A Hysteretic Aperture Model for Fractured Rocks

Josue Barroso[1],
Alexandr Zhemchuzhnikov[2],
Euripedes Vargas[2], Marcio Murad[1],
Matheus Peres[2], Tayna Lobo[1]

LNCC, PUC-Rio

May 22, 2026

CoMPore
Computational Modelling
of Porous Materials

GRUPO DE
GEOANÁLISE

LNCC
Laboratório Nacional de
Computação Científica

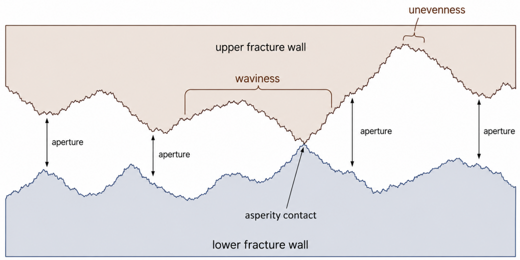
Pontifícia
Universidade
Católica do
Rio de Janeiro

Outline

CoMPore
Computational Modeling
of Porous Materials

Fractures as Contacting Rough Surfaces

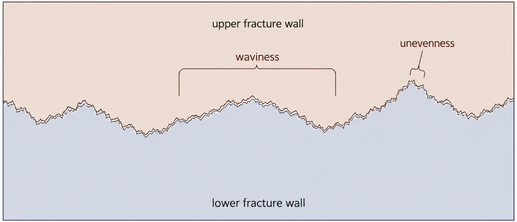
- Fractures are not planar; they are rough surfaces!
- Roughness can be decomposed into
  - Waviness: large-scale surface undulations.
  - Unevenness: small-scale asperities superimposed on the waviness.
- **Unmated surfaces:** Waviness controls global opening trends.



Fractures as Contacting Rough Surfaces

CoMPore Computational Modeling of Porous Materials

- **Mated surfaces:** opposite faces match closely.
- Asperities interlock during compression.
- Closure reduces aperture and flow paths.
- Unevenness controls local contact points.

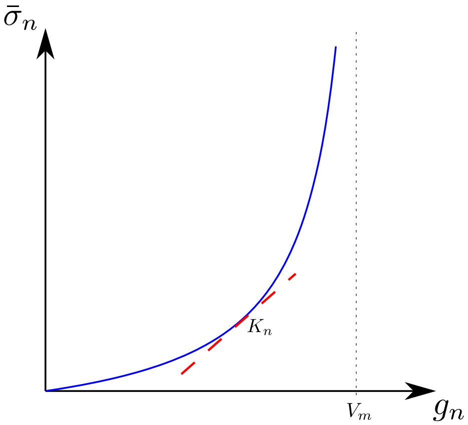


Fracture Closure

- Barton-Bandis Model
- (Bandis, Lumsden & Barton, 1983)
- **Nonlinear elastic** model for the **compressive** regime.
- Fracture stiffness increases with closure

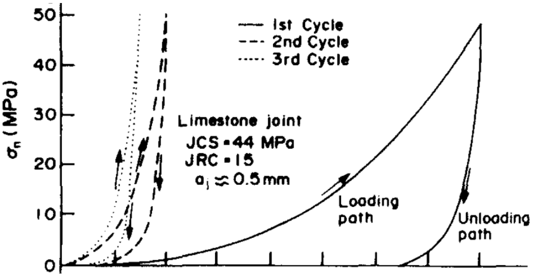
$$g_n\left(\bar{\sigma}_n\right) = \frac{\bar{\sigma}_n V_{\mathsf{m}}}{K_{\mathsf{ni}} V_{\mathsf{m}} + \bar{\sigma}_n},$$

where
K_{ni}: initial normal stiffness;
V_{m}: maximum closure;
$\bar{\sigma}_n$: contact pressure (normal compression).



Closure Hysteresis (Bandis, Lumsden & Barton, 1983)

- Tests with multiple loading cycles.
- Results show **hysteresis and permanent deformation**.
- Behavior varies with **stress history** and number of cycles.



