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Freeze–Thaw Damage in Granular Geomaterials Integrating Pore-Scale Thermodynamics with Contact-Network Degradation

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POSTER 20

Read the full paper
J. Rock Mech. Geotech. Eng. (2026)
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1 Why it matters

30–60% strength lost in 20–50 cycles (porous rock)

10–100× rise in hydraulic conductivity

- Roads, dams and slopes in cold regions degrade with every freeze–thaw cycle.
- **Design relies on empirical fits**, calibrated per material and not transferable to new pore structures or climates.
- **Existing models fall short:** they ignore contact topology, omit key mechanisms, or cover few cycles.

RESEARCH GAP
No closed-form model links pore-scale ice thermodynamics to the stability of the grain-contact network.

2 Objectives

One framework from pores to grains to continuum damage, to:

1. Separate **bond fracture** D_b from **contact loss** D_l.
2. Predict the **stability limit** from the coordination number Z.
3. Derive **closed-form thresholds** and scaling laws for design.

3 Approach

Ice forms in the largest pores first; five mechanisms scale its expansion:

$$\varepsilon_r = \tfrac{1}{3} A_{ice}(\beta - 1) S_i S_w \Psi_{pore} \Psi_{front} \Psi_{lens}$$

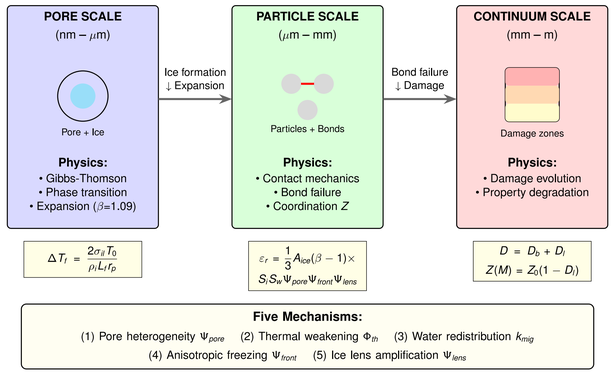
Ice stress reaches 6–7 MPa, but damage grows only if $\Pi_1 = \sigma_{ice}/\sigma_t^{max} > 1$:

$\Pi_1 < 1$	1–2	> 2
no damage	hundreds of cycles to fail	tens of cycles

Bond fracture and contact loss are tracked separately; failure comes as Z falls to $Z_{iso} = 2d$:

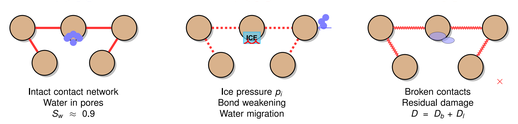
$$D = D_b + D_l \qquad Z(M) = Z_0 (1 - D_l)$$

4 A multiscale framework

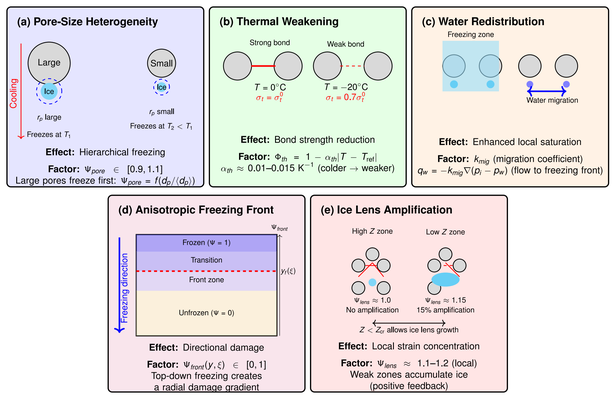


Pore → particle → continuum: ice breaks bonds and removes grain contacts; the loss accumulates as damage.

