Design of new laboratory earthquake experiment

Abdallah Aoude[1] , Ioannis Stefanou[1] , Jean-Francois Semblat[2] , Vito Rubino[1]
[1]Nantes Université, Ecole Centrale Nantes, CNRS, Institut de Recherche en Génie Civil et Mécanique (GeM), UMR 6183, F-44000 Nantes, France
[2]ENSTA-Paris, Institute of Mechanical Sciences and Industrial Applications
abdallah.aoude@ec-nantes.fr, ioannis.stefanou@ec-nantes.fr, jean-francois.semblat@ensta-paris.fr, vito.rubino@ec-nantes.fr

European Research Council
Established by the European Commission
CoQuake.com
This presentation participates in OSPP
Outstanding Student & PhD candidate Presentation contest

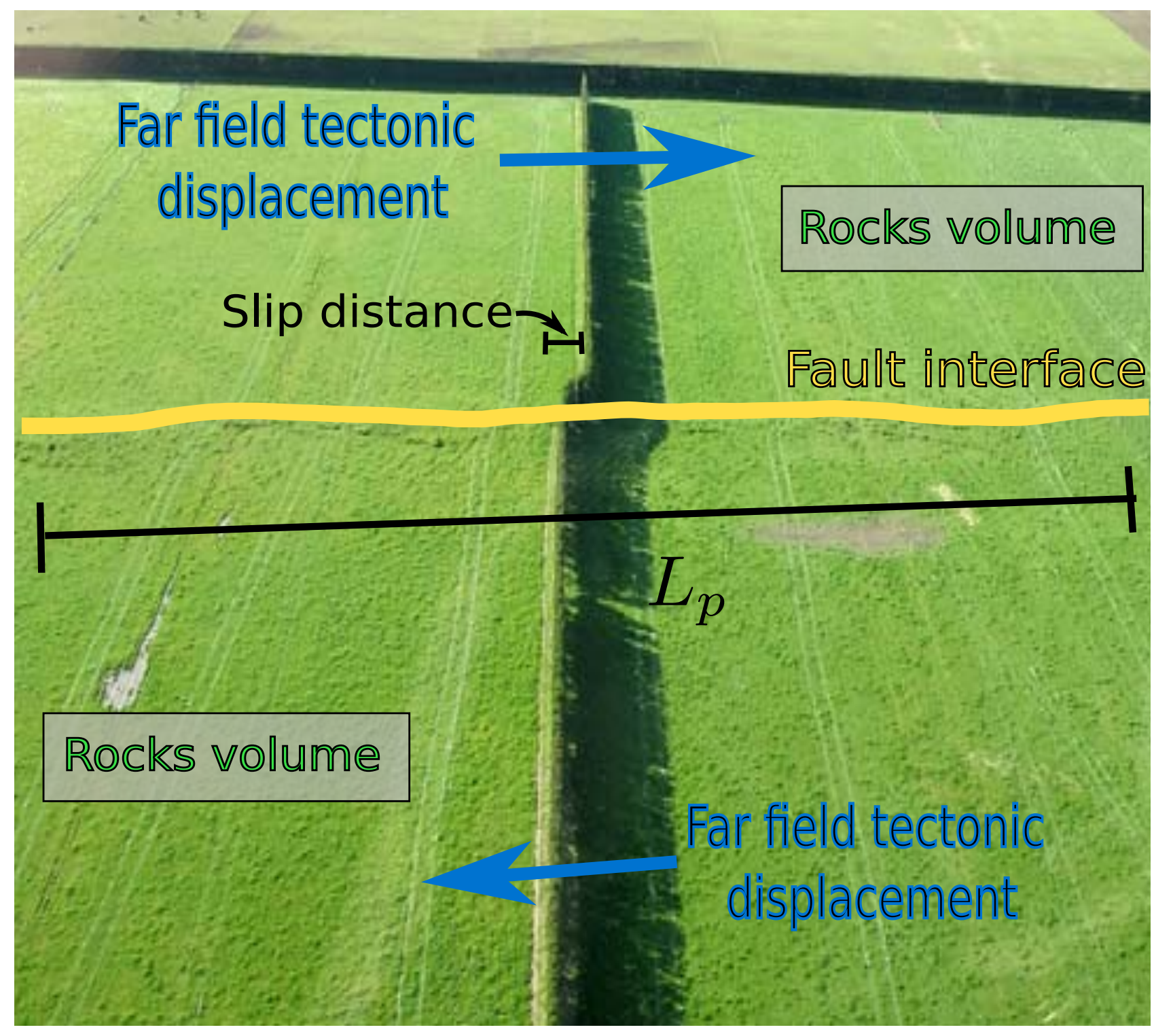
1-Context

Human activities can induce seismicity by injecting fluids into the Earth's crust, as observed in geothermal operations. Recently, it has been demonstrated that controlling the pressure of the injected fluids can mitigate earthquakes. These mitigation strategies are designed using the mathematical theory of control [1-4].

