

Viaduc de Millau

Descenderie Saint-Martin-la-Porte

Almost all rocks are **porous** to some degree and, under natural conditions, the pores are likely to contain one or several fluid phases (water, air, gas, oil, …)

The presence of **the fluid affects the behavior of the rock** through both chemical and mechanical interactions

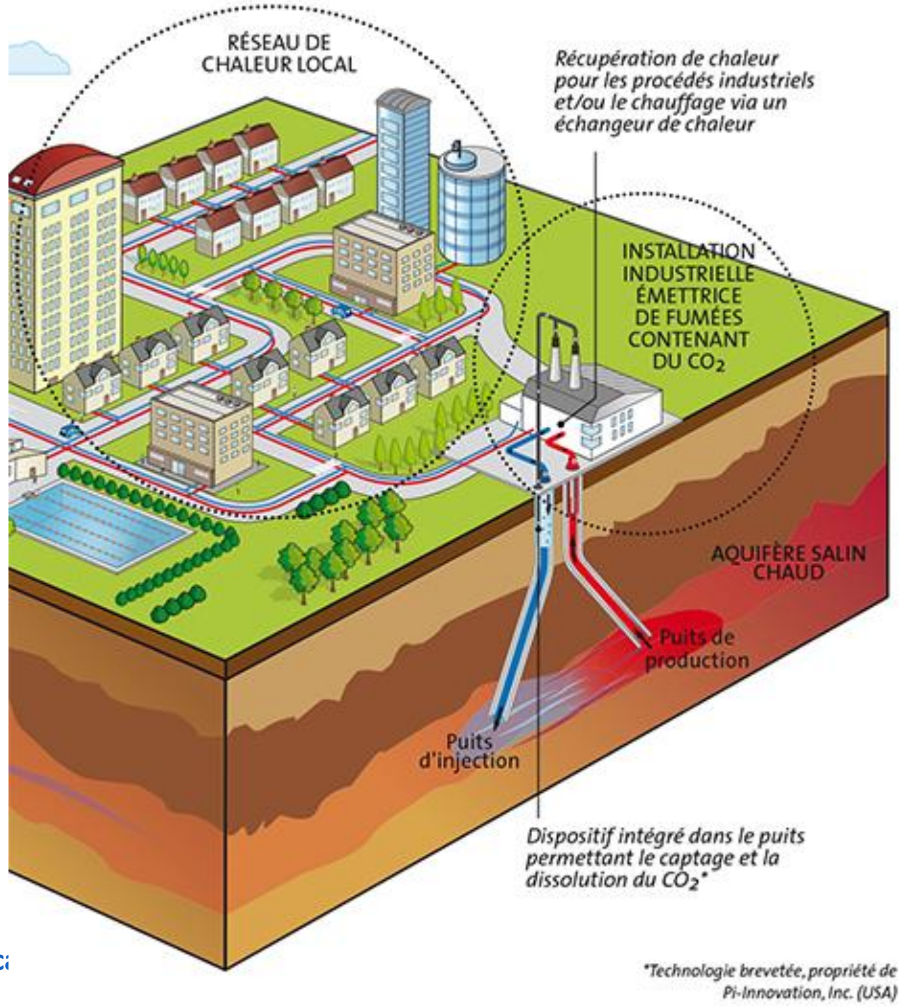
Importance of **teaching Poromechanics** in undergraduate courses of rock mechanics

New challenges in rock engineering

New challenges in Rock Mechanics

Energy transition towards renewable energy

- ✓ Geothermal systems: performance, economic viability, safety (induced seismicity)
- ✓ Underground storage: energy storage (e.g. H2), CO2 and nuclear waste sequestration (long term tightness)
- ✓ Complex geological conditions (great depth, high temperature)
- ✓ Risks control and acceptability
- ✓ …



Impact of climate change

- ✓ Rock slope and embankments: rock falls, rock avalanches, landslides
- ✓ Impact of drying and resaturation cycles on (clayey) rocks
- ✓ Impact of freeze and thaw cycles on rock weathering
- ✓ Coastal protection
- ✓ …

