Development of a Coupled Hydro-Mechanical Model for Fracture Aperture and Permeability Evolution in Dual-Porosity Media

Presenter: Kai-Lin Hsu

Advisor: Prof. Shih-Jung Wang

Date: 2025.03.21

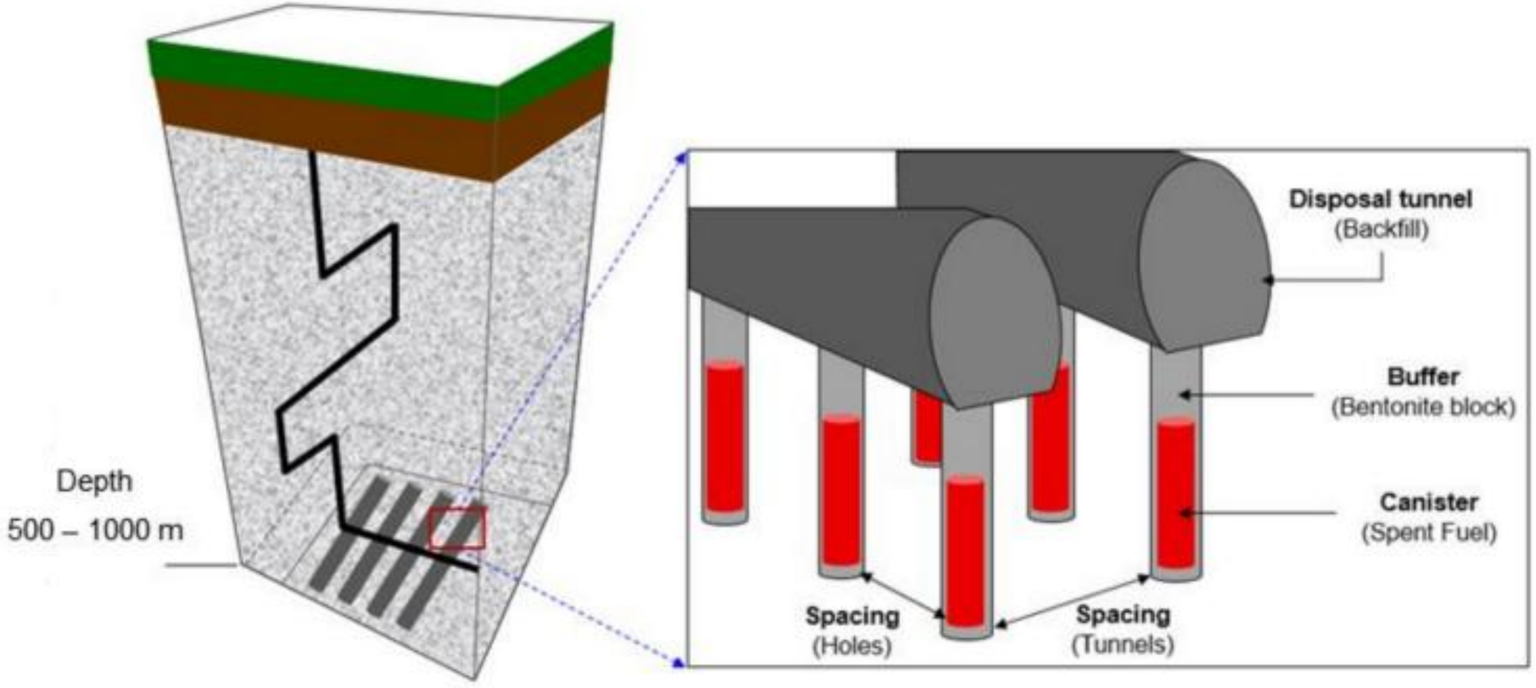
Outline

- Introduction
- Methodology
- Results
- Conclusions
- Future works

Introduction

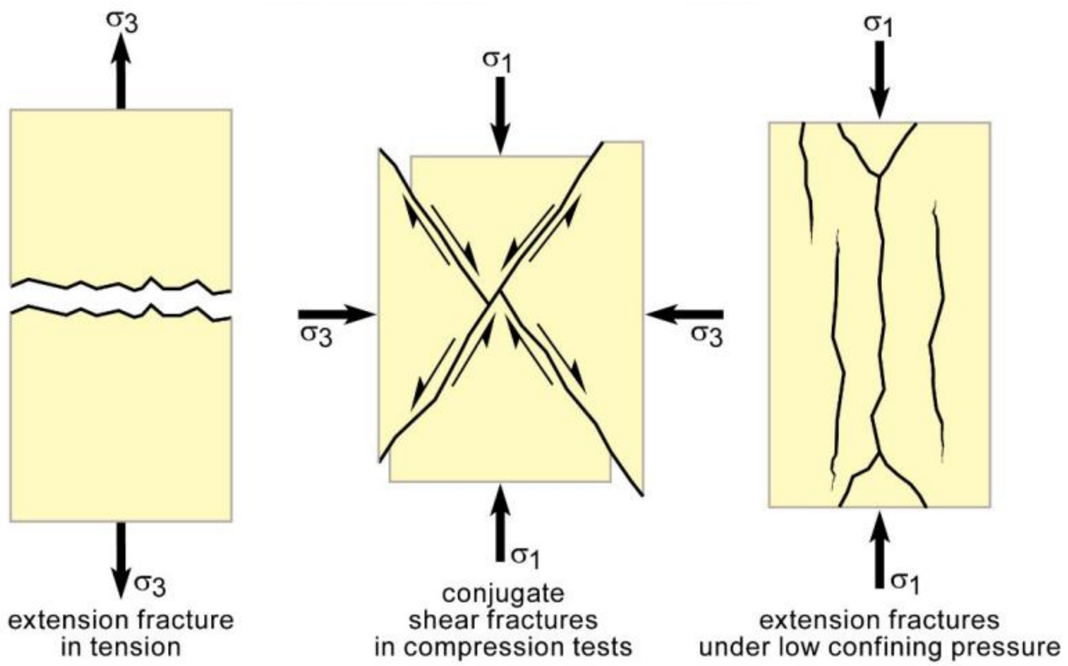
- The main international method for the final disposal of **high-level radioactive waste (HLW)** is to adopt the “Deep Geological Disposal” method.

- By burying high-level radioactive waste in stable strata at a depth of about 500 to 1,000 meters, and use multiple barriers to prevent nuclear species from affecting human beings health and environmental safety.



Schematics of deep geological repository and spacing of disposal tunnels and deposition holes. (Kim et al.,2023)

- **Fractures** in geological formations are formed due to the influence of stress on the bedrock, affecting hydraulic conductivity and the stability of the rock formations.



Three types of fractures observed in laboratory experiments (Burg, 2014)

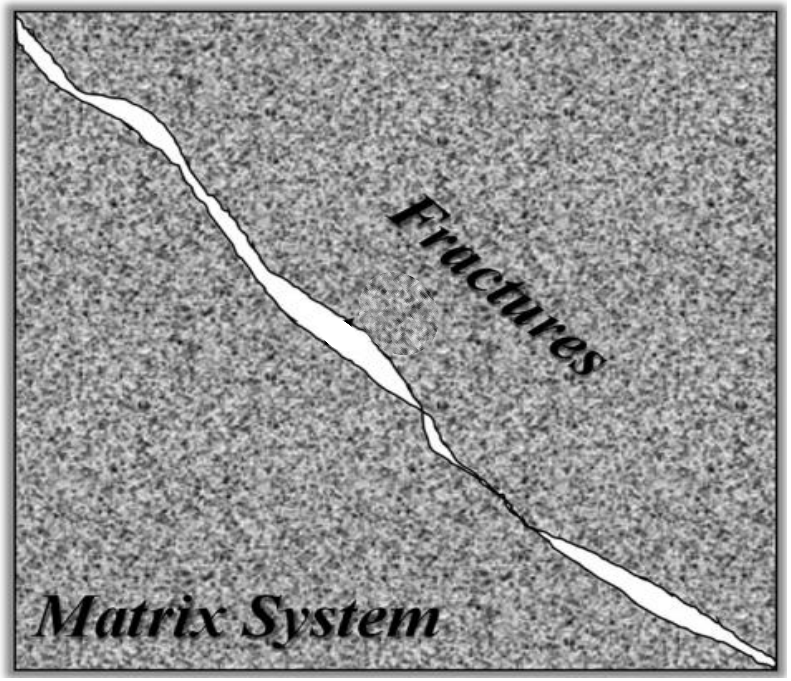
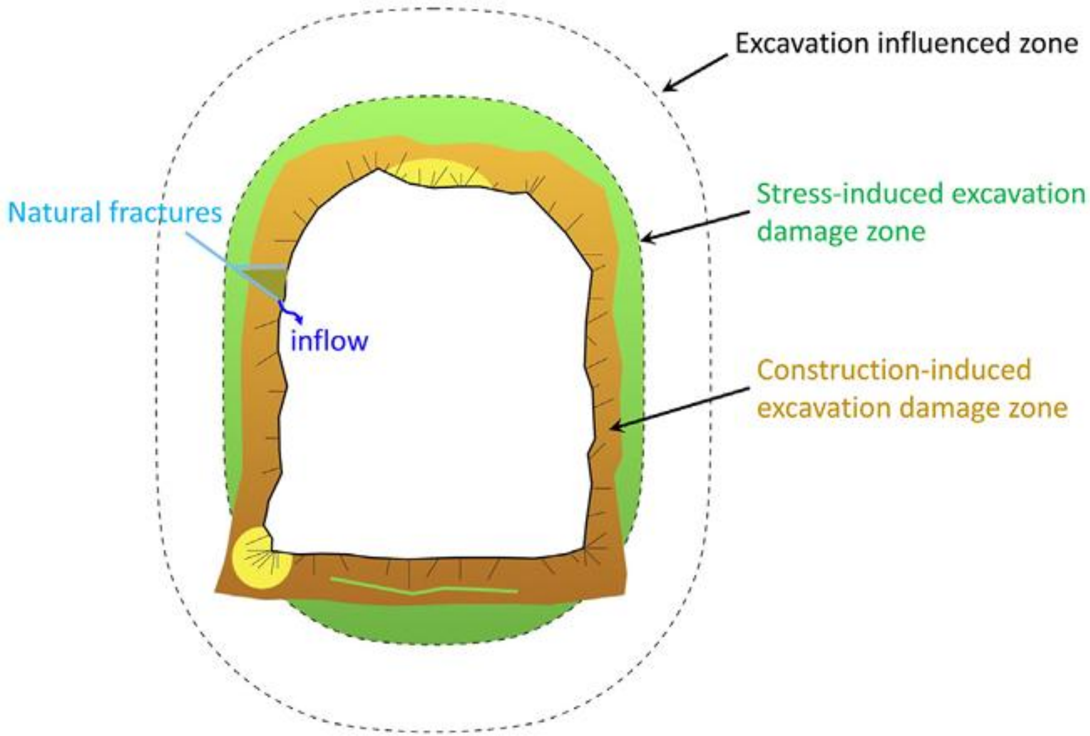


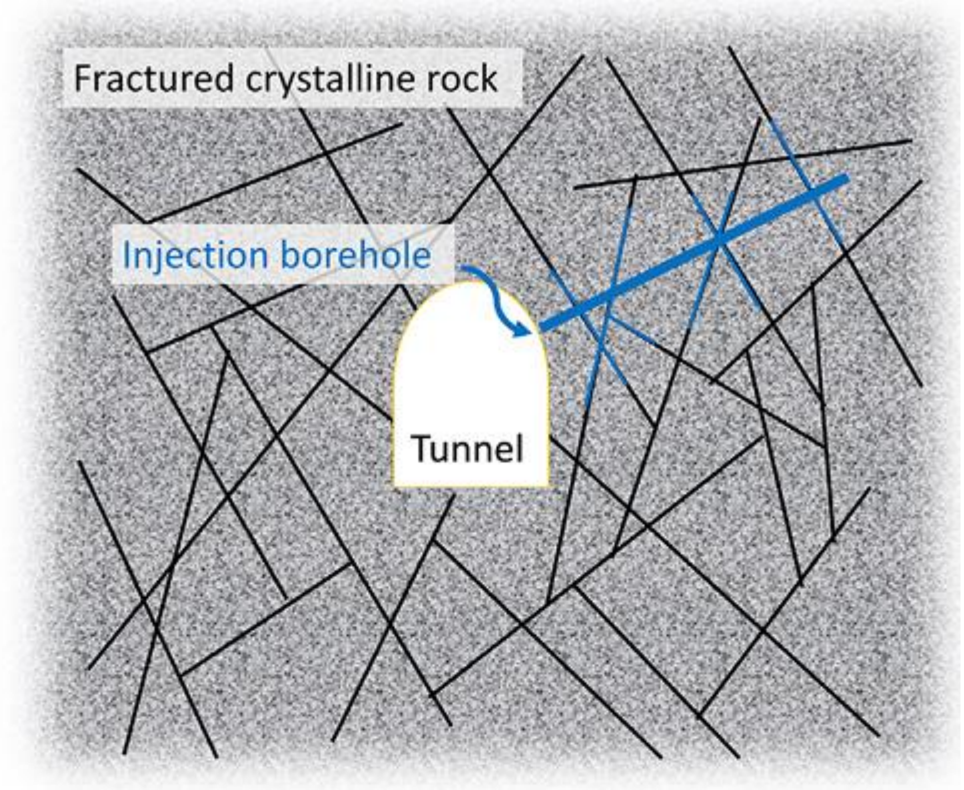
Diagram of fracture in Matrix system. (Song et al., 2023)

- In the EDZ (excavation damage zone), redistribution of in situ stresses and changes of the fracture structures will occur, which can consequently cause drastic changes in hydraulic and transport properties in the near-field of the host rock.

- The groundwater inflow may change the local hydro-geochemical conditions near the emplacement tunnels, which can affect the long-term safety of the final HLW repositories.

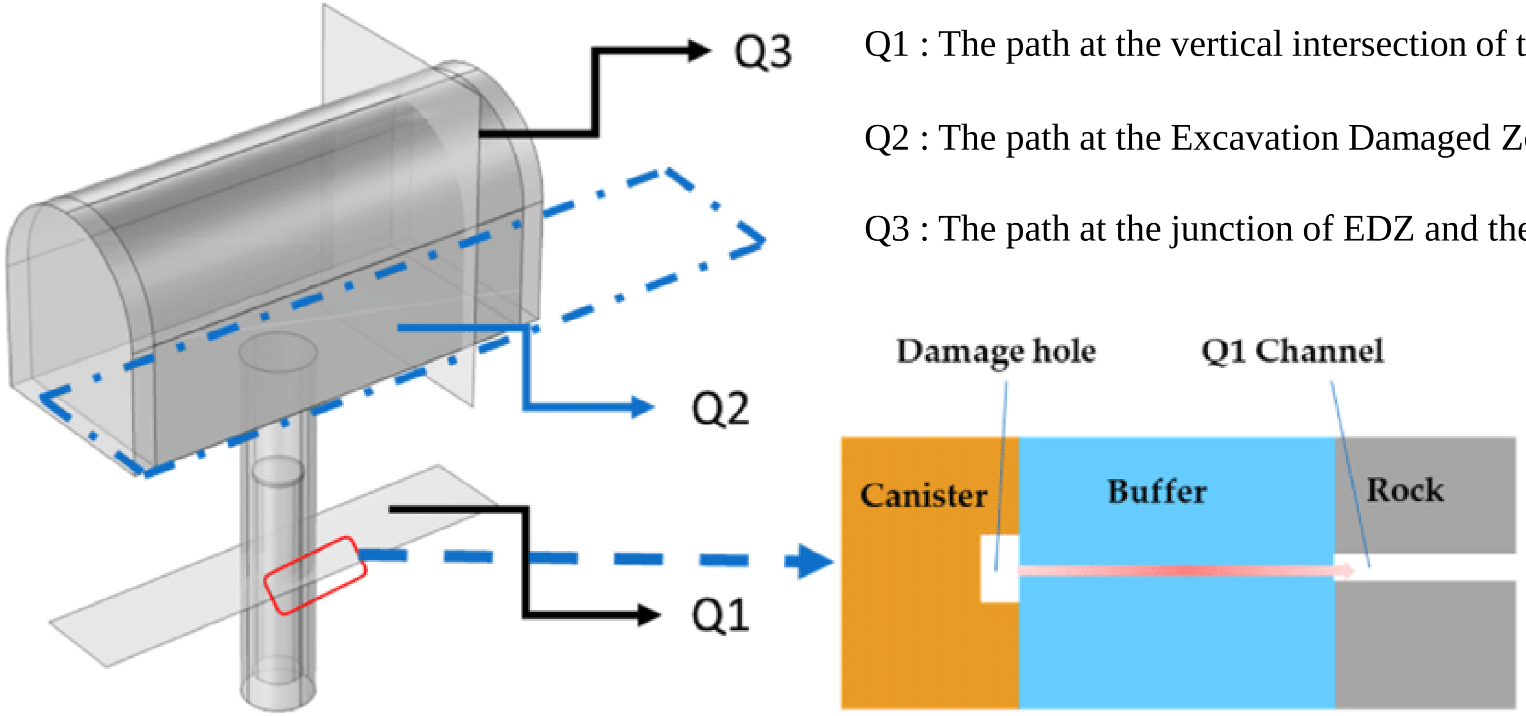


Damage zones in a tunnel constructed using the drill-and blast excavation approach in a generic stress field. (Siren et al., 2015)



The formation of hydraulic channels between tunnels and fractures will affect the transmission of radioactive waste.

