Hybrid FEM-Peridynamic Modelling of Supershear Earthquake Ruptures

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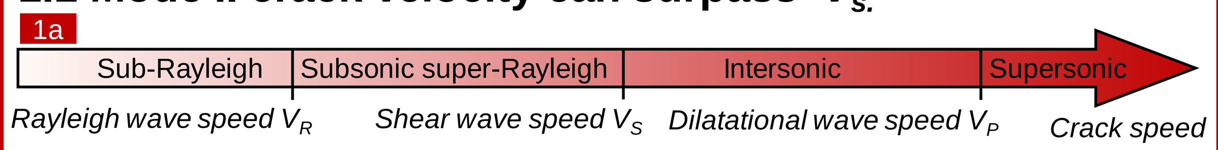
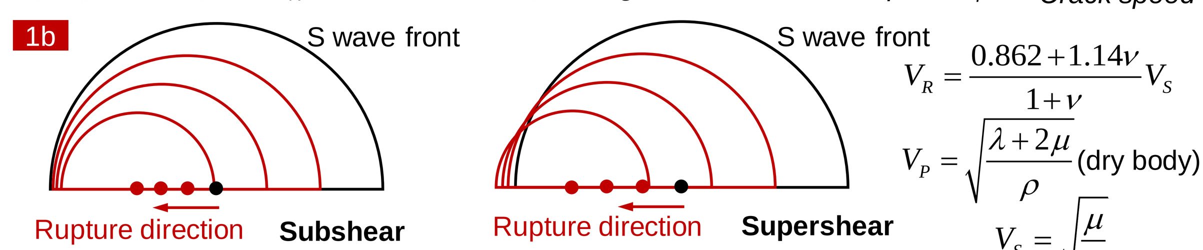
1. Motivation

1.1 Mode II crack velocity can surpass V_s.

1a



1b



$$V_R = \frac{0.862+1.14\nu}{1+\nu} V_S$$

$$V_P = \sqrt{\frac{\lambda+2\mu}{\rho}} \text{ (dry body)}$$

$$V_S = \sqrt{\frac{\mu}{\rho}}$$

1.2 The role of fluids on the supershear transition

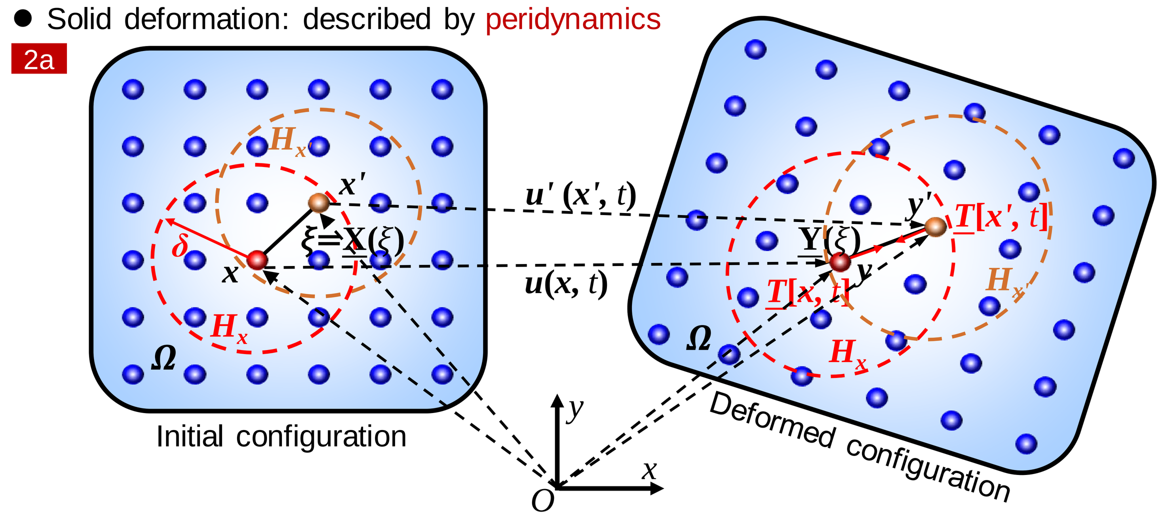
Supershear ruptures sometimes propagate along **sub-planar strike-slip mature faults** (Bao et al., 2022). Here we propose that **fluid saturated damage zones** may trigger the transition **from sub-shear to supershear**.