Exploring, understanding and modelling of involved **physico-mechanical processes** for **large scale** and/or **long term** predictions

Multi-physics phenomena

- ✓ Mechanical processes: damage, fracturing, cracks growth/healing
- ✓ Multi-phase fluid flow
- ✓ Effect of temperature (e.g. geothermal systems)
- ✓ Chemical and microbial reactions (e.g. CO_2/H_2 storage)
- ✓ **Multi-physics couplings**

Different time scales

- ✓ Characteristic time scale of mechanical/physico-chemical processes
- ✓ Relevant time scale of the problem at hand: laboratory experiments (hours/days), civil engineering structures (tens of years), nuclear waste storage (thousands of years), earthquakes (seconds), seismic cycle (hundreds of years)

Multi-scale processes

- ✓ **Heterogeneity** of rocks at various scales: grains, pores, micro-cracks, fractures, joints, faults
- ✓ Processes of **rock deformation/damage at the grain scale**: breakage of inter- granular bonds, the abrasion, breakage or crushing of grains, frictional intergranular sliding, reorientation of grains, growth of microcracks and dilatancy
- ✓ **Chemical interaction** between pore fluids and minerals (e.g. dissolution/precipitation, swelling) at **sub-micron scale** and affect fluid flow at larger scale (porous network, fractures)
- ✓ **Macro-scale** (engineering scale): constitutive modelling for equivalent **homogenized continuum** (upscaling) and for **macro discontinuities**
- ✓ **Interaction of processes at various scales**

Teaching geomechanics today
Graduate studies

Advanced courses on Couplings, Failure, Cracking

Coupled processes in rocks

Fluid flow in rocks

- ✓ Transport law: single/multi phase **flow in porous media**
- ✓ Fundamental **balance equations**
- ✓ **Thermo-Poro-Elasticity/Plasticity**
- ✓ Concepts of the mechanics of **unsaturated porous media**
- ✓ Fluid flow in **fractured rocks**
- ✓ **Analytical** solutions of some fundamental problems (e.g. pressurization/loading of a borehole, hydraulic fracturing)

Strength of rocks under coupled processes

Go beyond limit analysis (advanced course)

Limit analysis is commonly used in Geotechnical Engineering to compute limit loads. It can include pore pressure and dynamics effects but does not consider the **complete inelastic response** of the structure or the material which influences the conditions of **incipient failure** and **its evolution** beyond.

Applications to borehole stability, compaction and subsidence, slope stability, seismic slip etc. accounting for various **THMC couplings**

- ✓ Notions of stability and strain localization

Consider mathematical concepts of **uniqueness and bifurcation** for studying failure of materials

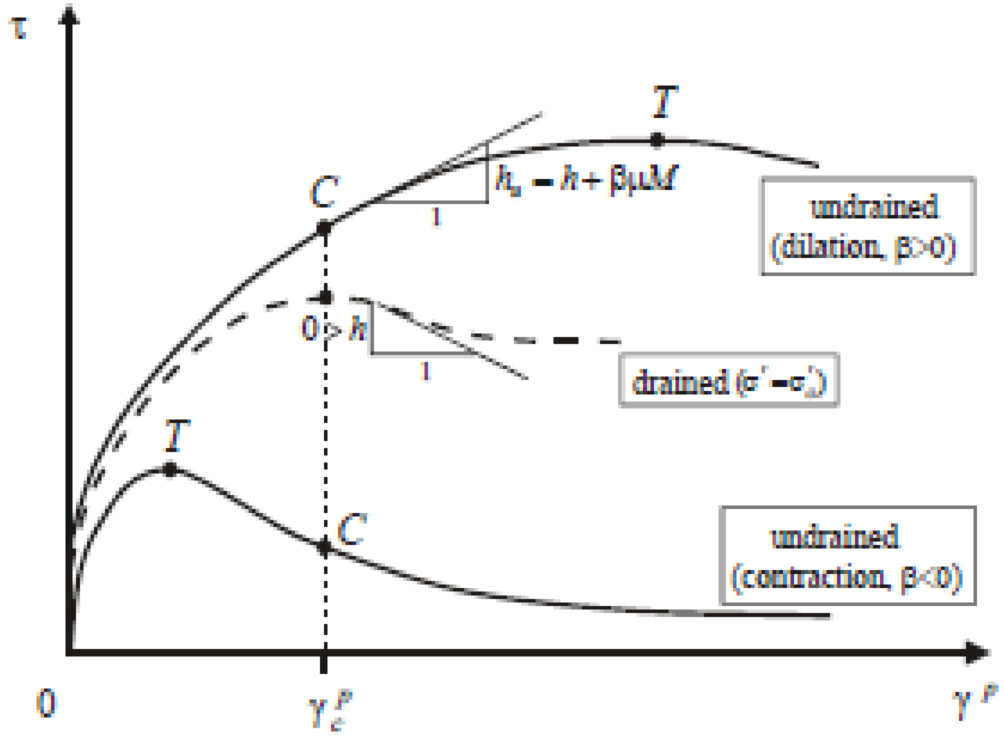
- ✓ Softening behavior and strain localization

