

Impact of 3D seismic soil-foundation-structure interaction on damage and settlement patterns of a masonry tower in southern Italy

Onur Deniz Akan¹⁾, Guido Camata¹⁾, Carlo G. Lai²⁾, Enrico Spacone¹⁾, and Claudio Tamagnini³⁾

¹⁾ Department of Engineering and Geology, University of Chieti-Pescara, Italy

²⁾ Department of Civil Engineering and Architecture, University of Pavia, Italy

³⁾ Department of Civil and Environmental Engineering, University of Perugia, Italy



Introduction & Digital Twin Modeling

Soil-foundation-structure interaction (SFSI) significantly influences the seismic performance of historical unreinforced masonry towers, yet the mechanisms leading to damage remain an open research question. To investigate this, a high-fidelity virtual SFSI laboratory was developed in OpenSees, creating a finite element digital twin of the St. Maria Maggiore Cathedral's bell tower in Guardiagrele, Italy.

The massive 220,000-element model incorporates stratified fine-grained soil, an explicit shallow foundation, and adjacent church walls to accurately capture pounding effects. Stable computation of these severe material and geometric nonlinearities is achieved using a mixed implicit-explicit (IMPL-EX) integration scheme for both the masonry damage-plasticity modeling and the contact friction interfaces. The model's seismic response was assessed using three-component ground motions matched to a conditional spectrum for a 475-year return period.

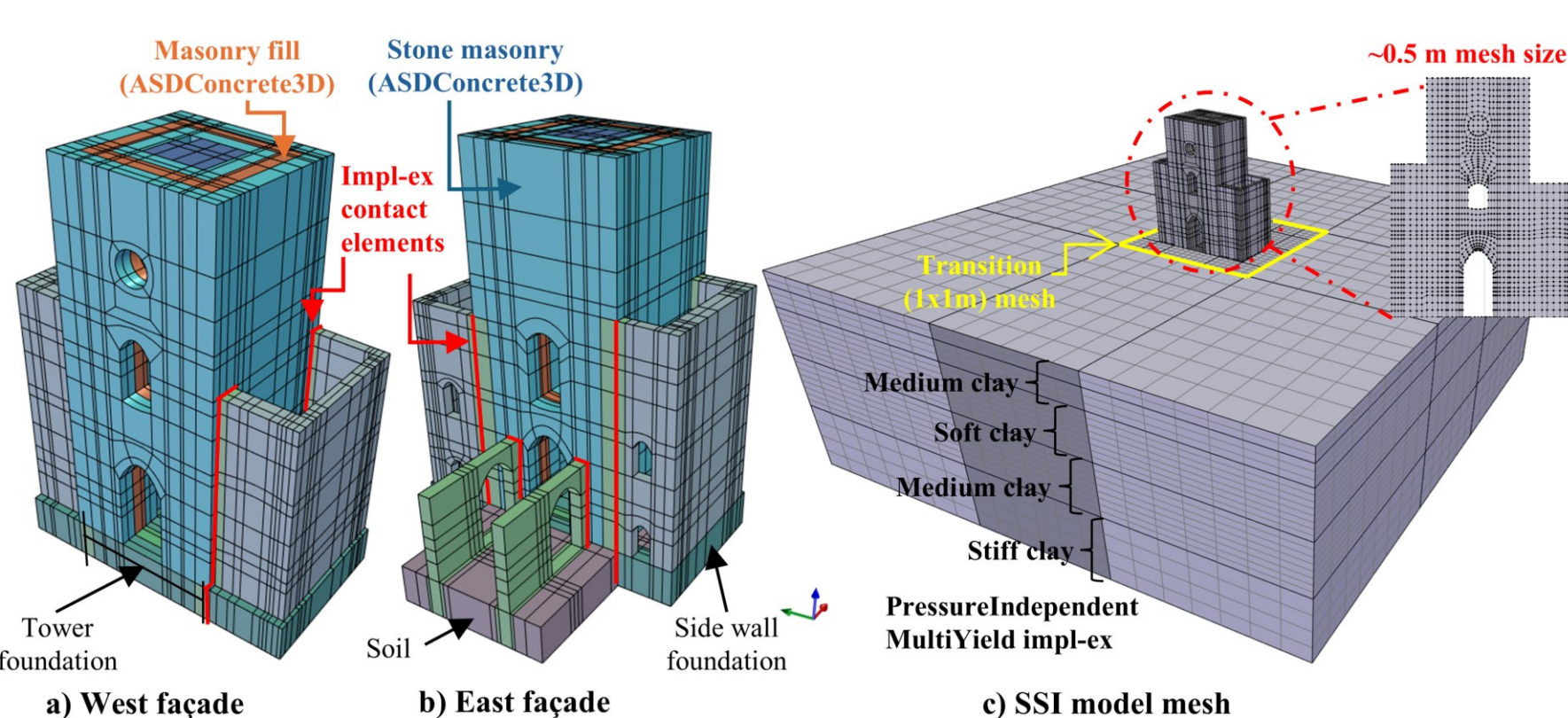


Figure 1. Digital twin of the bell tower: masonry material model (left) and the soil-foundation-structure interaction mesh with the stratified subsoil (right).