Outline

1. Motivation

2. **Proposed Model Considering Closure Hysteresis**

3. Possible Applications

4. Tests and Simulations Analysis to Model Validation

New Hysteretic Model

- Intermediate curves parameterized by $\chi = \bar{\sigma}_n^\chi / \bar{\sigma}_n^{\mathsf{max}}$

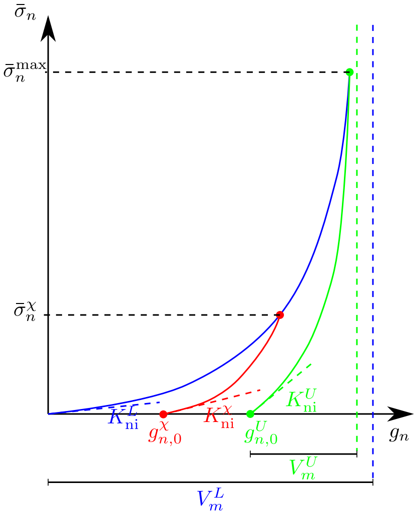
$$g_n^\chi\left(\bar{\sigma}_n\right) = g_{n,0}^\chi + \bar{g}_n^\chi\left(\bar{\sigma}_n\right)$$

with the auxiliary closure function defined as:

$$\bar{g}_n^\chi\left(\bar{\sigma}_n\right) = \frac{\bar{\sigma}_n V_{\mathsf{m}}^\chi}{K_{\mathsf{ni}}^\chi V_{\mathsf{m}}^\chi + \bar{\sigma}_n}.$$

- Linearly interpolated parameters

$$K_{\mathsf{ni}}^\chi = \chi K_{\mathsf{ni}}^U + (1-\chi) K_{\mathsf{ni}}^L;$$
$$V_{\mathsf{m}}^\chi = \chi V_{\mathsf{m}}^U + (1-\chi) V_{\mathsf{m}}^L.$$



New Hysteretic Model

- Permanent closure $\left(g_{n,0}^{\chi}\right)$: reduction of the initial maximum aperture.
- Loading and unloading curves χ intersect at $\bar{\sigma}_n^{\chi}$; therefore:

$$g_n^L\left(\bar{\sigma}_n^{\chi}\right) = g_n^{\chi}\left(\bar{\sigma}_n^{\chi}\right);$$
$$g_n^L\left(\bar{\sigma}_n^{\chi}\right) = g_{n,0}^{\chi} + \bar{g}_n^{\chi}\left(\bar{\sigma}_n^{\chi}\right);$$
$$g_{n,0}^{\chi} = g_n^L\left(\bar{\sigma}_n^{\chi}\right) - \bar{g}_n^{\chi}\left(\bar{\sigma}_n^{\chi}\right).$$

- Finally, given $\bar{\sigma}_n$ and χ, the aperture is computed as

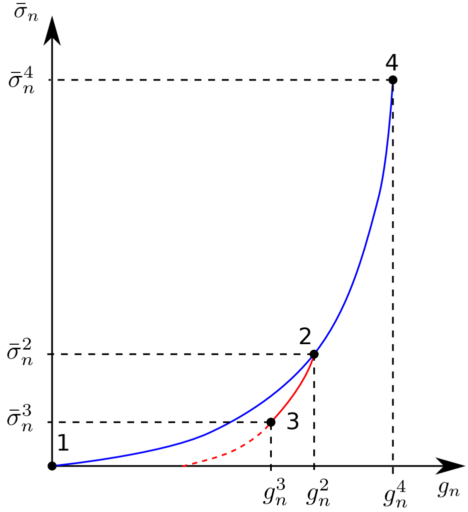
$$d\left(\bar{\sigma}_n\right) = \bar{d} - g_n^{\chi}\left(\bar{\sigma}_n\right).$$

Outline

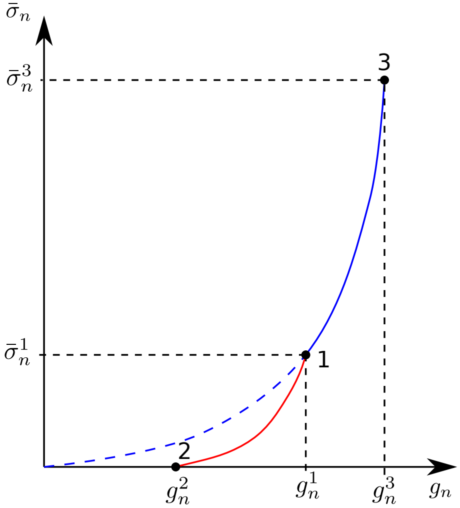
CoMPore
Computational Modeling of Porous Materials

