Workshop on
Nonlinear Modeling of Geotechnical Problems:
From Theory to Practice
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Thermo-Hydro-Mechanical Effects in Fluid-
Saturated Poroelastic Geomaterials

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BACKGROUND

The topic of **Thermo-Hydro-Mechanics (THM)** is important to a variety of applications in the geo-engineering sciences:

- **Energy resources extraction**: steam heating
- **Geothermal energy**: ground source energy extraction
- **Thermal stability**: buried power lines, fire engineering
- **Buried pipelines**: transportation of chilled gas
- **Earthquake fault mechanisms**: frictional heating
- **Nuclear waste disposal**: heat-emitting spent fuel

These are **non-routine specialist applications** where the thermal effects influence the fluid transport and the mechanical deformations; (less so, vice versa)

The problem can be made **more challenging** by introducing chemical couplings (**THMC**)
Median Tectonic Line, Mie Prefecture, Japan
CONSTITUTIVE MODELLING

The scope of this presentation is largely directed to examining the THM processes in competent geologic media such as intact rocks, on most occasions.

The applications to clays, argillite and other saturated and unsaturated geomaterials has also been considered in the literature.

A useful first approximation is to extend the classical theory of poroelasticity developed by Biot (1941) to include thermal effects.
CONSTITUTIVE RESPONSES

- The pore fluid (a mixture of fluids) and the porous skeleton occupy the same point space.

- A largely conductive Heat transfer process: Fourier's Law
  \[ q = -K_T \nabla T \]

- Fluid transport: Modified Darcy flow
  \[ \mathbf{v}_f - \mathbf{v}_s = -\frac{\rho_w K_r}{\mu} \mathbf{K}_F \mathbf{\nabla} p + \mathbf{g} \]

- Mechanical behaviour: Duhamel-Neumann-Biot form of Hooke's law (modified to account for pore fluid effects)
  \[ \sigma = G(\nabla \mathbf{u} + \mathbf{u} \nabla) + (\lambda \nabla \cdot \mathbf{u} - \beta K_D T) \mathbf{I} + \left(1 - \frac{K_D}{K_s}\right) S p \mathbf{I} \]

- Effective stress relationship: Modified Biot-type:
  \[ \sigma = \sigma' + \alpha S p \mathbf{I} \]
EQUATIONS OF THERMO-POROELASTICITY

The resulting partial differential equations governing classical thermo-poroelasticity are linear and weakly-coupled:

Heat Conduction (T):
\[ \gamma_1 \nabla^2 T = \gamma_2 \frac{\partial T}{\partial t} \]

Fluid transport (THM):
\[ \beta_1 \nabla^2 p = \beta_3 \frac{\partial p}{\partial t} + \beta_4 \frac{\partial T}{\partial t} + \beta_5 \frac{\partial}{\partial t}(\nabla \cdot \mathbf{u}) \]

Skeletal Deformations (THM):
\[ \alpha_1 \nabla^2 \mathbf{u} + \alpha_2 \nabla(\nabla \cdot \mathbf{u}) + \alpha_3 \nabla p + \alpha_4 \nabla T = \alpha_5 \mathbf{f} \]
Thermodynamic arguments can be invoked to establish bounds for the constitutive parameters governing heat conduction, fluid flow and mechanical deformations of the porous skeleton.

In the case of linear thermo-poroelasticity the weakly-coupled PDEs are elliptic-parabolic and theorems relating to existence and uniqueness of solutions are available in the literature. [i.e. the problem is well-posed in a Hadamard sense]
An elementary experiment can be performed to assess the signature of pore pressure development in a saturated rock due to thermal effects.

The experiment involves the heating of a fluid filled cavity in a cylindrical sample of granite that has been vacuum saturated for several weeks.
THE EXPERIMENTAL CONFIGURATION

Selvadurai (1991) [ Unpublished ]
TIME HISTORIES OF TEMPERATURE AND CAVITY FLUID PRESSURE: GRANITE
TIME HISTORIES OF TEMPERATURE AND CAVITY FLUID PRESSURE: TEMPERATURE CYCLES
TIME HISTORY OF CAVITY FLUID PRESSURE: SANDSTONE
SIMILAR EXPERIMENTAL OBSERVATIONS

There are other observations of pore pressure amplification resulting from thermo-poroelastic effects.

The tests conducted at McGill University on large diameter cylinders of Barre granite.

In situ tests conducted at the AECL-URL Site in Pinawa, Manitoba, involving a granitic rock mass.