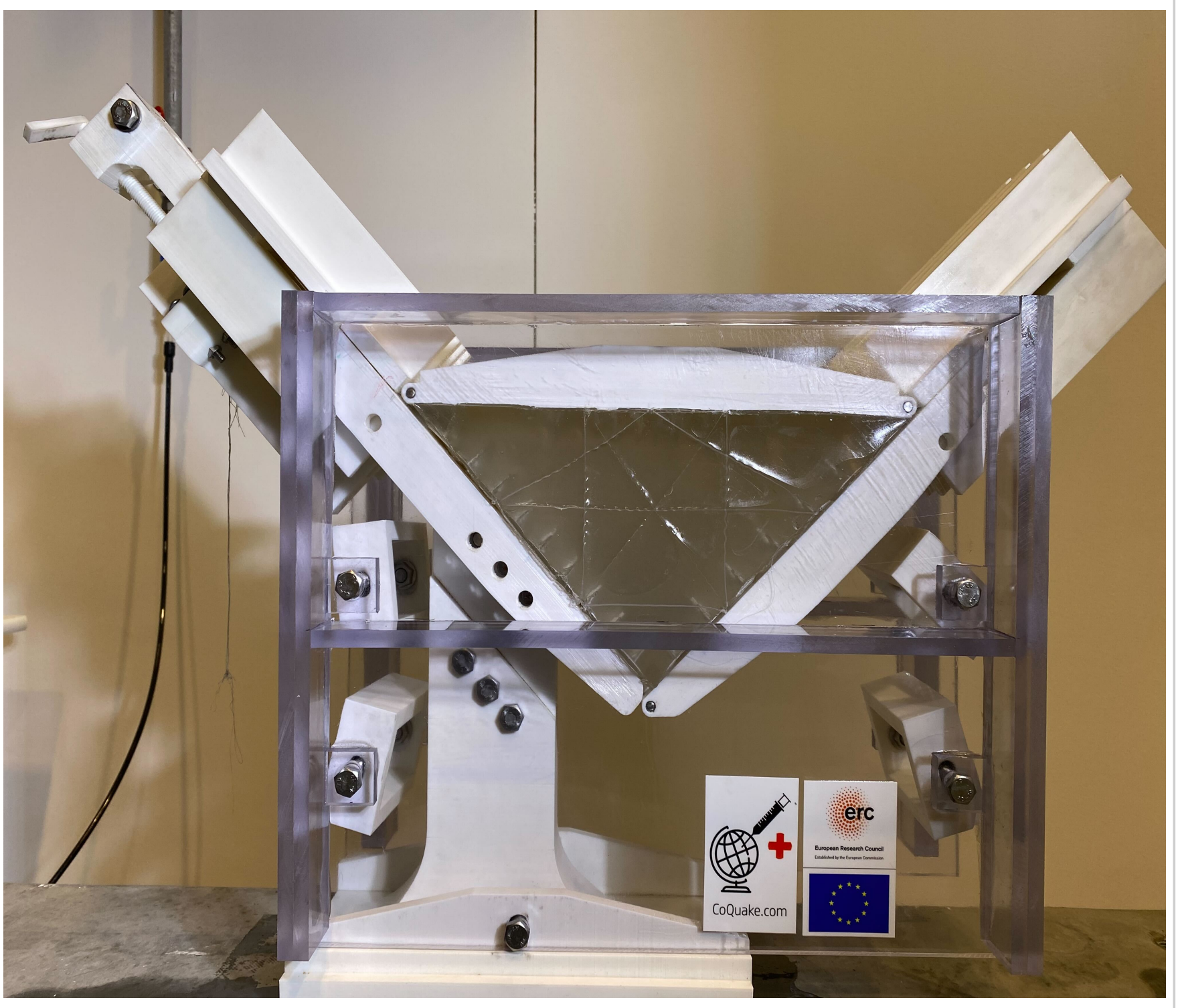
In this study, we present a new experimental setup designed to test the mathematical theory of control. It consists of an analog fault surrounded by an elastic material, enabling us to study slip propagation.

2-Laboratory experiment: Scaling laws

The design is based on scaling rules used to downscale instabilities of earthquakes from natural faults (prototypes) to laboratory (models).



https://www.geonet.org.nz/news/3G1zOkLuWbwLdrDF6Klq5x



Scaling rules:

$$\lambda_{\Delta\tau} = \frac{\lambda_G \lambda_\delta}{\lambda_L}$$

$$\lambda_t = \frac{\lambda_L}{\lambda_{c_s}}$$

$$\lambda_L = \frac{\lambda_{\Delta\tau}}{\lambda_{M_0}}$$

$$\lambda_X = \frac{\text{model quantity } X_m}{\text{prototype quantity } X_p}$$

