Mechanical anisotropy of Opalinus Clay shale: a multiscale approach

Aldo Madaschi[1 *], Eleonora Crisci[1], Alessio Ferrari[1], Andres Alcolea Rodríguez[2], Lukas Keller[3], Paul Marschall[4], Lyesse Laloui[1]

[1] École Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Soil Mechanics, Lausanne, Switzerland.
[2] HydroGeomodels AG, Tösstalstrasse 23, 8400 Winterthur, Switzerland
[3] ZHAW, Zurich University of Applied Sciences, Institute of Computational Physics, Winterthur, Switzerland
[4] NAGRA, Wettingen, Switzerland
* aldo.madaschi@epfl.ch

Introduction

The mechanical behaviour of layered geomaterials involves several levels of hierarchy describing different physical and depositional processes at different scales (Li et al., 2017). Such lengths are material dependent and challenging to identify; moreover, classical modelling approaches rely on representative distributions of the mechanical properties that are challenging to infer from available data sets. This constraint hinders the correlation of high-accuracy mechanical characterizations performed on small samples (i.e., at the laboratory scale) with information from logs or boreholes on a larger length scale.

In this work, a multiscale workflow is proposed that combines the information obtained from petrophysical investigations at the core scale (continuum in depth) with laboratory mechanical characterizations of collected specimens (discrete local information). The combination of data sources with radically different scales enhances the calibration and validation of a suitable numerical approach for the upscaling of the mechanical behaviour from the laboratory to the core scale using a finite element model developed with the commercial code Abaqus®.

The multiscale workflow

The workflow is applicable to all cases for which meaningful characterizations of the material behaviour can be inferred from physical properties obtained from petrophysical investigations. It proceeds on two domains, namely, (i) the physical domain representing the real material properties at the three analysed scales (Figure 1 a to c) and (ii) the modelling domain representing the abstraction of the considered physical problem (Figure 1 d to e).

The borehole scale (a), of interest for the engineering problem, is analysed through log investigation. Samples of material sourced from the borehole are studied using non-destructive techniques at the core scale (b). Successively, small parts of the core are tested at the laboratory scale (c) to obtain detailed information (e.g., mechanical behaviour and mineralogical composition). In this work, the path from the borehole scale to the laboratory scale is termed downscaling.

The information derived at different scales of the physical domain (a to c) feeds into the modelling (d to f). The experimental results from core and laboratory scales render a simplified characterization of the shale as a sequence of layers (d and e). The layering configuration at the core scale is used to generate, through a geostatistical approach, a prediction of the layers' alternation over depth at the borehole scale (b to f). The abstracted layered representation at the smallest scale is obtained from the localization of the sample on the core scale (from b to d). The combination of this information with an accurate laboratory mechanical characterization of the material provides the setting for the calibration of a suitable finite element model that reproduces the outcomes of the laboratory tests (step c to d). The definition of the mechanical properties at the smallest scale in different sections allows so-called upscaling to the core scale, considering the layers' properties and alternation (step d to e). Finally, the finite element simulation performed adopting the core layering settings (step e) and the mechanical properties of the calibrated models (step d) provides piece-wise homogeneous fields of mechanical properties at the core and borehole scales (step e and f).