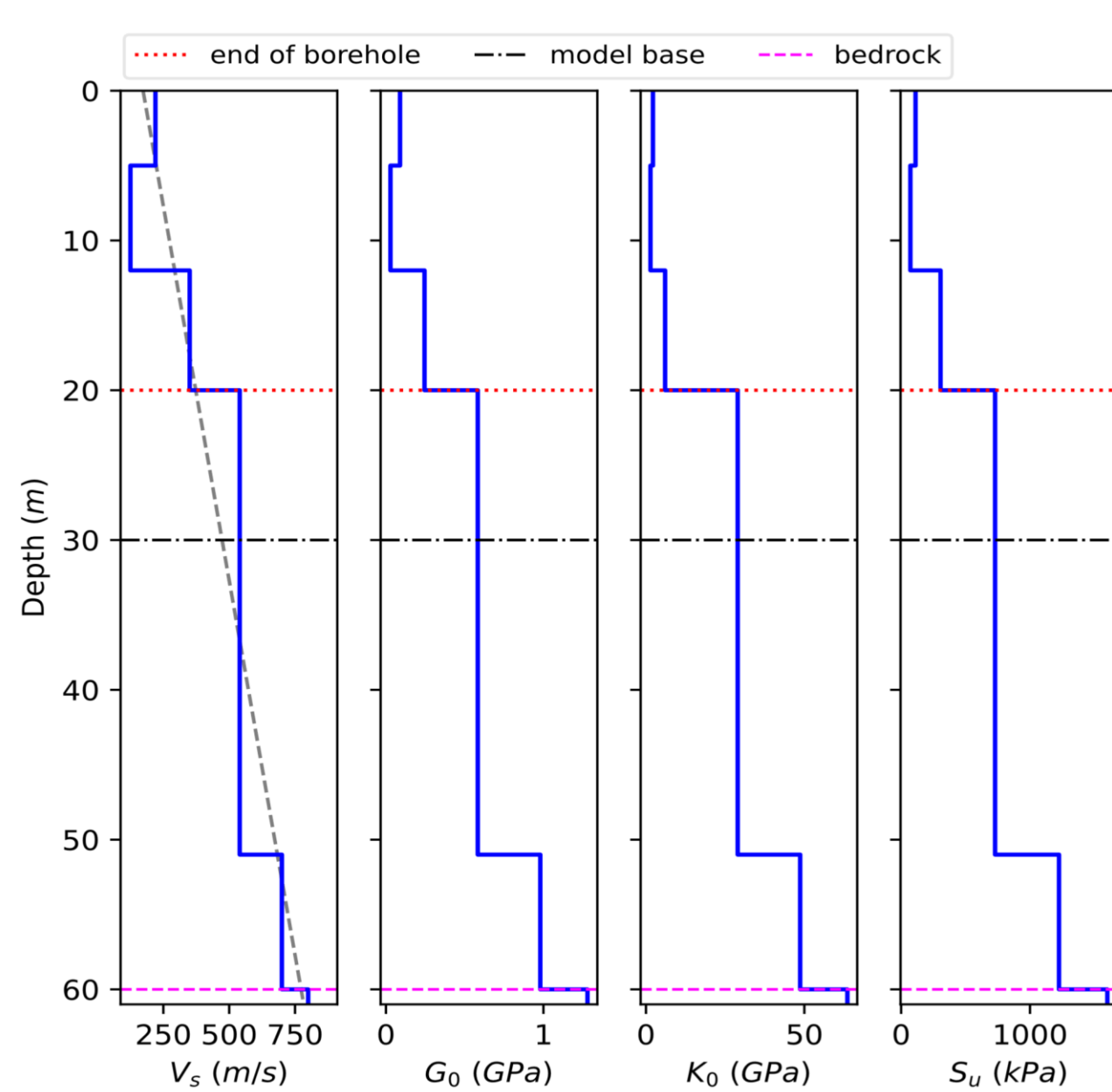


Figure 2. Site profile adopted in the analyses: depth variation of V_s , G_0 , K_0 , and S_u .