- When the tunnel and canister is damaged, radionuclides will leak out from the canister and migrate into the buffer material.



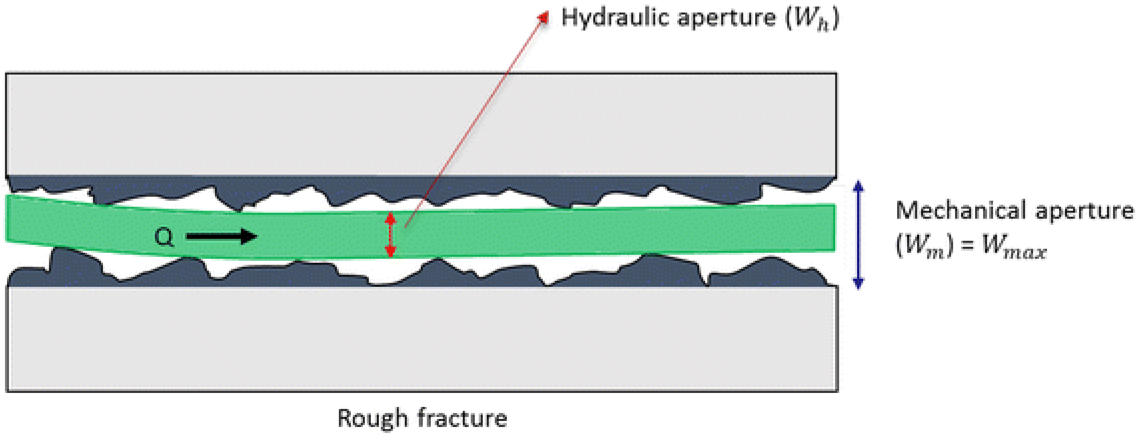
Q1 : The path at the vertical intersection of the canister and fracture

Q2 : The path at the Excavation Damaged Zone (EDZ) under the disposal tunnel

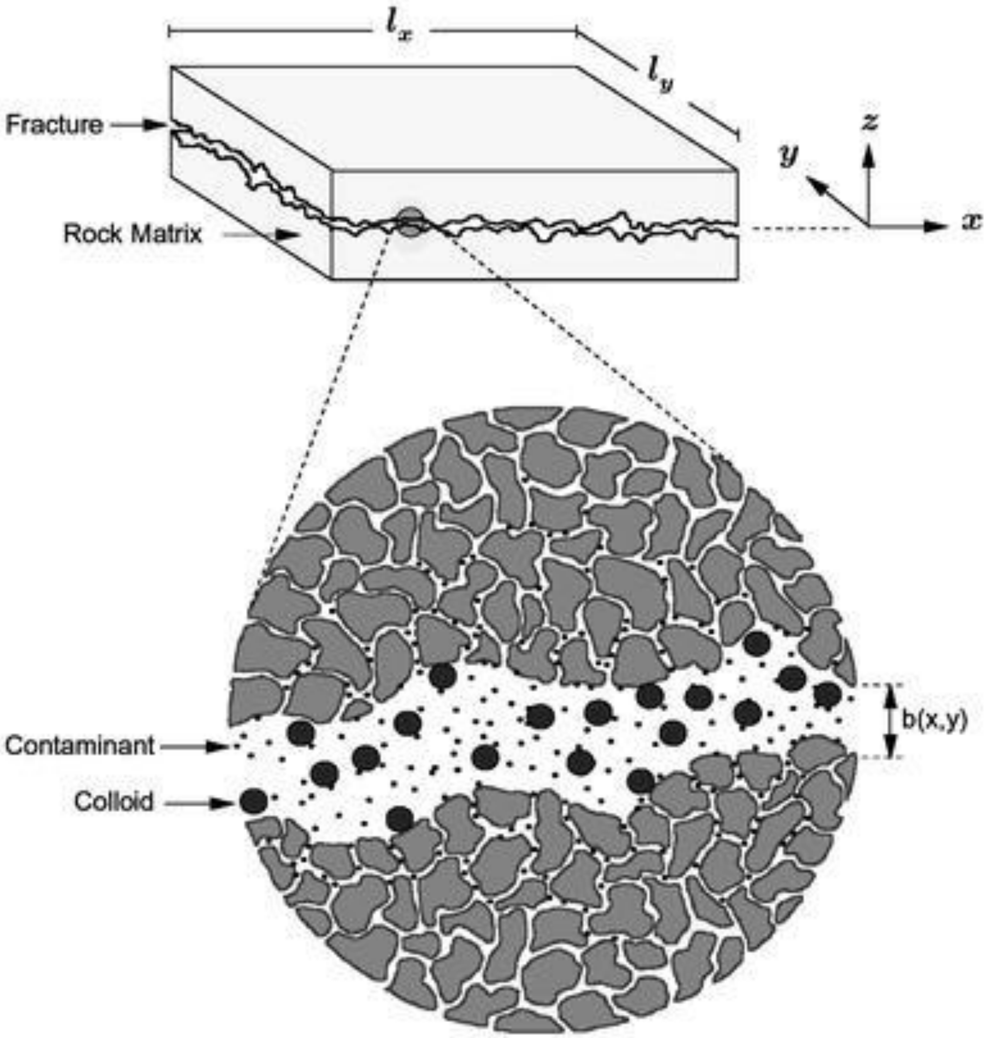
Q3 : The path at the junction of EDZ and the disposal tunnel top

Fig 3. Schematic illustration for the Q1-Q3 transport path of radionuclide. (Liang et al., 2021)

Since fracture have **high permeability**, contaminants are easily transported through the fracture and cause pollution.



A schematic illustration of fracture hydraulic and mechanical apertures with flow (Q) passing through them.



Schematic illustration of contaminant transport in a fracture.

- When the fracture asperities (粗糙點) contact each other, they are subject to compressive stress causing dissolution.
- The phenomenon is called pressure solution, which contribute to a significant closure of the fracture, causing permeability decrease.

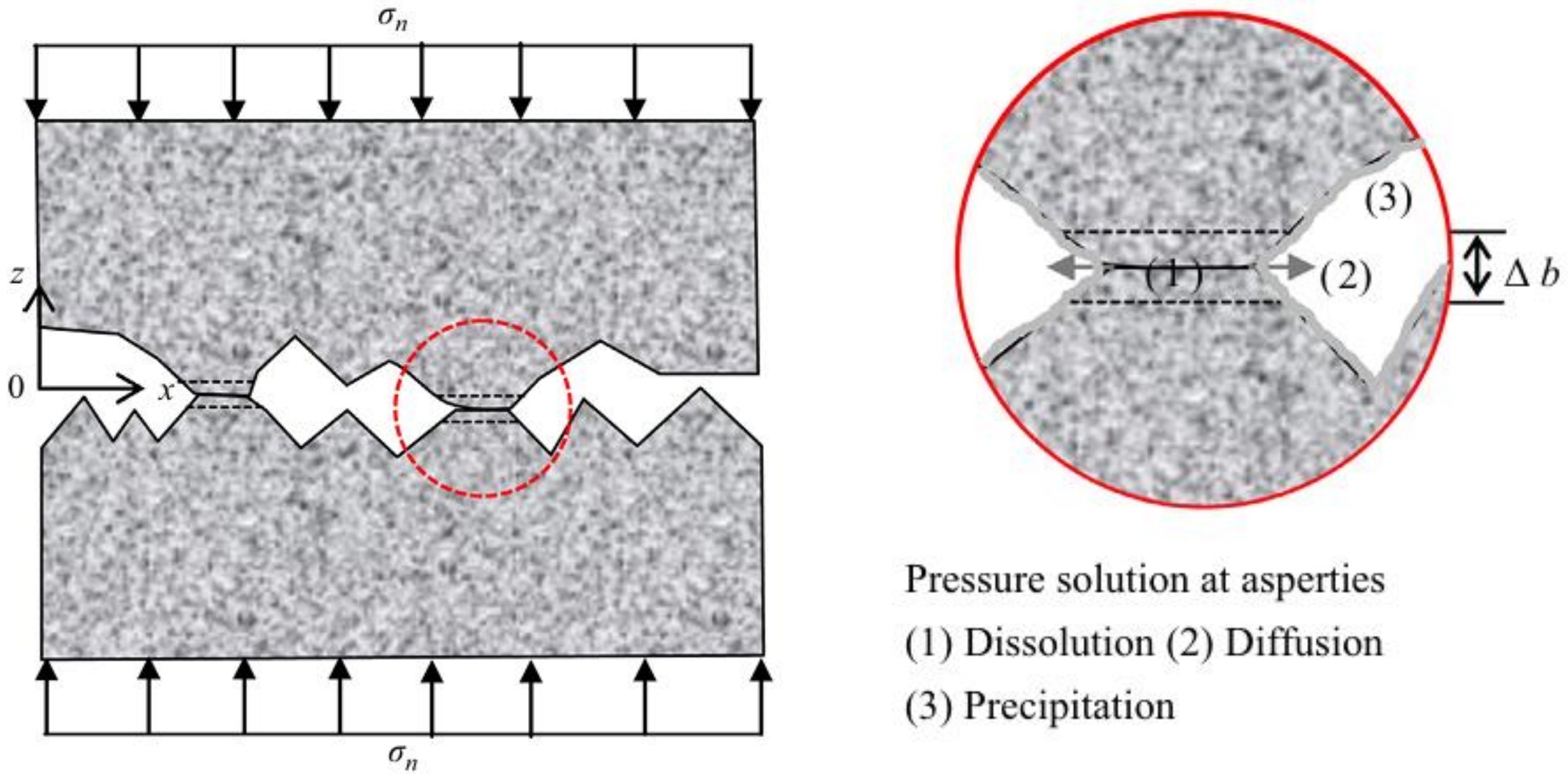


Fig 5. Schematic views of fracture aperture reduction due to pressure solution under normal stress.

- Objective

By developing a hydro-mechanical model to simulate the mechanism of fractures under pressure solution and free-surface dissolution, calculating the evolution of equivalent hydraulic conductivity and fracture aperture based on the variation of fracture aperture over time.

Methodology

- **Governing equations**

The conservation of water mass by assuming the Darcy's law :

➢ $\frac{\partial(\rho_w \phi)}{\partial t} + \nabla \cdot (\rho_w u) = \mathrm{Q}_m$,

$$u = -\frac{k}{\mu}(\nabla p + \rho_w g \nabla h)$$

Force equilibrium by assuming Hook's law :

➢ $-\nabla \cdot \sigma = F_v$,

$$\sigma = E \cdot \varepsilon$$

ρ_w : density of the fluid $\left({}^{\mathrm{kg}}/_{\mathrm{m}^3}\right)$

ϕ : porosity $(-)$

u : fluid velocity $({}^{\mathrm{m}}/_{\mathrm{s}})$

$\mathrm{Q_m}$: source term for the flow $\left({}^{\mathrm{kg}}/_{\mathrm{m}^3 \cdot \mathrm{s}}\right)$

k : rock permeability tensor $[\mathrm{m}^2]$

μ : fluid dynamic viscosity $[\mathrm{Pa} \cdot \mathrm{s}]$

p : fluid pressure [Pa]

g : gravity acceleration $[{}^{\mathrm{m}}/_{\mathrm{s}^2}]$

h : elevation head [m]

σ : stress tensor [Pa]

F_v : body force $[{}^{\mathrm{Pa}}/_{\mathrm{m}}]$

E : elasticity tensor [Pa]

ε : strain tensor $[-]$

- **Conceptual model**

Limestone

Size : 10 (mm) x 5 (mm)

Aperture (b) : 1 (mm)

Total stress : 3.5 (MPa)

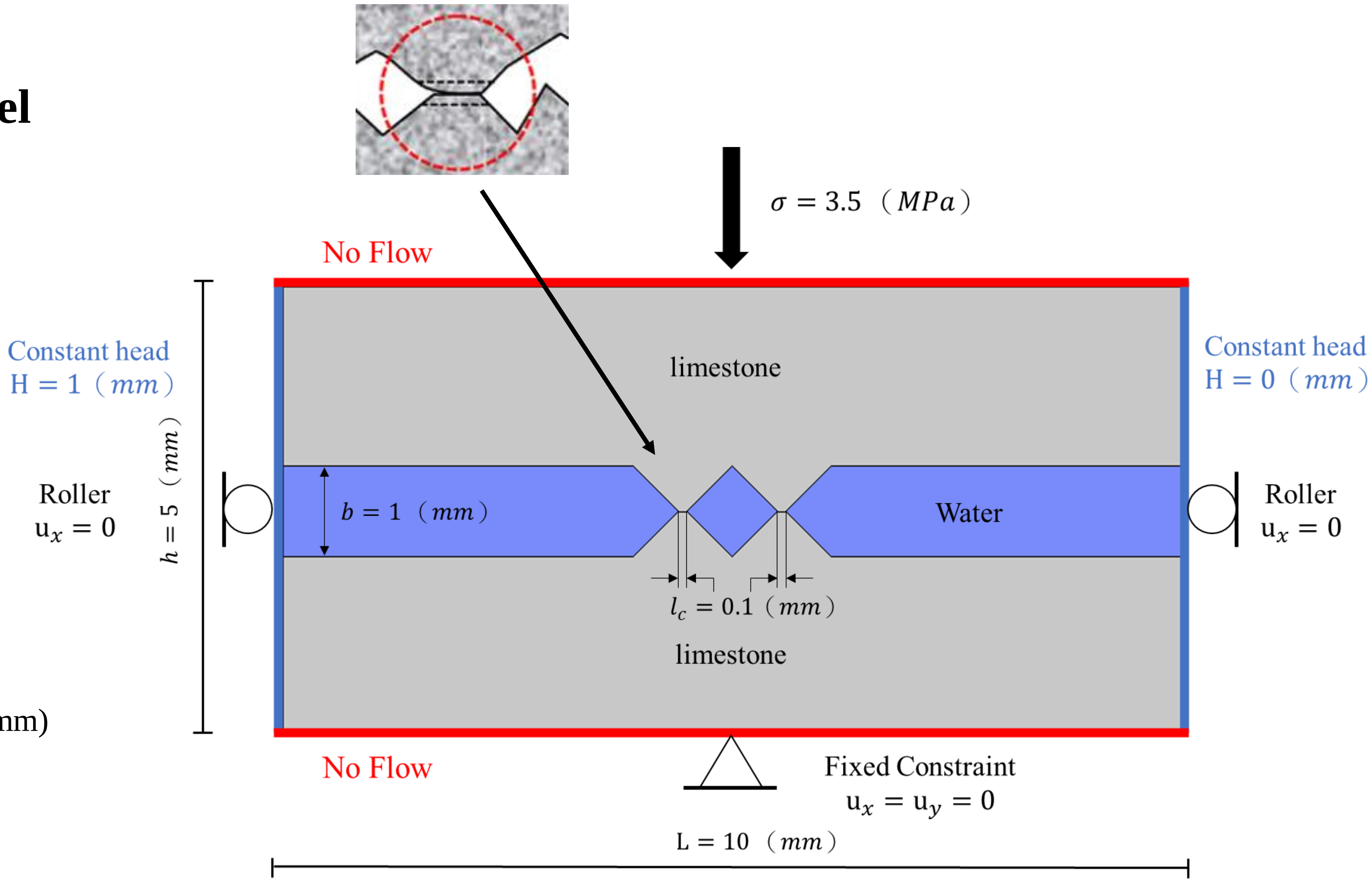
Permeability : 10^{-15} m^2

Temperature : 20°C (isothermal)

