Split-Node Physics-Encoded Finite Element Network for Forward and Inverse Modeling of Fault-Slip-Induced Discontinuous Deformation

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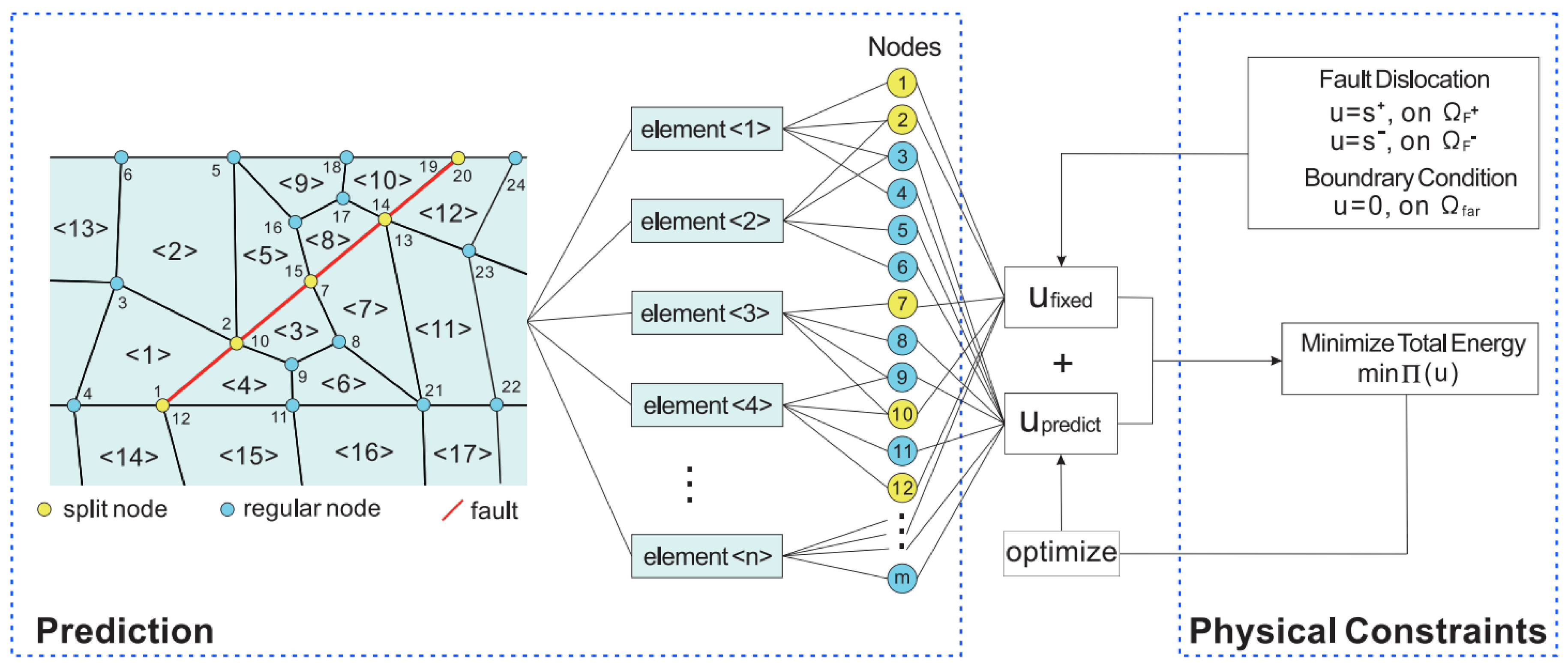
ABSTRACT

Modeling crustal deformation induced by fault dislocation is a cornerstone problem in structural geology and seismology. Its inherent data sparsity and spatial displacement discontinuities make conventional forward and inverse modeling simultaneously slow and inaccurate. Although AI-driven approaches such as Physics-Informed Neural Networks (PINNs) and Physics-Encoded Finite Element Networks (PEFENs) have opened new avenues for problems that are data-poor yet governed by clear physics, their underlying assumption of continuously differentiable fields clashes with the intrinsic displacement jumps across faults, leaving a substantial gap. Here we introduce a Split-Node PEFEN (SN-PEFEN) that embeds the classic split-node technique into the PEFEN framework. By pre-processing the mesh to split nodes along fault interfaces, we explicitly encode spatial discontinuities in the nodal topology, overcoming the continuity limitation of existing PEFENs. The method is demonstrated on both 2-D and 3-D heterogeneous media. For meshes with ~1 million degrees of freedom, the proposed forward solver is more than 40 × faster than a standard finite element analysis (≈ 1800 s → 42 s) while maintaining comparable accuracy. The inverse problem converges within 60 iterations, finishing in less time than a single forward run of the traditional FEM (≈ 2000 s). SN-PEFEN therefore offers a new paradigm for multi-fault system analysis, slip distribution inversion, and other discontinuous deformation problems.

