Imperial College London

BGA Annual Conference 2021
Experimental and modelling challenges on temperature effects on granular materials

Marina S. Bortolotto, Tokio Morimoto, David M. G. Taborda and Catherine O'Sullivan

Introduction

Geomaterials can experience a variety of thermal loads, these include natural phenomena that impose sub-zero temperatures, soil adjacent to thermo-active piles (temperatures ranging between 5℃-40℃) and nuclear waste repositories where temperatures can exceed 100℃. Although there are clear economic and environmental drivers to better understand the behaviour of granular materials at high temperatures, little attention has been given to characterising on the coupled thermo-hydro-mechanical (THM) response of these materials. Ongoing research at Imperial College London is developing high quality experimental and numerical techniques to improve understanding of the response of soil to thermal loads.

Experimental Challenges

A bespoke triaxial apparatus (MKII cell) is being developed to perform hydraulic conductivity tests. Due to the high permeability of sands and gravels, head losses in the apparatus complicate hydraulic conductivity tests even at room temperature. Measurements at higher temperatures led to additional sources of error, motivating further investigations using an infrared camera to identify temperature variations within the equipment. Additionally, non-isothermal hydraulic conductivity tests require corrections to account for variations in the viscosity of water and thermally-induced mechanical strains.

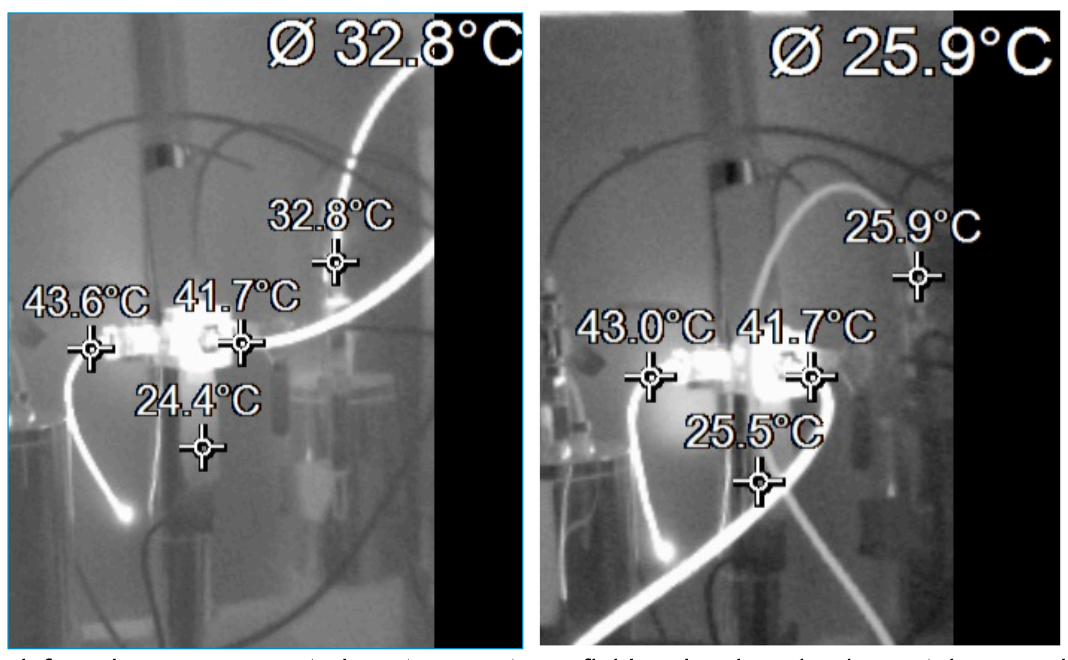
Temperature effects on instrumentation

Images obtained from the infrared camera have been crucial to identify temperature differences within the instrumentation. For example, volume gauges can only be accurately calibrated at room temperature, so it was important to avoid warm water reaching these gauges. Infrared images revealed that temperatures as high as ~33℃ were observed on the surface of the external tubing while 60℃ tests were conducted. A heat exchanger was added before the volume gauge to effectively cool down the water from ~33℃ to 25 ℃.

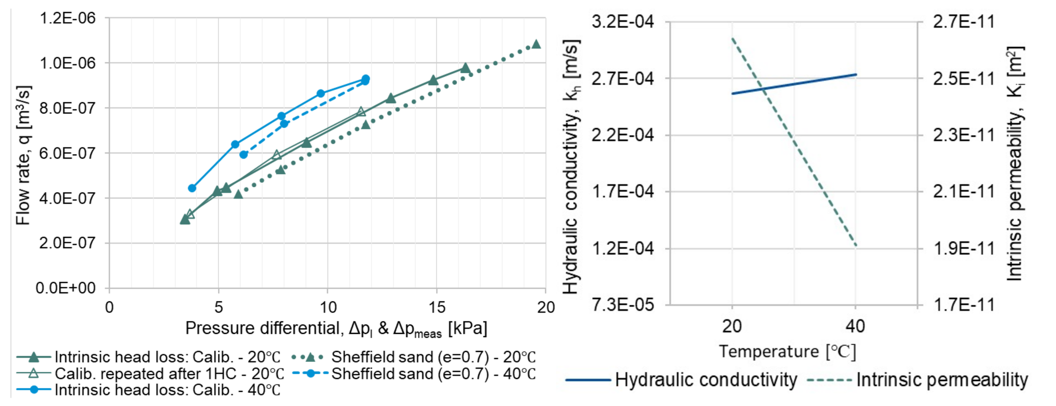
We also noticed a significant amount of radiation reaching the instrumentation while using only one layer of insulation (polyethylene closed cell foam) around the cell.