Possible Applications

Complete Model



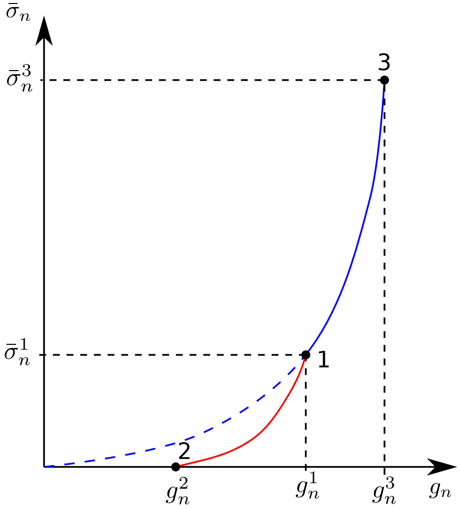
- Starting from zero stress, **loading** induces closure along the **blue** curve $(1 \to 2)$;
- **Stress reduction** from 2 follows the **red** curve $(2 \to 3)$;
- For subsequent **stress increases** that do not exceed $\bar{\sigma}_n^2$, closure follows the **red** curve $(3 \to 2)$;
- If $\bar{\sigma}_n > \bar{\sigma}_n^2$, we return to the **blue** curve $(2 \to 4)$.



Alternative: consider distinct **fixed** curves in **different regions**.

- Near **injection** wells, stress is reduced from the *in situ* value: we use the red curve $(1 \to 2)$;
- Near **production** wells, stress increases from the *in situ* value: we use the blue curve $(1 \to 3)$.

CoMPore
Computational Modeling of Porous Materials



- **Stress reduction** in the **core** after collection: fracture **aperture increases** along the **red** curve $(1 \to 2)$;
- If the sample is tested under **compression** lower than the *in situ* stress $(\bar{\sigma}_n^1)$, closure follows the **red** curve $(2 \to 1)$;
- **Stress increase** above the *in situ* value induces **closure** along the **blue** curve $(1 \to 3)$;
- A **compression test** would be sufficient to characterize **closure hysteresis**.

Outline

CoMPore Computational Modeling of Porous Materials

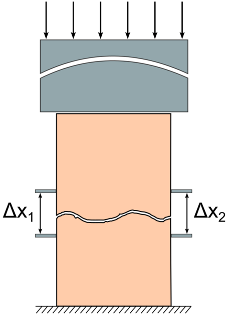
Workflow

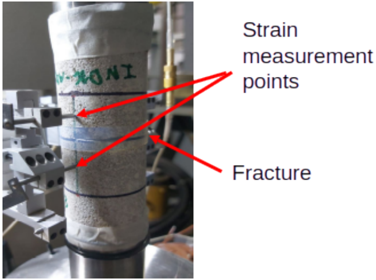
CoMPore Computational Modeling of Porous Materials

1. Compression tests on fratured rock (one or more cycles with different maximum stress);
2. Calibration with tests of parameters to perform contact simulation;
3. Use simulation to generate fracture closure curve and more data (additional cycles);
4. Simulation data is used to validate and potentially understand aperture hysteresis.

Mechanical Tests

- Uniaxial loading: sample with a transverse fracture
- Measurement of axial deformation near the fracture





Digital Model Construction

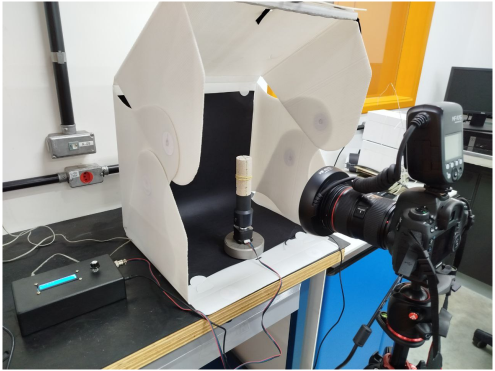
CoMPore
Computational Modeling
of Porous Materials

- Microscale numerical simulation depends on
  - Mechanical properties obtained by calibration with **test results**;
  - Geometry characterization done using **photogrammetry**.