Porosity : 0.2

Young's modulus : 60 (GPa)

Initial contact length (l_c) : 0.1 (mm)



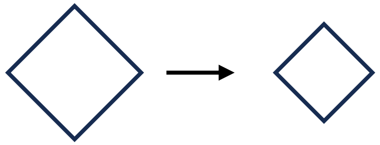
- **Pressure dissolution** **(make pores space smaller)**

$$\frac{dM_{diss}}{dt} = \frac{3\pi {V_m}^2(\sigma_{\mathrm{eff}} - \sigma_c)k_+\rho_{\mathrm{g}}{d_c}^2}{4RT} = \alpha(\sigma_{\mathrm{eff}} - \sigma_c)$$

(Yasuhara et al., 2003)

extension

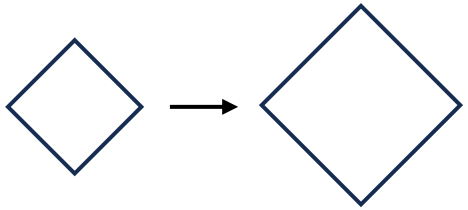
$$\frac{dG_{\mathrm{a}}}{dt} = \alpha(\sigma_{\mathrm{eff}} - \sigma_c)^{\beta}$$



- **Free-surface dissolution** **(make pores space larger)**

$$\frac{dG_{\mathrm{f}}}{dt} = \gamma$$

where $\gamma = k_+V_m$



(Tada et al., 1986)

dM_{diss}/dt : the dissolution mass flux

V_m: molar volume of the solid

σ_{eff} : effective stress

σ_c: critical stress

k_+: dissolution rate constant of the dissolved mineral

ρ_{g}: grain density

d_c: diameter of the grain-to-grain contacts

R : gas constant

T : temperature of the system

α : constant

β : constant

G_a: change in width due to dissolution at the contact area

G_{f}: the retreat rate of the fracture wall due to free-face dissolution

- **Geometrical model**

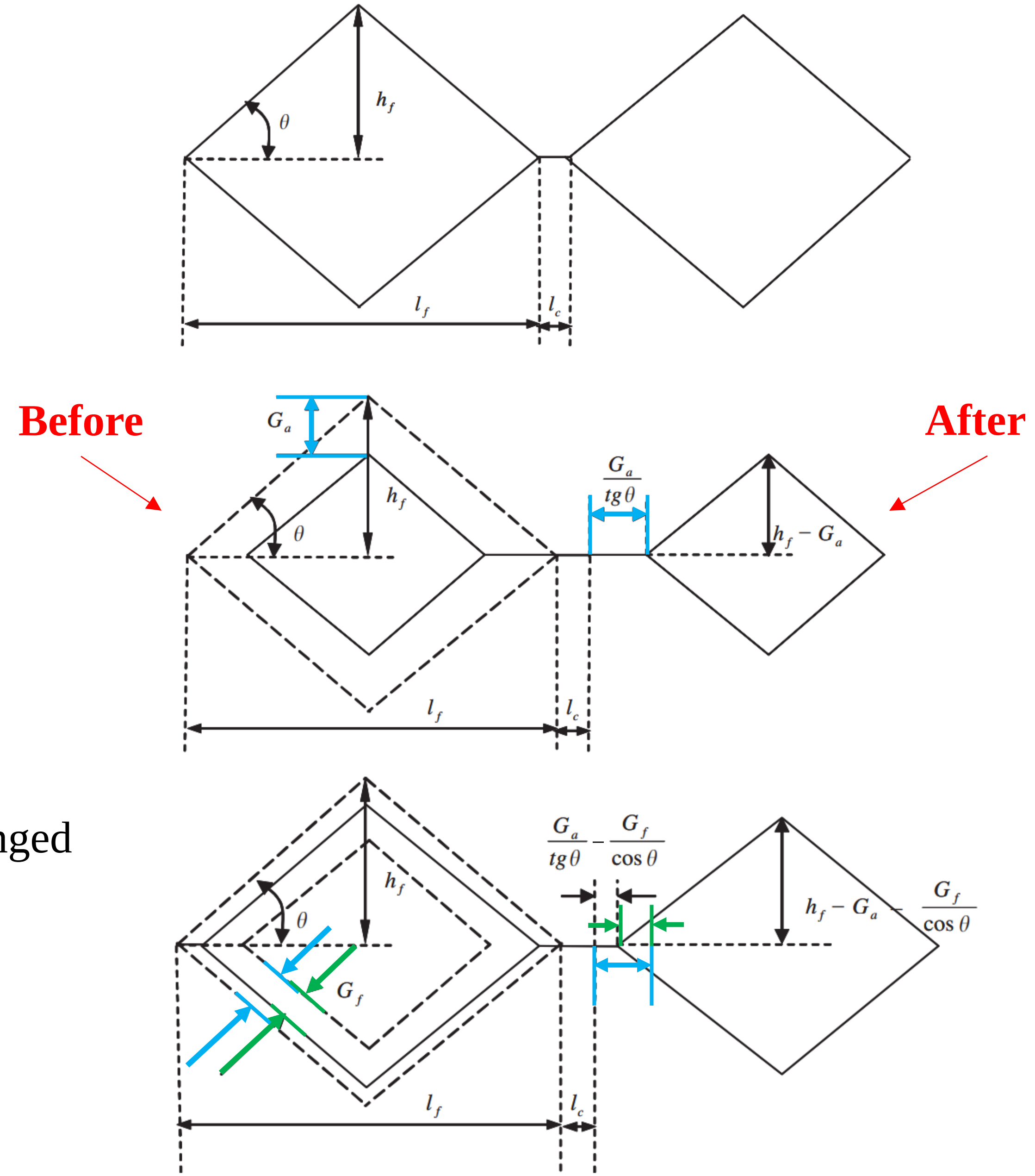
Pressure dissolution   Free-surface dissolution

$$\Delta h_f = \boxed{G_a} - \boxed{\frac{G_f}{\cos\,\theta}},$$

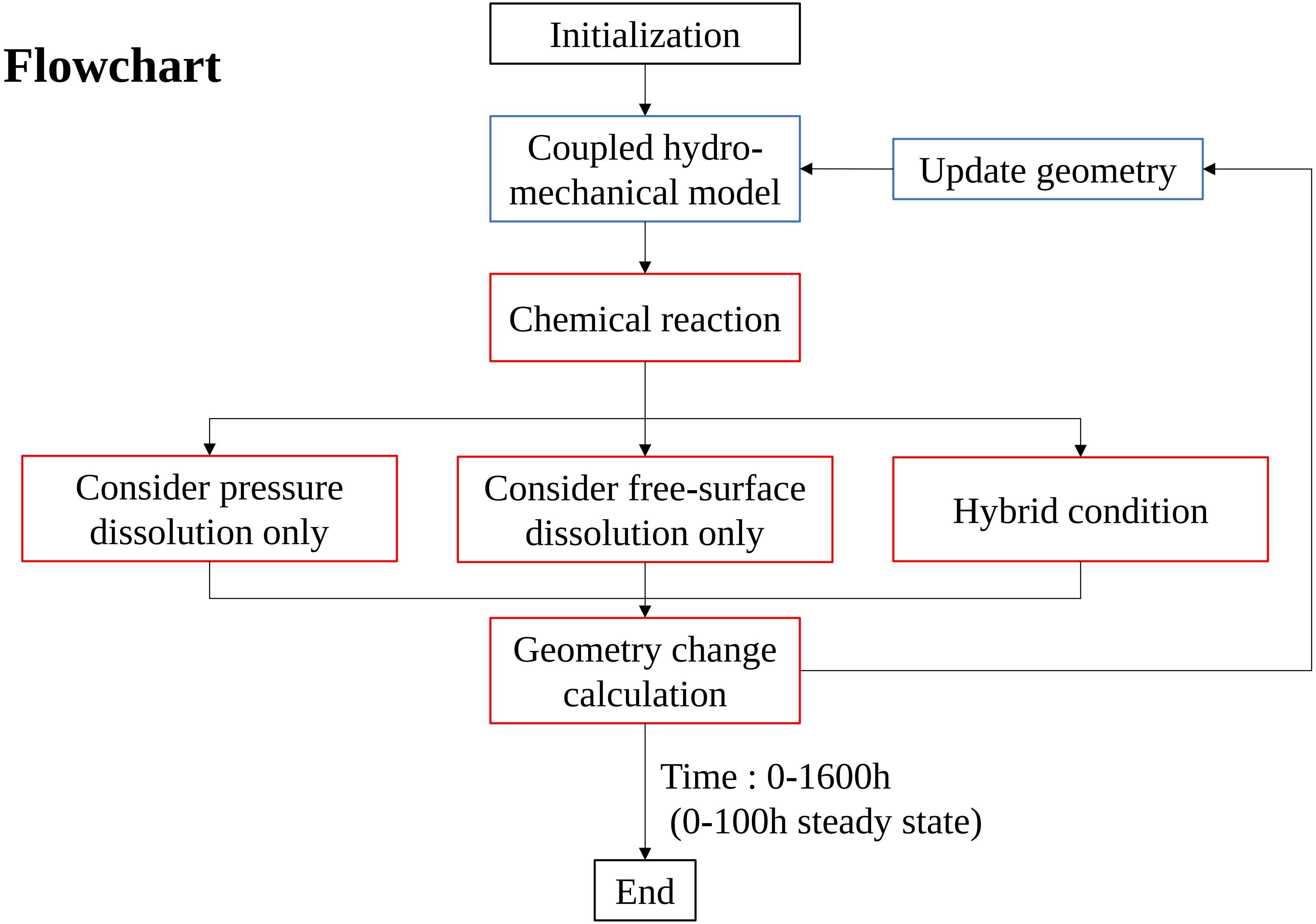
$$\Delta l_c = \boxed{\frac{G_a}{\tan\,\theta}} - \boxed{\frac{G_f}{\sin\,\theta}}.$$

Δh_f : Changes in pore height Δl_c : Changes in contact length

- $\Delta l_c = 0$; $\Delta h_f = 0$, the pore size will remain unchanged
- $\Delta l_c > 0$; $\Delta h_f > 0$, the pore size will decrease
- $\Delta l_c < 0$; $\Delta h_f < 0$, the pore size will increase