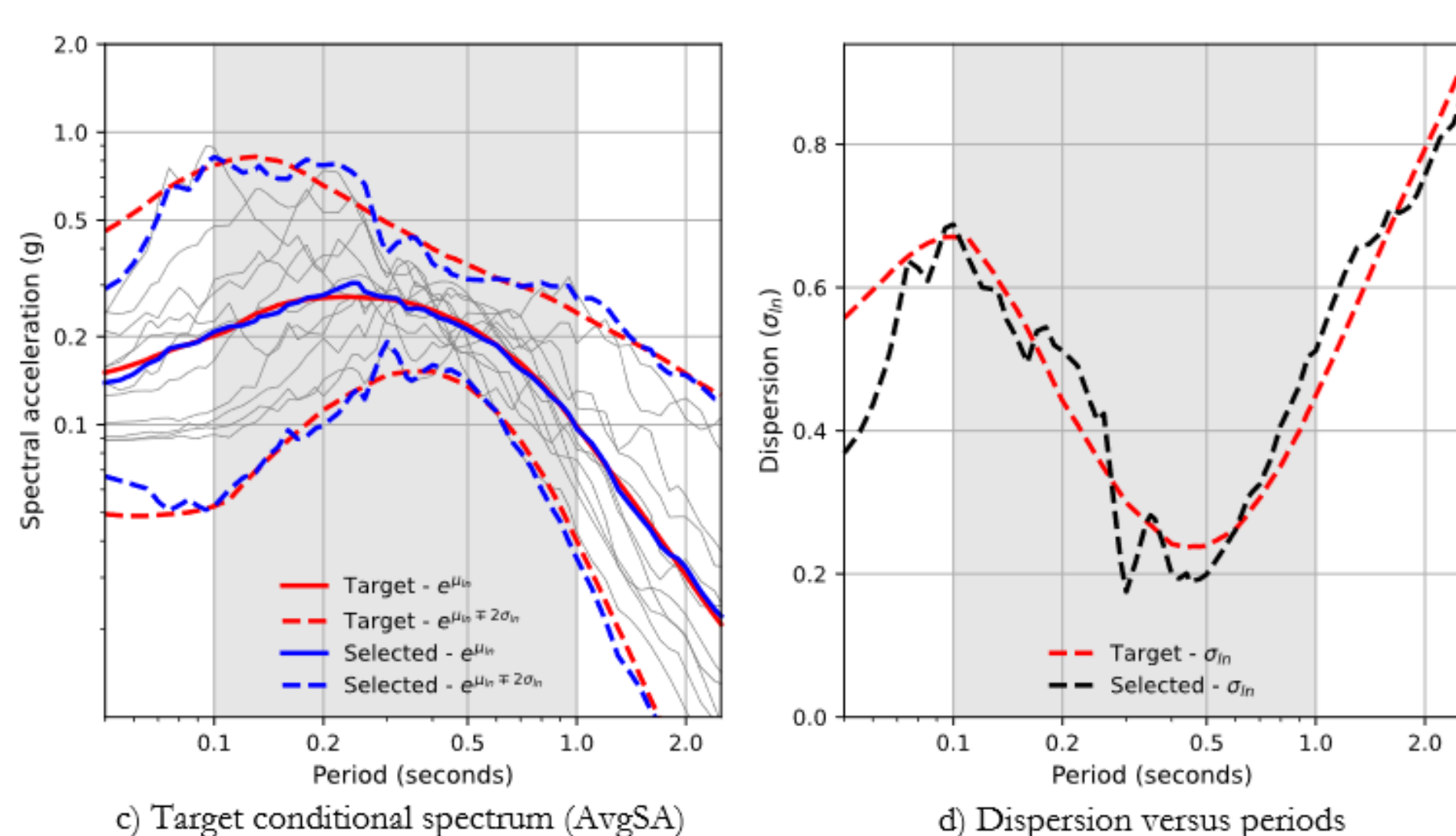


Figure 3. Selected ground-motion set; the suite mean and dispersion match the target AvgSA conditional spectrum for a 475-year return period.

Foundation Rotation & Soil Nonlinearity

Analyses show that foundation rotation is the dominant mechanism governing the fundamental period of the interacting system, compared to fixed-base models. While foundation rocking can act as an isolation mechanism that reduces seismic forces on the superstructure, the extent of structural damage is heavily dependent on the foundation soil's behavior.

Specifically, the shape of the soil's shear modulus reduction curve is a critical driver of structural damage. Foundation soils that exhibit a slower rate of stiffness reduction transfer more high-frequency seismic energy to the tower before yielding occurs. For brittle structures like masonry towers, this early-cycle, high-frequency energy transmission leads to much more intense cracking damage.