Strain localization is favored by **softening** behaviour due to the **degradation** of rock properties (microcracking, grain crushing…) or other **multi-physics** processes (pore fluid, temperature, chemical reactions)

✓ Role of fluids in strain localization processes

Inelastic volume changes (dilation or compaction) in fluid-saturated porous materials tend to cause a **change in pore fluid pressure**.

The effect of pore fluid interacting with a rock mass can result in either **hardening or softening** depending on the volumetric response of the rock (dilatant hardening or contractant softening)



from D. Garagash, 2005, *Proceedings of the first Japan-US Workshop on testing, modelling and simulation*

- ✓ Coupled processes and strain localisation

Thermal pore fluid pressurization is a softening mechanism due to the reduction of effective mean stress and consequently of shear strength.

Chemical reactions such as dissolution/precipitation, thermal decomposition of minerals affect the solid and fluid phases and influence instabilities and strain localisation.

- ✓ Robust numerical modelling

Ill-posedness of the governing equations in the post-localisation regime resulting in **mesh-dependency** of the results in FEM simulations and the tendency of the deformation to localize within a single element.

Generalized continuum theories (e.g. Cosserat continuum, higher grade continuum): **Material length** of the **smaller scale physics** that limits localization zone thickness and permits **robust post localization computations**

Modelling cracking

Numerical fracture models for modelling of **rock breakage** mechanisms, **cracks propagation** and **coalescence**: **Weak** discontinuity vs **Strong** discontinuity

- ✓ Cracks as bands of strain localisation (weak discontinuity)

  Continuous approach for localised failure

- ✓ Cracks as material discontinuities (strong discontinuity)

  Linear Elastic Fracture Mechanics, Stress intensity factor, Fracture toughness, Crack propagation, Rock fragmentation, Sub-critical crack growth, Plastic flow, Cohesive zone models, Laboratory testing of rock fracture

Strong discontinuity approach: Sharp or Diffuse crack models

Sharp crack models

The displacement field is **discontinuous** across the crack

- ✓ Finite Element Methods (FEM)

  High computational costs, limited numbers of cracks, necessity of frequent remeshing

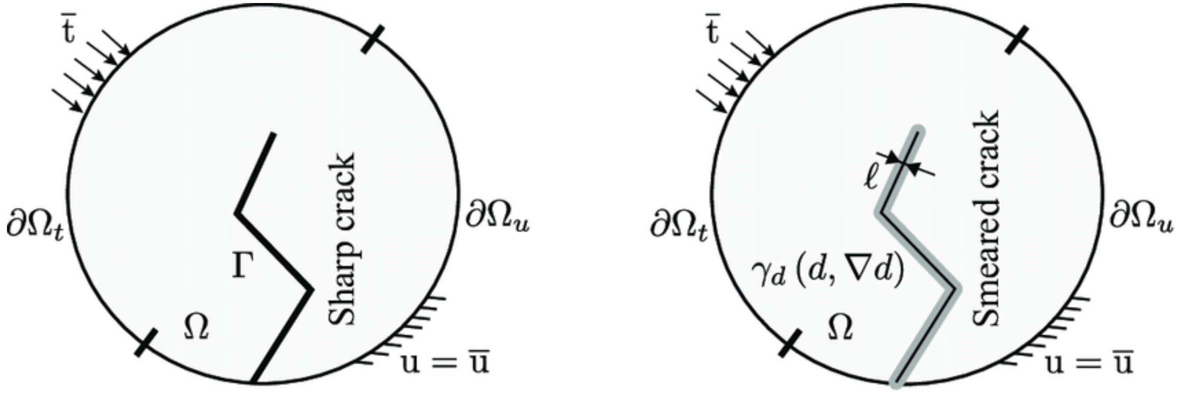
- ✓ Extended Finite Element Methods (XFEM)