Physical quantities	Non-dimensional ratio
$\Delta\tau$ shear stress drop	$\lambda_{\Delta\tau} = \frac{(\Delta\tau)_\mathrm{m}}{(\Delta\tau)_\mathrm{p}}$
δ slip distance	$\lambda_\delta = \frac{\delta_\mathrm{m}}{\delta_\mathrm{p}}$
L length scale	$\lambda_L = \frac{L_\mathrm{m}}{L_\mathrm{p}}$
c_s shear wave velocity	$\lambda_{c_s} = \frac{(c_s)_\mathrm{m}}{(c_s)_\mathrm{p}}$
G shear modulus	$\lambda_G = \frac{G_\mathrm{m}}{G_\mathrm{p}}$
M_0 seismic moment	$\lambda_{M_0} = \frac{(M_0)_\mathrm{m}}{(M_0)_\mathrm{p}}$
t time	$\lambda_t = \frac{t_\mathrm{m}}{t_\mathrm{p}}$

3-Technical constraints and scenarios

Reference parameters:

$G_p = 30$ GPa	$(\Delta_\tau)_p = 3$ MPa	$L_m^{max} = 0.2$ m
Typical shear modulus for rocks	Typical shear stress drop for an earthquake	Desired fault length in the laboratory

Constraints:

Minimum time required to sample data and control instabilities, $t^{sample}>10$ ms → $G_m = 8000$ Pa, $(c_s)_m = 3.07$ m/s — properties of the material selected to reduce the time scale

Minimum slip to be measured with sensors $\delta_m^{min} = 0.7\mathrm{mm}$ → $(\Delta_\tau)_m = 1000$ Pa — Shear stress drop needed at the analogue fault

Scenario 1: Maximum earthquake magnitude $M_w = 4$

Using empirical equations, L_p for $M_w=4$ is: $L_p^{max} = 1100$ m

$$\lambda_L = \frac{L_m^{max}}{L_p^{max}} = 1.2^{-4} \longrightarrow L_m^{min} = \lambda_L L_p = 0.02 \text{ m}$$

Maximum slip time estimation: $t_m^{max} = 100$ ms

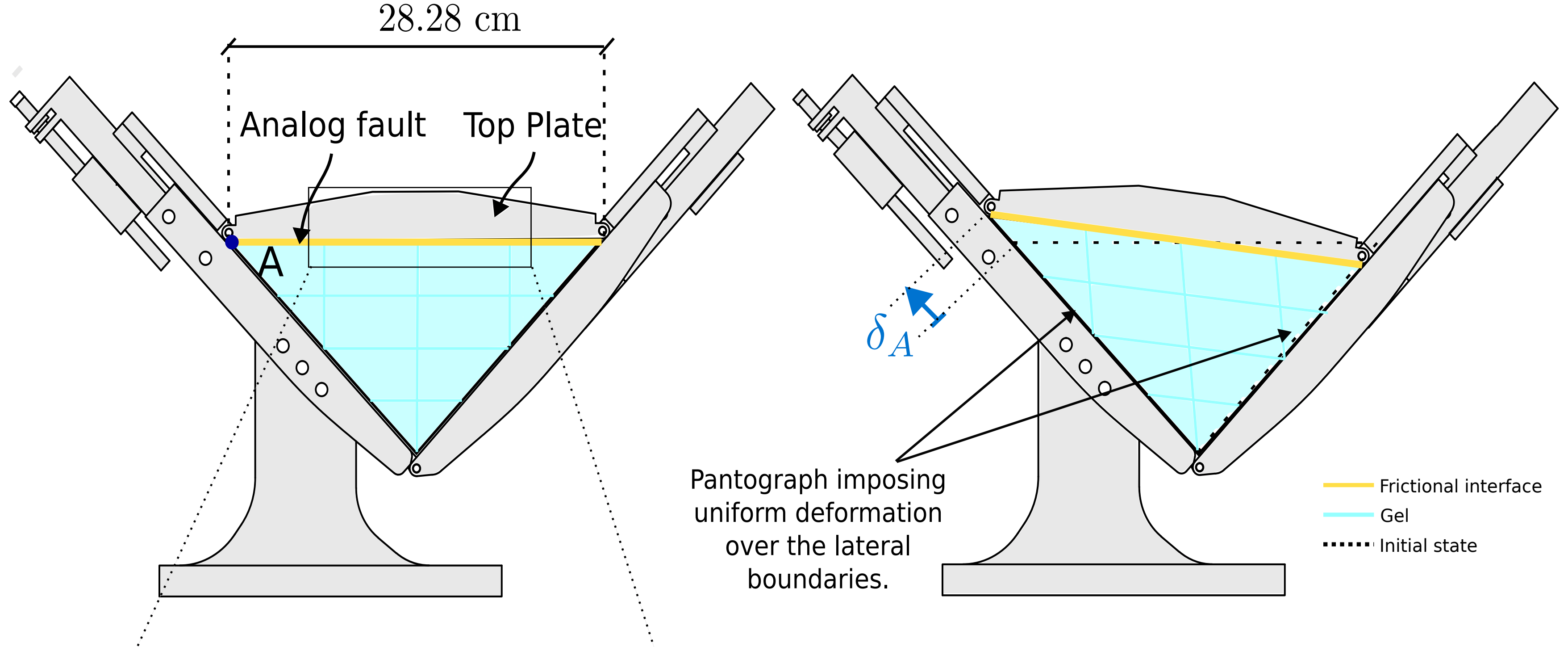
Scenario 2: Minimum Earthquake magnitude $M_w = 2$