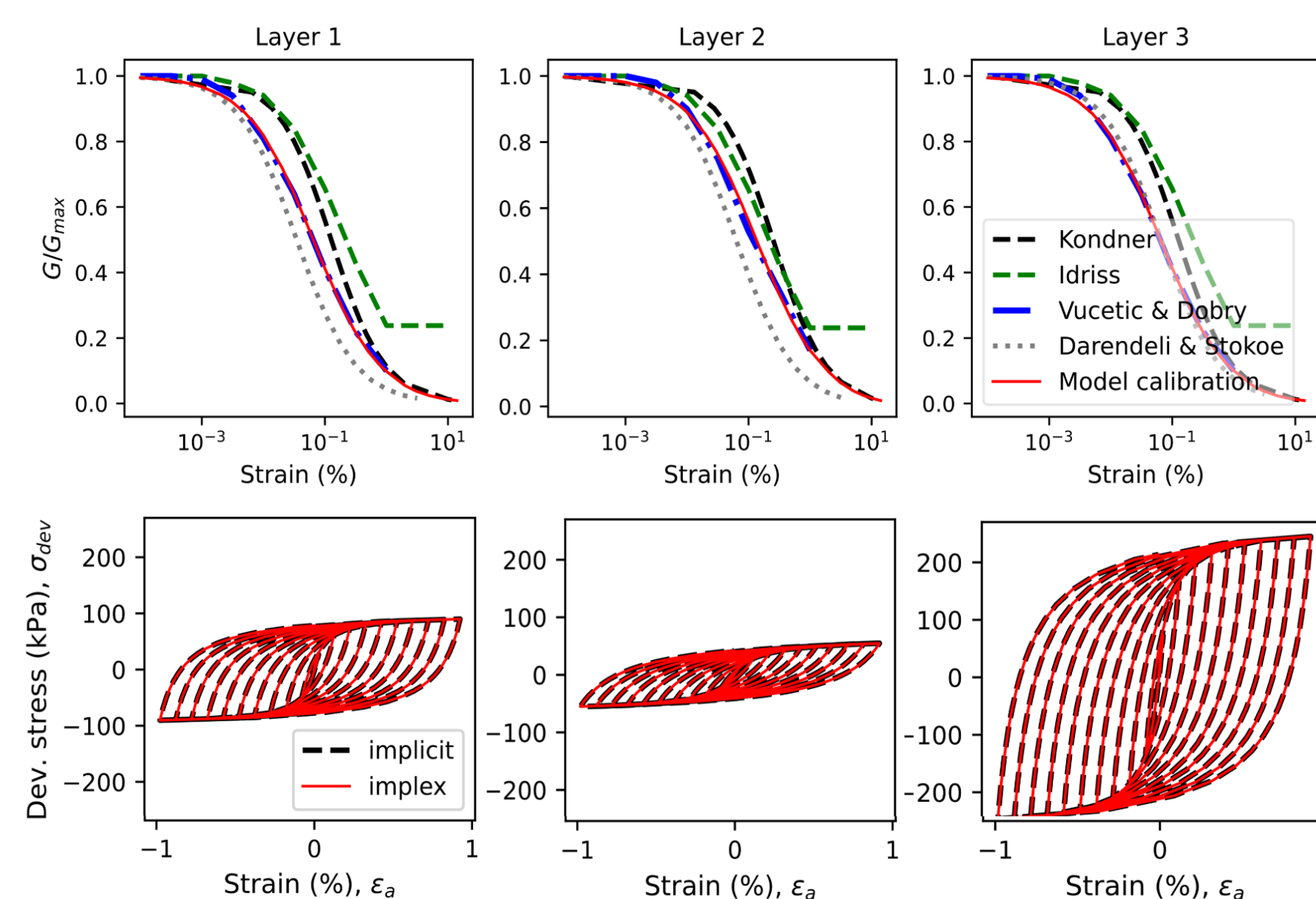


Figure 4. Pressure-independent multi-yield calibration matching the G/G_{max} shear modulus reduction and damping curves of Vucetic and Dobry (1991).

