Modeling shallow crustal nonlinearity in physics-based earthquake simulations: Beyond perfect plasticity

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1. Motivation

Overarching goal:

Computing the effects of shallow crust nonlinearities in broadband earthquake simulations using a total stress bounding surface plasticity model to capture inelastic soil behavior.

Toward achieving this goal:

- We implemented a multi-axial constitutive soil model in Hercules, one of SCEC's three-dimensional wave propagation codes for regional scale earthquake simulations.
- We compiled a catalog of numerical experiments, which are also conducted using OpenSees – an open-source finite element code for earthquake engineering simulations (McKenna et al. 2000) to verify the model.
- We used the verified model to assess nonlinearity effects in an idealized shape basin.

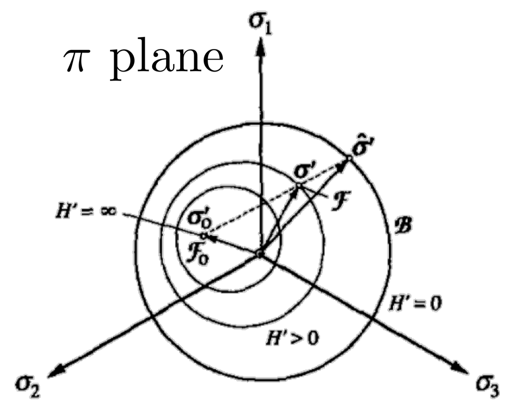
2. Plasticity model specifications

- Bounding surface plasticity model (BAE) with vanishing elastic region, which can go beyond perfect plasticity (Borja & Amies 1994)
- Hardening modulus (H') is defined based on a mapping rule from the current stress point to its image on bounding surface ($\mathcal{B}$) with radius R

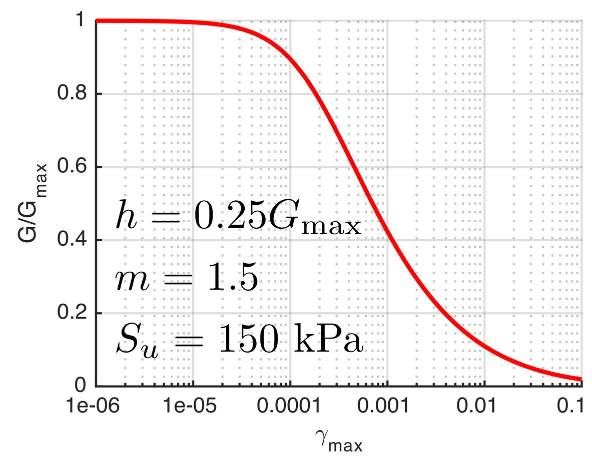
$$||\hat{\boldsymbol{\sigma}}'|| = ||\boldsymbol{\sigma}' + \kappa(\boldsymbol{\sigma}' - \boldsymbol{\sigma}'_0)|| = R \qquad H' \to \infty \text{ as } \kappa \to \infty$$

$$R = \sqrt{8/3}S_u \qquad H' \to 0 \text{ as } \kappa \to 0$$

- Can be fully calibrated based on a given shear modulus reduction curve (e.g., exponential hardening modulus $H' = h\kappa^m$); therefore, suitable for regional scale simulation with scarce geotechnical data.