2. Method

2.1 Hybrid peridynamic-FEM framework (Silling, 2007)

- Solid deformation: described by peridynamics

2a

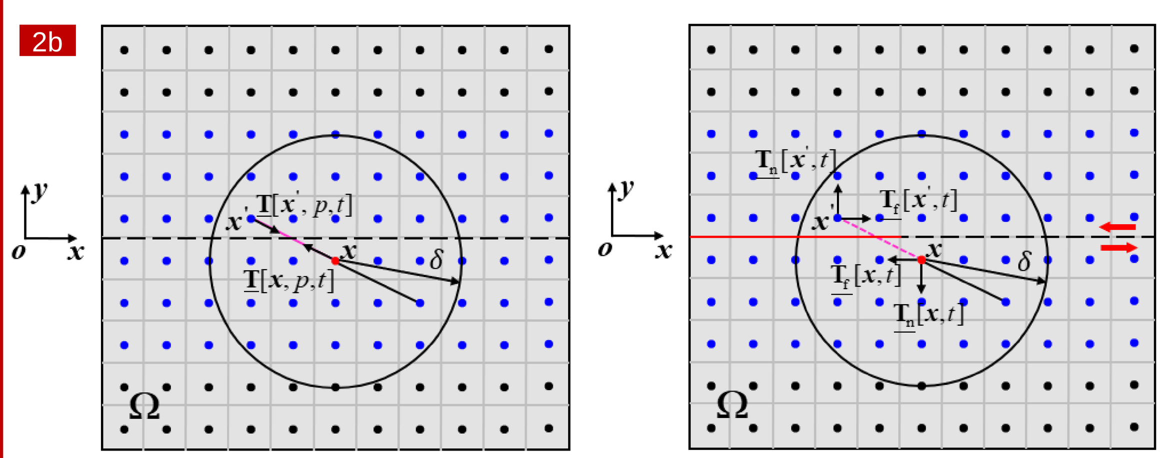


- Fluid flow: described by FEM

$$\rho(x)\ddot{u}(x,t) = \int_{H_x} \left\{ \underline{T}[x,p,t]\langle x'-x\rangle - \underline{T}[x',p',t]\langle x-x'\rangle \right\} dV_{x'} + b(x,t)$$

2.2 Nonlocal friction interface model (Lu et al., 2021)

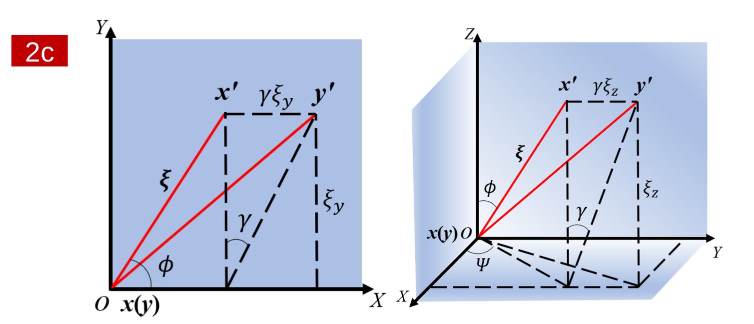
2b



Peridynamic force on the interface — Contact force and friction force

2.3 Failure criterion for mode II crack (Zhang and Qiao, 2019)

2c



2D contition — 3D condition

$$\gamma_c = \begin{cases} \sqrt{\dfrac{75\pi G_c}{64\mu\delta}} & \text{in 2D case} \\ \sqrt{\dfrac{288\pi G_c}{75\mu\delta}} & \text{in 3D case} \end{cases}$$