Method

Forward Modeling

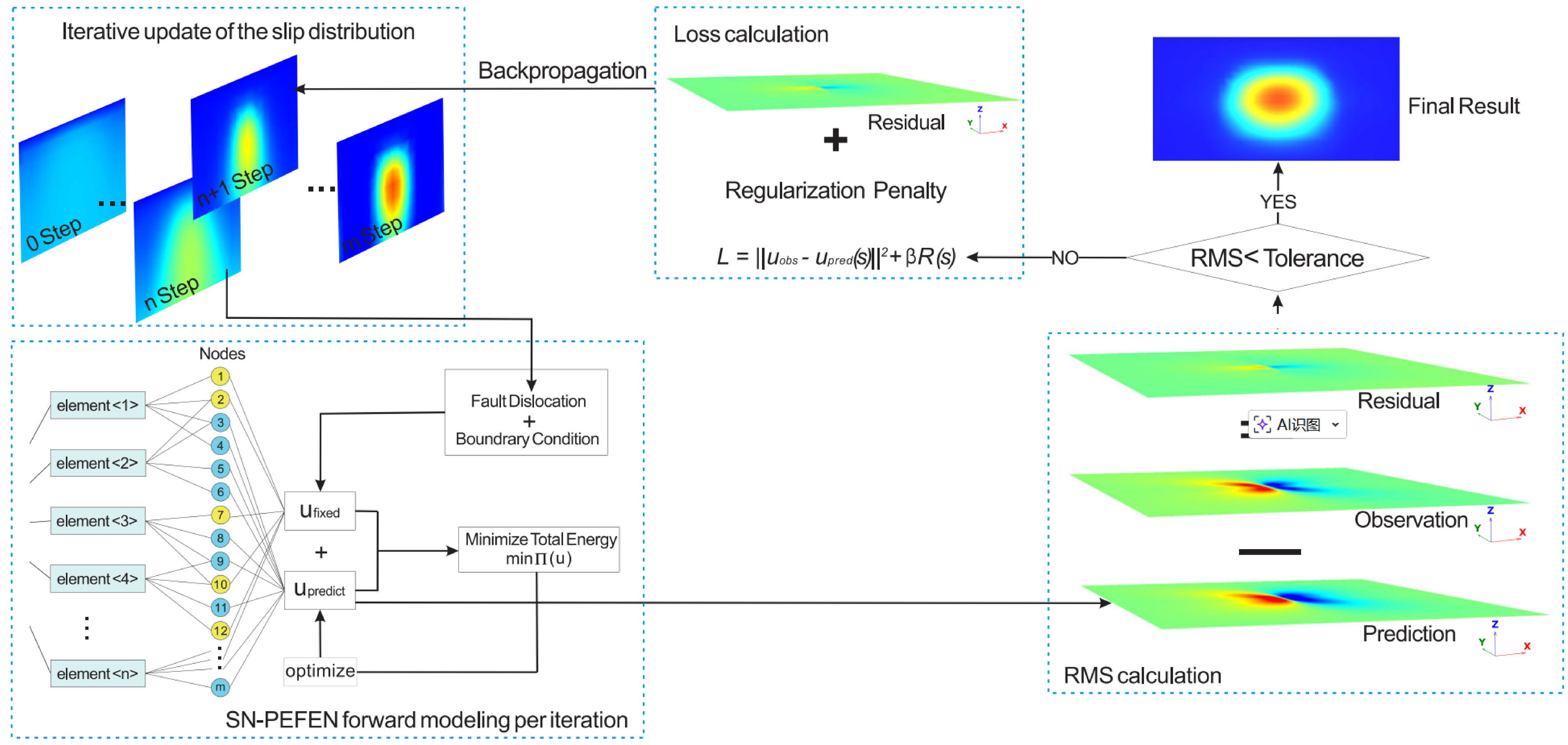


The forward run starts from a conventional FE mesh, but duplicates every fault node (split-node technique) so the prescribed slip jump is written directly into the loss. Minimising the total potential energy then optimises the nodal DOFs within standard ML frameworks—no global stiffness matrix needs to be assembled. The loss function is:

$$\Pi(u) = \sum_e \sum_g \omega_g^{(e)} \left(\frac{1}{2}\lambda(\nabla \cdot u^{(e,g)})^2 + \mu\epsilon : \epsilon\right)$$