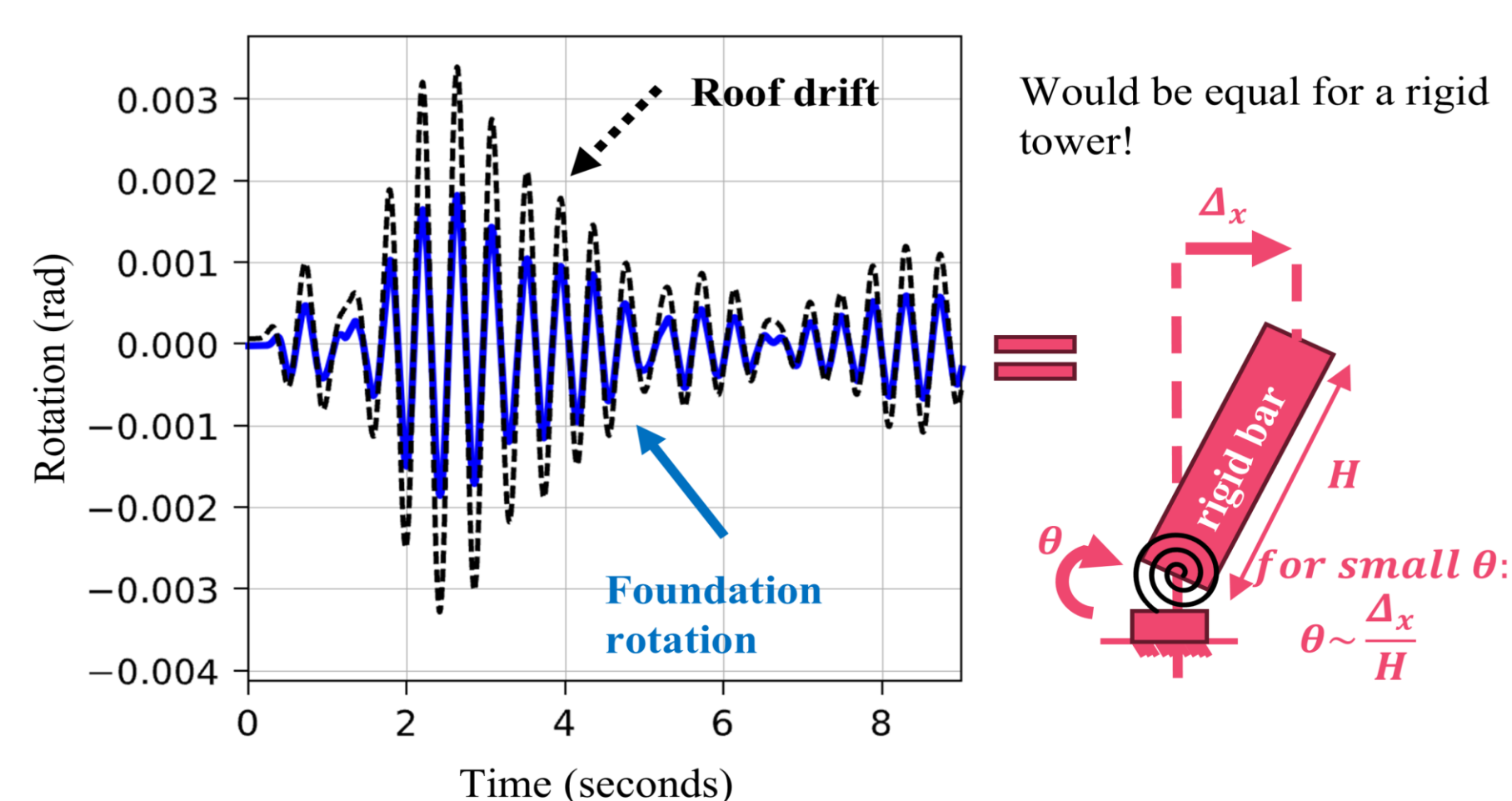


Figure 5. Foundation rotation from edge displacements (blue) versus roof drift ratio (black); the schematic gives the rigid-body relation for small angles.

