

A Hysteretic Aperture Model for Fractured Rocks

Josue Barroso¹,
Alexandr Zhemchuzhnikov²,
Euripedes Vargas², Marcio Murad¹,
Matheus Peres², Tayna Lobo¹

LNCC, PUC-Rio

May 22, 2026

CoMoPore
Computational Modelling
of Porous Materials

 **LNCC**
Laboratório Nacional de
Computação Científica

**GRUPO DE
GEOANÁLISE**



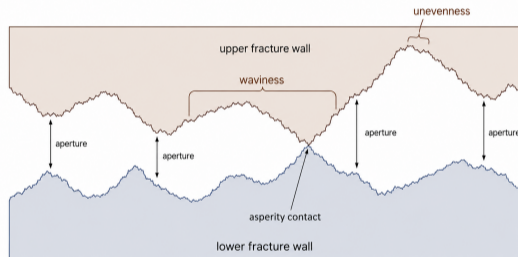
Pontifícia
Universidade
Católica do
Rio de Janeiro

1. Motivation

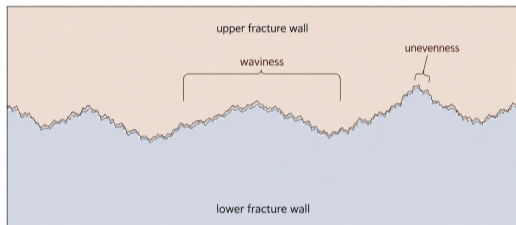
2. Proposed Model Considering Closure Hysteresis

3. Tests and Simulations Analysis to Model Validation

- 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.



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



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

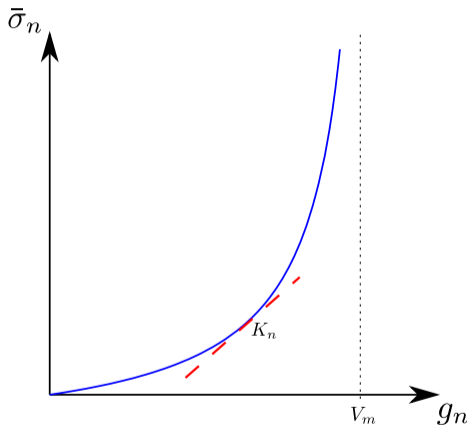
$$g_n(\bar{\sigma}_n) = \frac{\bar{\sigma}_n V_m}{K_{ni} V_m + \bar{\sigma}_n},$$

where

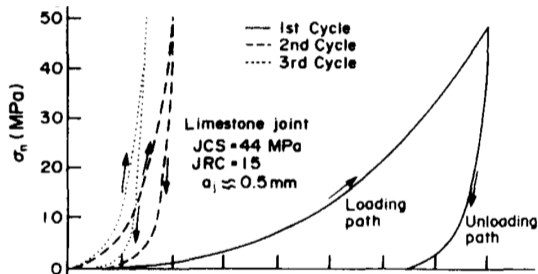
K_{ni} : initial normal stiffness;

V_m : maximum closure;

$\bar{\sigma}_n$: contact pressure (normal compression).



- Tests with multiple loading cycles.
- Results show **hysteresis and permanent deformation**.
- Behavior varies with **stress history** and number of cycles.
- In this work, we focus only in the effect of stress history.



1. Motivation

2. Proposed Model Considering Closure Hysteresis

3. Tests and Simulations Analysis to Model Validation

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

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

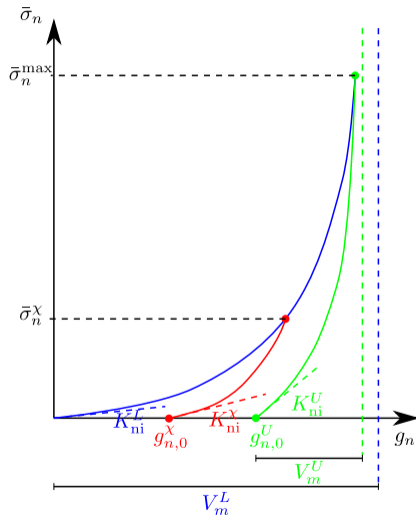
with the auxiliary closure function defined as:

$$\bar{g}_n^\chi(\bar{\sigma}_n) = \frac{\bar{\sigma}_n V_m^\chi}{K_{ni}^\chi V_m^\chi + \bar{\sigma}_n}$$