Method

Inverse Modeling



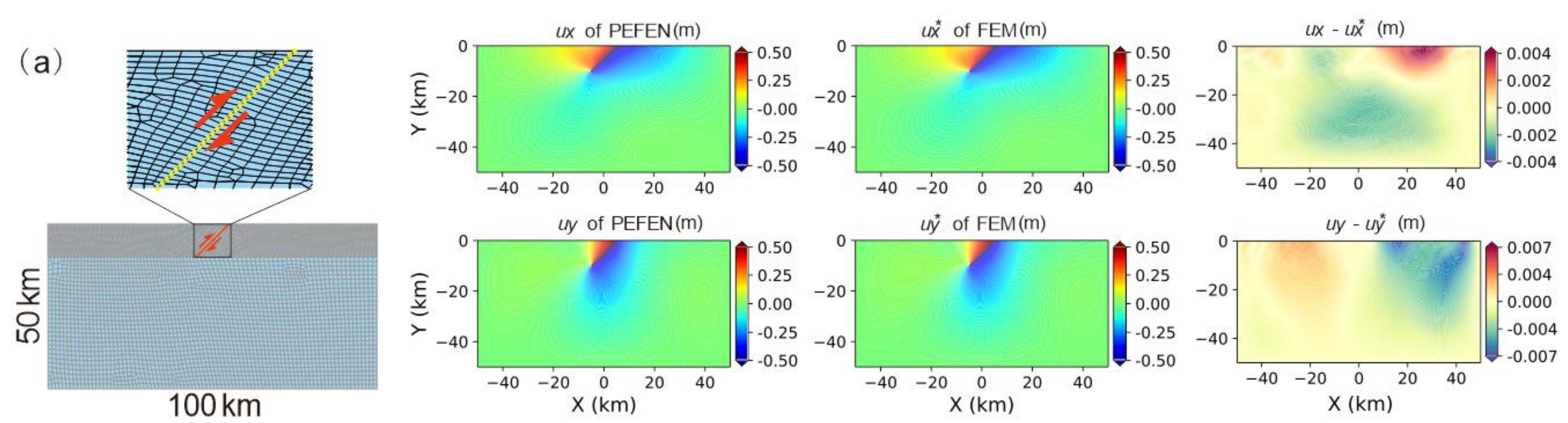
In the inversion, unknown parameters are refined by repeatedly fitting the observations; each iteration comprises one forward solve and one back-propagation step. The loss function is:

$$L_{total} = \left\| u_{obs} - u_{pred}(\theta) \right\|^2 + \lambda R(\theta)$$

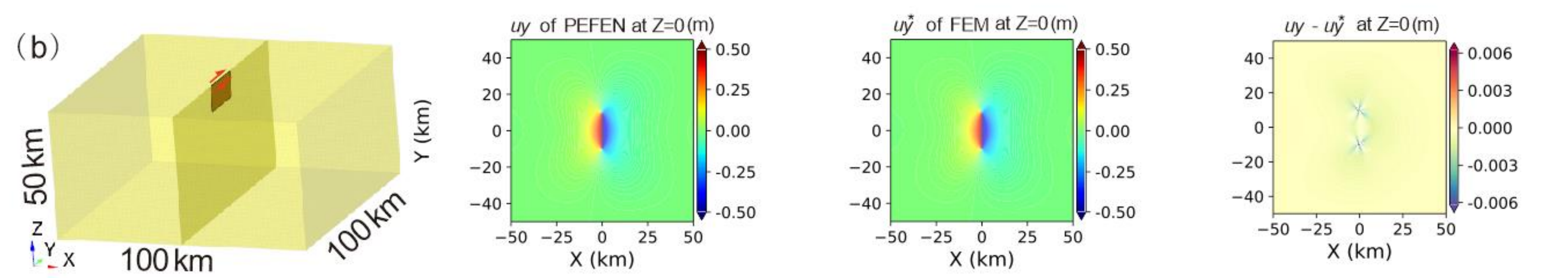
Results

Forward and inverse modeling cases were run on a workstation equipped with an Intel® Xeon® Gold 5218R (2.10 GHz), 128 GB RAM, and an NVIDIA RTX A4000 GPU (16 GB). For comparison, the corresponding forward finite element solutions were computed with the commercial FEM package ABAQUS using the same mesh and boundary conditions.