  The shape functions are enriched with a discontinuous displacement field. Cracks can propagate along **arbitrary paths. No need for remeshing**.

  Limited number of cracks.

Diffuse (smeared) crack model

The displacement field is **continuous** but exhibits very **high gradient** along the crack path. A characteristic length is introduced (**non local model**)



N. Moës, 2023, 'Take the best of both worlds' in : *MEALOR II Damage Mechanics and Local Approach to Fracture*.

✓ Phase-field models (PFM)

Application to **many different physical contexts** (hydraulic fracturing, heterogeneous materials, ductile behaviour, finite deformation, multiphysics couplings).

Ability to master crack nucleation, growth, branching, coalescence, complex crack paths, networks of cracks

Mesh free methods: Lagrangian approach

Discretization of the domain into particles that represent specific material volumes and that interact with each other

- ✓ Smoothed Particle Hydrodynamics (SPH)
- ✓ Material Point Method (MPM)

  Large deformation, discontinuities, fragmentation process. Impact problems, collision, fractures, multiphase flow.

  Computationally expensive, adapted for relatively small size problems

Combined methods for bridging between the scales

Hybrid models: FEM/DEM, DEM/FEM, DDA/FEM for multi-scale analysis

Computational limitations of microscopic simulations

Project based learning

Project based learning

How to address complex and challenging questions/problems

- ✓ Address real world problems
- ✓ Apply and acquire knowledge
- ✓ Link academic research and engineering applications
- ✓ Make choices in problems solving and have a critical look on them
- ✓ Collaborate, discuss, share
- ✓ Scientific integrity
- ✓ Scientific reporting
- ✓ Develop new skills
- ✓ Learn about decision making
- ✓ Acquire autonomy, responsability…

Good practice for the use of numerical codes in projects

Choose the appropriate method

- ✓ FEM, DEM, DDA, BEM, Hybrid…

Choose the appropriate, available numerical code

- ✓ Commercial/open-source/in-house

Key steps in numerical modelling

- ✓ Definition of appropriate **time and space scales**
- ✓ Time and space **discretization**
- ✓ **Check convergence**
- ✓ **Check mesh-independency**
- ✓ **Critical analysis of the results** (relevance, physical meaning, limitations of the model…)
- ✓ **Scientific integrity**
- ✓ Best practices for **managing and valuing research data** (storage, sharing, accessibility)

Continuing Education

Continuing education in geomechanics

Advanced courses on specific/new topics: Bridging the gap between academics and practitioners

- ✓ Modelling of **Thermo-Hydro-Mechanical Processes** in Geomechanics
- ✓ **Numerical Methods** in Geomechanics (Computational plasticity, Phase field models, Meshless methods (MPM, SPH), Hybrid methods (e.g. DEM-FEM)…)
- ✓ **Machine Learning** in Geomechanics
- ✓ Advanced **Experimental Rock Mechanics** (Imaging, Fluid flow, Dynamics, Physical models,…)
- ✓ …

Conclusions

- ✓ **Strong theoretical** background in mathematics, physics and mechanics
- ✓ Theoretical bases of **THMC couplings**
- ✓ Develop **computing skills**
- ✓ Bridge **academic** research and engineering **practice**
- ✓ Needs of **multidisciplinary approach** to address complexity: Learn how to bridge different disciplines
- ✓ Valuing **master's and doctoral** studies for well-trained engineers