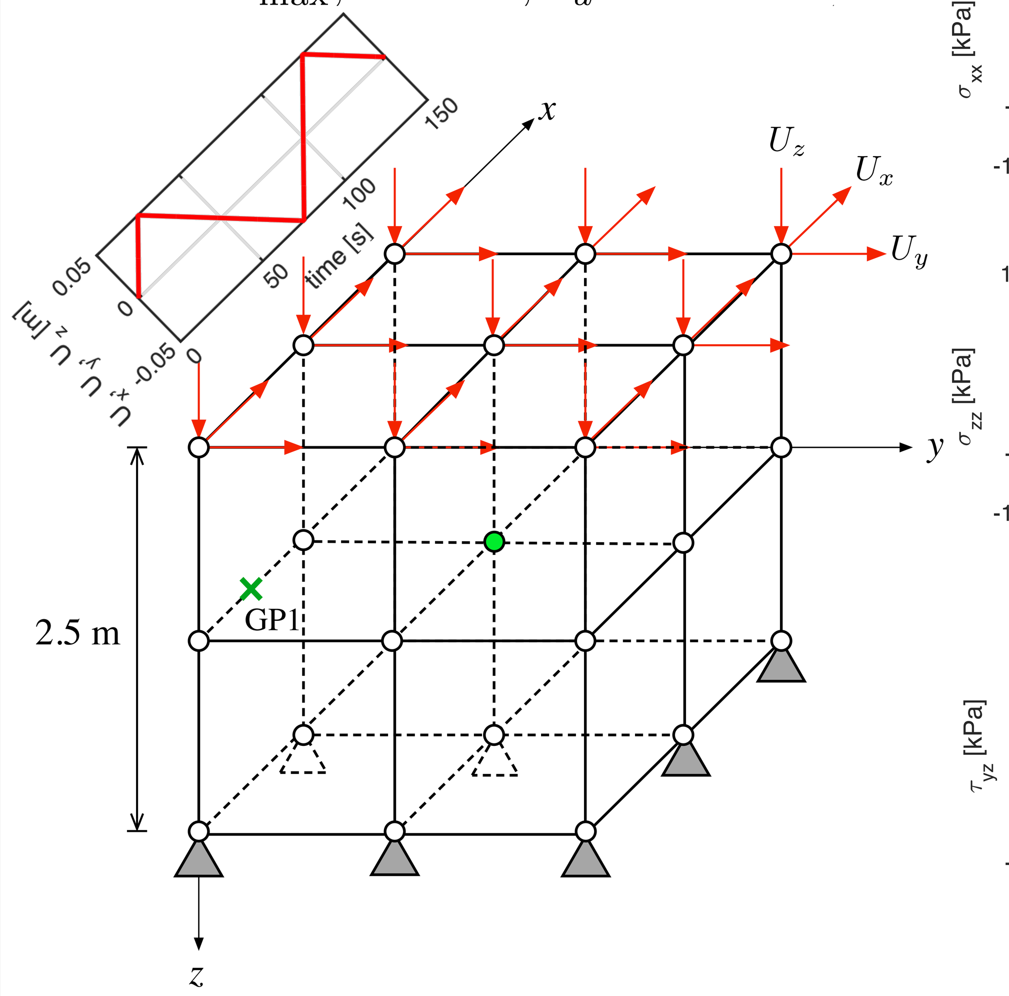
Borja & Amies (1994)