Forward Modeling Results: PEFEN vs. FEM

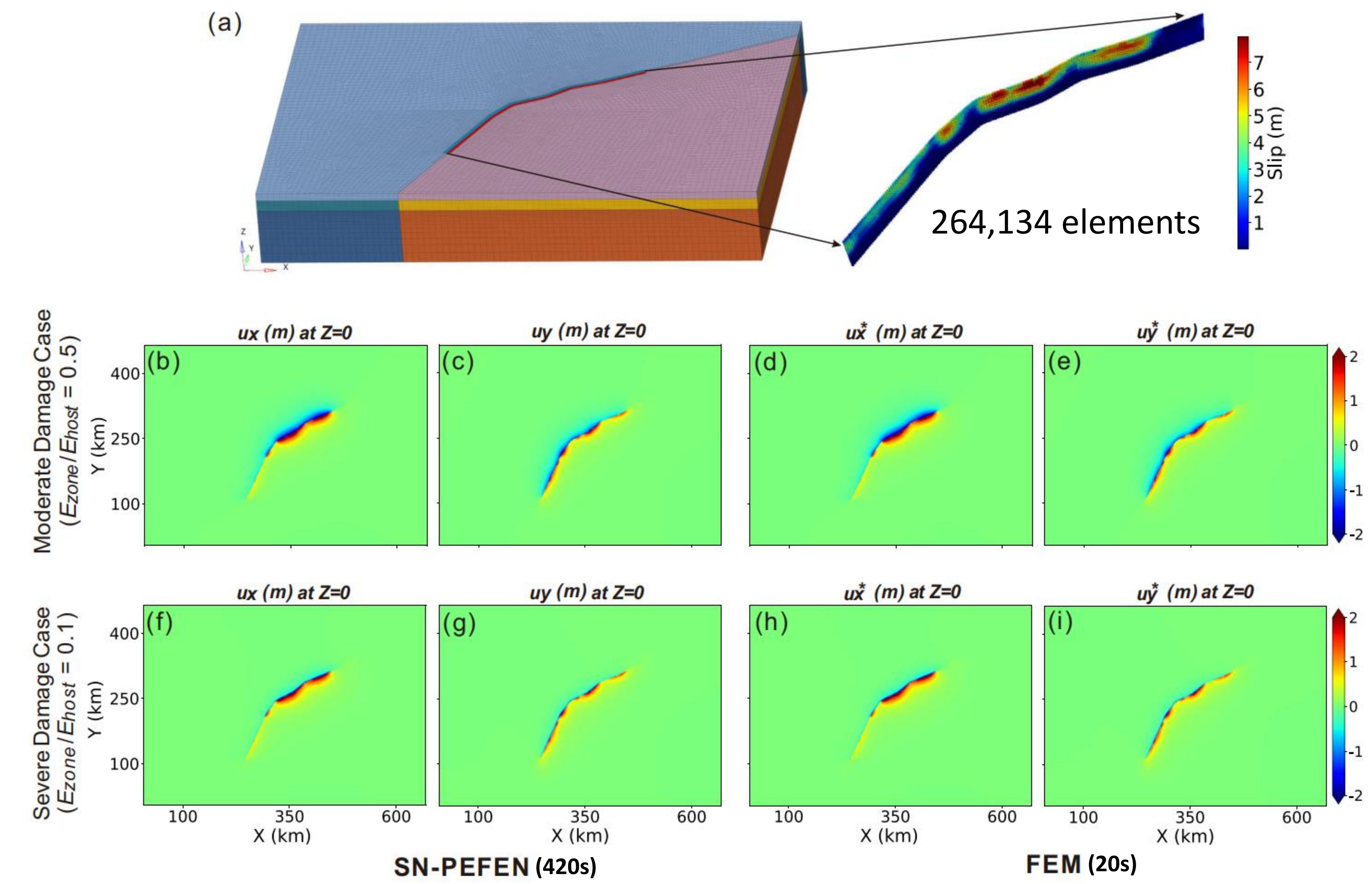


2D thrust fault dislocation model in homogeneous medium (4029 elements). Runtime comparison: PEFEN (4.5 s) vs. FEM (4 s)