- Linearly interpolated parameters

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

$$V_m^\chi = \chi V_m^U + (1 - \chi) V_m^L.$$

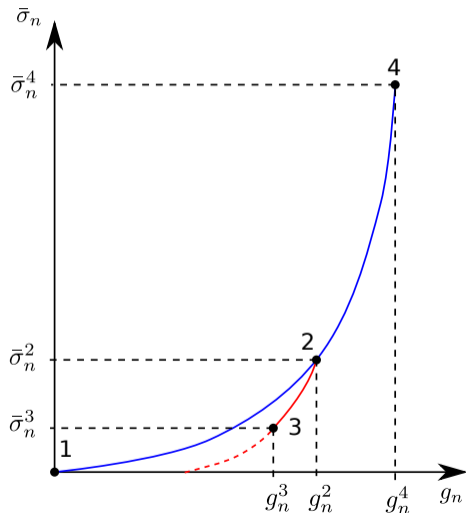


- Permanent closure ($g_{n,0}^\chi$): reduction of the initial maximum aperture.
- Loading and unloading curves χ intersect at $\bar{\sigma}_n^\chi$; therefore:

$$\begin{aligned}g_n^L(\bar{\sigma}_n^\chi) &= g_n^\chi(\bar{\sigma}_n^\chi); \\g_n^L(\bar{\sigma}_n^\chi) &= g_{n,0}^\chi + \bar{g}_n^\chi(\bar{\sigma}_n^\chi); \\g_{n,0}^\chi &= g_n^L(\bar{\sigma}_n^\chi) - \bar{g}_n^\chi(\bar{\sigma}_n^\chi).\end{aligned}$$

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

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

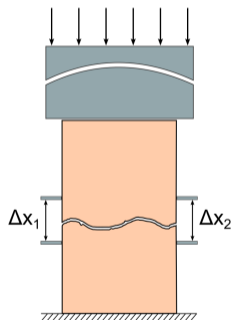


- Starting from zero stress, **loading** induces closure along the **blue** curve ($1 \rightarrow 2$);
- **Stress reduction** from 2 follows the **red** curve ($2 \rightarrow 3$);
- For subsequent **stress increases** that do not exceed $\bar{\sigma}_n^2$, closure follows the **red** curve ($3 \rightarrow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

1. Motivation
2. Proposed Model Considering Closure Hysteresis
- 3. Tests and Simulations Analysis to Model Validation**

1. Compression tests on fractured 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.

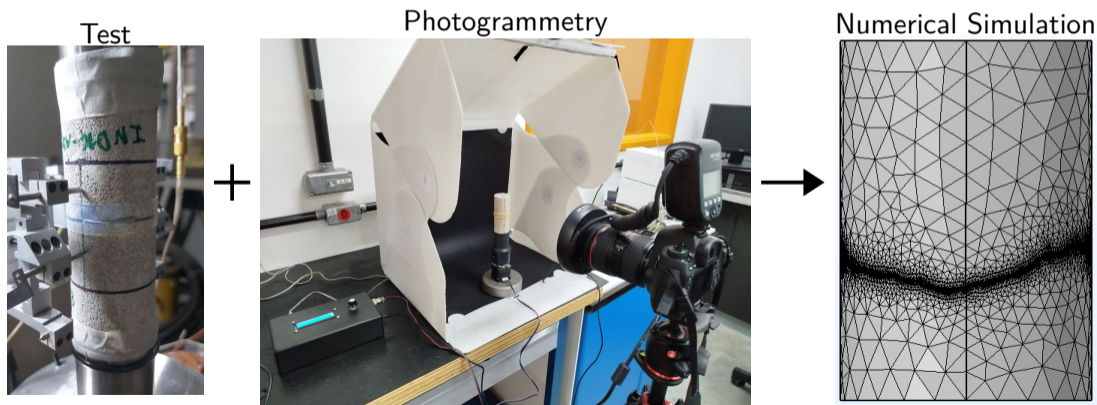
- Uniaxial loading: sample with a transverse fracture
- Measurement of axial deformation near the fracture