- **Flowchart**

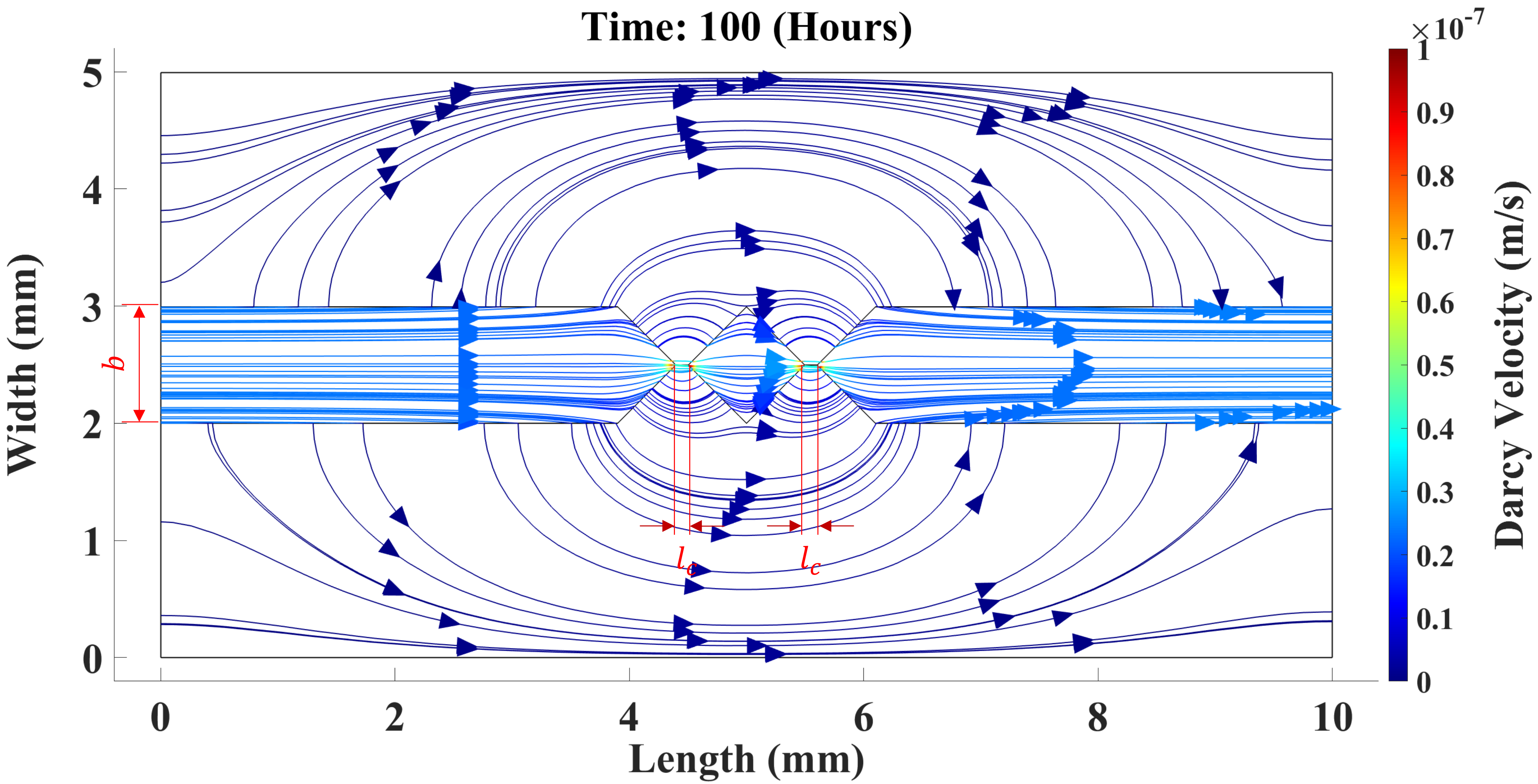


COMSOL MULTIPHYSICS®

MATLAB®

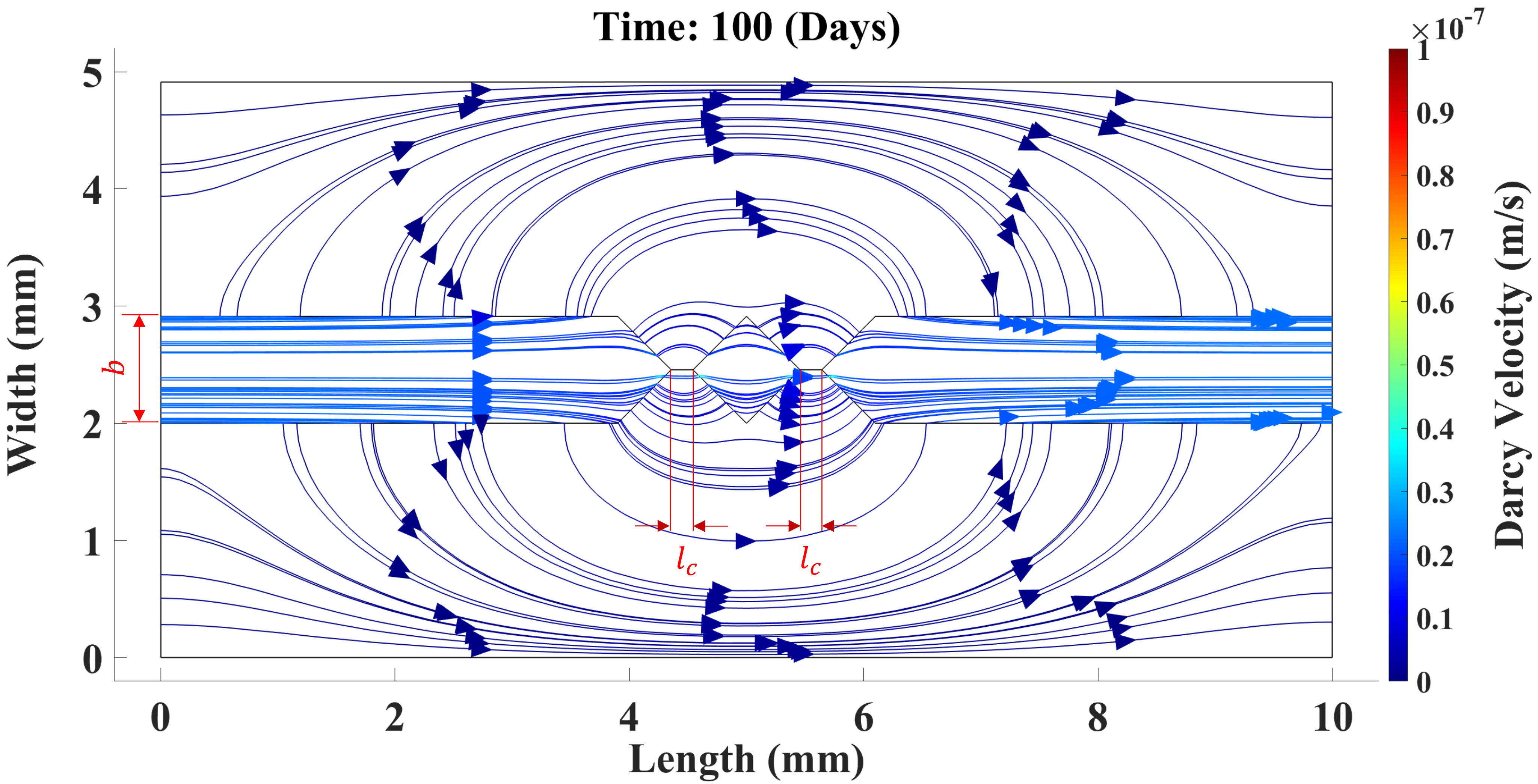
Results

- **Loading in 3.5MPa (Pressure dissolution only)**



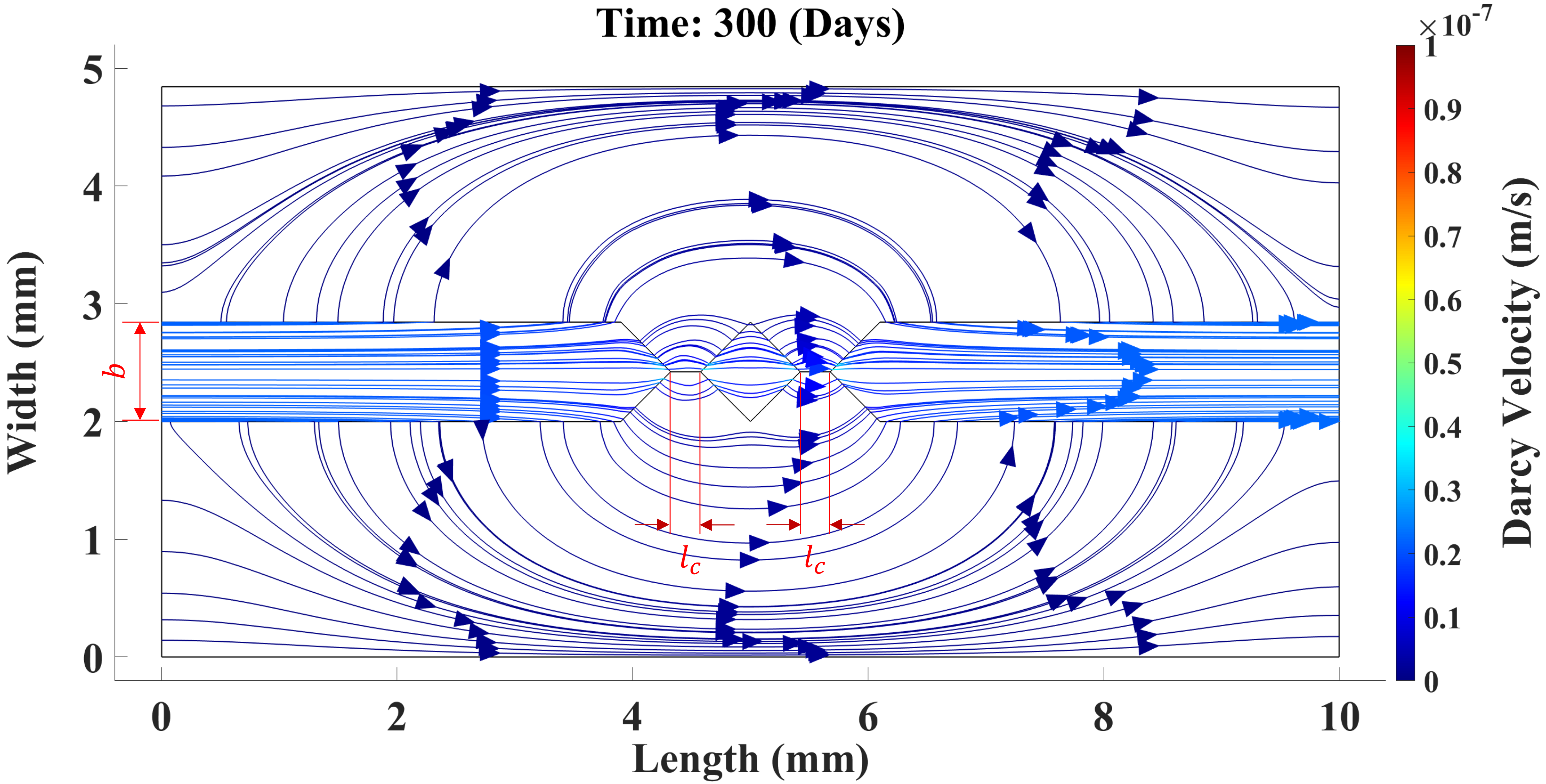
Fracture aperture change after 100 hours. (b = 1.00, l_c = 0.10)

- **Loading in 3.5MPa (Pressure dissolution only)**



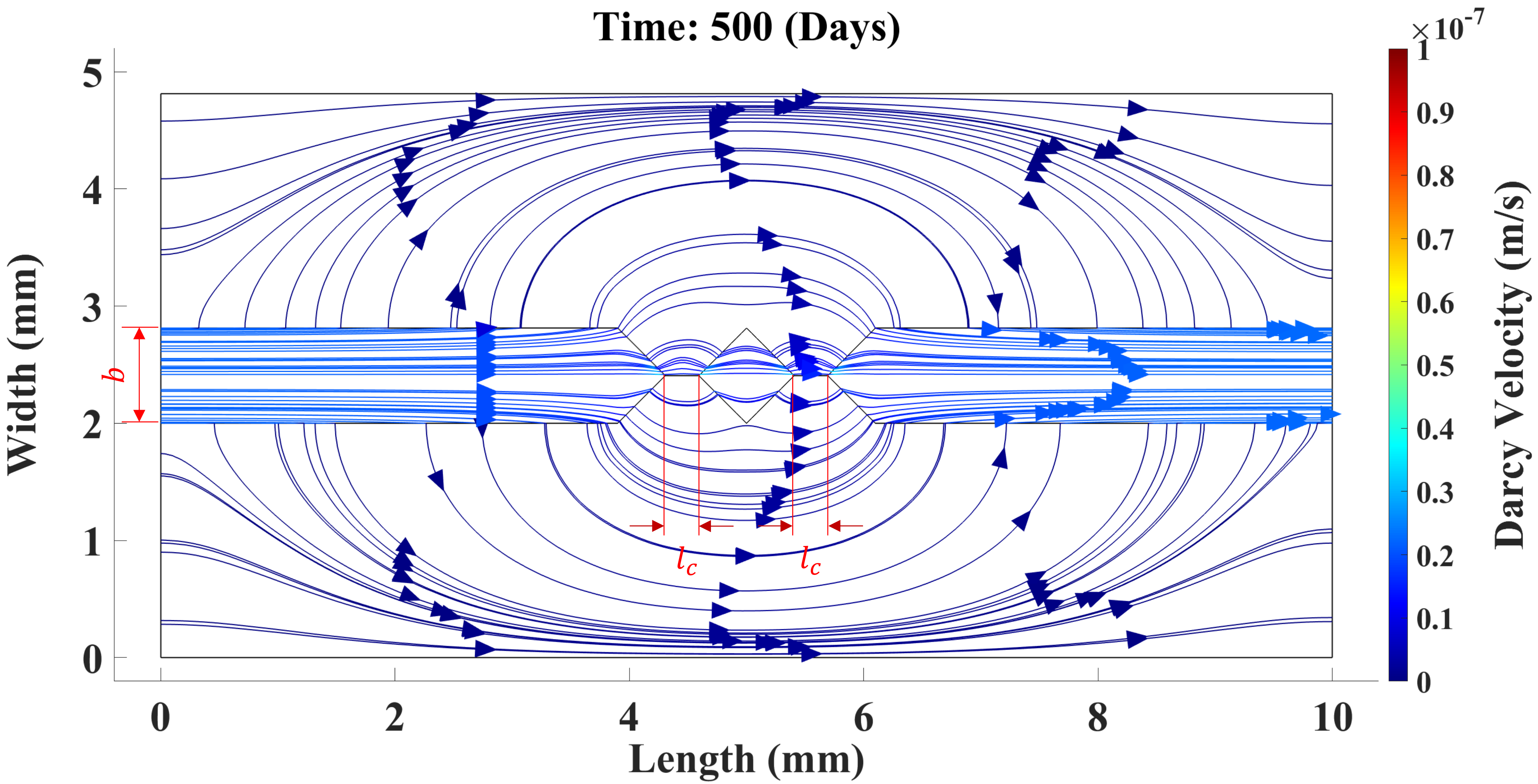
Fracture aperture change after 100 days. (b = 0.91, l_c = 0.19)

- **Loading in 3.5MPa (Pressure dissolution only)**



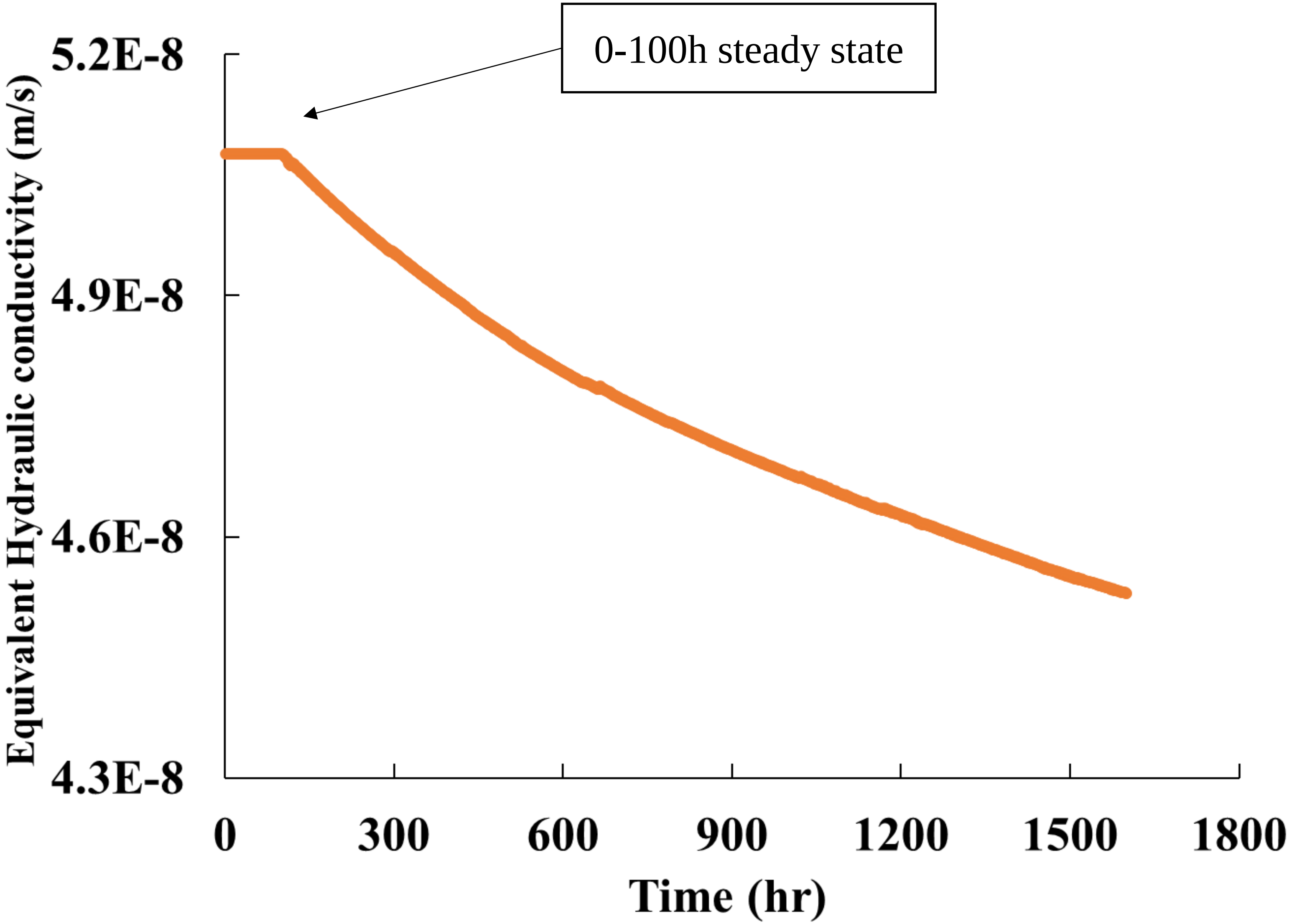
Fracture aperture change after 300 days. (b = 0.84, l_c = 0.26)