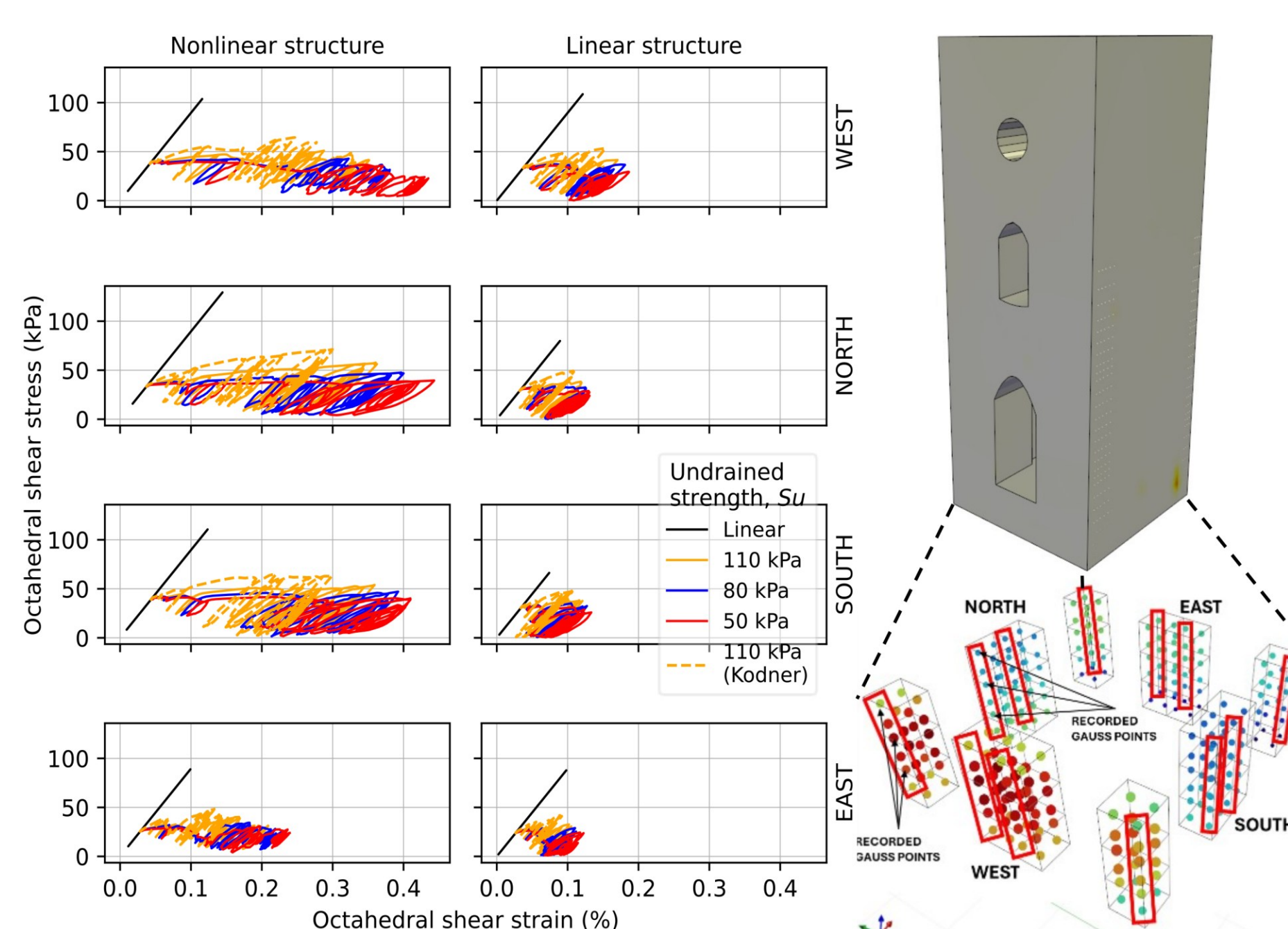


Figure 9. Soil stress-strain loops and cracking patterns reveal larger nonlinear strains when the tower-foundation system cracks.

Novel Discoveries on Permanent Settlement

A crucial finding of this study is that structural cracking in the foundation masonry drastically increases the permanent settlement of the tower. As the foundation sustains early-cycle damage, it softens and loses its ability to effectively confine the underlying soil.

This loss of confinement amplifies toe contact pressures during rocking and induces ratcheting-type cyclic shear deformations. The resulting stress-strain behavior generates orders-of-magnitude larger nonlinear strains in the soil. Ultimately, contrary to the conventional assumption that softer foundations simply reduce superstructure demand, the destructive interplay between foundation cracking and soil nonlinearity produces significantly larger and more hazardous settlements.