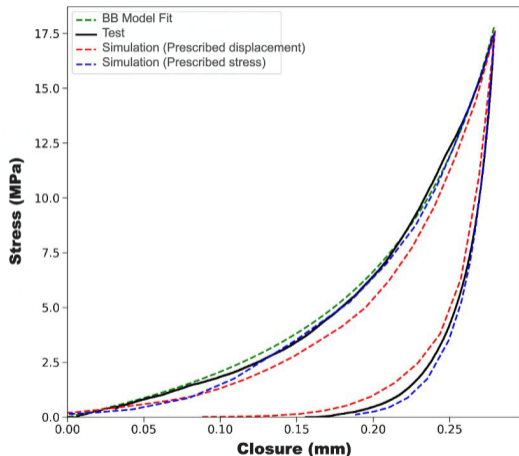
Strain
measurement
points

Fracture

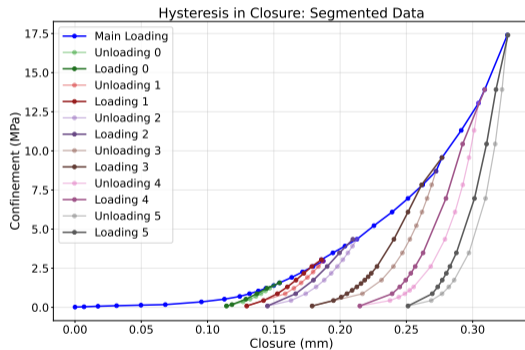
- Microscale numerical simulation depends on
 - Mechanical properties obtained by calibration with **test results**;
 - Geometry characterization done using **photogrammetry**.



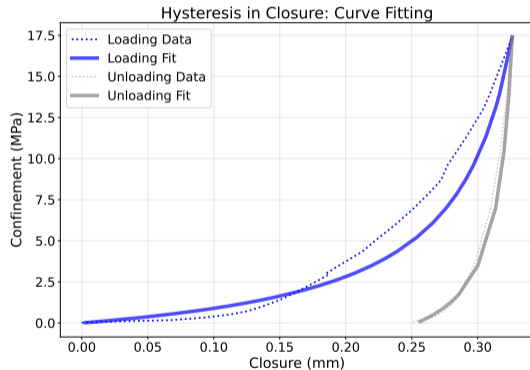
- Rock sample: Indiana Limestone
- Mechanical model: elastoplasticity
- Two variations: **prescribed stress** and displacement
- Parameters for prescribed stress (calibrated)
 - Coesion: 10 MPa
 - Angle of internal friction: 35°
 - UCS: 38.42MPa



- 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.



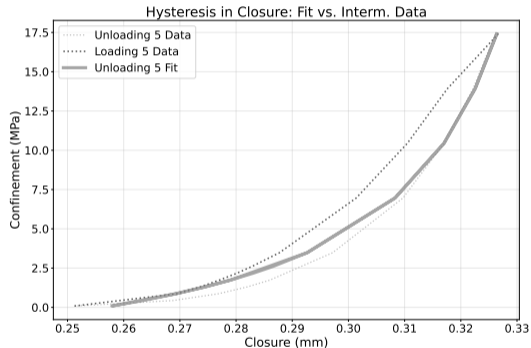
- Bounding data.
- Fixed maximum point.
- Discrepancy between loading data and fit.



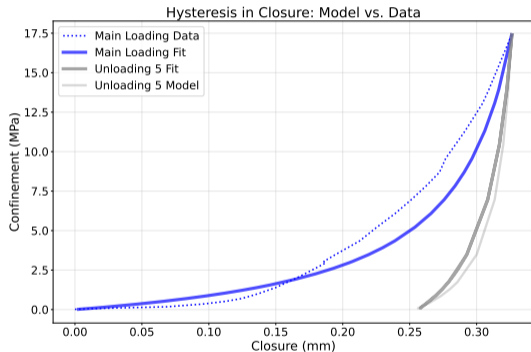
- Simplification of hysteresis in the unloading and loading segment

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

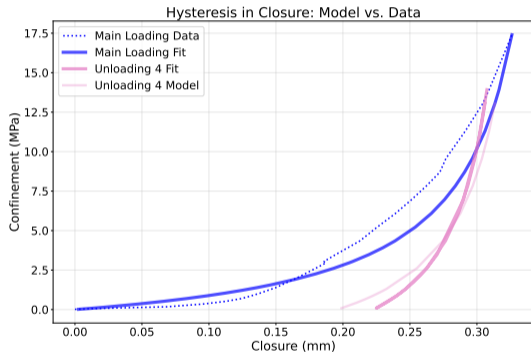
- Curve fitting to loading/unloading data.
- Goal: approximate an average intermediate curve.