Other results available in the literature point to similar effects of thermally induced pore pressure rise.
THM EXPERIMENTS ON LARGE GRANITE CYLINDERS

Granite cylinders measuring:
460mm in diameter and 508mm in height
THE TEST FACILITY

Hydraulic Jack
- capacity = 4448 kN

Crosshead

Web Stiffeners

Piston
- diam. = 203mm

To Data Acquisition System

Granite Cylinder
- height = 508mm
- diam. = 457mm

Water Filled Cavity
- diam. = 51mm

Piston

Saddle

Thermocouple Probe

Pressure Transducer

Laboratory Floor

To Data Acquisition System

Hydraulic Pump

To Air Trap

To Water Pump
THE HEATER EXPERIMENTS
EXPERIMENTAL DETAILS
EXPERIMENTAL RESULTS

Selvadurai (1997) [Unpublished]
IN SITU HEATER EXPERIMENT
AT AECL-URL

[Martin and Chandler, 1999]
EXPERIMENTAL RESULTS FROM IN SITU HEATER TESTS
COST CONSIDERATIONS

Hydraulic Jack
- capacity = 4448 kN

Crosshead

Web Stiffeners

To Data Acquisition System

Granite Cylinder
- height = 508mm
- diam. = 457mm

Water Filled Cavity
- diam. = 51mm

Piston
- diam. = 203mm

Saddle

To Air Trap

To Water Pump

To Data Acquisition System

Laboratory Floor

Pressure Transducer

Temperature Transducer & Power Source

Thermocouple Probe

To Data Acquisition System

Granite Cylinder
- height = 508mm
- diam. = 457mm

Water Filled Cavity
- diam. = 51mm

Total Cost: $ 600

Total Cost: $ 40,000

Total Cost: $ 1,000,000
THE FEBEX PROJECT

A Full-Scale Engineered Barrier EXperiment was conducted at the Grimsel Test Site Underground Laboratory in Switzerland. The Project was sponsored by ENRESA (Spain).

Prediction exercises for the THM experiment were conducted by Ten Modelling Groups from Europe, Japan and North America, under the auspices of the DECOVALEX International Project.

The tunnel was excavated using a full face TBM. The tunnel was approximately 2.28 m in diameter, 70.4 m in length and located at a depth of 450 m.

The tunnel was driven through fracture zones, and lamprophyres*

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[*compact intrusive rock with phenocrysts** of black mica, hornblende, etc., but not feldspar:
** a larger crystal in a porphyritic*** rock:
***like, or in the nature of porphyry, having large crystals scattered among small ]
THE GEOLOGY OF THE FEBEX GALLERY
THE GEOMETRY OF THE FEBEX GALLERY
Heater (diameter 0.9)
Bentonite blocks
Steel liner
Granite

Heaters
Bentonite barrier
Concrete plug
Granite

Service zone, control and data acquisition system
Principal access tunnel to KWO

Heaters

(Dimensions in meters)
THE COMPUTATIONAL APPROACH

In the modelling of the bentonite THM response, the constitutive relations are assumed to be incrementally non-linear.

The dependence of the incremental poroelastic parameters on $S$, $e$, $T$, etc., is modelled through a “State Surface Approach”.

The constitutive behaviour of the rock mass is modelled as a linear poroelastic material(s), with provision for degrees of saturation less than unity.

The governing equations are solved in the Finite Element Code FRACON-3D UNSAT which is a proprietary Research FE Code of the Canadian Nuclear Safety Commission.
PARAMETERS FOR COMPUTATIONAL MODELLING

The parameters governing elastic, hydraulic and thermal phenomena in the various zones of the FEBEX gallery are obtained from the Reports produced by CIEMAT and UPC-DIT.

The hydraulic properties of the geologic strata are well documented. (Extensive in situ characterization of the crystalline rock was conducted by the several agencies and research contractors in Europe.)

The thermo-physical properties can be estimated reasonably accurately.

The mechanical properties of the fractured zones and intrusions, are somewhat lacking.

This last item adds a degree of uncertainty (or flexibility) to the prediction exercise.
THE MODEL OF THE FEBEX DRIFT

Use Although the entire THM problem of the FEBEX Gallery is three-dimensional, the present modelling exercise restricts attention to a simplified axisymmetric model, where the axis of symmetry coincides with the axis of the heaters.

This approximation is justified in view of the approximations embodied in the theoretical concepts and the limitations that can be ascribed to the determination of the input parameters.
The modelling is restricted to a finite domain of the rock mass surrounding the FEBEX gallery.

The choice of this external boundary is not arbitrary; the modelling of the entire site including the depth of 450m and depths beyond FEBEX tunnel, and similar lateral extents, is not entirely justifiable.