- **Loading in 3.5MPa (Pressure dissolution only)**



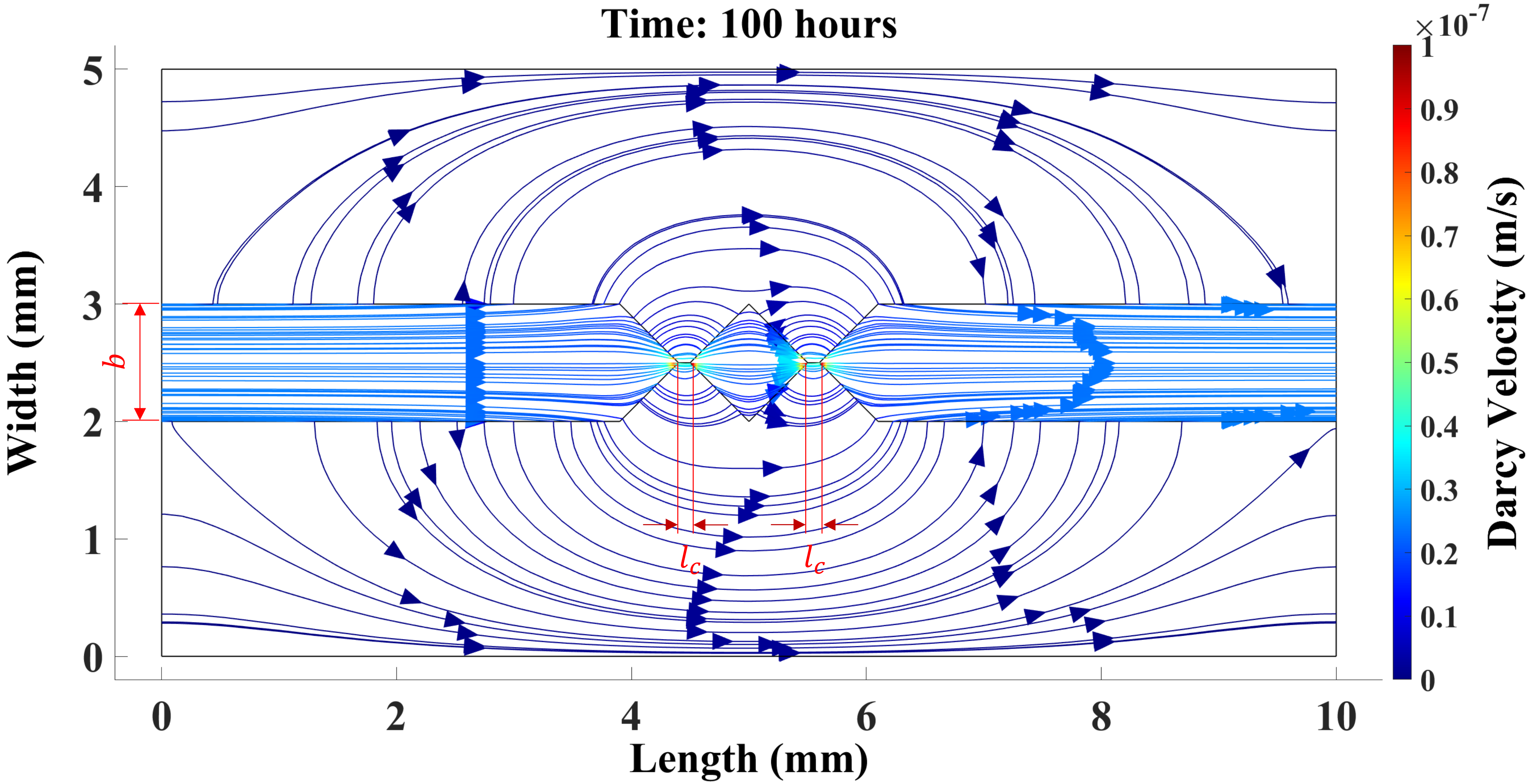
Fracture aperture change after 500 days. (b = 0.81, l_c = 0.29)

- **Loading in 3.5MPa (Pressure dissolution only)**



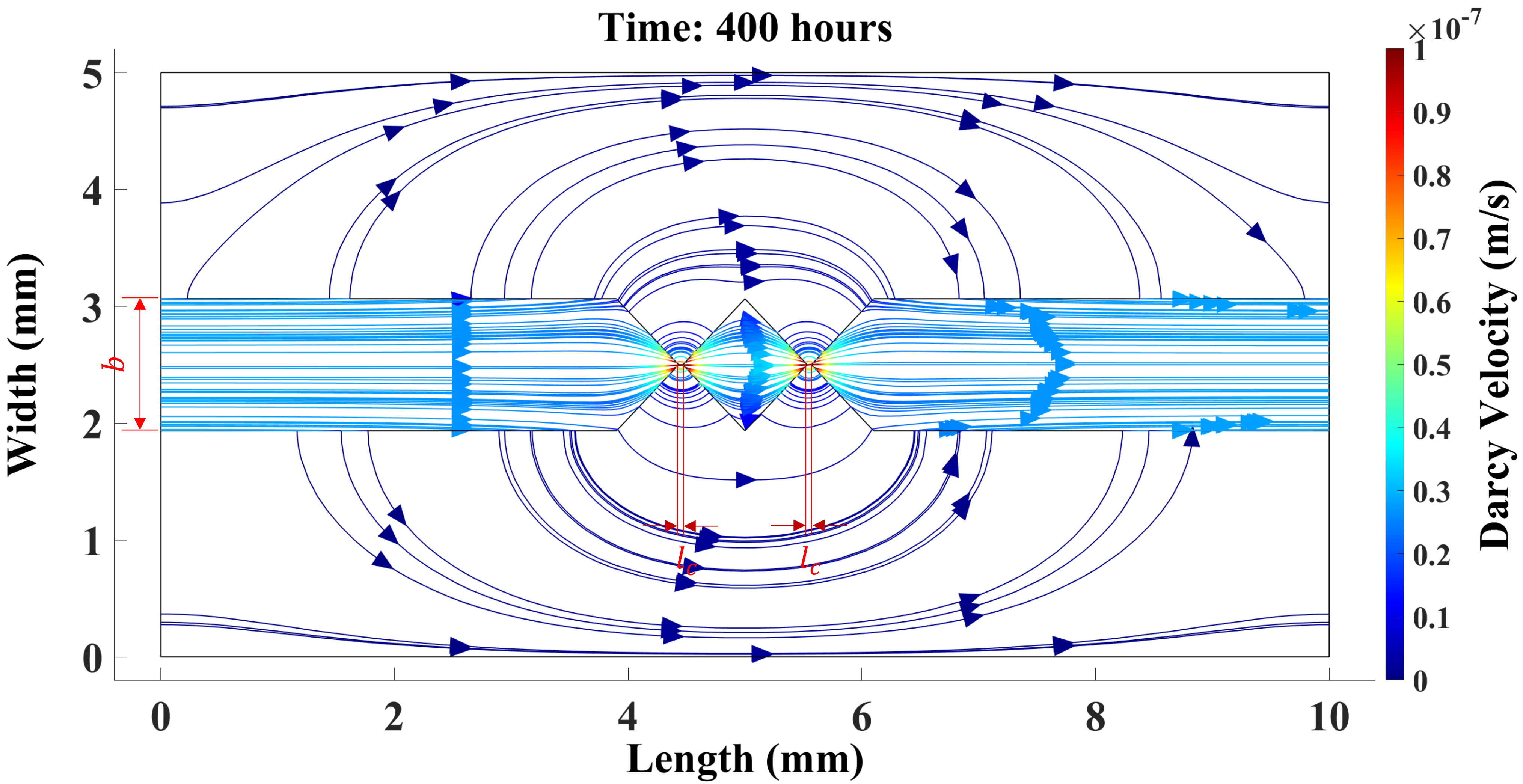
Equivalent Hydraulic conductivity change over time. (0-1600h)

- **Loading in 3.5MPa (Free surface dissolution only)**



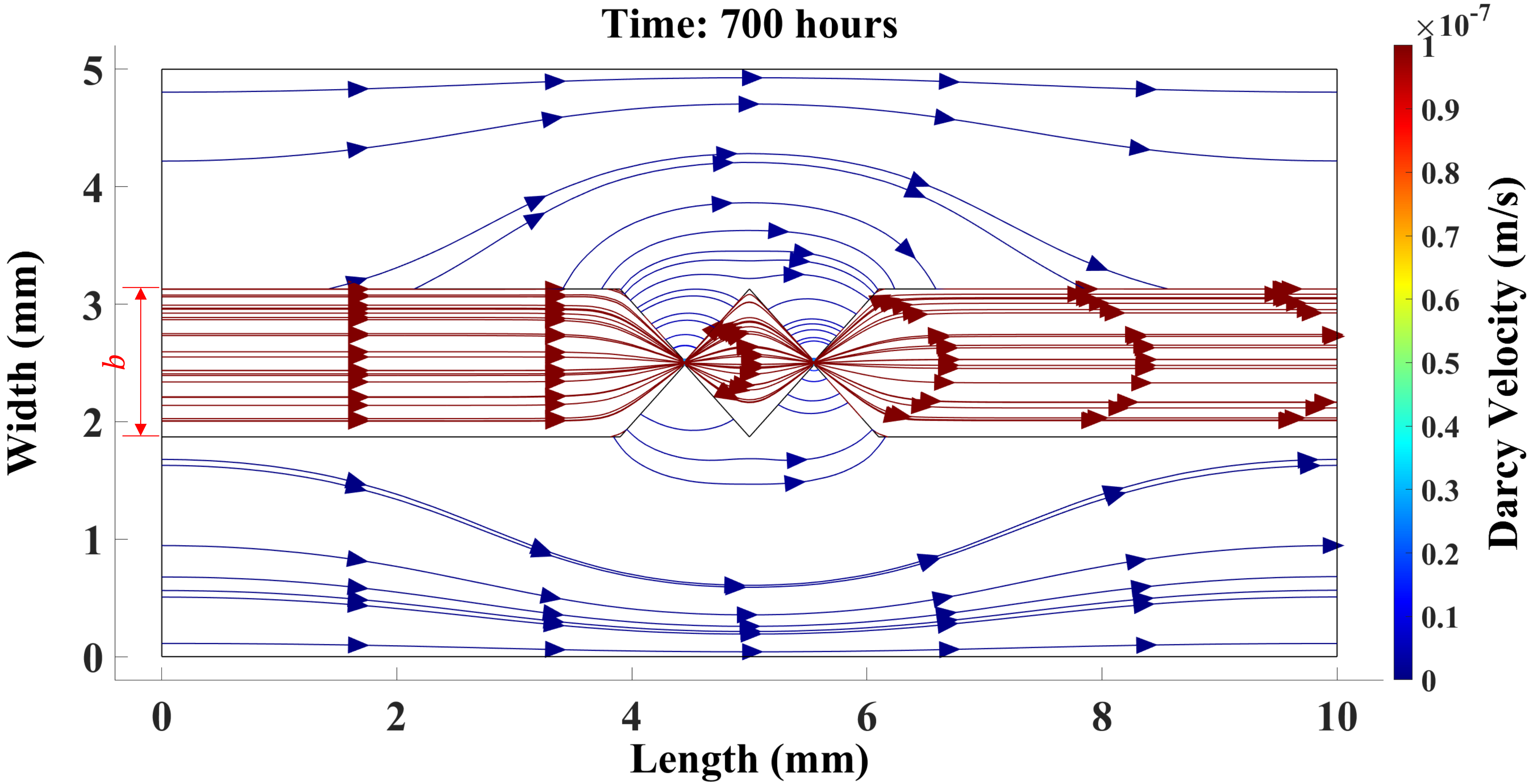
Fracture aperture change after 100 hours. (b = 1.00, l_c = 0.10)

- **Loading in 3.5MPa (Free surface dissolution only)**



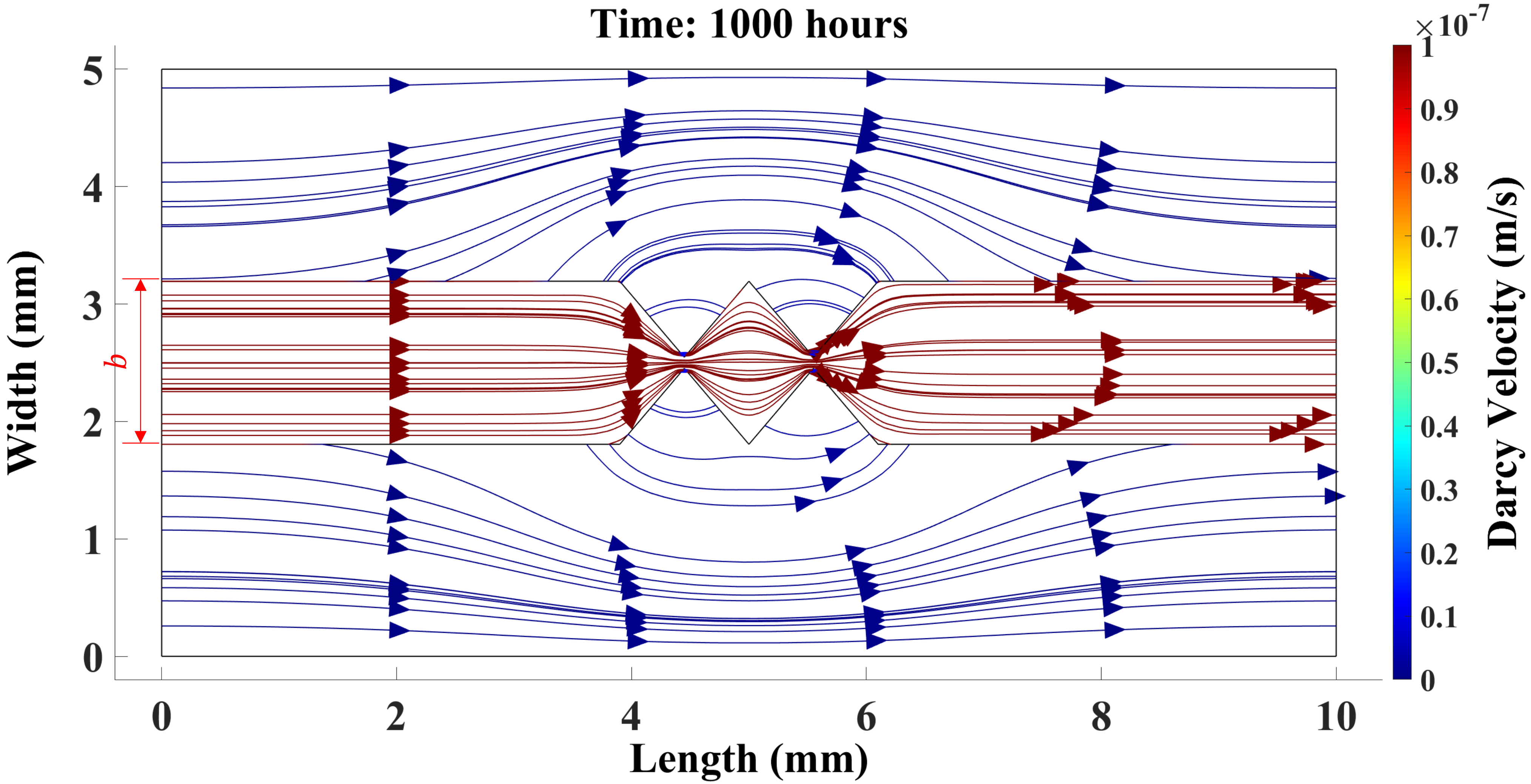
Fracture aperture change after 400 hours. (b = 1.13, l_c = 0.03)

