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Mechanical degradation characterization in remolded moraine soils and microstructure evolution under freeze–thaw cycles

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1. Background, Gap and Study Objectives

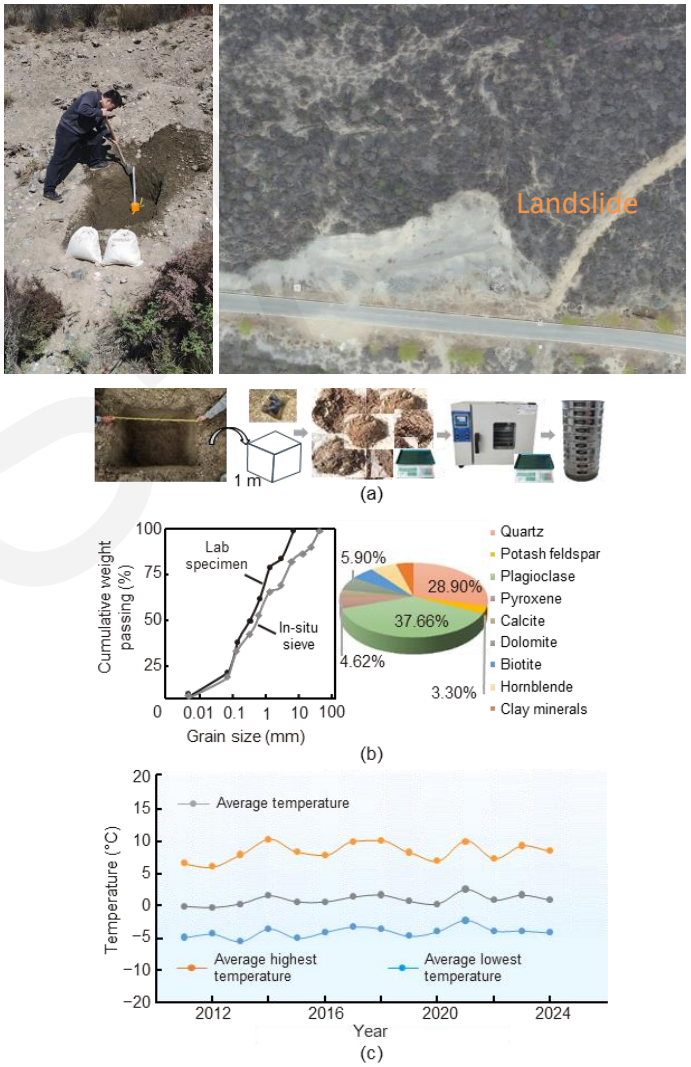
Moraine soils are widely distributed in high-altitude cold regions and are strongly affected by repeated freeze–thaw (F–T) cycles.

Mechanical deterioration of these soils directly threatens slope stability, roadbeds, and cold-region infrastructure.

Key gaps before this work: limited quantitative prediction models and insufficient 3D evidence for pore-crack evolution.

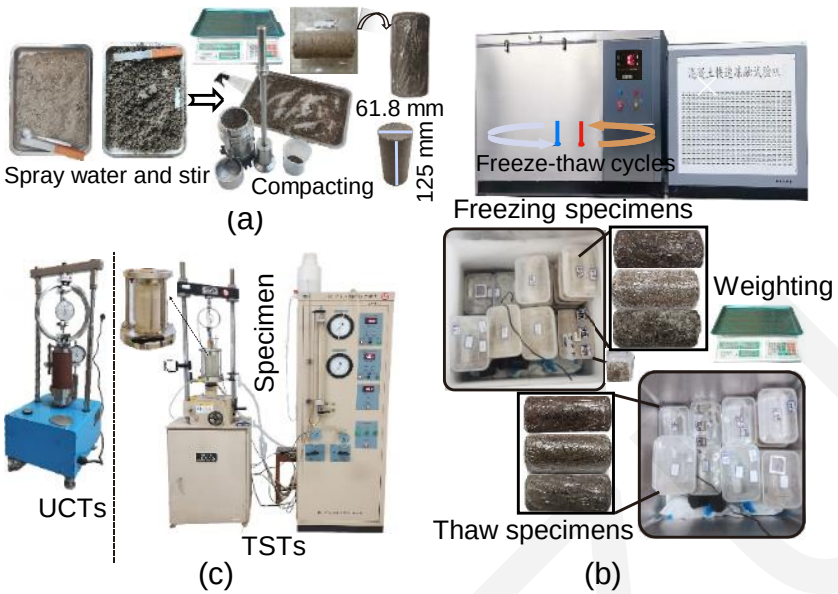
Study objectives

1) quantify strength and stiffness degradation under F–T cycles;
2) reveal microstructural evolution using micro-CT + deep learning;
3) develop a practical gray model for later-cycle prediction.