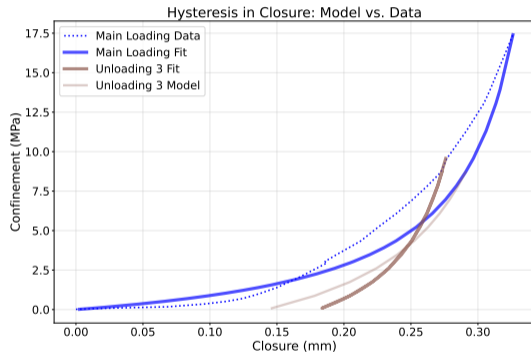
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



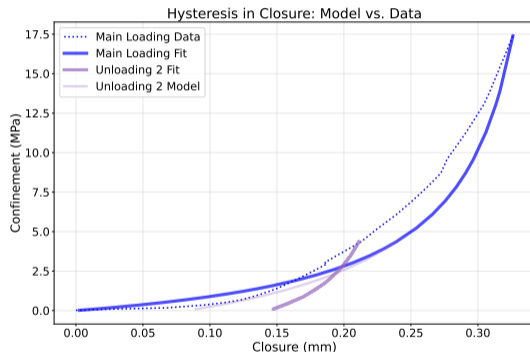
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



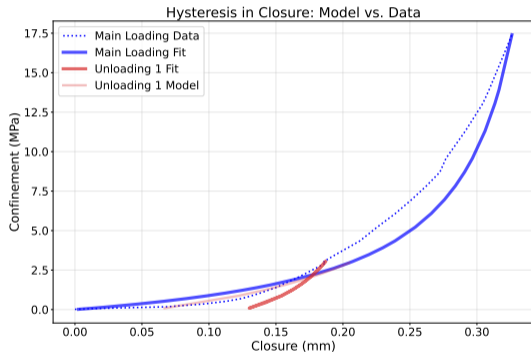
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



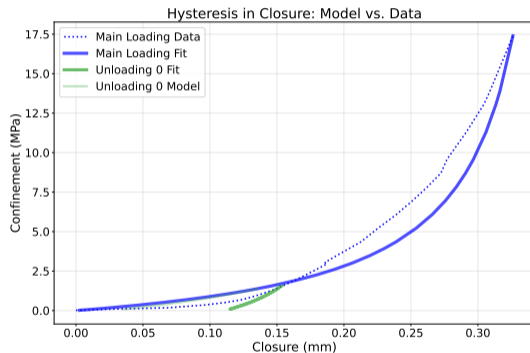
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



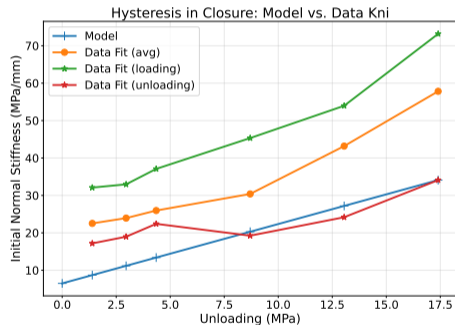
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



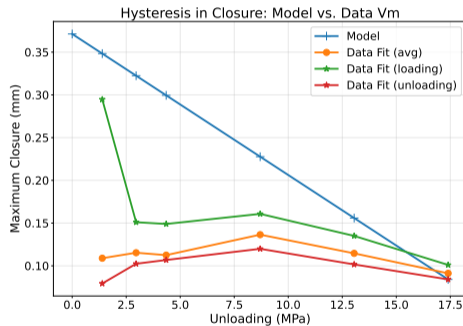
- Comparison between model prediction and data.
- Goal: approximate an average intermediate curve.
- Error increases as unloading stress decreases.



- Comparison of K_{ni} between the model and fitted curves.
- Unloading value = maximum stress value before unloading starts
- 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.



- 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.



- 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.

Thank you for your attention!

Funding



PETROBRAS

Contact: `jsantos@lncc.br`