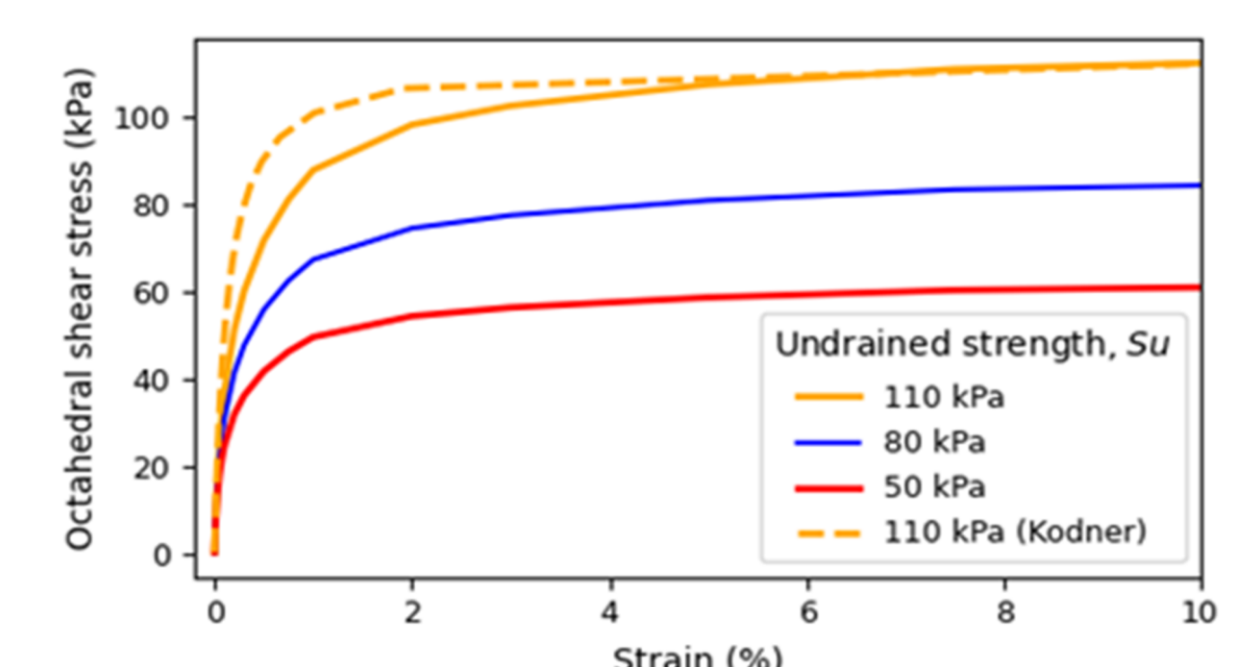


Figure 6. Foundation-soil stress-strain backbones: effect of undrained strength S_u and stiffness-degradation law