Study area, grain-size/mineralogical information, and regional January temperature conditions

2. Experimental Program and Workflow



Remolded specimen preparation, freeze–thaw cycling, UCT and TST testing

Test matrix

F–T cycles: N = 0, 2, 5, 10, 15, 20
Mechanical tests: UCT and unconsolidated-undrained TST
Confining pressures: 50, 100, 200 kPa

Thermal path

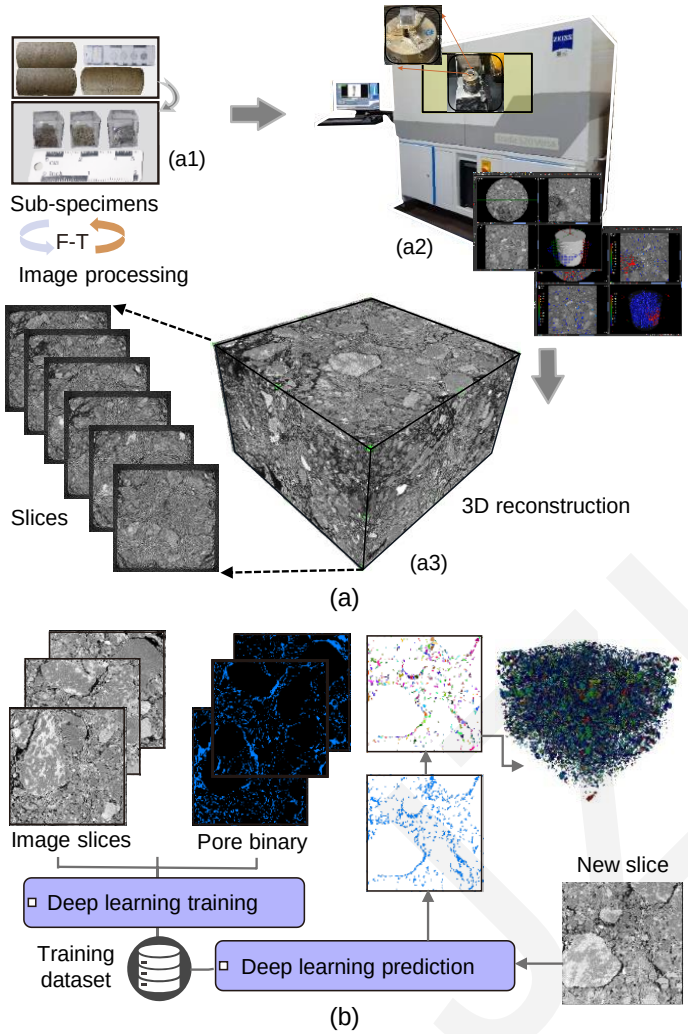
Freezing: −6 °C for 13 h
Thawing: 10 °C for 11 h
One cycle = freezing + thawing

Why this matters

The design captures both macro-scale mechanical response and the accumulation of F–T damage over time.

Source: adapted from the uploaded manuscript

3. Micro-CT and Deep Learning Characterization



Sub-specimen selection, CT scanning, 3D reconstruction, and U-Net-based pore-crack segmentation

Micro-CT setup

System: Zeiss Xradia 520 Versa
Resolution: 8.0 µm/pixel
Approx. 1200 grayscale slices per scan