Test

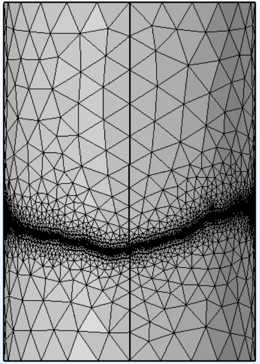
+

Photogrammetry



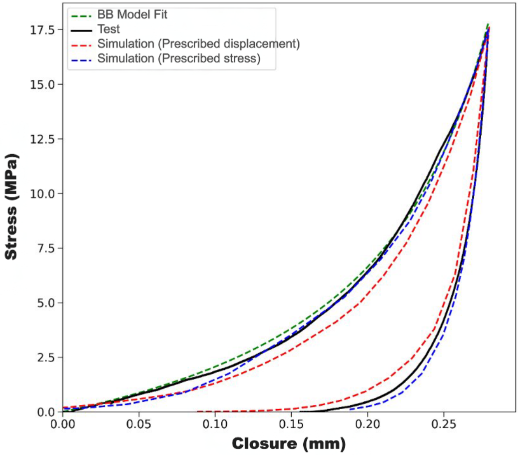
→

Numerical Simulation



Calibration

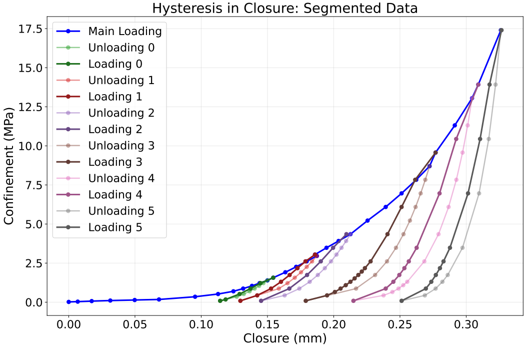
- Rock sample: Indiana Limestone
- Mechanical model: elastoplasticity
- Two variations: **prescribed stress** and displacement
- Parameters for prescribed stress (calibrated)
  - Coesion: 10 MPa
  - Angle of internal friction: 35°
  - UCS: 38.42MPa



Experimental Data

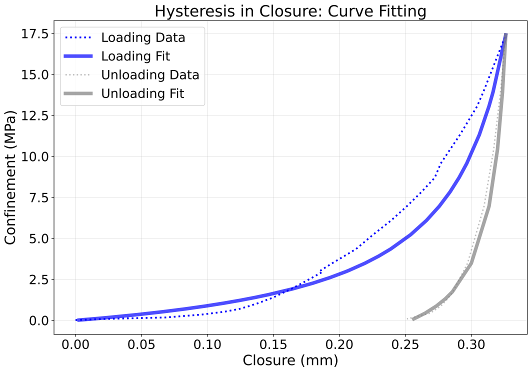
CoMPore
Computational Modeling of Porous Materials

- Data source: fractured-rock simulated test.
- 6 cycles with different maximum loads: 1.392, 2.958, 4.35, 8.7, 13.5 and 17.4 MPa.
- Closure vs. stress.
- **Data segmentation**:
  - Identification of each cycle segment;
  - Identification of the loading bounding curve.



Data Fitting: Reference Curves

- Bounding data.
- Fixed maximum point.
- Discrepancy between loading data and fit.

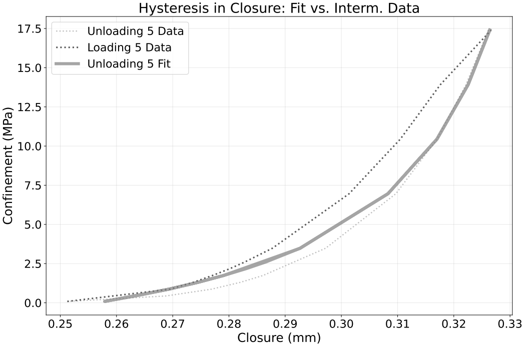


Approximation Target

- Simplification of hysteresis in the unloading and loading segment

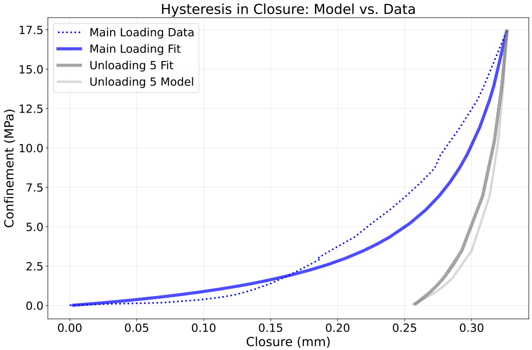
$$\bar{\sigma}_n^{\chi} \to 0 \to \bar{\sigma}_n^{\chi}.$$

- Curve fitting to loading/unloading data.
- Goal: approximate an average intermediate curve.