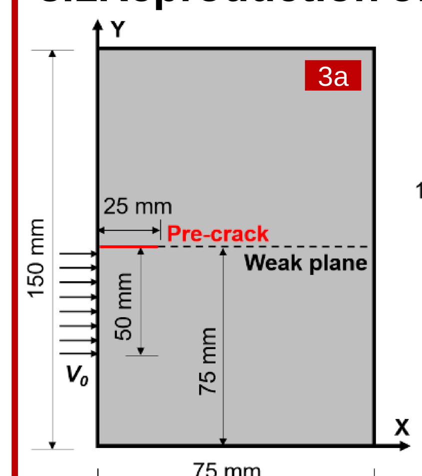
G_c: critical energy release rate
μ: shear modulus
δ: horizon radius

3. Hybrid FEM-perydynamic modeling of rupture and sub-shear to supershear transitions

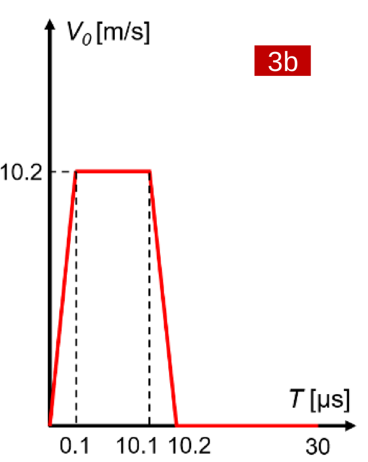
3.1 Reproduction of experiment for bullet impacting homalite plate

(Yolum et al., 2021)