Segmentation strategy

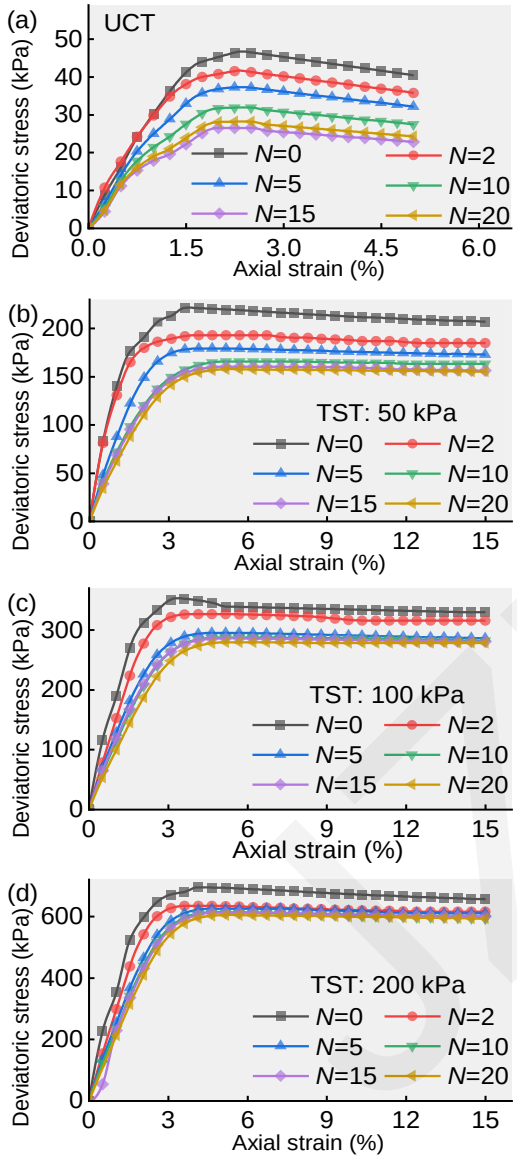
Enhanced U-Net model trained on 4000 images and tested on 8000 images to separate pore-crack networks.

Outputs extracted

3D porosity, equivalent pore width (W_{EqW}), and fractal dimension (D_v) to link microstructure with macroscopic degradation.

Source: adapted from the uploaded manuscript

4. Stress–Strain Response under Freeze–Thaw Cycles



UCT and TST stress–strain curves at different confining pressures

Source: adapted from the uploaded manuscript

Key observation 1

All specimens show typical strain-softening behavior, but peak deviatoric stress decreases continuously as F–T cycles increase.

Key observation 2

The gap between peak strength and residual strength becomes narrower after repeated F–T cycles, indicating structural weakening.

Take-home

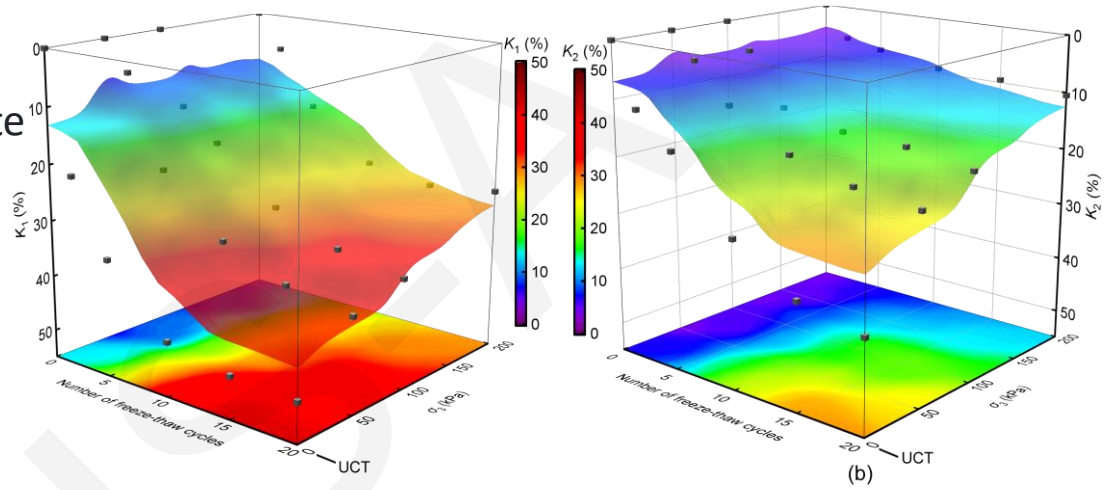
Degradation is more evident at low confinement, while higher confining pressure partly suppresses damage accumulation.

5. Mechanical Deterioration: Three-Stage Evolution

Mechanical parameters degrade in three stages: rapid decline → moderate reduction → plateau.

Low confining pressure is more vulnerable to deterioration than high confining pressure.

The deterioration rate surfaces help visualize the combined effects of F–T cycles and test condition.