Pore water pressure transducer measurements are compromised once their surface temperatures are 4-5 ℃ higher than room temperature; infra red images revealed this is the case in our apparatus.

An additional sensor was added to the sample to verify the temperature within the sample while warming up / cooling down the system and performing hydraulic conductivity tests.



Infrared camera capturing temperature fields developed along tubes and instrumentation connected to the top of specimen. The main measurements correspond to the tube's surface right before the volume gauge: before any intervention (LHS) and after adding the heat exchanger (RHS).



Hydraulic conductivity tests on MKII cell at different temperatures: System's intrinsic head loss (calibration) and Sheffield sand curves (LHS). Hydraulic conductivity (corrected using intrinsic head losses) and intrinsic permeability for Sheffield sand (RHS).

Temperature corrections

A new methodology for interpreting thermally induced mechanical strains has been developed. This mechanical strain accounts for relative movement of particles due to thermal loading.

Plastic deformation of the drainage lines during thermal loading has posed a particular challenge.

Water viscosity variations with temperature affect measurements of hydraulic conductivity; this can be addressed by working in terms of intrinsic permeability. Viscosity variations also affect the the system's head losses; this can be corrected using a new calibration method.

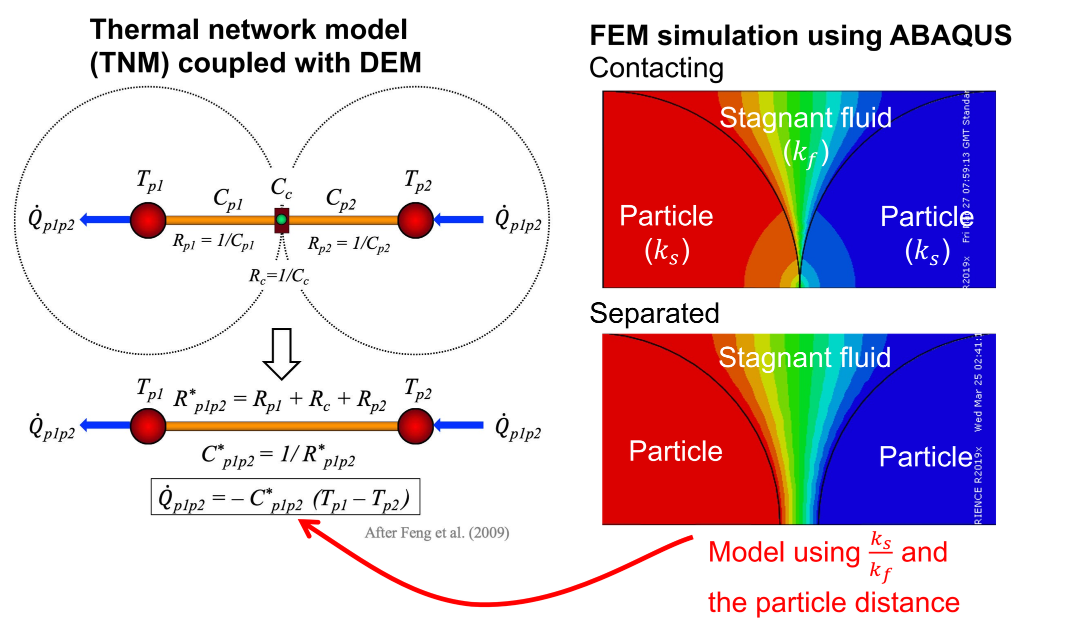
DEM Challenges

The Discrete Element Method (DEM) provides particle-scale information (e.g. changes in particle configurations and contact forces between particles), which is difficult to obtain in laboratory studies. This study aims to reproduce laboratory experiment samples in DEM to gain microscopic insights into the thermo-hydro-mechanical coupled behaviour of soils. The original DEM formulation (Cundall and Strack, 1979) only considers the mechanical behaviour of particles and so accurate and efficient thermal conduction and fluid transport models need to be developed.