3a



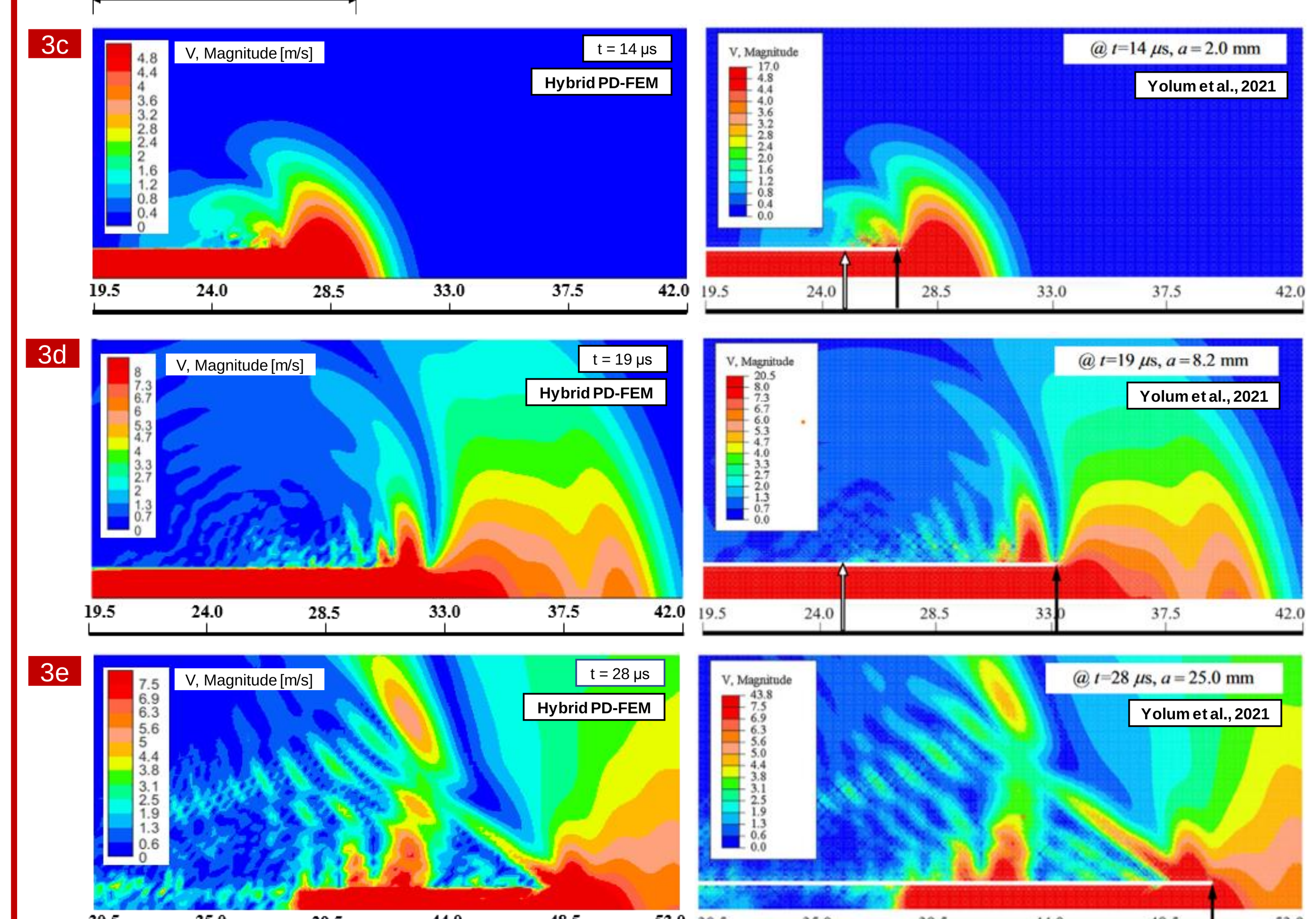
3b



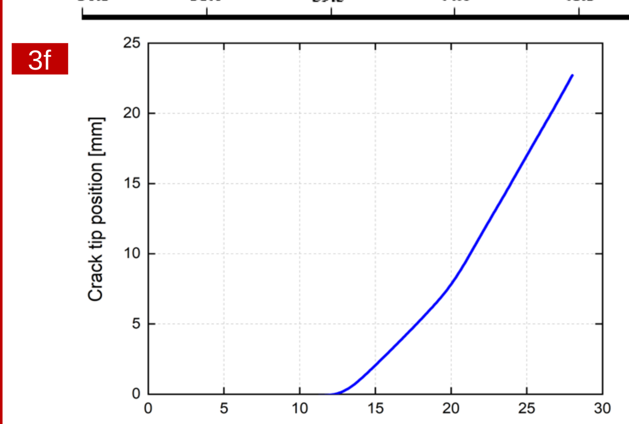
Mechanical parameters of the plate

Material property	Value
Thickness	1 mm
Pre-crack length	25 mm
Elastic modulus	5.2 GPa
Poisson's ratio	1/3
Solid density	1246 kg/m³
Interface fracture toughness	1.2 J/m²

3c, 3d, 3e

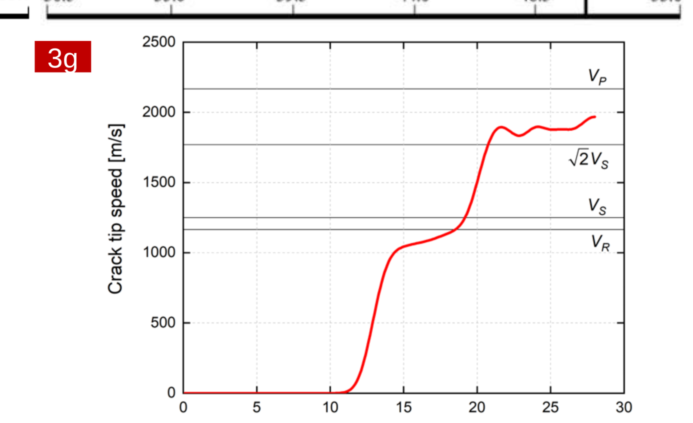


3f



Evolution of crack tip position

3g

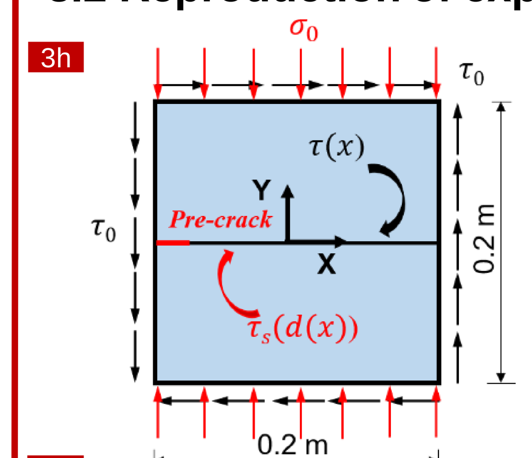


Evolution of crack tip velocity

3.2 Reproduction of experiment for rupture along PMMA fault

(Svetlizky et al., 2016)