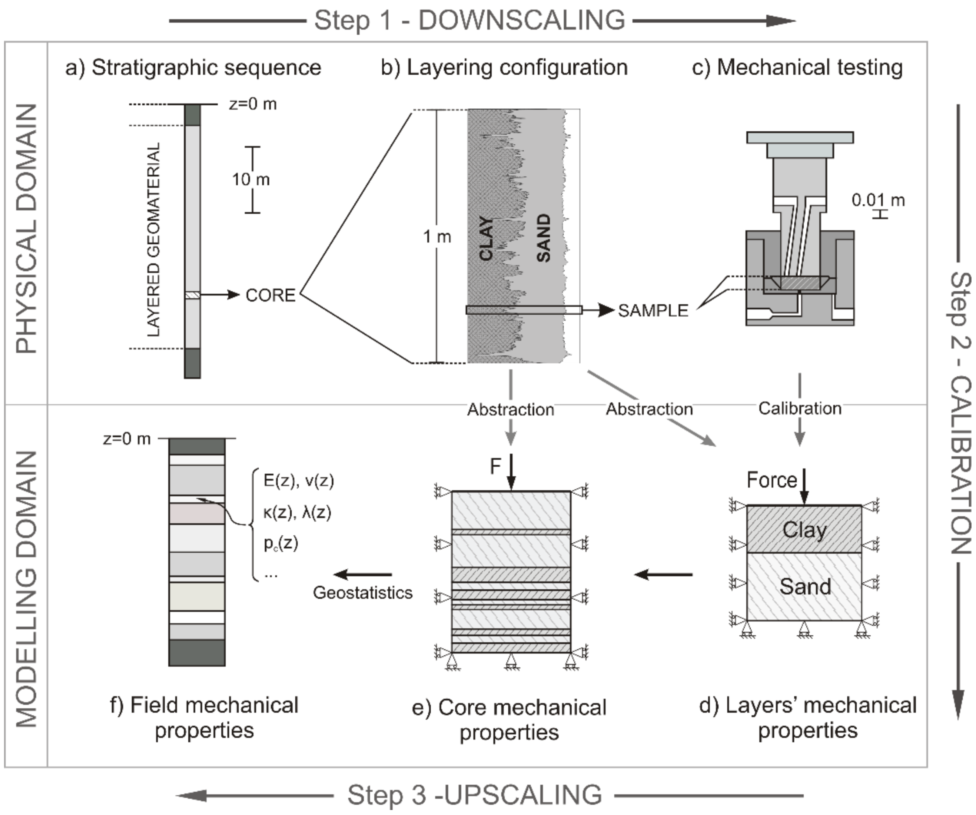

Fig. 1: Schematic representation of the physical and modelling domains used in the workflow.

Case of study: Opalinus Clay shale

The approach has been applied to the case of a Opalinus Clay shale, characterized by the presence of interbedding layers with different mineralogical properties, in oedometric loading conditions (Ferrari & Laloui, 2013; Crisci et al., 2017). The layering setting was defined based on the results of a series of XCT scans that were elaborated on to consider the depositional conditions and the effect of diagenesis (Keller et al., 2013). The approach can be extended to more complex test conditions, using more detailed information on the mineralogical and depositional settings and more sophisticated numerical techniques.

After defining a set of reference parameters based on published data, the model was validated based on the experimental tests that were performed. A stochastic sensitivity analysis was conducted to highlight the effect of model parameters on the results.

To upscale the results to the borehole length scale, the material compositions of two cores were used to simulate the layer distribution of shale over a depth of 62 m using a multiple point statistical approach. The distributions of the simulated material composition were used as input parameters for the finite element model. The procedure resulted in a map of the anisotropic mechanical parameters, in both elastic and elastoplastic regimes, which summarized the variability of the parameters versus depth that can be expected in an investigation at the borehole scale.

By following the presented workflow, a finite element analysis of engineering problems at the scale of the site/borehole can be performed taking into account the variation of mechanical properties, such as the compressibility indexes in the presented case, depending on the variability of the mineralogical composition of the analysed formation.

References

Crisci, E., Ferrari, A., Giger, S., & Laloui, L. (2017). One Dimensional Consolidation of Opalinus Clay from Shallow Depth. In A. Ferrari & L. Laloui (Eds.), Advances in Laboratory Testing and Modelling of Soils and Shales (ATMSS) (Vol. 1, pp. 338–344). Cham: Springer International Publishing

Ferrari, A., & Laloui, L. (2013). Advances in the Testing of the Hydro-mechanical Behaviour of Shales. In L. Laloui & A. Ferrari (Eds.), Multiphysical Testing of Soils and Shales (pp. 57–68). New York: Springer-Verlag

Keller, L. M., Schuetz, P., Erni, R., Rossell, M. D., Lucas, F., Gasser, P., & Holzer, L. (2013). Characterization of multi-scale microstructural features in Opalinus Clay. Microporous and Mesoporous Materials, 170, 83–94

Li, W., Rezakhani, R., Jin, C., Zhou, X., & Cusatis, G. (2017). A multiscale framework for the simulation of the anisotropic mechanical behavior of shale. International Journal for Numerical and Analytical Methods in Geomechanics, (March 2017), 189–213