

## **Computational modeling of instrumented indentation testing with application to creep in shale**

Y. Liu<sup>a\*</sup>, Q. Yin<sup>a</sup> and R.I. Borja<sup>a</sup>

<sup>a</sup> Stanford University, Stanford, CA, USA

\*corresponding author: liuyx@stanford.edu

### **Abstract:**

Instrumented indentation testing is a common technique to measure the hardness of small volumes of material. More recently, it has also been used to investigate the creep response of the indented material over short periods of time. The process involves indenting a polished surface of the material being tested by gradually applying the load on the indenter, holding it constant for several minutes, and gradually removing the load. Traditionally, attention has been paid to the initial loading stage where the elastic constants and fracture toughness of the material are measured. In this work, however, we focus on the creep response of the indented material, more specifically, on shale, a highly heterogeneous and anisotropic sedimentary rock with complex mineralogical composition. We distinguish between nanoindentation (up to several hundred nanometers) that captures the creep response of the minerals and organics comprising the rock, and micro-indentation (up to several micrometers) that captures the creep response of the rock matrix. To numerically model the indentation process, we use the finite element method and an incremental frictionless two-body contact algorithm based on the Lagrange multipliers method. To model the time-dependent response of the rock, we formulate a viscoplastic version of the modified Cam-Clay model that accommodates for anisotropy and heterogeneity. The mechanical model is then calibrated and tested for real shale.