- **Loading in 3.5MPa (Free surface dissolution only)**



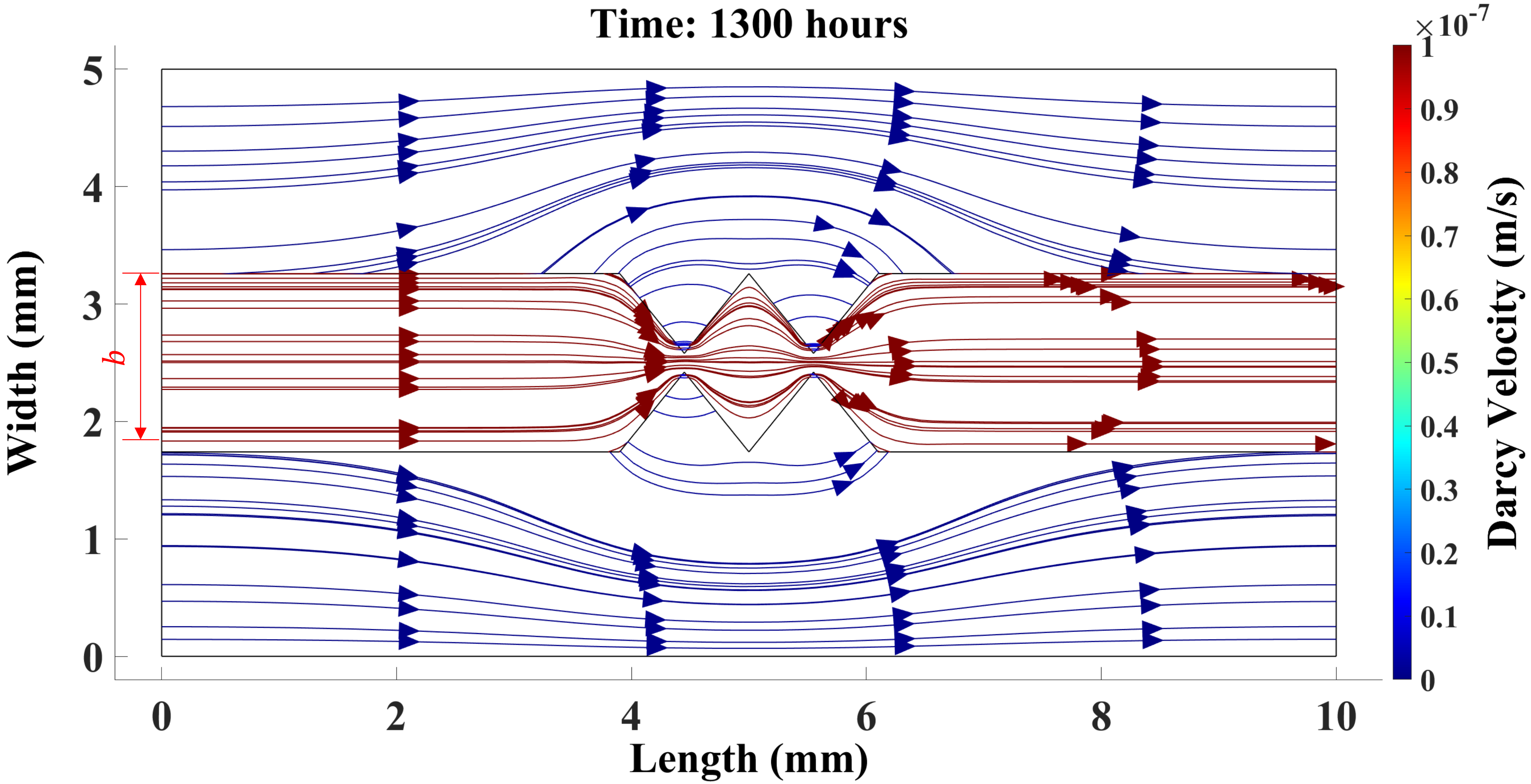
Fracture aperture change after 700 hours. (b = 1.26, l_c = 0)

- **Loading in 3.5MPa (Free surface dissolution only)**



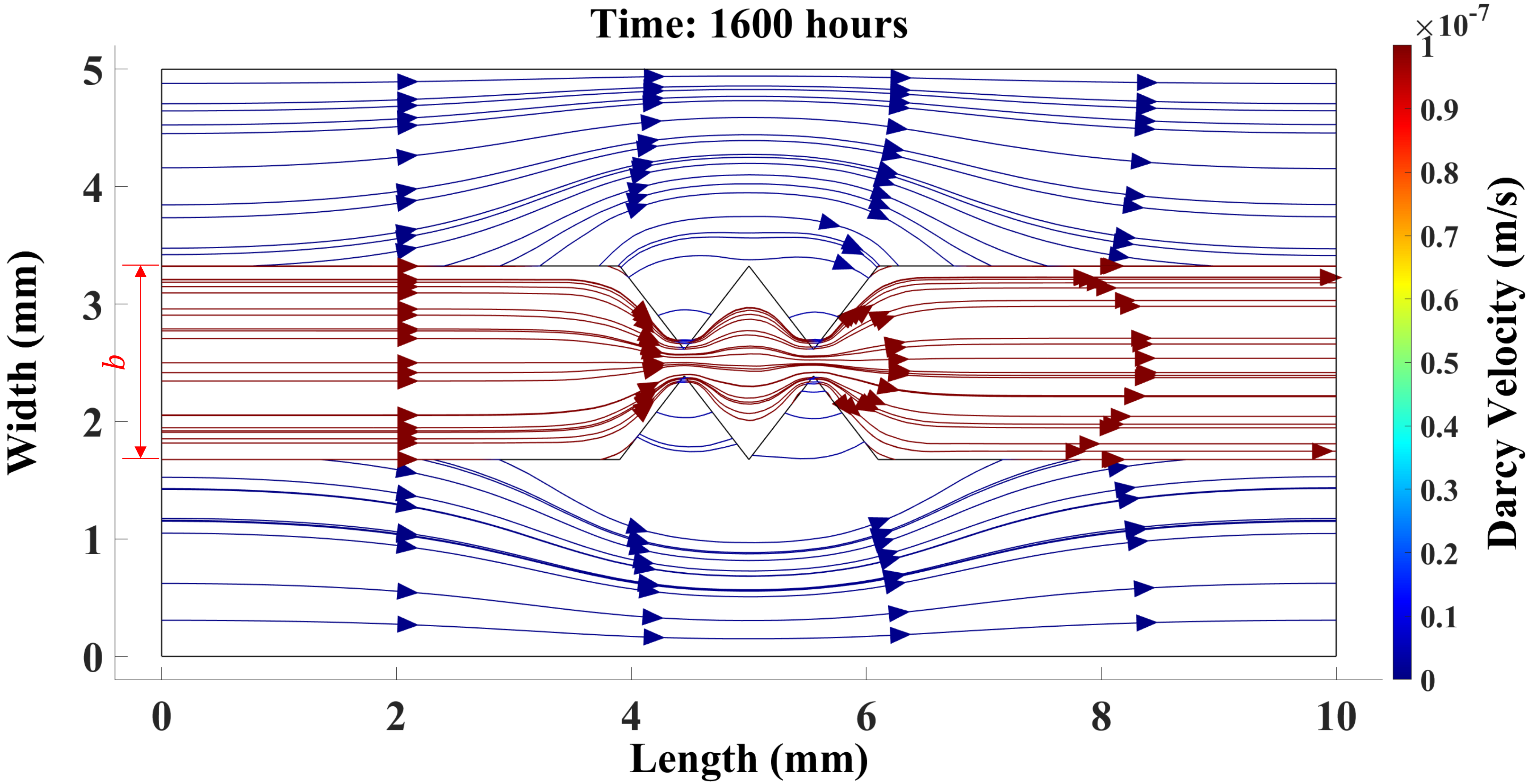
Fracture aperture change after 1000 hours. (b = 1.39, l_c = 0)

- **Loading in 3.5MPa (Free surface dissolution only)**



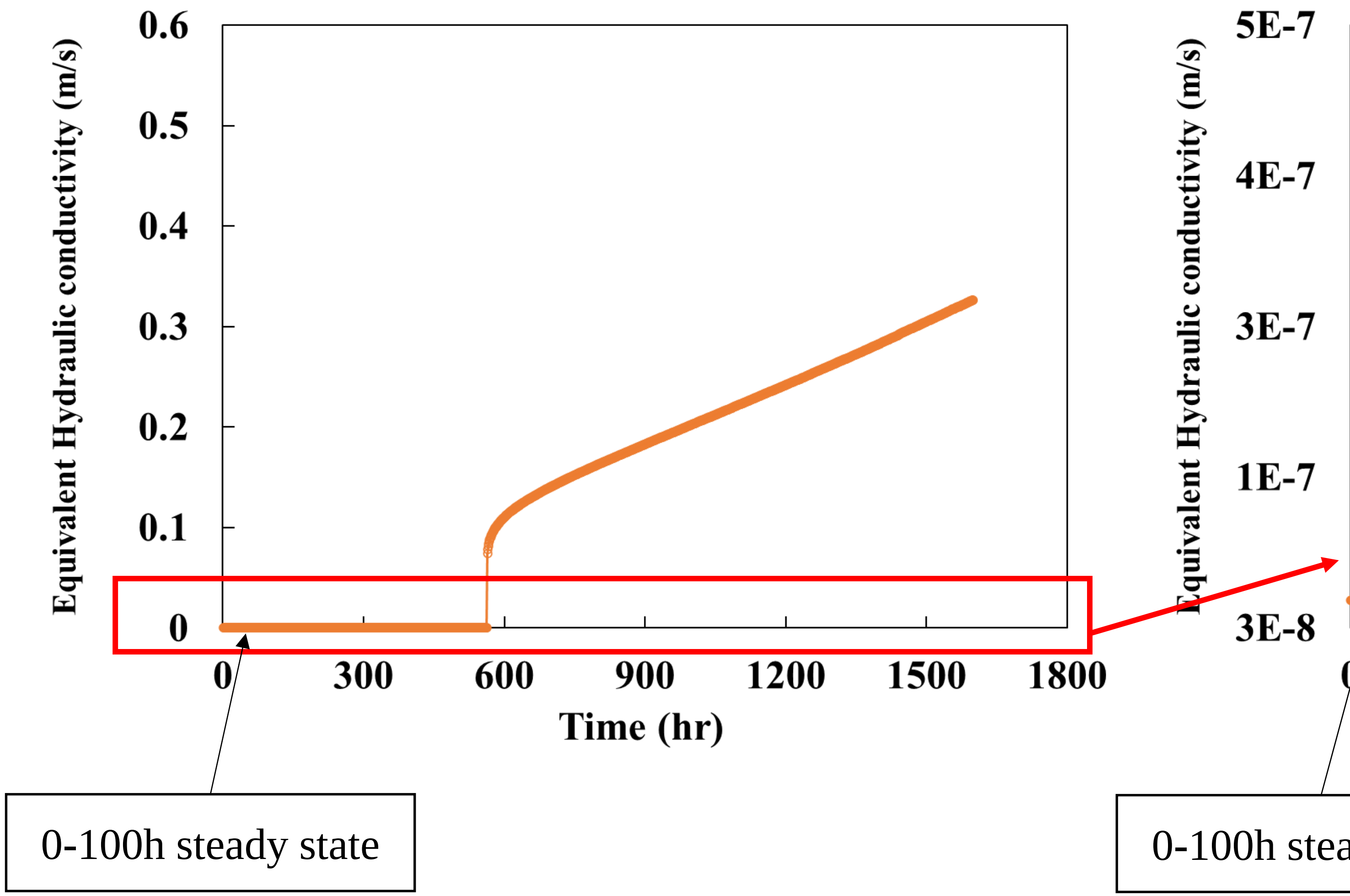
Fracture aperture change after 1300 hours. (b = 1.52, l_c = 0)

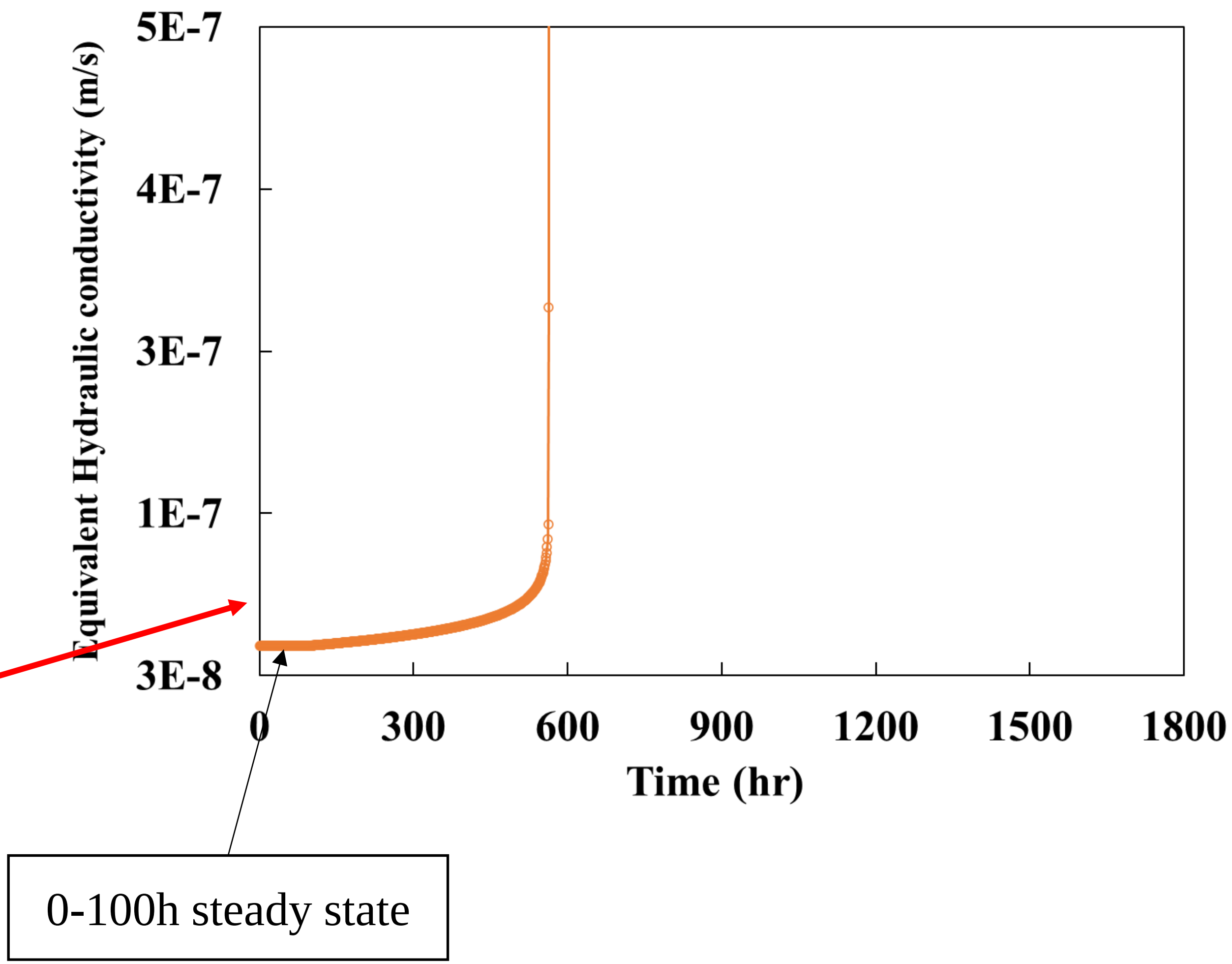
- **Loading in 3.5MPa (Free surface dissolution only)**



Fracture aperture change after 1600 hours. (b = 1.65, l_c = 0)