Representative reductions from N=0 to N=20

UCT: E_o 3.20 → 1.50 MPa; q_u 40.80 → 24.08 kPa

TST (50 kPa): E_o 14.24 → 8.82 MPa; q_t 202.07 → 157.75 kPa

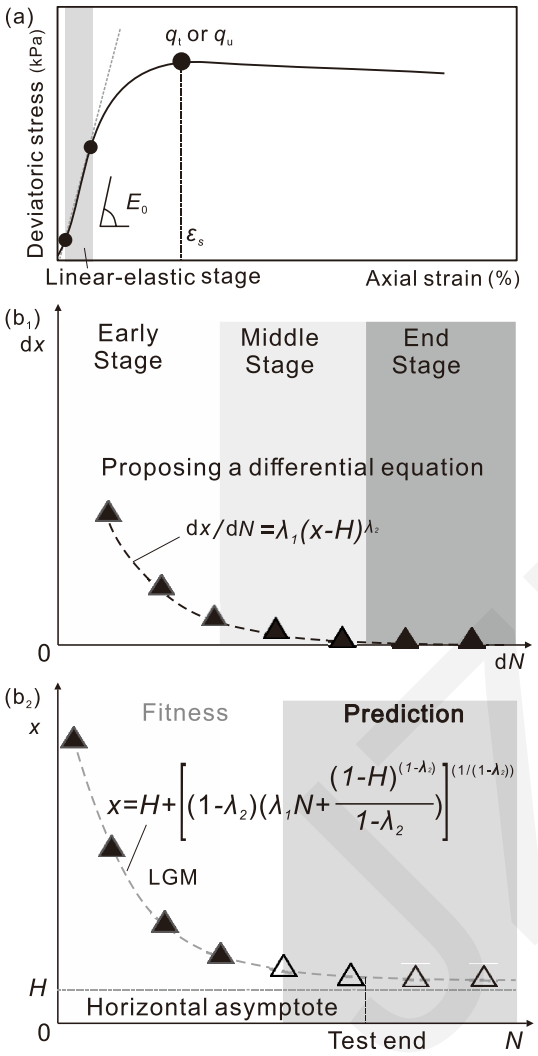
Cohesion: 10.83 → 6.50 kPa

Interpretation

K_1 and K_2 indicate that both stiffness and strength are most sensitive in the early F–T cycles; higher confinement partially closes cracks and mitigates loss.

Source: adapted from the uploaded manuscript

6. New Gray Model: Main Idea and Physical Meaning



Schematic illustration of the proposed gray model

Model concept

A nonlinear gray differential equation was proposed to capture the degradation path of mechanical parameters under repeated F–T cycles.

Why it is useful

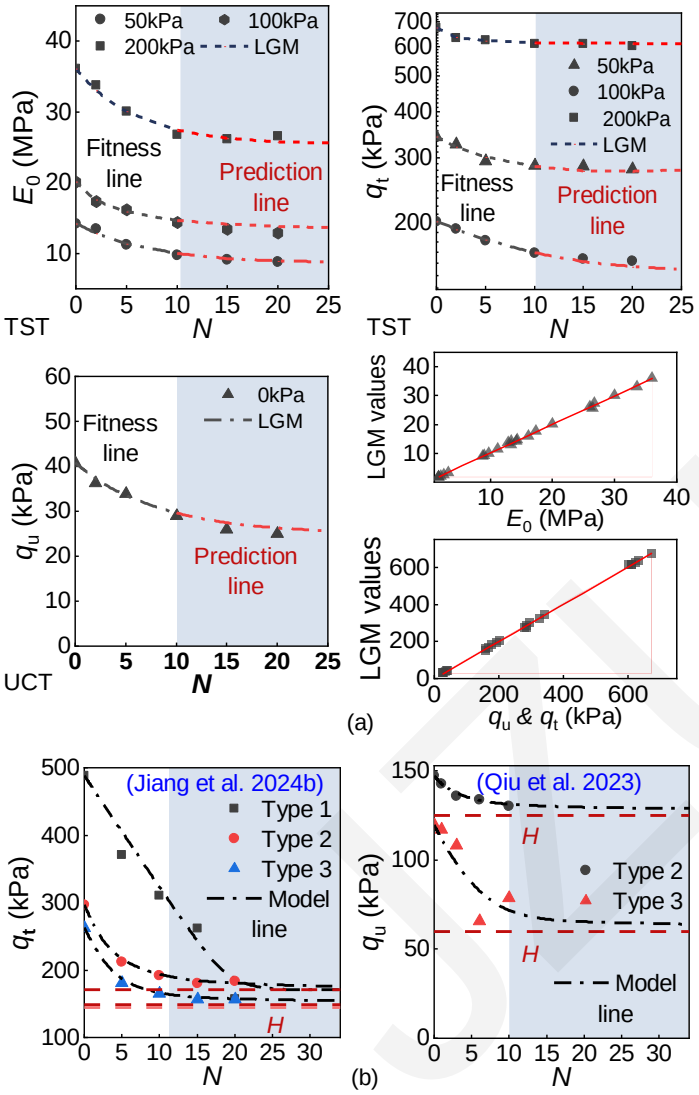
The model explicitly reflects the three-stage trend and introduces H as the long-term asymptotic deterioration limit.