Using empirical equations, L_p for $M_w=2$ is: $L_p^{min} = 110$ m

Minimum slip time estimation: $t_m^{min} = 10$ ms

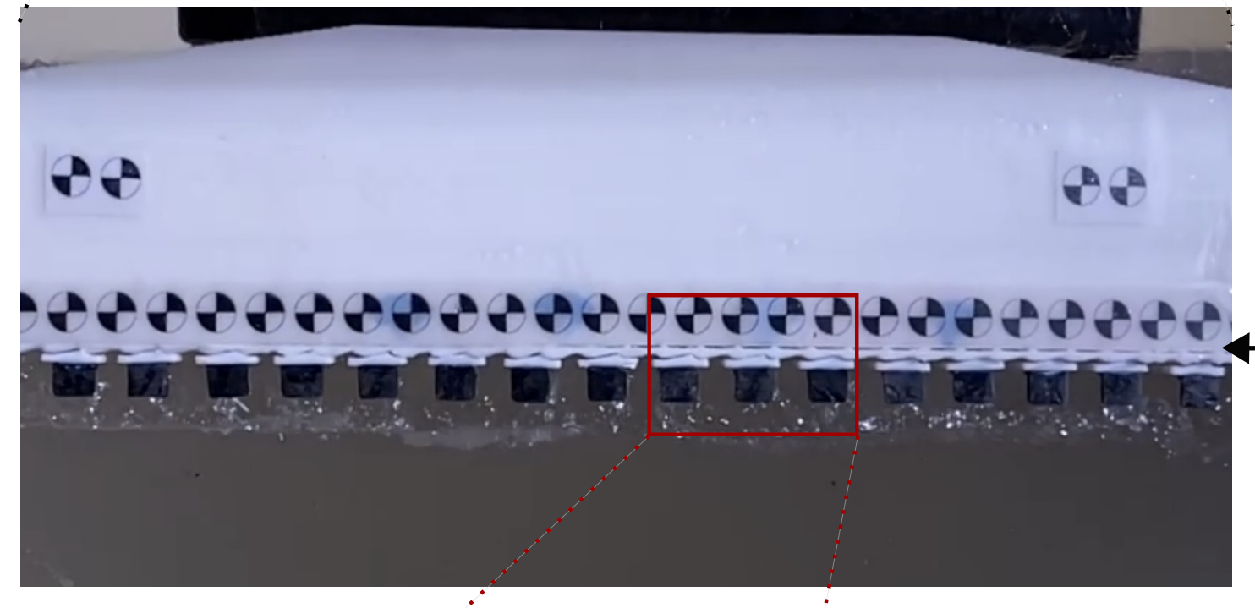
4-Earthquake mechanical apparatus

Assuming the gel is incompressible, the system has a single degree of freedom, which is choosen to be the position of point A.