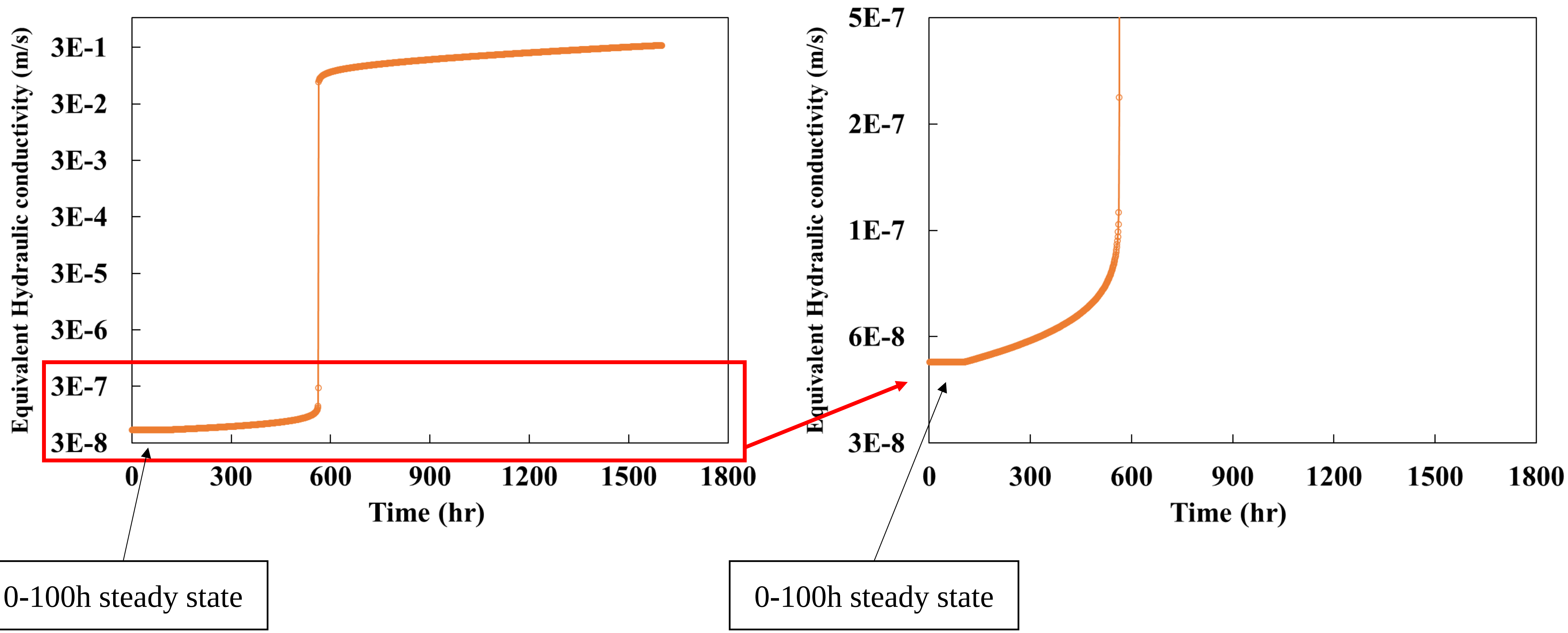
- **Loading in 3.5MPa (Free surface dissolution only)**





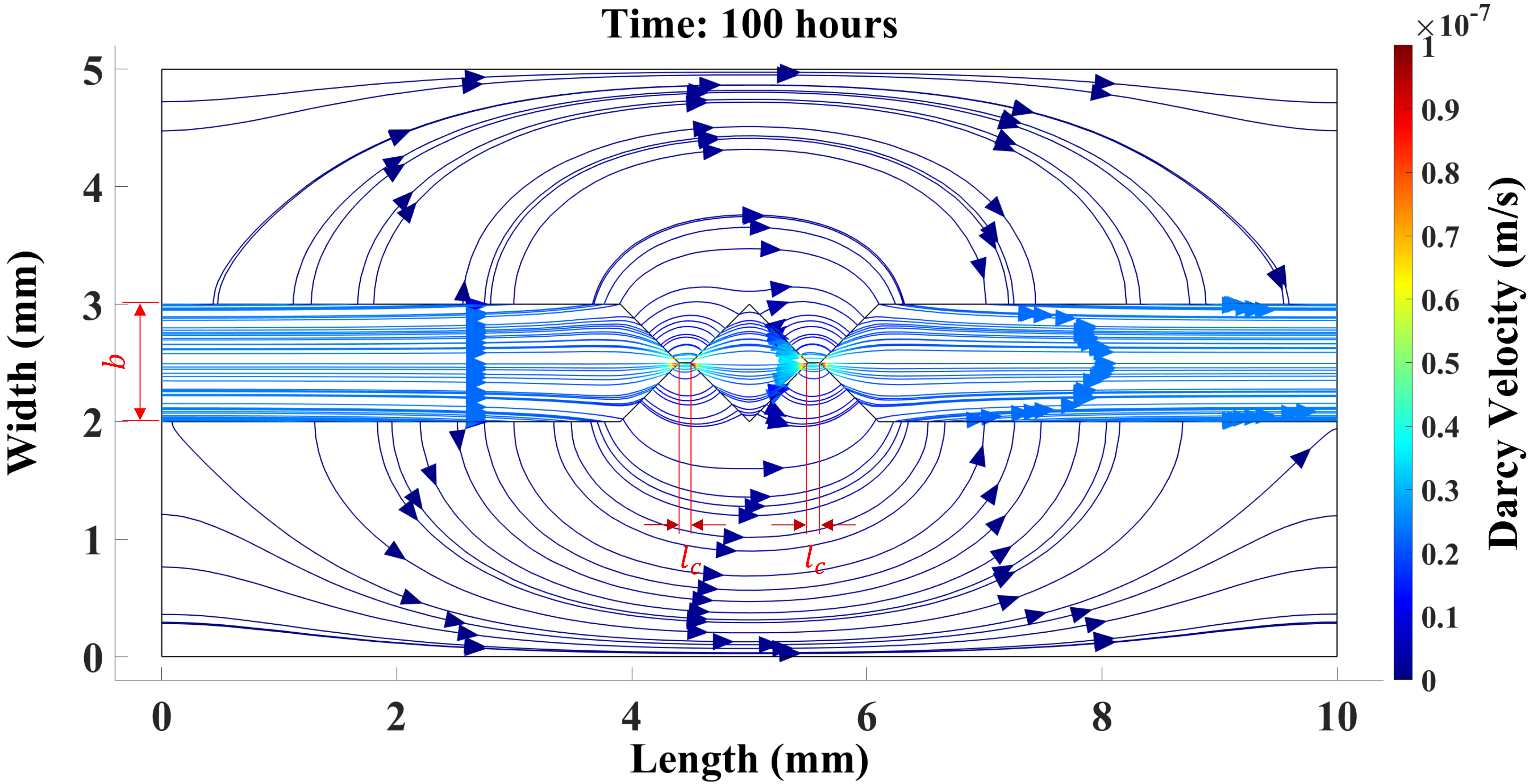
Equivalent Hydraulic conductivity change over time. (0-1600h)

- **Loading in 3.5MPa (Free surface dissolution only) [Logarithmic scale]**



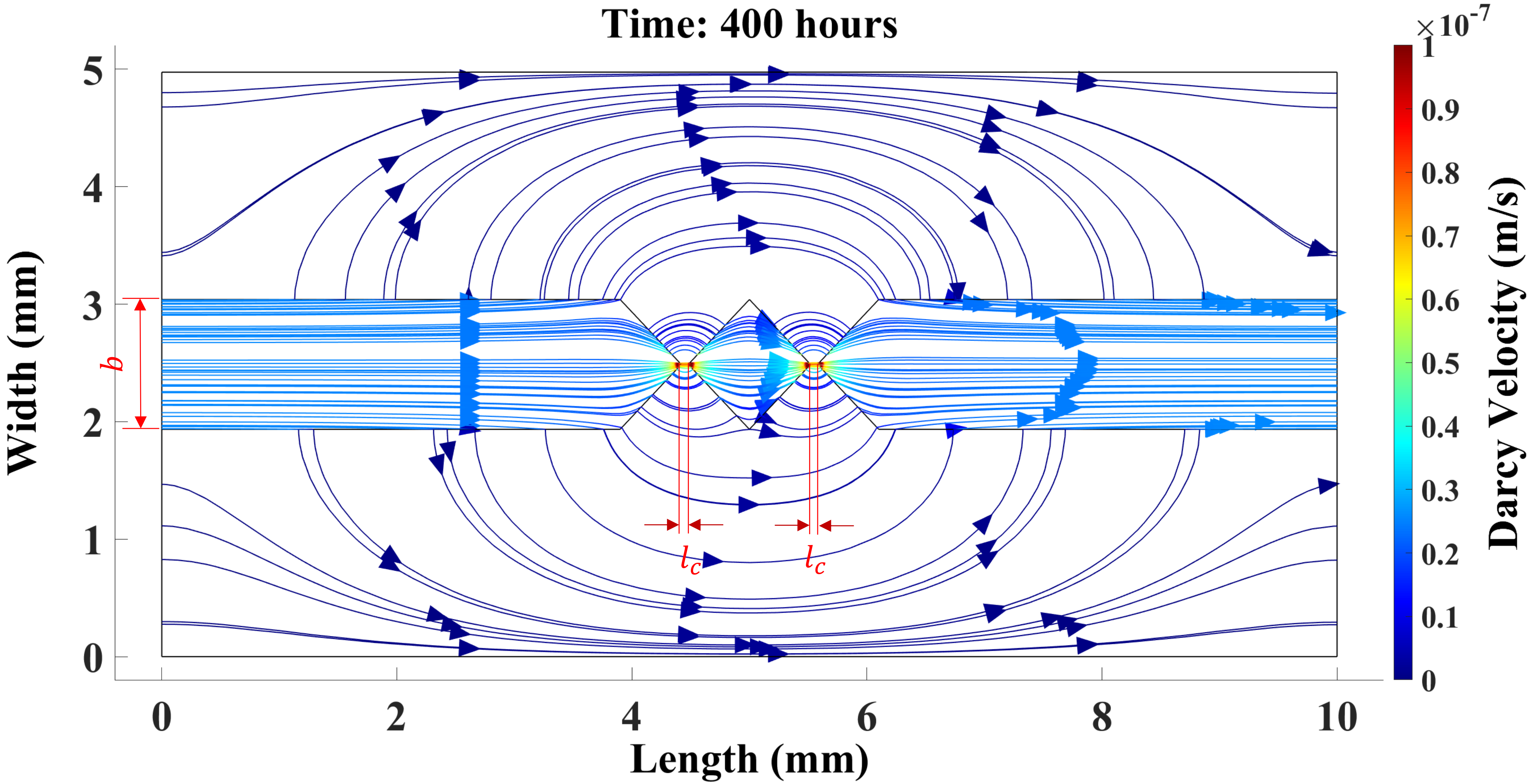
Equivalent Hydraulic conductivity change over time. (0-1600h)

- **Loading in 3.5MPa (Hybrid condition)**



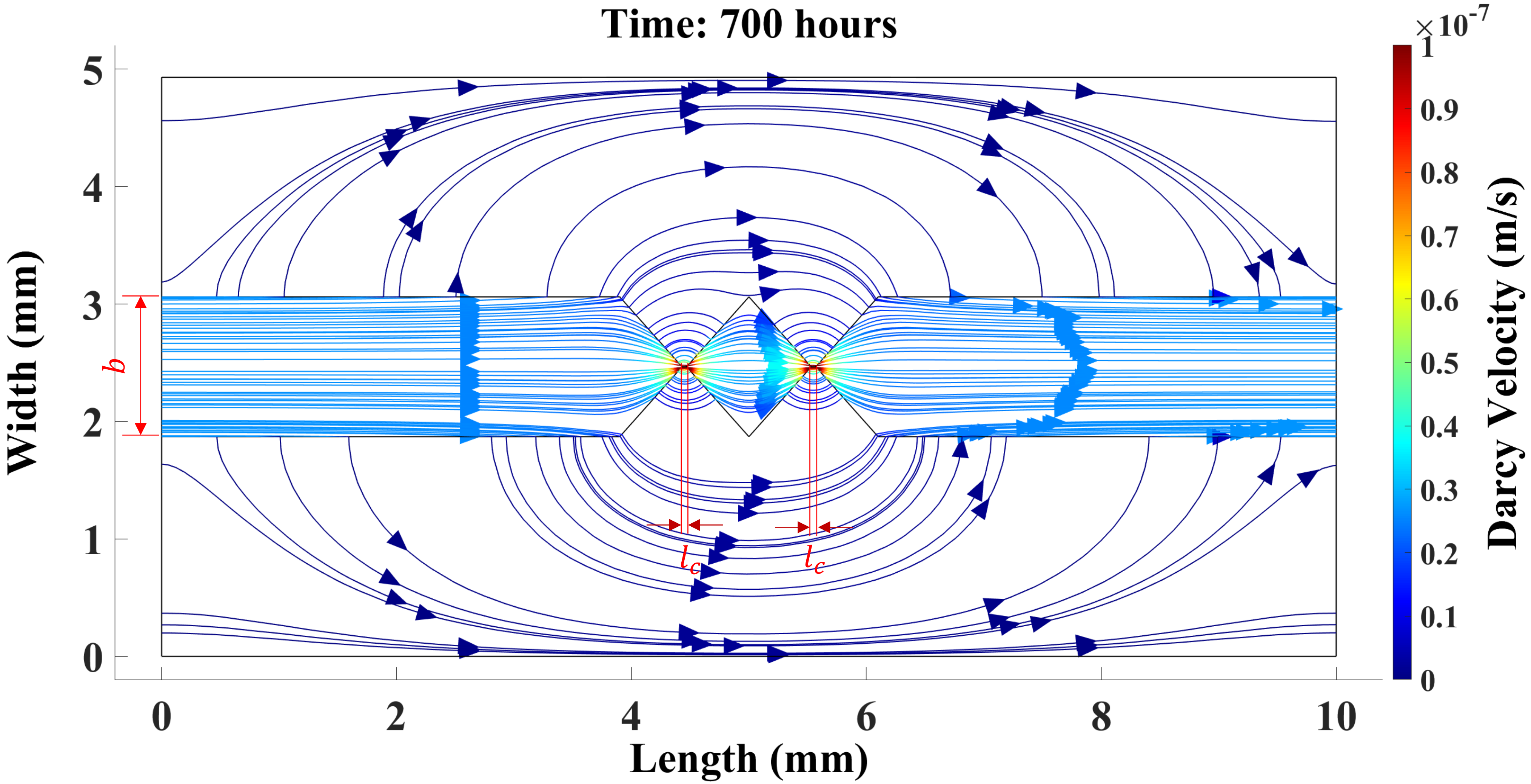
Fracture aperture change after 100 hours. (b = 1.00, l_c = 0.10)