The results of the HM modelling can be used as a guide to prescribe the mechanical, kinematic, hydraulic and thermal boundary conditions on the exterior surface of this reduced model.
THE AXISYMMETRIC COMPUTATIONAL MODEL

- Granite
- Concrete Bulkhead
- Lamprophyres
- Bentonite Buffer
- Fracture Zones
- Heaters
THE COMPUTATIONAL MODEL BOUNDARY AND SYMMETRY CONDITIONS

- $p = 0$
- $T = 12^\circ C$
- $u_x = 0$

- $\frac{\partial p}{\partial y} = 0$; $\frac{\partial T}{\partial y} = 0$; $u_y = 0$

- $\frac{\partial p}{\partial r} = 0$
- $T = 12^\circ C$
- $u_r = 0$

- $\frac{\partial p}{\partial z} = 0$; $\frac{\partial T}{\partial z} = 0$
- $u_z = 0$

- $p = 1.6 \text{ MPa}$
- $T = 12^\circ C$
- $u_x = 0$
THE FINITE ELEMENT DISCRETIZATION
THE DETAIL OF THE FINITE MODEL IN THE VICINITY OF THE TUNNEL

- Granite
- Lamprophyres
- Fractured Zone
- Concrete Bulkhead
- Bentonite Buffer
- Heaters
Phase 1: Constant power, 1200 W per heater

Phase 2: Constant power, 2000 W per heater

Phase 3: Constant temperature, $T=100\, ^\circ C$
LABORATORY EXPERIMENTS
Carleton University, Ottawa, Canada, ca.1985
50-50, Bentonite-Sand Mixtures
Heater Temperature: 150 °C
HEATER POWER INPUT
Required to maintain a heater temperature of 100 Deg. Celsius
EVOLUTION OF TEMPERATURE AND RELATIVE HUMIDITY IN THE BENTONITE
EVOLUTION OF TEMPERATURE AND RELATIVE HUMIDITY IN THE BENTONITE
DISTRIBUTION OF TEMPERATURE IN THE BENTONITE

FRACON calculation
- - - t = 90 days
- - - t = 1000 days

Experimental data
- - - t = 90 days
- - - t = 1000 days

r = 0.81 m
EVOLUTION OF RADIAL STRESSES IN THE BENTONITE
EVOLUTION OF RADIAL STRESSES IN THE BENTONITE

![Graph showing the evolution of radial stresses over time with comparison to FRACON calculations and experimental data.](image)
CONCLUDING REMARKS

There is an extensive collection of problems in geomechanics and in the geosciences where THM effects are essential to the modelling exercise.

Unfortunately, these arise in non-routine applications involving projects of critical importance and either economic or social benefit can be gained through an in-depth study combined with the use of advanced computational approaches.

The extension of the classical theory of poroelasticity to include heat conduction is the most favoured approach for examining THM effects in fluid-saturated rocks.
CONCLUDING REMARKS....contd.

The limitations to the approach arises from the stress-induced alterations of the mechanical and hydraulic behaviour porous fabric; i.e. A non-linear problem.

For rocks, the extension of the THM theory to include continuum damage mechanics is one possible way to account for such changes.

The topic of THM modelling can benefit from some discerning experiments to confirm the validity of CDM.

If localized fractures follow continuum damage, then the emphasis should shift to the THM modelling of fractures.

For other geomaterials, including clays, the conceptual issues related to the transport processes are much more complicated.
ADVANCED COMPUTATIONAL METHODS AND GEOTECHNICAL PRACTICE

My observations are that geotechnical practice has a wide spectrum of activities ranging from either very routine (<20%?) to extremely specialized (or site specific) (<20%?) applications.

In the former extreme, the profession is less inclined to deviate from traditional approaches. Understandably so!! Natural geomaterial variability competes with excessive or over-zealous mathematical or constitutive refinements (Usually viewed by the profession as 5th decimal place research).
In the latter extreme, the type of problems and the critical peer review of solutions will more than often demand recourse to advanced computational approaches.

The intermediate group tends to vacillate between traditional and more advanced approaches depending on the urgency and economics of their activities.

There are no quick fixes to this situation. Restrictive Codes of Practice are viewed as an impediment to the ready implementation of innovative computational approaches.
The computational geomechanics profession ought to look beyond the traditional areas to emphasize their capabilities.

Popularize Computational Geomechanics the same way the Multi-Physics people do! [They use the same physical laws, the same equations and probably get significantly greater access to research funding!]

It is also the obligation of the geotechnical profession to publicize vigorously instances where the use of sound computational methodologies have led to better and economical solutions even to routine problems.