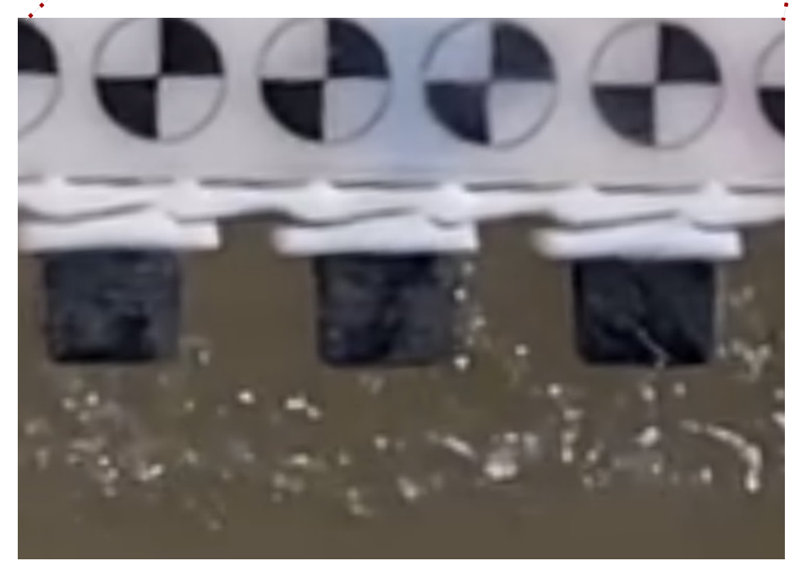


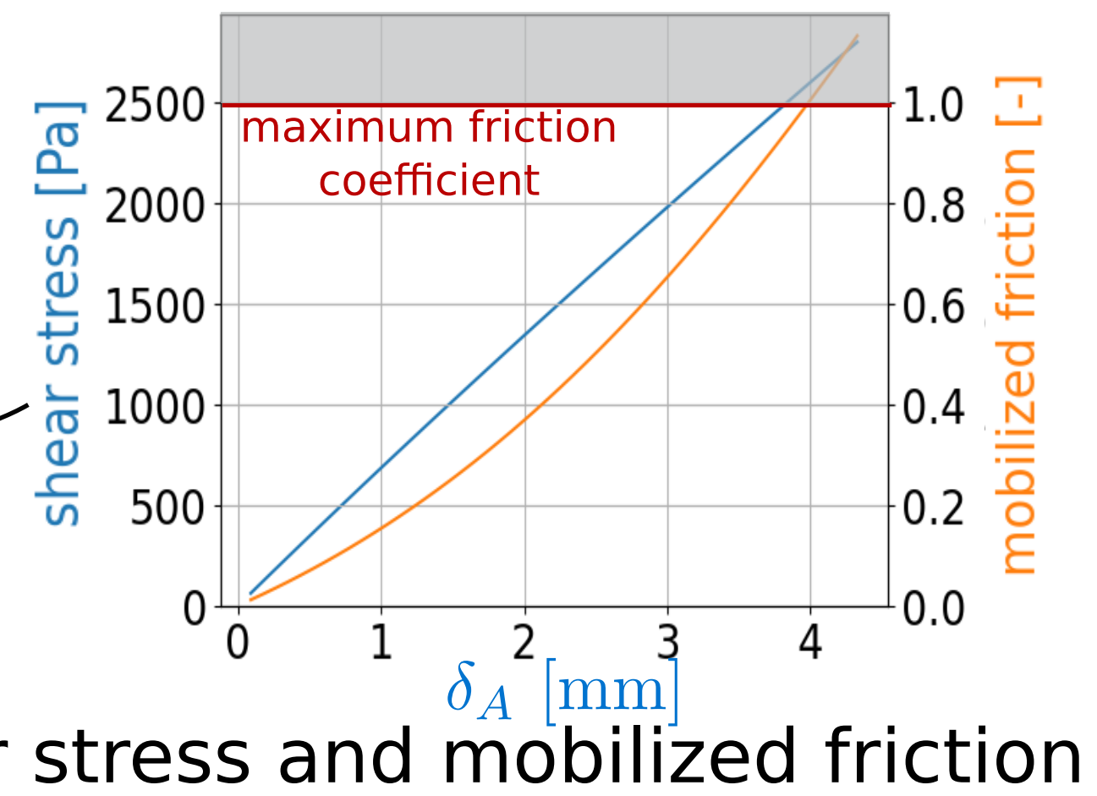
Before deformaton

After deformaton