- **Loading in 3.5MPa (Hybrid condition)**



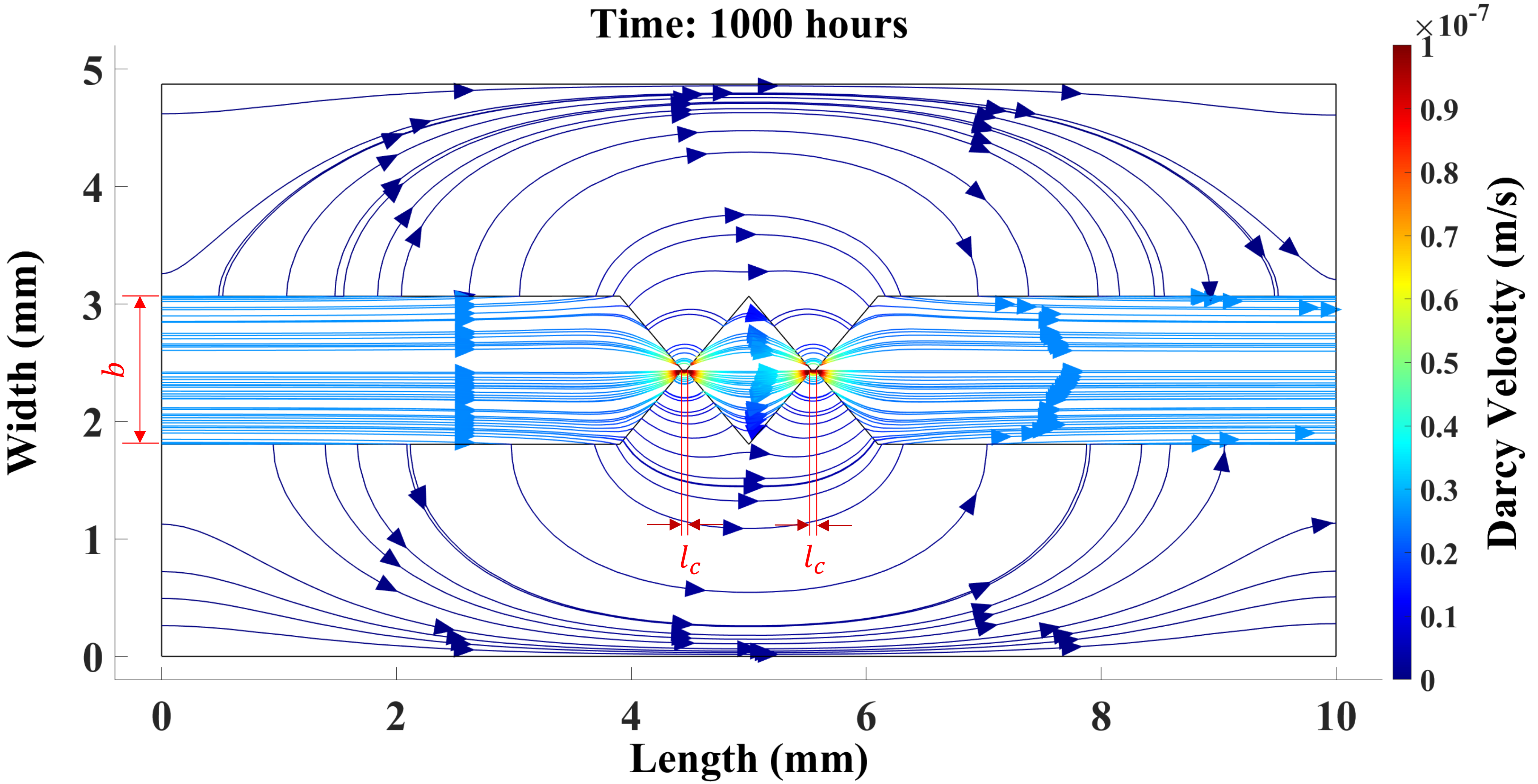
Fracture aperture change after 400 hours. (b = 1.11, l_c = 0.06)

- **Loading in 3.5MPa (Hybrid condition)**



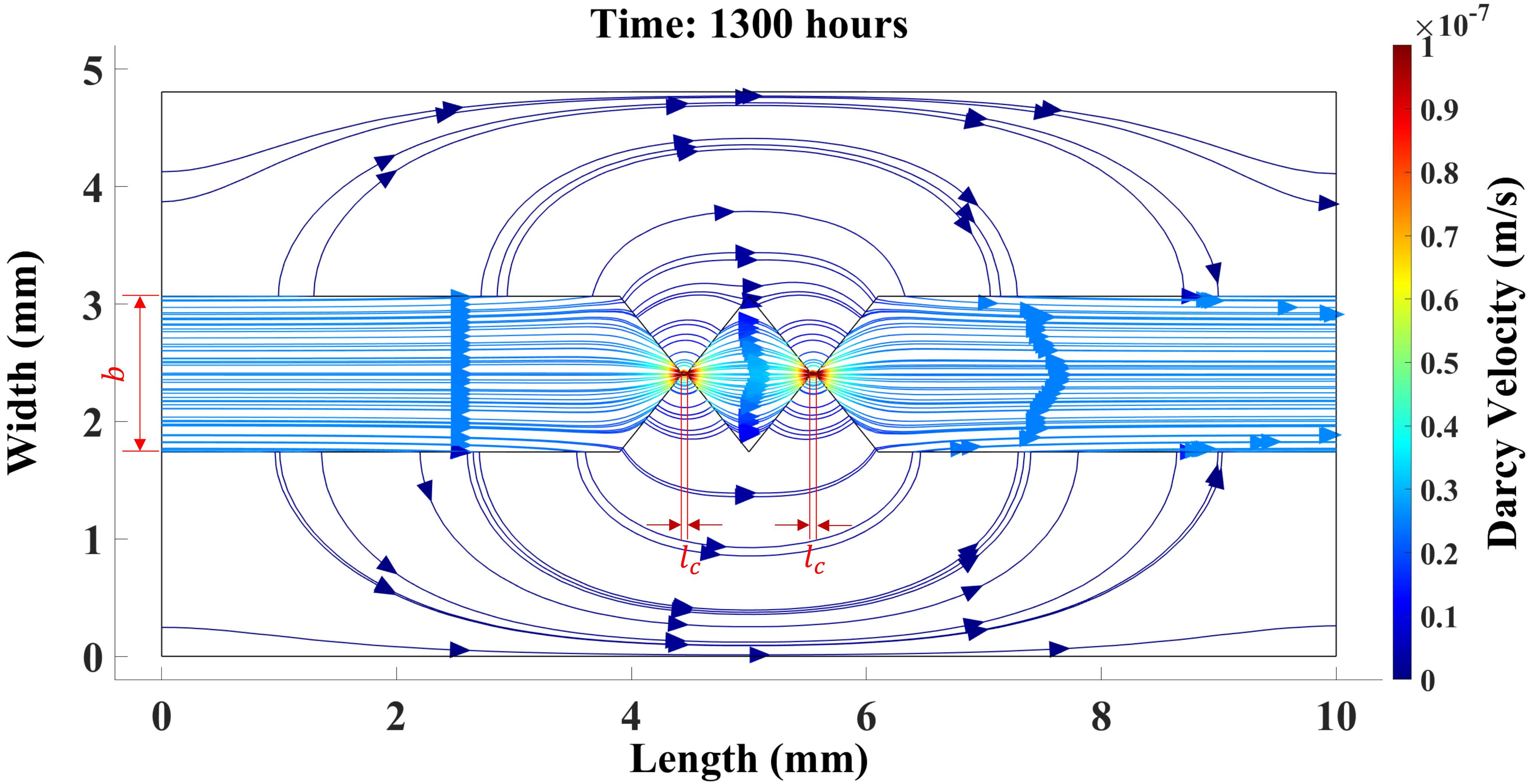
Fracture aperture change after 700 hours. (b = 1.19, l_c = 0.04)

- **Loading in 3.5MPa (Hybrid condition)**



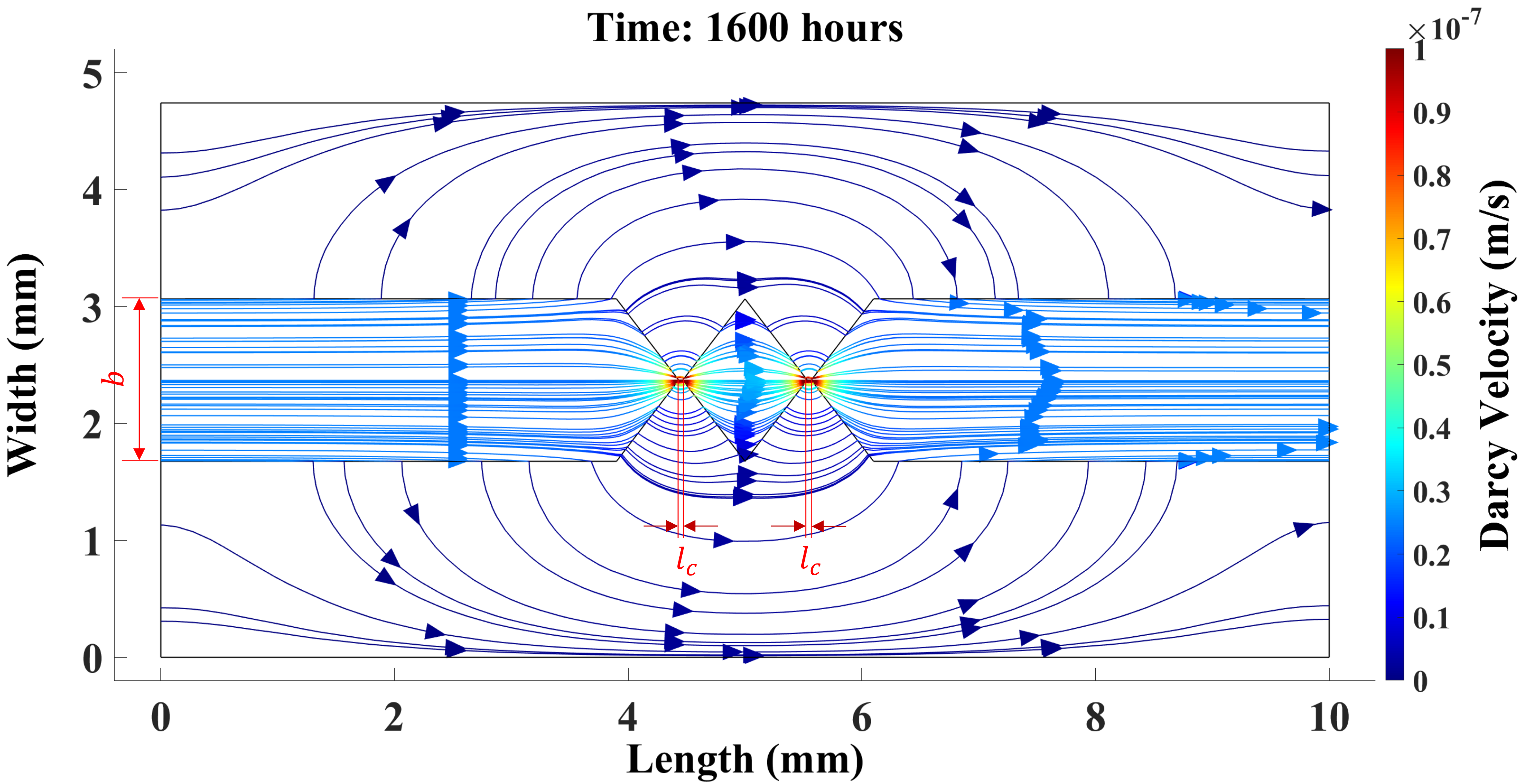
Fracture aperture change after 1000 hours. (b = 1.26, l_c = 0.03)

- **Loading in 3.5MPa (Hybrid condition)**



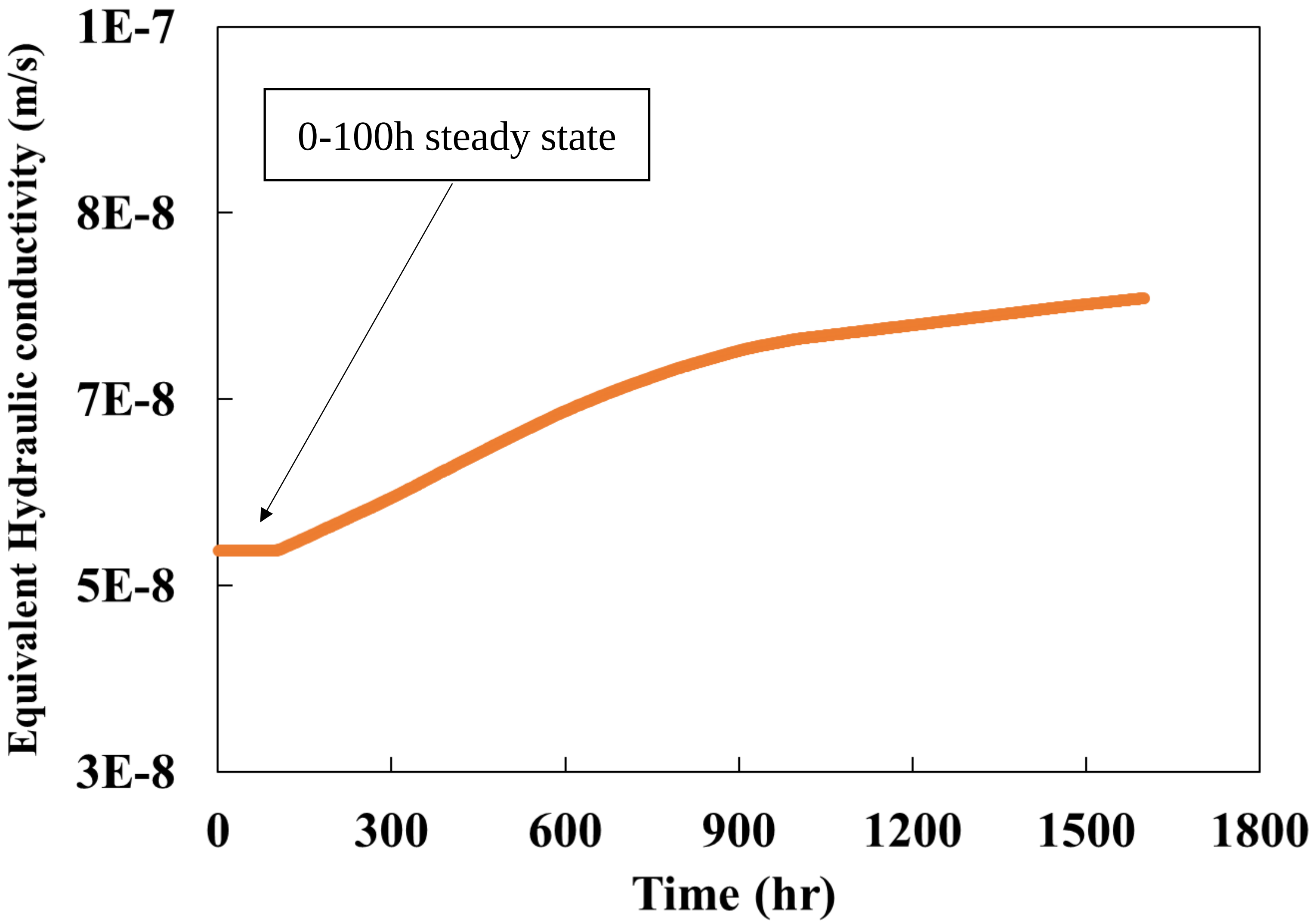
Fracture aperture change after 1300 hours. (b = 1.33, l_c = 0.03)

- **Loading in 3.5MPa (Hybrid condition)**



Fracture aperture change after 1600 hours. (b = 1.39, l_c = 0.03)

- **Loading in 3.5MPa (Hybrid condition)**



Equivalent Hydraulic conductivity change over time. (0-1600h)

Parameter	Unit	Pressure solution	Free-surface dissolution	Hybrid
Initial Equivalent hydraulic conductivity	$\frac{m}{s}$	5.08×10^{-8}		
Final Equivalent hydraulic conductivity	$\frac{m}{s}$	4.53×10^{-8}	0.33	7.45×10^{-8}
Rate of change	-	-10.78%	$+6.49\times10^{8}$ %	+46.72%

Equivalent hydraulic conductivity change under different effects

1) When considering only the effects of pressure solution, the equivalent hydraulic conductivity **decreases** by approximately 11%.
2) When considering only free surface dissolution, the equivalent hydraulic conductivity **increases** by approximately seven orders of magnitude.
3) When both effects are considered simultaneously, the equivalent hydraulic conductivity **increases** by approximately 47%.
4) According to the current results, it can be seen that since the free face dissolution rate is greater than the pressure dissolution rate, the fracture aperture will **continue to increase**.

➢ Future works

1. By changing the contact angle, length and width of the fracture asperity to calculate the impact of geometry on the results.
2. Conduct sensitivity analysis based on relevant parameters and compare the influences of parameter changes.

Thank you for listening !