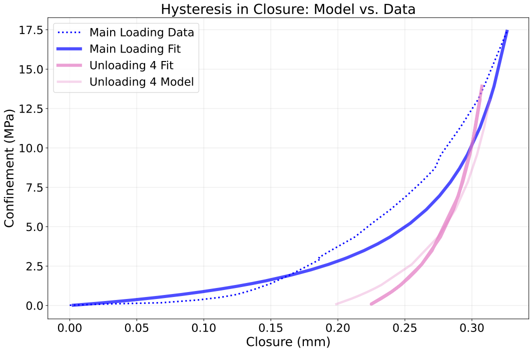
Error Assessment

- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



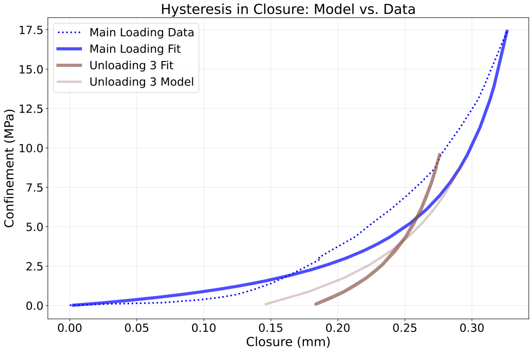
Error Assessment

- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



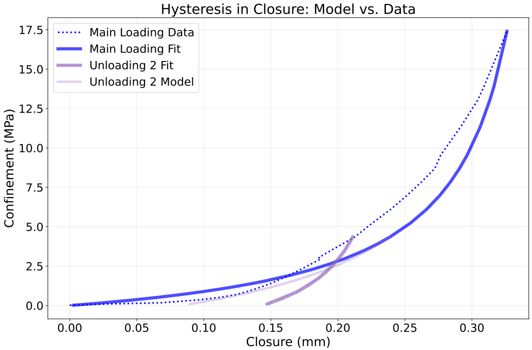
Error Assessment

- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



Error Assessment

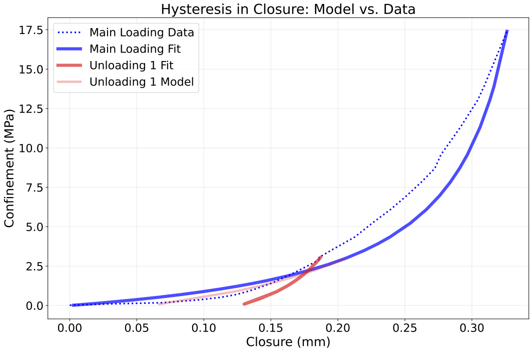
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



Error Assessment

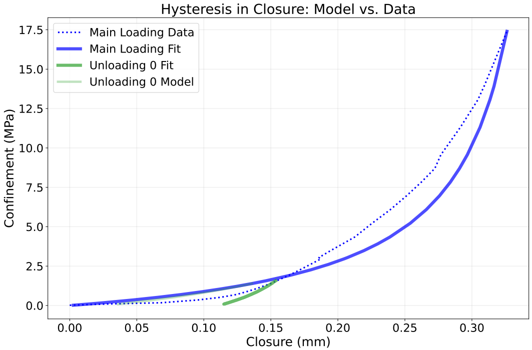
CoMPore
Computational Modeling of Porous Materials

- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



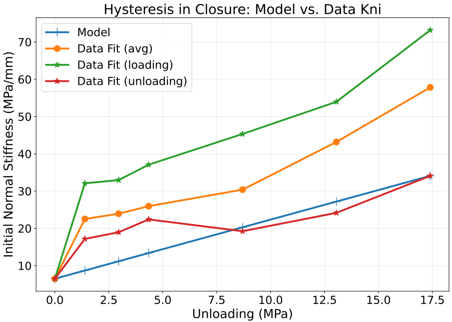
Error Assessment

- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



Error Assessment: Parameter Comparison

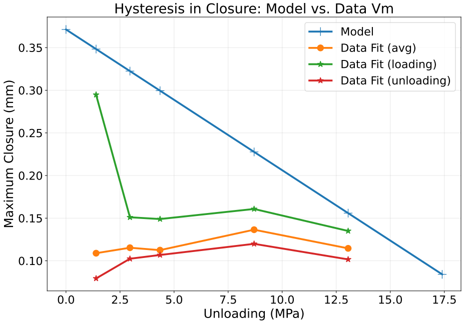
- Comparison of K_{ni} between the model and fitted curves.
- As expected, stiffness decreases with unloading stress, except for low-stress unloading curves.
- Loading and average curves show an approximately linear trend.
- Results do not appear to converge to the main loading curve.



Error Assessment: Parameter Comparison

CoMPore
Computational Modeling
of Porous Materials

- Comparison of V_m between the model and fitted curves.
- Values are approximately constant.
- A decrease with unloading stress was expected.
- Behavior appears to diverge from the loading curve.



Conclusions and Next Steps

- Interpolation between bounding curves did not accurately predict intermediate curves.
- The data do not appear to converge to the loading bounding curve.
- Alternative strategy: interpolate selected intermediate curves.
- BB parameters do not always show a clear pattern: K_{ni} for unloading and V_{m} for loading.
- Validate simulated intermediate curves against mechanical tests.
- Perform tests and simulations with additional samples.

Acknowledgments

Thank you for your attention!

Funding

PETROBRAS

Contact: `jsantos@lncc.br`