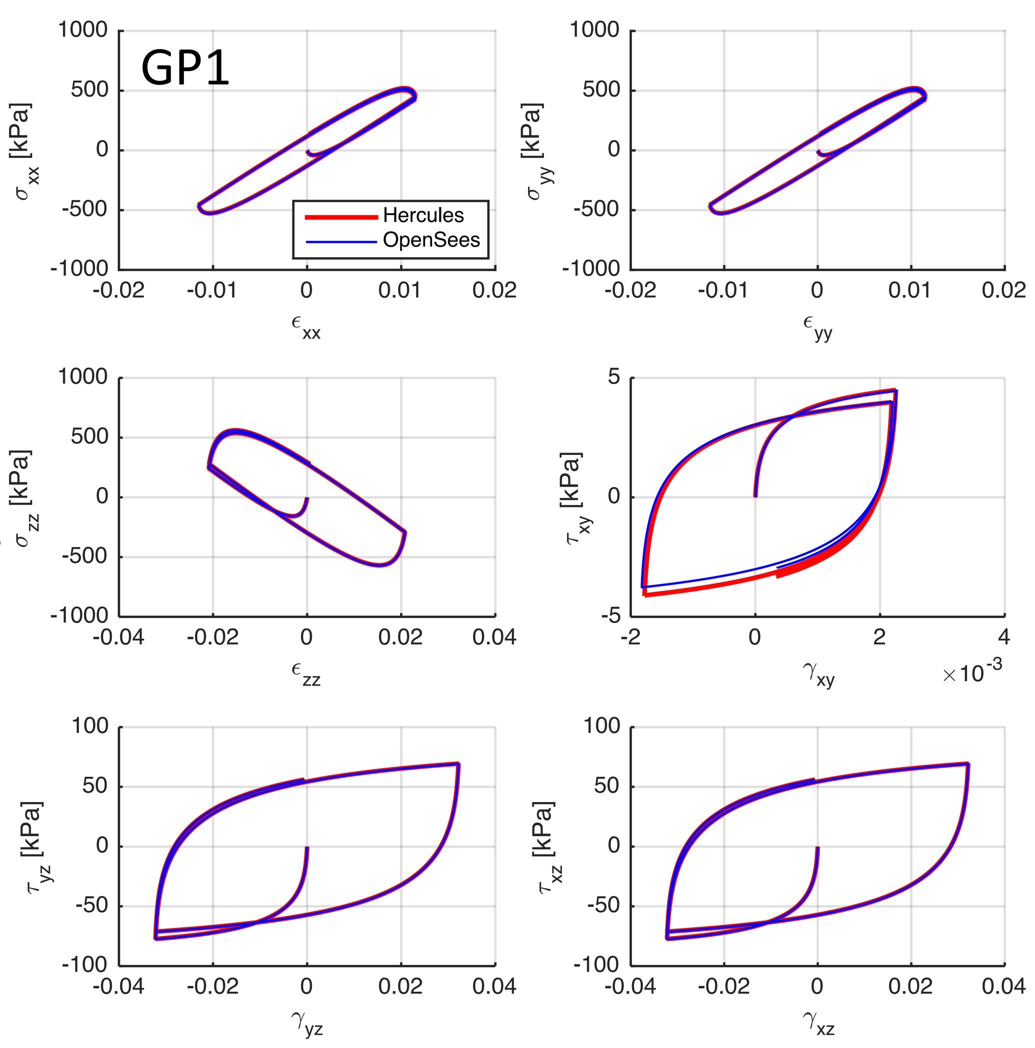


3.1. Model verification: pseudo-static test

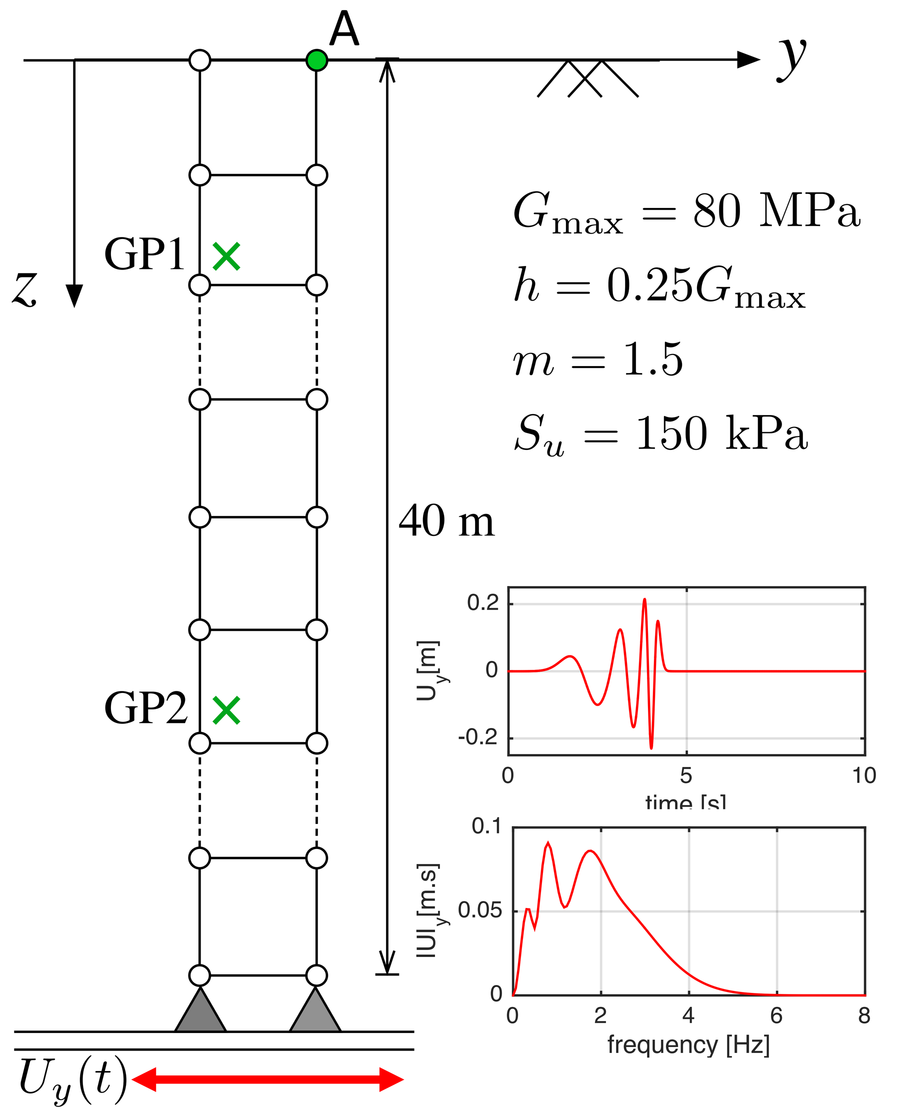