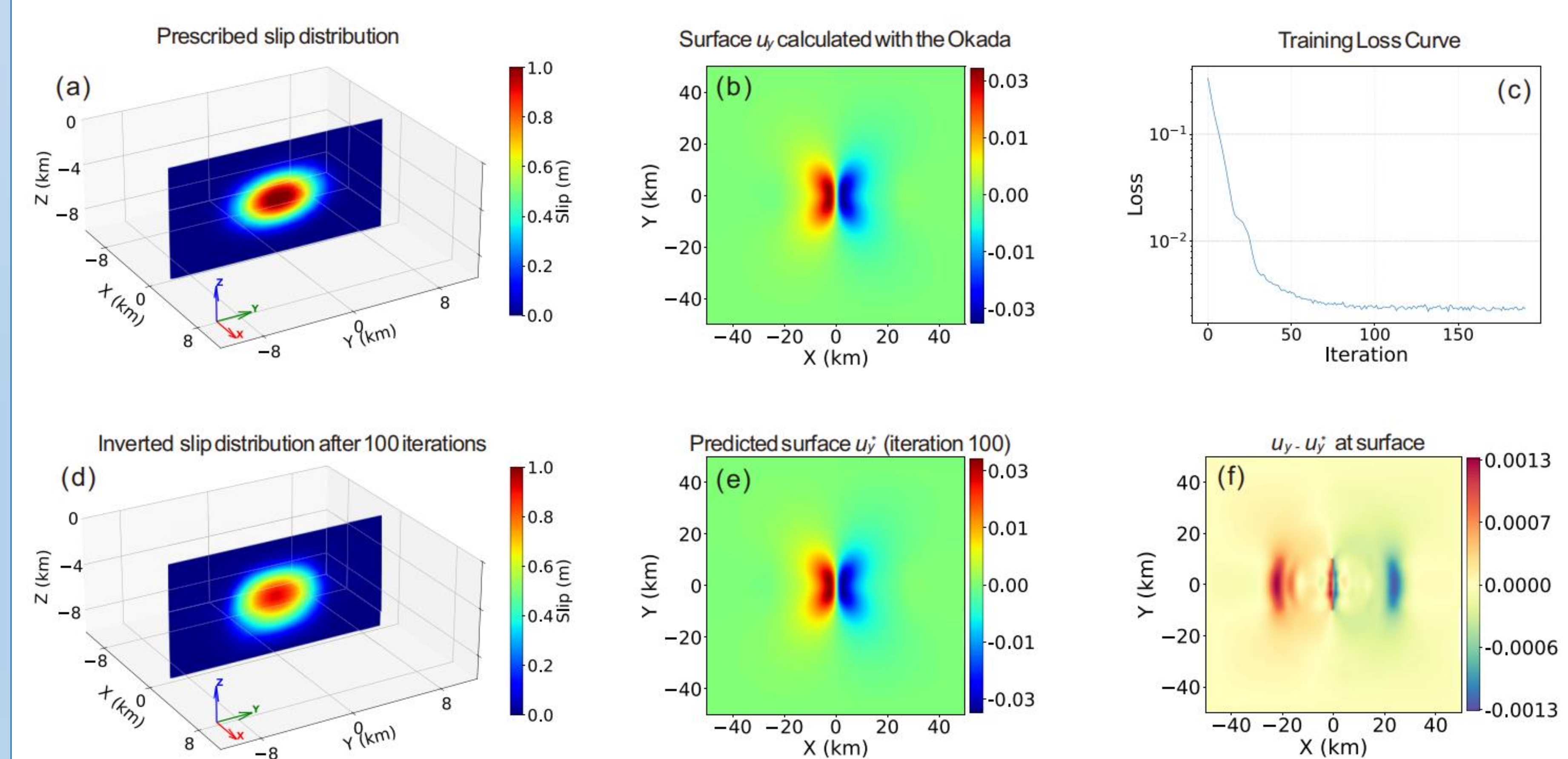


3D strike-slip fault dislocation in a homogeneous medium(500,000 elements). Runtime comparison:PEFEN(41s) vs. FEM(1831s)

Forward modelling results of the 3-D complex heterogeneous model based on the 2023 Turkey Mw 7.8 earthquake



Inverse modelling performance for 3-D strike-slip fault



Reference

➢ Yang X, Tao W. Split-node physics-encoded finite-element network for forward and inverse modeling of fault-slip-induced discontinuous deformation. Geophys J Int. 2026:ggag74. doi: 10.1093/gji/ggag074

➢ The code developed in this study is available at https://doi.org/10.5 281/zenodo.16623837