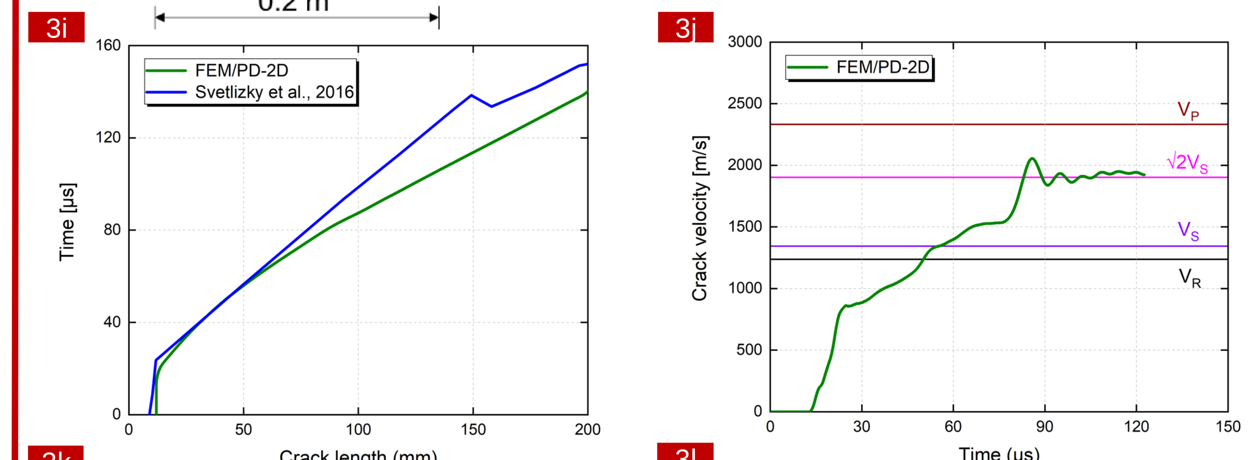
3h



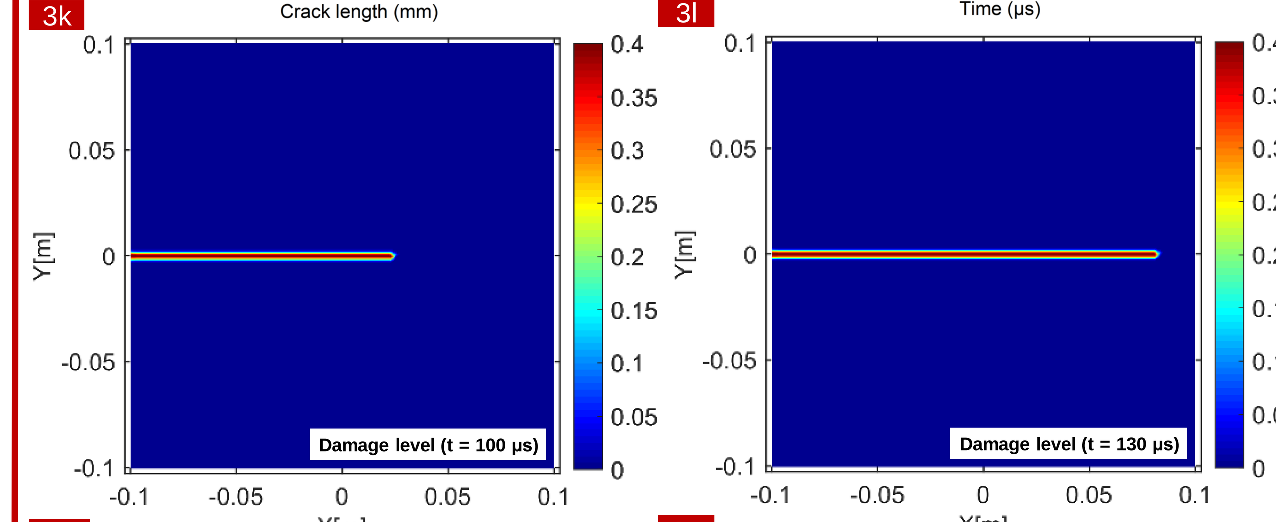
Mechanical parameters of the PMMA blocks