$G_{\max} = 80$ MPa, $\nu = 0.3$

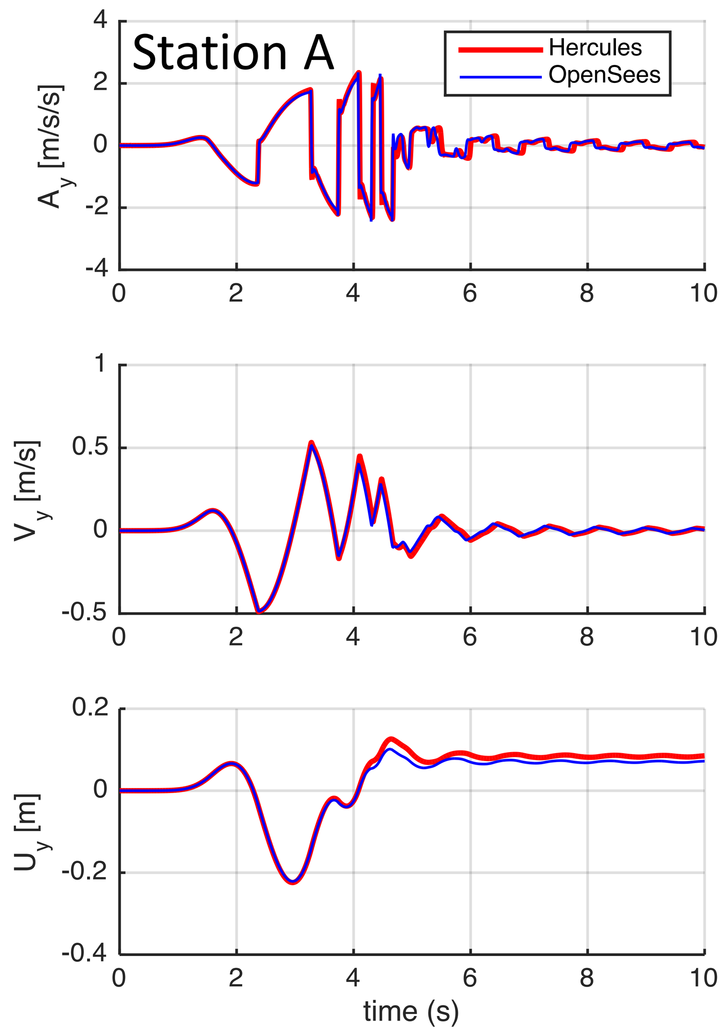
$h = 0.25G_{\max}, m = 1.5, S_u = 150$ kPa.