ONE FREEZE–THAW CYCLE AT THE GRAIN SCALE



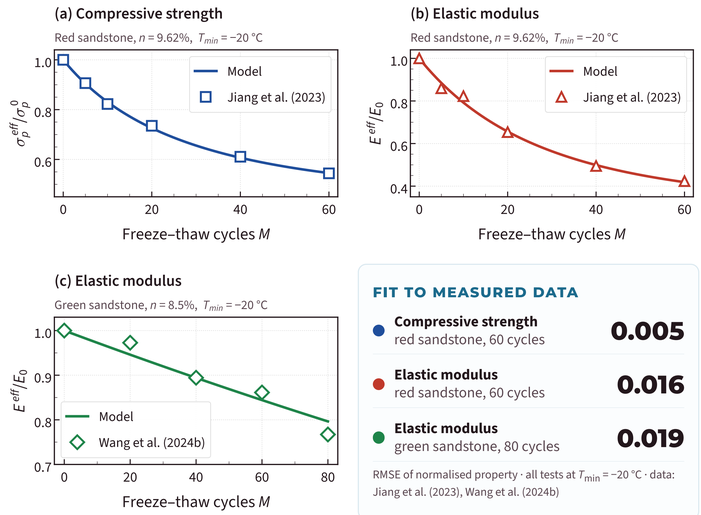
5 Five coupled damage mechanisms



RANKED BY INFLUENCE ON DAMAGE

1	Anisotropic freezing front	0–100% · dominant
2	Ice-lens amplification	+10–20% locally
3	Thermal weakening of bonds	20–30% loss
4	Water redistribution	moderate
5	Pore-size heterogeneity	±10% · smallest

6 Validated against experiments



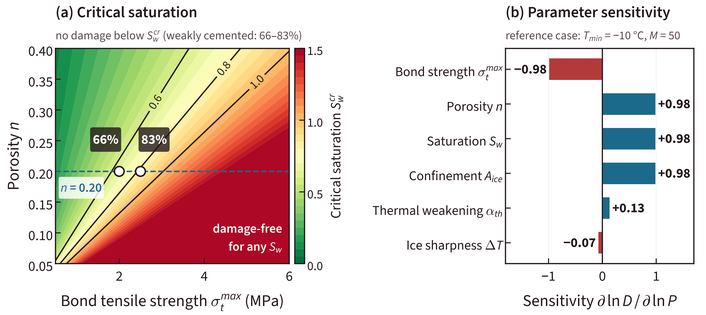
FIT TO MEASURED DATA

Compressive strength red sandstone, 60 cycles	**0.005**
Elastic modulus red sandstone, 60 cycles	**0.016**
Elastic modulus green sandstone, 80 cycles	**0.019**

RMSE of normalised property · all tests at T_{min} = −20 °C · data: Jiang et al. (2023), Wang et al. (2024b)

Two rock types, two laboratories, three properties: the model reproduces the concave decay in every case, with no parameters adjusted after plotting. Markers: measured data; lines: model.

7 When does damage start?



CRITICAL SATURATION

$$S_w^{cr} = \frac{3\,\sigma_t^{max}}{E\,A_{ice}\,n\,S_i\,(\beta - 1)}$$

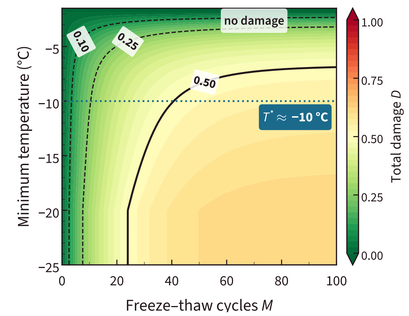
(a) No damage forms below the critical saturation: 66% for weakly cemented (σ_t = 2 MPa) and 83% for moderately cemented (2.5 MPa) material at n = 0.20. **(b) Sensitivity ≈ ±1** at the reference case; it eases from 1.4 at 20 cycles to 0.8 at 100.

−0.98
Bond strength: doubling it roughly halves the damage

+0.98
Porosity, saturation, confinement: damage grows in proportion

TAKEAWAY
Keeping the material drier than S_w^{cr} prevents freeze–thaw damage altogether, so **drainage is the first line of defence**.

8 Temperature & failure



Weakly cemented sandstone. Damage is negligible above about −3 °C. It rises steeply with cooling down to T^* ≈ −10 °C, where ice content controls, and only gradually below it, where bond weakening controls.

66–83% critical saturation: drier material does not degrade

14–25% contact loss at instability; failure at 30–50% damage

≈ −10 °C crossover: colder cycles add little extra damage

9 Conclusions

- Five mechanisms combine in **one composite strain**; the freezing front dominates.
- Losing **14–25% of contacts** destabilises the skeleton.
- Stiffness falls as $(1–D)^2$, tensile strength as $(1–D)^{2.5}$; permeability rises 10–100×.
- Damage saturates at an upper bound set by the material and thermal regime.

DESIGN IMPLICATIONS

Drainage keep saturation below the threshold

Gradation raise initial coordination

Cementation raise bond tensile strength

Insulation limit temperature swings

Monitoring estimate residual life from the coordination number

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