Material property	Value
Elastic modulus	5.65 GPa
Poisson's ratio	0.33
Solid density	1160 kg/m³
Static friction	5.3 MPa
Sliding friction	3.7 MPa
Critical slip distance	1.4 μm
Interface fracture energy density	1.12 J/m²

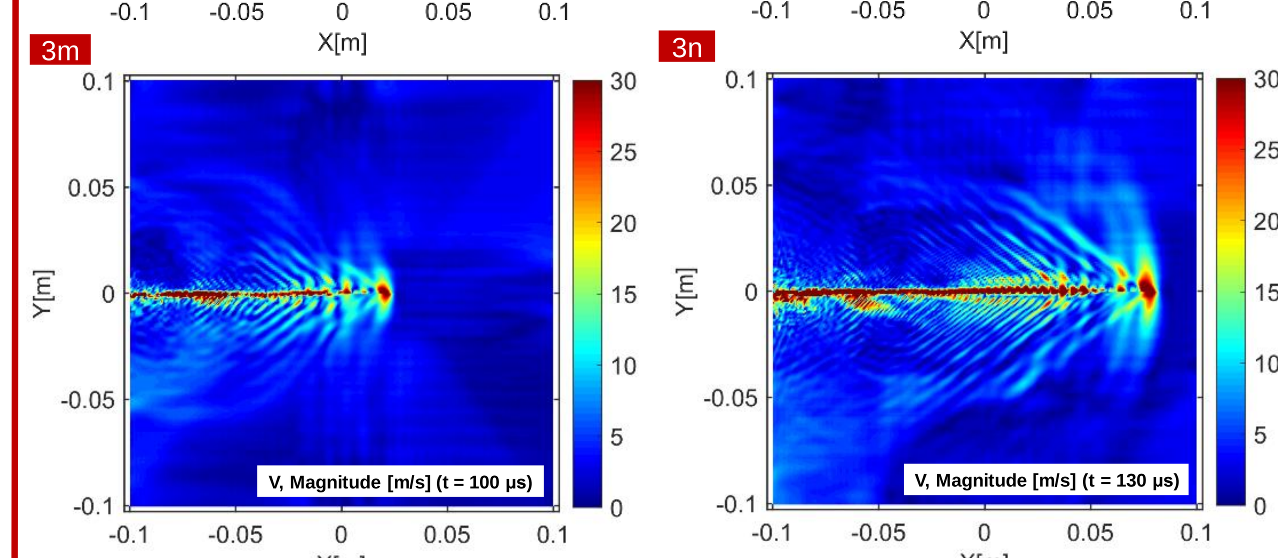
3i, 3j



3k, 3l



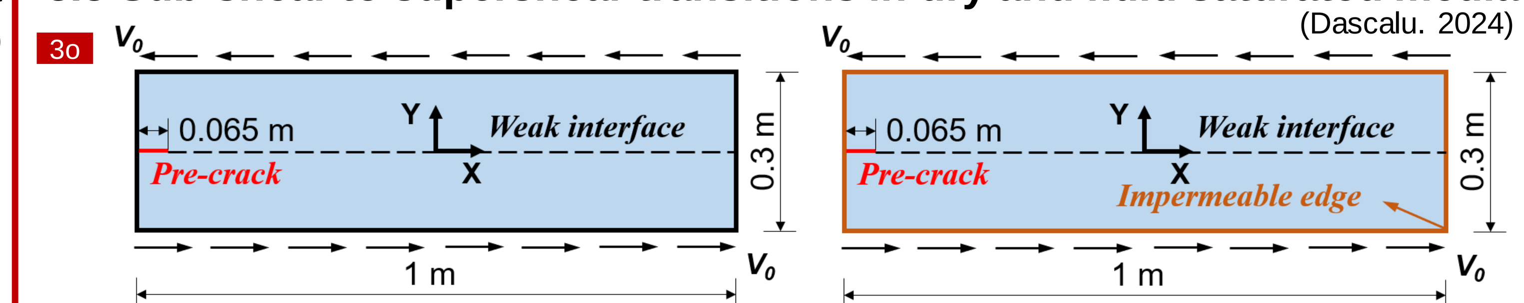
3m, 3n



3.3 Sub-shear to supershear transitions in dry and fluid saturated media

(Dascalu. 2024)

3o



Dry condition — Saturated condition

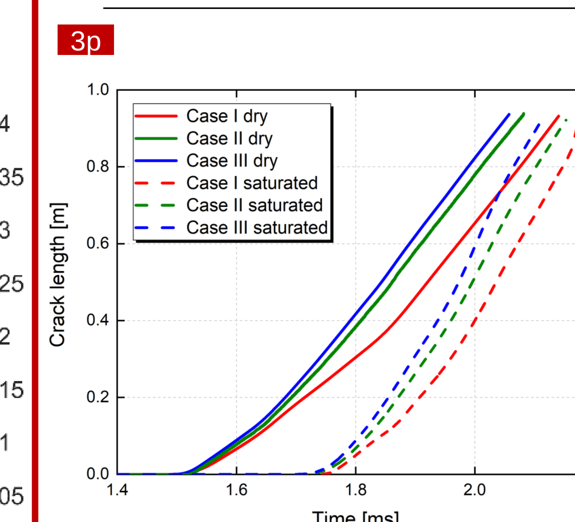