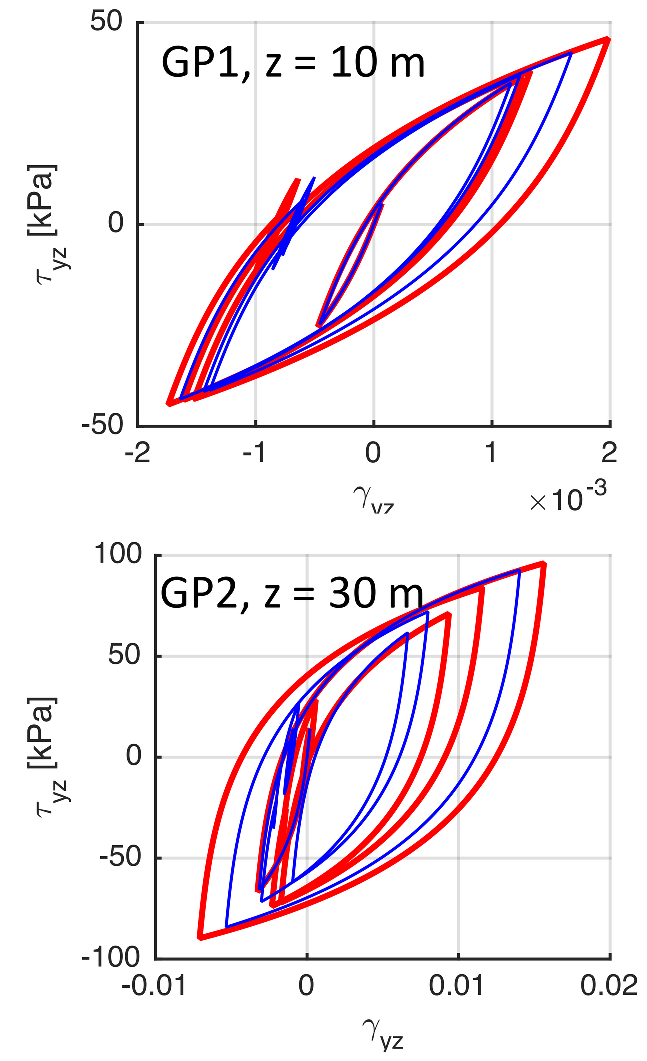




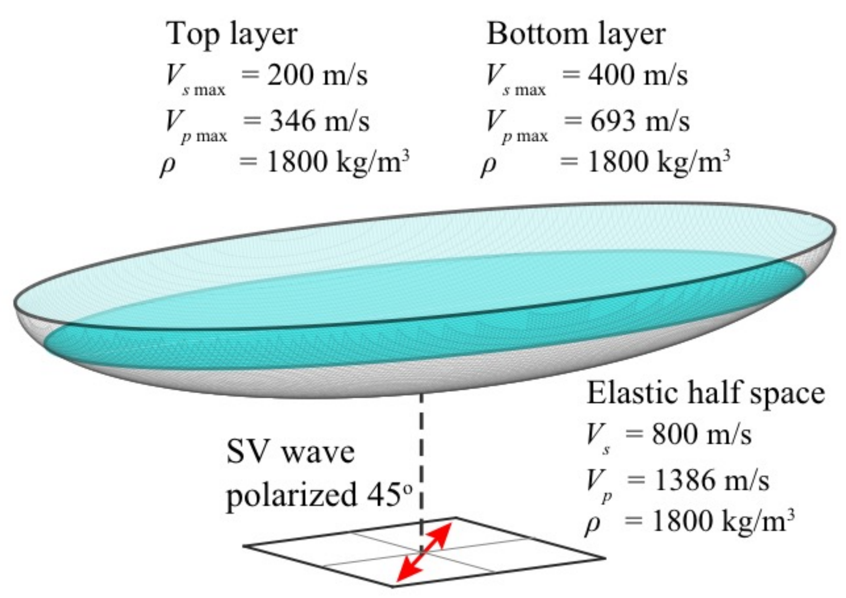
3.2. Model verification: 1D site response analysis