Practical advantage

Only limited early-cycle data are needed to fit the model, making it suitable for engineering prediction when test data are scarce.

Source: adapted from the uploaded manuscript

7. Model Validation and Prediction Performance



Fitness and prediction results of the new gray model

Accuracy

The model reproduces the attenuation trend consistently with $R^2 > 0.96$ across different confining pressures.

Prediction quality

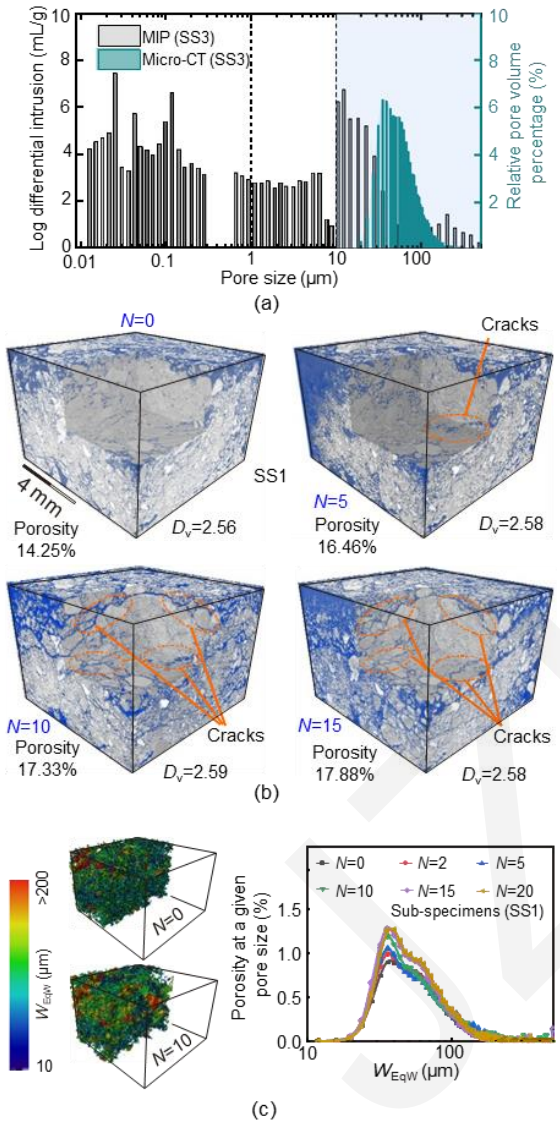
For q_t, q_u and E_o, prediction errors at the 15th and 20th cycles are below 6%, showing good reliability for later-cycle estimation.

Generalization

The model also performs well when applied to data from previous moraine-soil studies, demonstrating broader applicability.

Source: adapted from the uploaded manuscript

8. Microstructural Evolution Mechanism



MIP vs. micro-CT results, 3D pore-crack evolution, and equivalent pore-width distribution

Porosity increase

Microporosity rises from 14.25% to 18.69% from N=0 to N=20, corresponding to a 31% increase.

Pore-size coarsening

Average equivalent pore width increases from 69.83 to 90.44 μm, indicating progressive crack enlargement and connectivity growth.

Mechanistic interpretation

Freeze–thaw cycles initiate and propagate pore-crack networks, coarsen the soil skeleton, reduce bonding/interlocking, and ultimately drive macroscopic strength loss.

9. Conclusions and Take-Home Messages

Conclusion 1

Mechanical degradation of remolded moraine soils under F–T cycles follows a clear three-stage path: rapid decline, moderate reduction, and plateau.

Conclusion 2

Microstructural deterioration is the key driver: porosity and pore size increase substantially, while the pore-crack network becomes more connected.

Conclusion 3

The proposed gray model predicts later-cycle mechanical parameters accurately and provides a practical tool for cold-region engineering assessment.

Engineering implication

The new framework (mechanical tests + micro-CT + gray model) offers a reliable basis for evaluating the long-term stability of moraine slopes and infrastructure in freeze–thaw environments.

Thank you!

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