Shear loading velocity in different cases

Boundary velocity	Case I	Case II	Case III
Value [m/s]	3.75×10⁻²	3.875×10⁻²	4.00×10⁻²

Fluid and mechanical parameters adopted in the FEM/PD-2D model

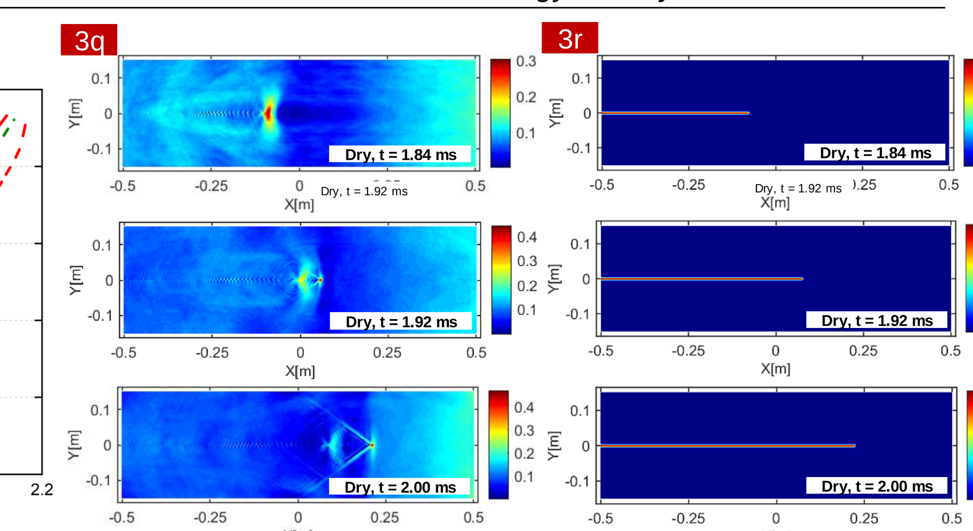
Material property	Value	Material property	Value
Elastic modulus	5.3 GPa	Permeability	10⁻¹² m²
Poisson's ratio	0.35	Porosity	0.01
Solid density	1180 kg/m³	Dynamic viscosity	10⁻³ Pa·s
Fluid density	1000 kg/m³	Biot coefficient	1
Fluid bulk modulus	2.2 GPa	Interface fracture energy density	1 J/m²