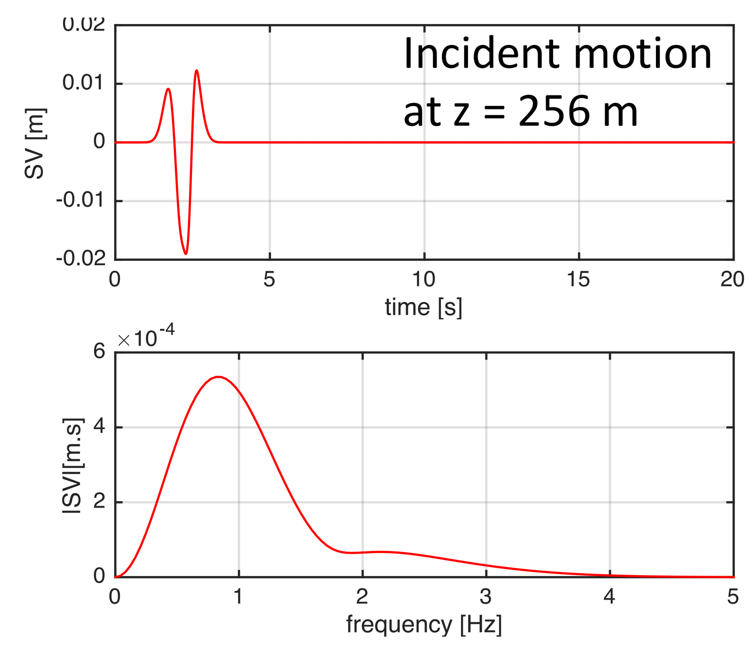


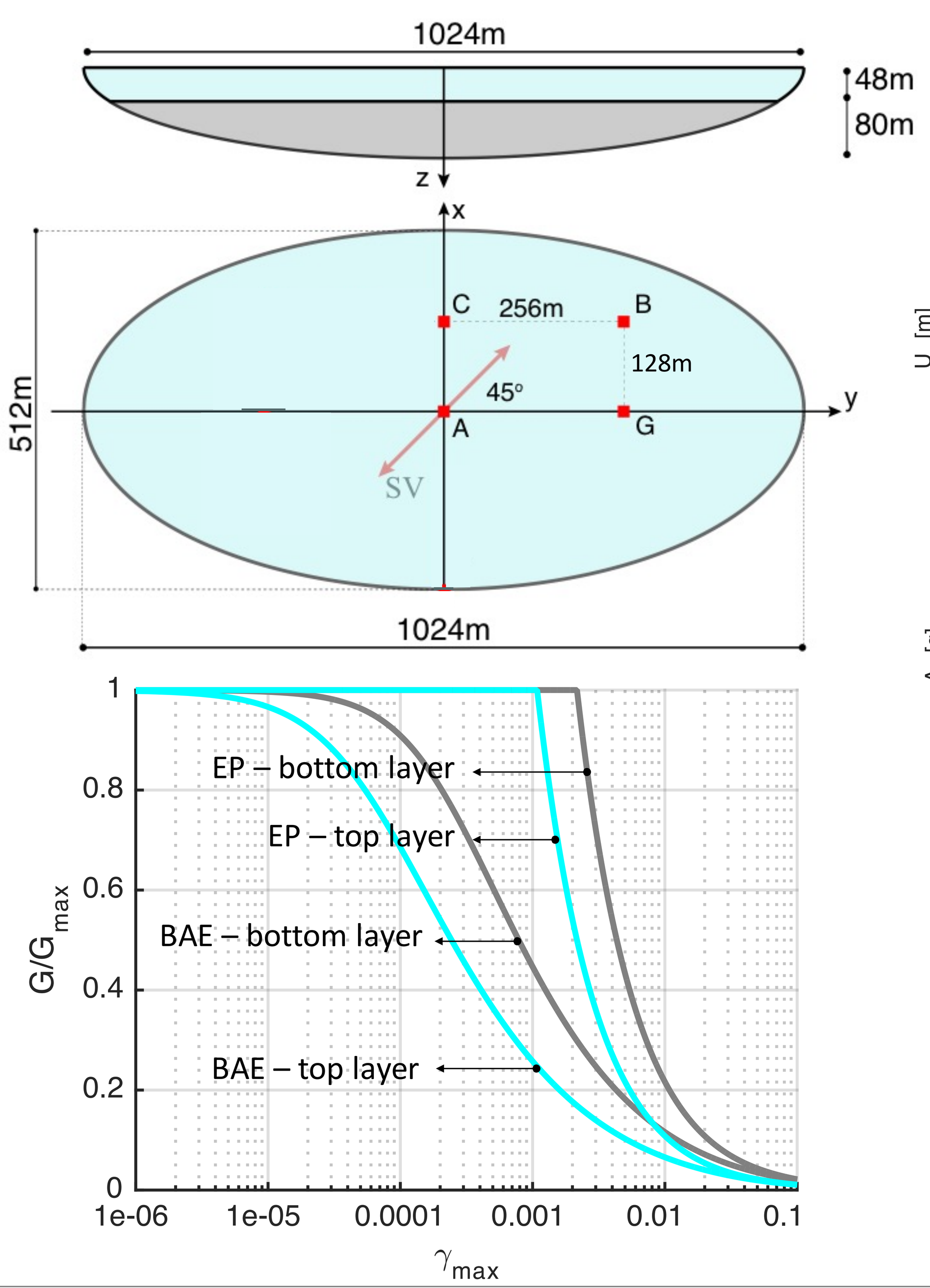


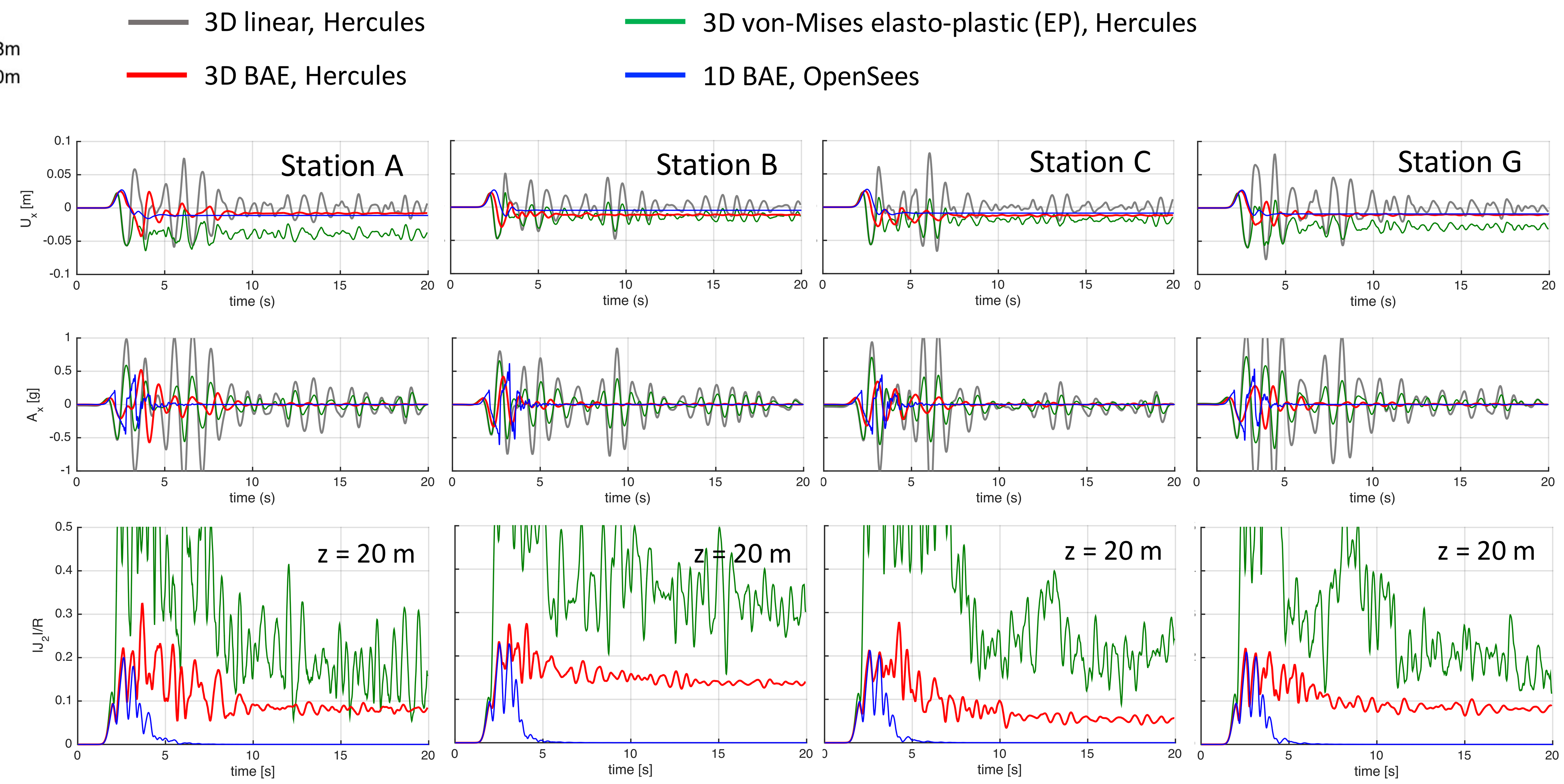


4. Quantitative assessment of going beyond perfect plasticity in an idealized shape basin









5. Summary

In this study, by the implementation and testing of a more rigorous plasticity model, we showed an example in which simplified approaches such as 1D site response analysis and 3D analysis with a perfect plasticity model fail in capturing the expected nonlinearity in an idealized shape basin.

6. References

R. I. Borja, A. P. Amies (1994). Multiaxial cyclic plasticity model for clays. Journal of geotechnical engineering, 120:1051–1070.

F. McKenna, G. Fenves, M. Scott (2000). Open system for earthquake engineering simulation. Technical report, University of California, Berkeley, CA.