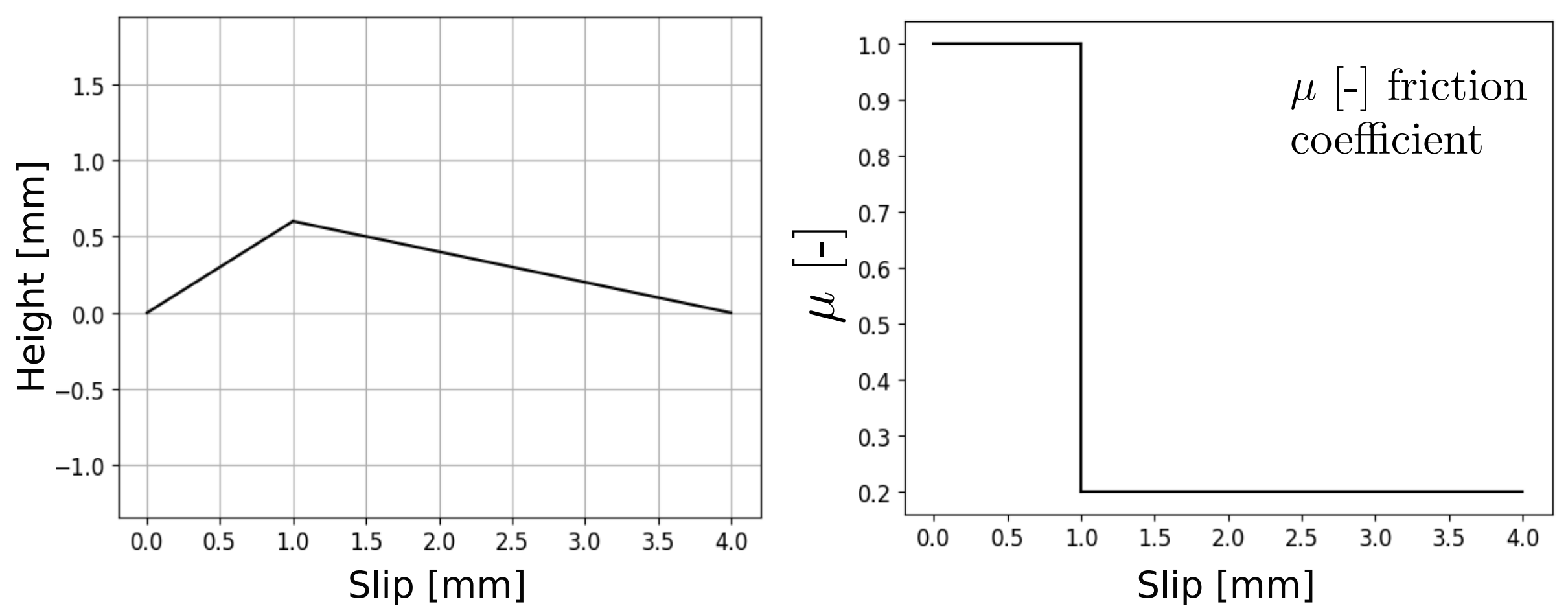


16 patches



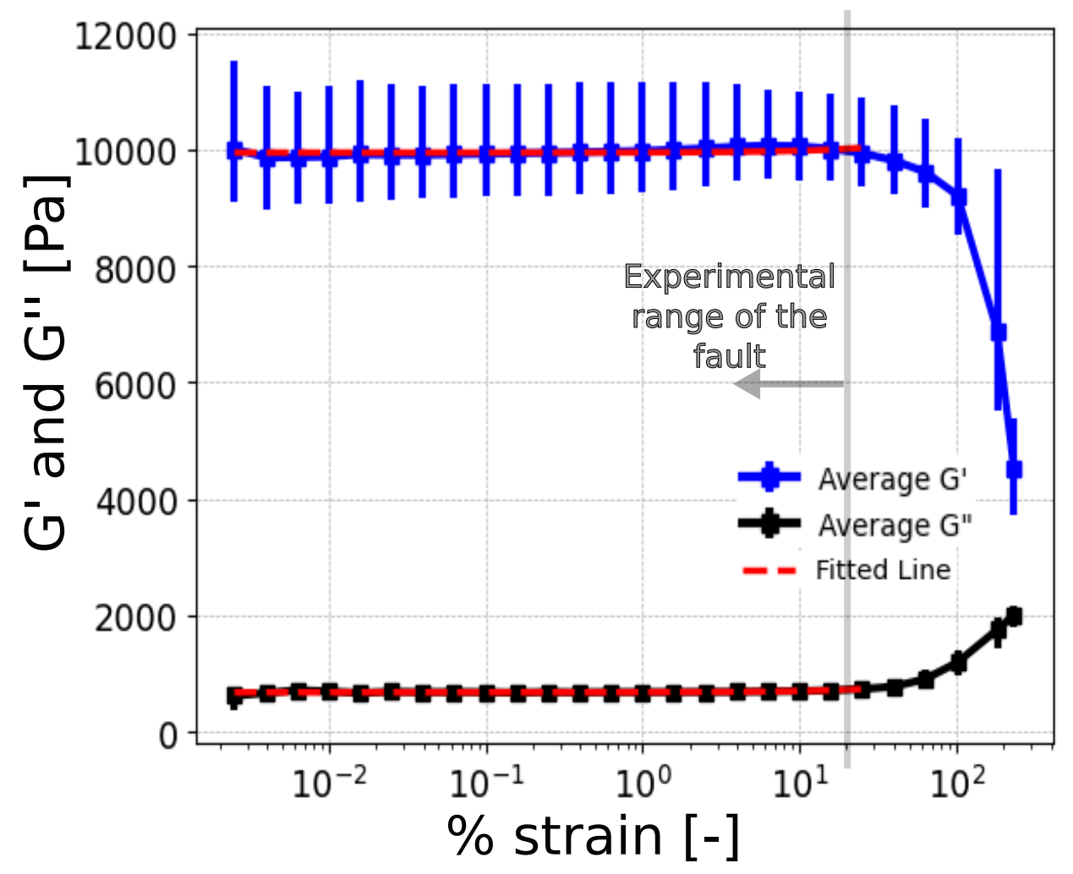


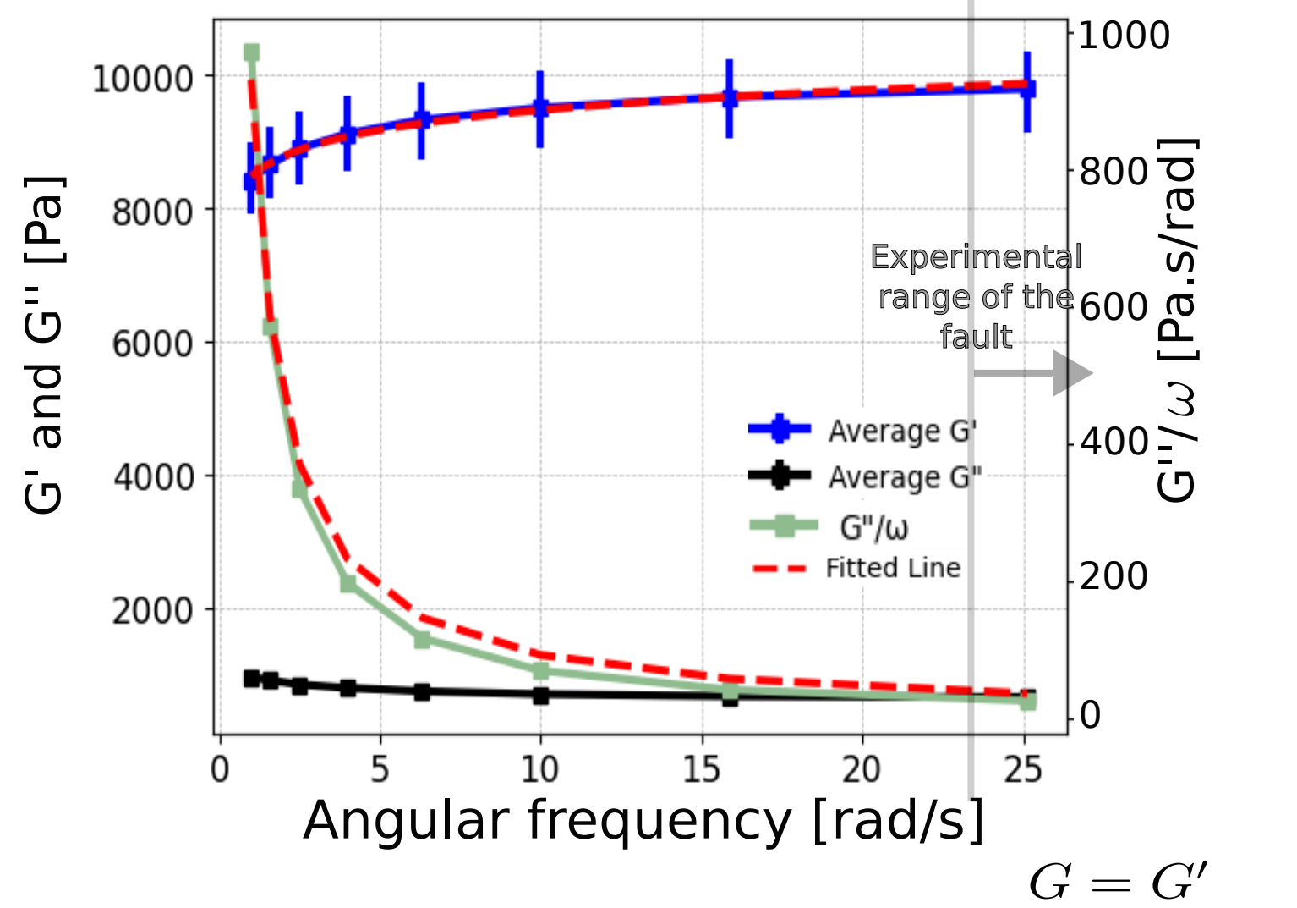
Shear stress and mobilized friction at the analogue fault



Geometric profile of 1 patch and its corresponding frictional evolution with slip