3p



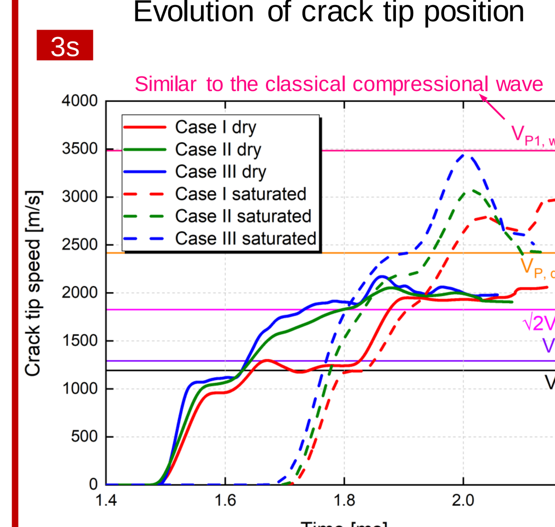
Evolution of crack tip position

3q, 3r



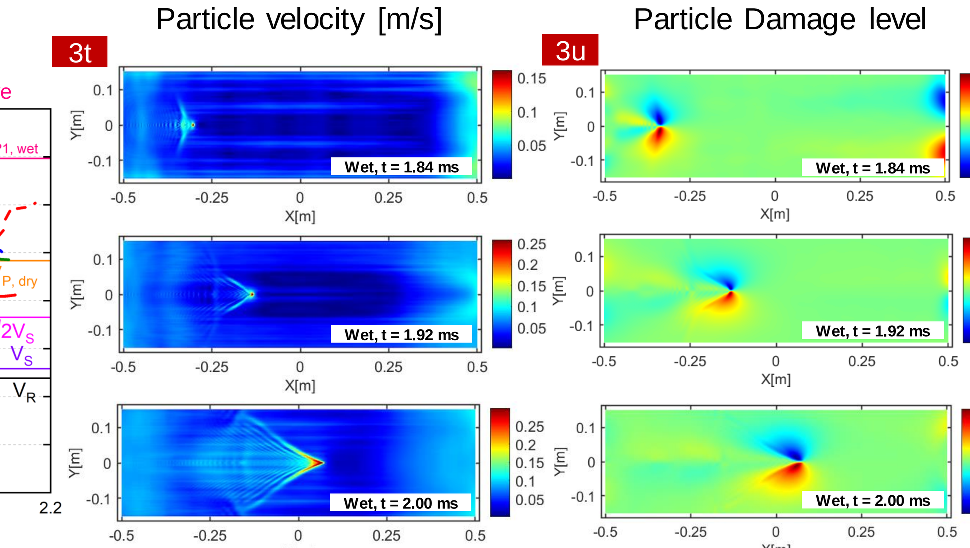
Particle velocity [m/s] — Particle Damage level

3s



Evolution of crack tip velocity

3t, 3u



Particle velocity [m/s] — Pore pressure [Pa]

4. Conclusion

- Supershear rupture can be achieved through either the indirect (Burridge-Andrews mechanism) or a direct transition.
- The velocity of shear cracks can surpass the shear wave speed (V_s) in dry media, and even approach the faster dilatational wave speed (V_{P1}), particularly in the fluid-saturated condition.
- The presence of the fluid phase enhances the sub-Raileigh to supershear transition due to poroelastic effects at the rupture front.

Reference

[1] Bao et al., Nature Geoscience (2022)
[2] Silling et al., Journal of Elasticity (2007)
[3] Lu et al., Theoretical and Applied Fracture Mechanics (2021)
[4] Zhang & Qiao, International Journal of Fracture (2019)
[5] Yolum et al, International Journal of Fracture (2021)
[6] Svetlizky et al., PNAS (2016)
[7] Dascalu. Engineering Fracture Mechanics (2024)

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