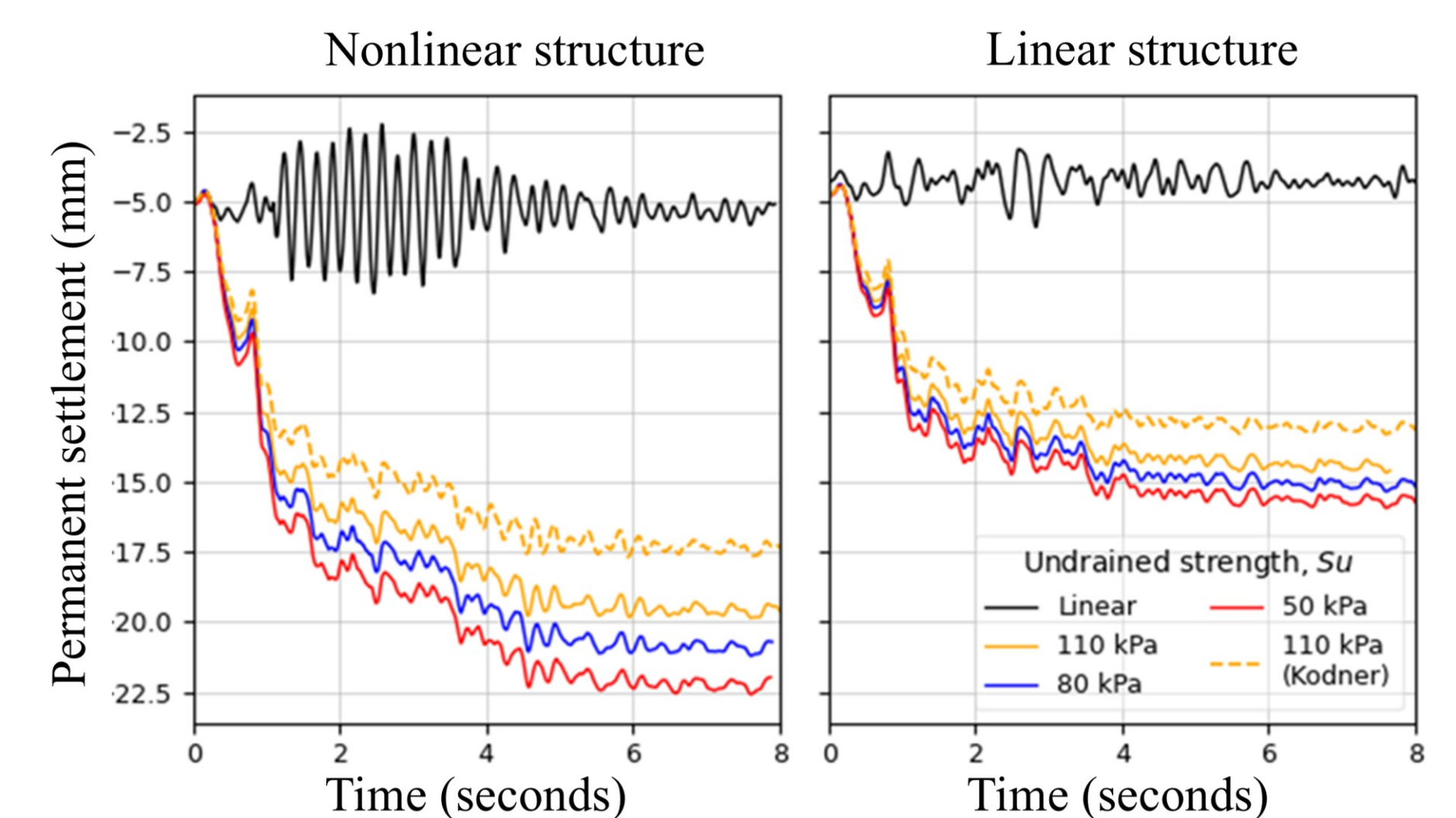


Figure 7. Permanent settlement histories for a nonlinear (left) and linear (right) superstructure across the foundation-soil cases.

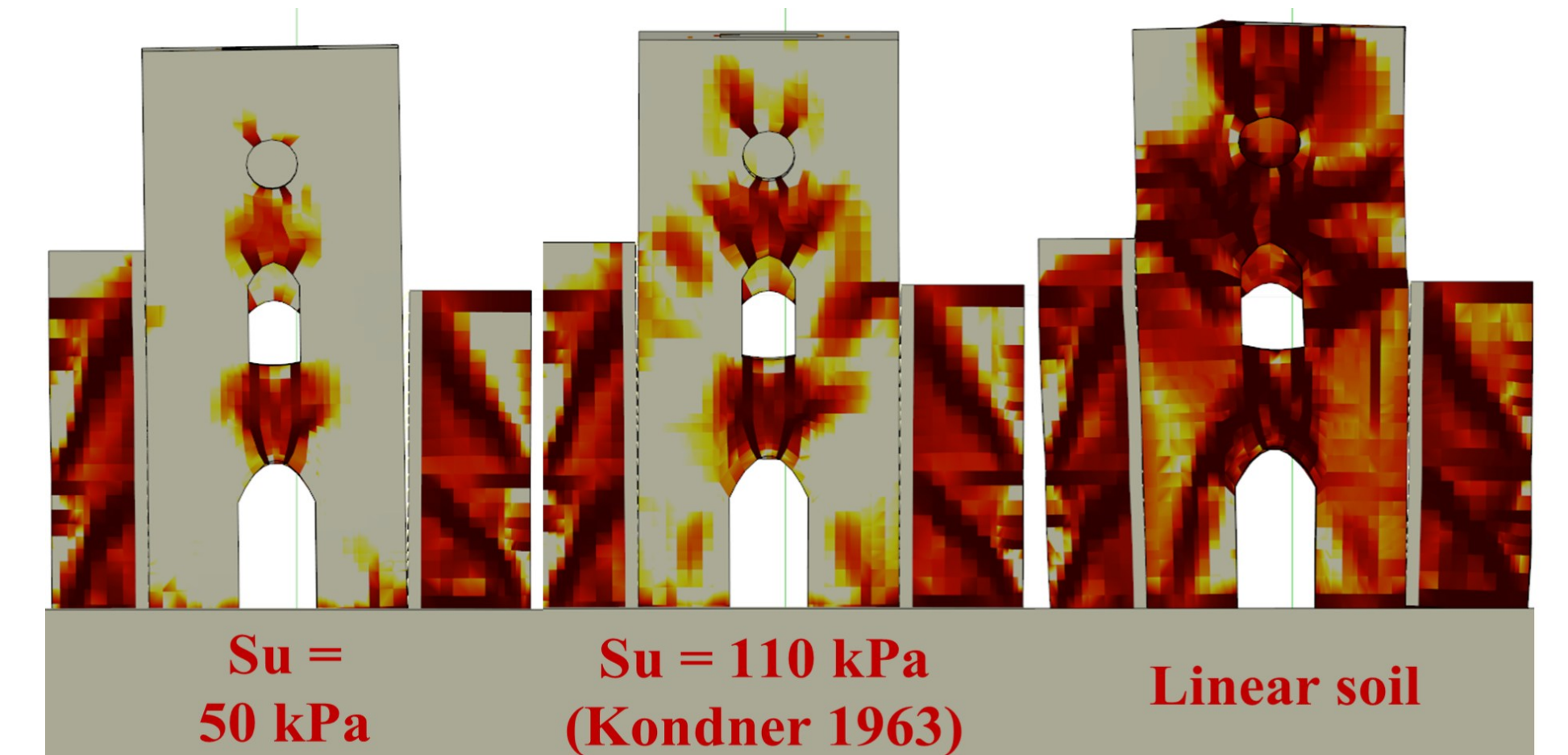


Figure 8. Cracking patterns versus foundation-soil stiffness; slower stiffness reduction transmits more high-frequency energy and intensifies masonry damage.

References

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