5-Rheology of the gel

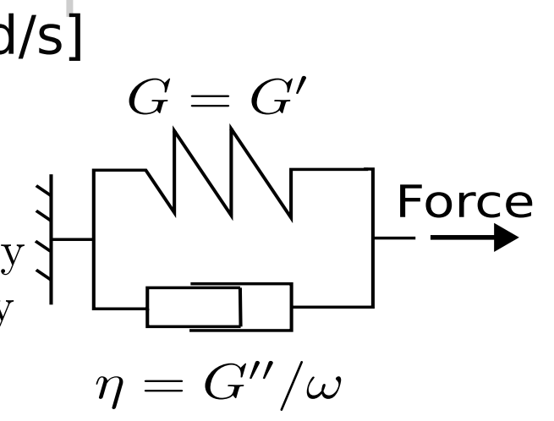




Linearity → 0% to 300% strain

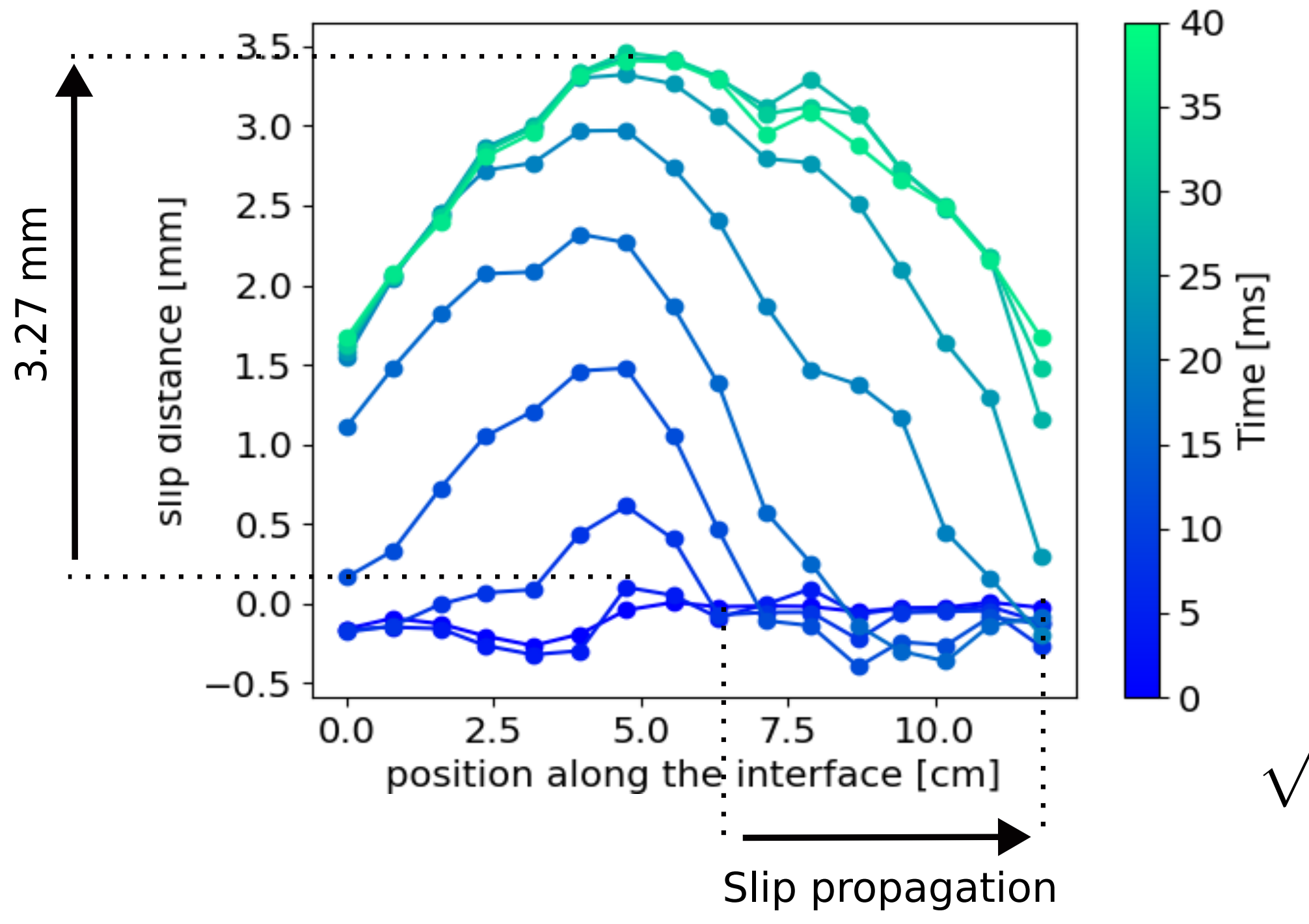
High strain rate → Low viscosity

Kelvin-Voigt model:



G' storage modulus ω angular frequency
G" loss modulus η dynamic viscosity

6-Slip propagation measured experimentally



Particle tracking velocimetry

Rupture speed $v_r = 4.4$ m/s

Theoretical [5] and experimental [6] range for v_r:

$$c_s < v_r < \sqrt{2}c_s$$

$$\sqrt{G/\rho} \approx 3.4 \text{ m/s} \qquad 4.8 \text{ m/s}$$

7-Conclusions and perspectives

A new laboratory earthquake experiment is designed, composed of an analogue fault surrounded by elastic media.

Deforming the analog rock increases the shear stress at the interface, thus allowing instabilities to take place.

The slip measured using particle tracking velocimetry propagates at a speed between c_s^{gel} and $\sqrt{2}c_s^{gel}$, as expected.

Next step: adjust the effective stress over the analogue fault using control theory [1-4], to avoid instabilities and achieve controlled slip rates.

References

[1] Stefanou, Ioannis. "Controlling anthropogenic and natural seismicity: Insights from active stabilization of the spring-slider model." Journal of Geophysical Research: Solid Earth 124.8 (2019): 8786-8802. doi: https://doi.org/10.1029/2019JB017847

[2] Stefanou, Ioannis, and Georgios Tzortzopoulos. "Preventing Instabilities and Inducing Controlled, Slow-Slip in Frictionally Unstable Systems." Journal of Geophysical Research: Solid Earth 127.7 (2022): e2021JB023410. doi: https://doi.org/10.1029/2021JB023410

[3] Tzortzopoulos, G., Controlling earthQuakes (CoQuake) in the laboratory using pertinent fault stimulating techniques. PhD thesis, École centrale de Nantes (2021). doi: https://tel.archives-ouvertes.fr/tel-03670423

[4] Gutiérrez-Oribio, D., Tzortzopoulos, G., Stefanou, I., & Plestan, F. (2022). Earthquake Control: An Emerging Application for Robust Control. Theory and Experimental Tests. IEEE Transactions on Control Systems Technology. doi: https://doi.org/10.1109/TCST.2023.3242431

[5] Huang, Y., Wang, W., Liu, C., & Rosakis, A. J. (1998). Intersonic crack growth in bimaterial interfaces: an investigation of crack face contact. Journal of the Mechanics and Physics of Solids, 46(11), 2233-2259. https://doi.org/10.1016/S0022-5096(98)00003-9

[6] Latour, S., Gallot, T., Catheline, S., Voisin, C., Renard, F., Larose, E., & Campillo, M. (2011). Ultrafast ultrasonic imaging of dynamic sliding friction in soft solids: The slow slip and the super-shear regimes. Europhysics Letters, 96(5), 59003. doi: https://doi.org/10.1209/0295-5075/96/59003

Acknowledgments. The authors would like to acknowledge the support of the European Research Council (ERC) under the EUH 2020 program (Grant ID 757848 CoQuake).