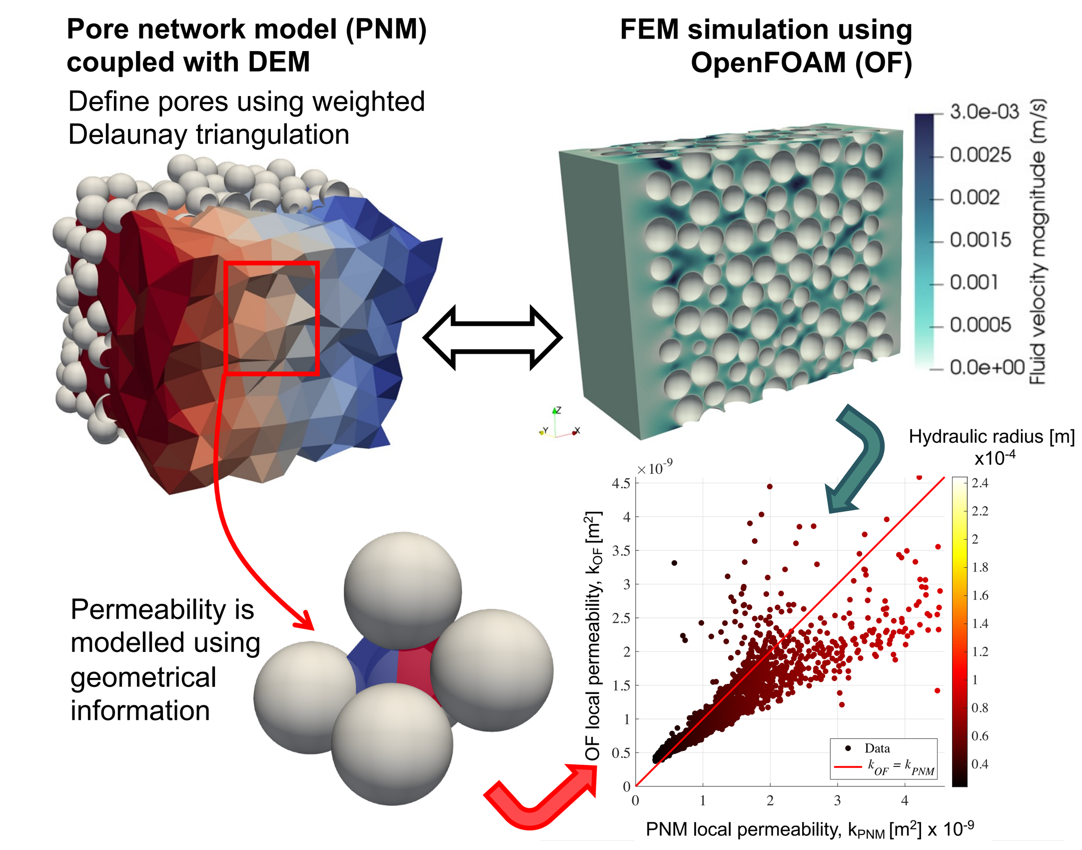
Thermal conduction in DEM

Here DEM was coupled with a thermal network model (TNM), where DEM particles are considered as nodes with specific temperatures and thermal pipes connect pairs of adjacent particles.

An accurate model of thermal conductivity of the thermal pipes is required. The pipes' thermal conductivities depend on the distance between particles. While the thermal conductivity of soil particles is higher than that of air or water, the thermal conduction through the pore-fluid must be considered.



Schematic illustration of thermal network model and FE models with a variety of the distances between two particles for calibrating a BOB model.



Schematic illustration of a pore network model and an FE model for validating a local permeability model. Comparison is shown in the right bottom of the figure.

We implemented a modified BOB model (Batchelor and O'Brien, 1977; Dai et al., 2019), which considers the ratio of thermal conductivity of fluid (k_f) to that of solid particles (k_s). This model was validated using FEM models developed in this study.

Fluid transport in DEM

This study coupled DEM with a pore network model (PNM), where the fluid domain is discretized into individual pores and fluid transport between connected pores is simulated. In a PNM, the local permeability between two pores is modelled using geometrical information of the pores; however, the accuracy of existing local permeability models has not been fully explored.

We conducted a number of OpenFOAM steady state flow simulations employing a mesh developed by Knight et al. (2020) for different local void ratios and particle size distributions. Comparison of local permeabilities extracted from OpenFOAM with an existing model developed by Chareyre et al. (2012) indicates the potential to improve existing local permeability models.

References

BATCHELOR, G. K., & O'BRIEN, R. W. (1977).. PROCEEDINGS OF THE ROYAL SOCIETY OF LONDON. A. MATHEMATICAL AND PHYSICAL SCIENCES, 355(1682), 313-333.

CHAREYRE, B., CORTIS, A., CATALANO, E., & BARTHÉLEMY, E. (2012).. TRANSPORT IN POROUS MEDIA, 94(2), 595-615.

CUNDALL, P. A., & STRACK, O. D. (1979). GÉOTECHNIQUE, 29(1), 47-65.

DAI, W., HANAOR, D., & GAN, Y. (2019). INTERNATIONAL JOURNAL OF THERMAL SCIENCES, 142, 266-279.

KNIGHT, C., O'SULLIVAN, C., VAN WACHEM, B., & DINI, D. (2020). COMPUTERS AND GEOTECHNICS, 117, 103210.

Acknowledgements

Marie SKŁODOWSKA-CURIE Innovative training network MATHEGRAM is funded through the People Programme (Marie SKŁODOWSKA-CURIE Actions) of the European Union's Horizon 2020 Programme H2020 under REA grant agreement No. 813202.

MATHEGRAM