Deterministic Ground Motion Simulations with Shallow Crust Nonlinearity

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1. Introduction

- Shallow crust nonlinearity can cause reduction in shear wave velocity and increase in energy dissipation in the form of damping, thus lowering site amplification factors with increasing seismic loading, and increasing residual displacements.
- The consequent differential ground motions, permanent deformations, shifts in the predominant resonant frequencies and site de-amplifications can lower or increase seismic risk on civil infrastructure including both distributed lifelines and buildings.
- Up until recently, the most feasible approaches to modeling the effects of nonlinearity in near-surface layers were:
  1) coupled 3D linear - 1D nonlinear simulations.
  2) 3D nonlinear simulations with bilinear models (e.g., pure J2, Drucker-Prager).

- Our **goal** is to go beyond bilinear models to quantitatively assess:
  1) how idealized models of sediment nonlinearity influence the amplitude, frequency content, and duration of ground motion in broadband earthquake simulations.
  2) how predictions of the hybrid 3D linear–1D linear/nonlinear site response analysis compare to the 3D linear/nonlinear ground response analyses.

2. Methodology

- We use the Garner Valley region in southern California as a test case where near-surface nonlinearity has been reported for peak ground accelerations (PGAs) as small as 0.05-0.2g.

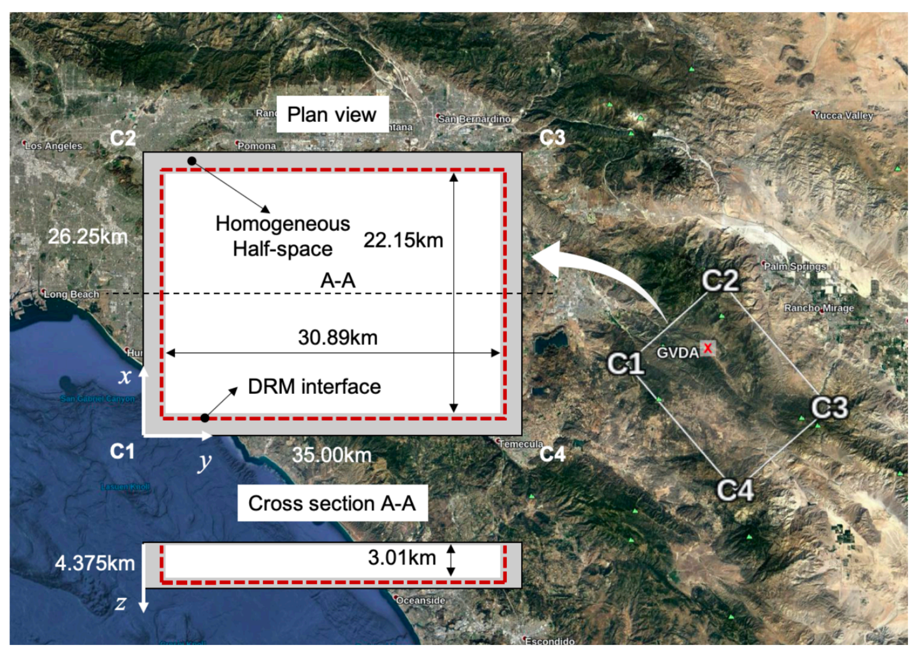

Figure 1: Garner Valley region, Southern California.

- The incoming waves are modeled as vertically propagating shear waves polarized in x direction to exclude the source and path effects. Domain reduction method is used for this purpose. We consider two time series with low and high frequency contents to model the temporal variation of the incoming waves.

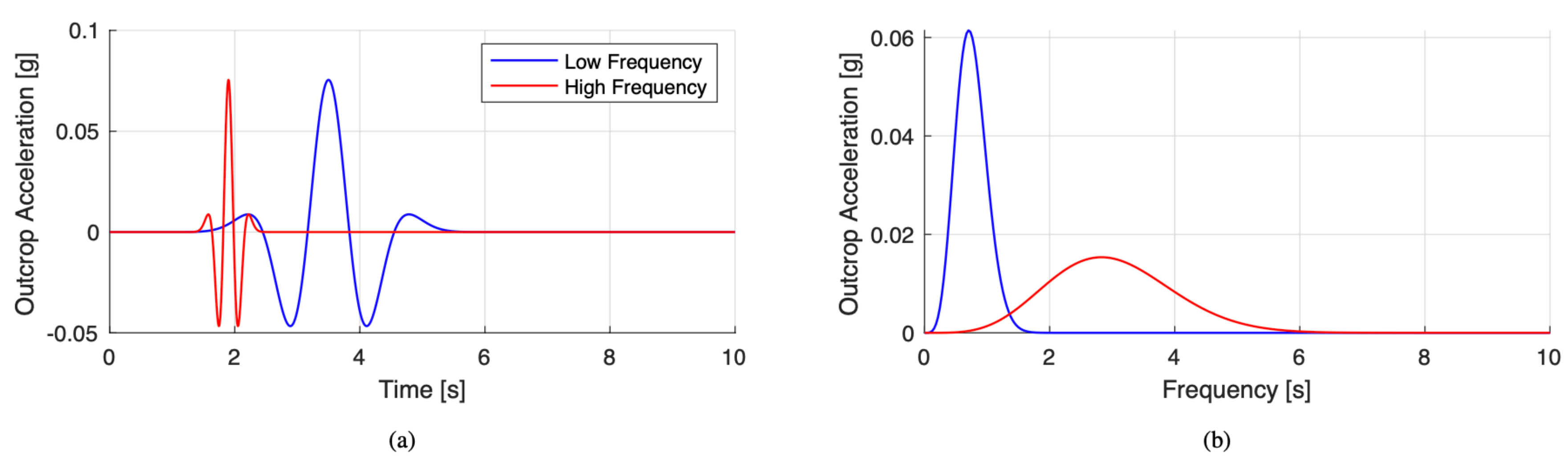

Figure 2: (a) Time histories and (b) Fourier amplitude of the outcrop acceleration responses.

- We model the sediment cyclic response using a multi-axial constitutive model formulated within the framework of bounding surface plasticity in terms of total stress. In all simulations, we extract the small-strain material properties from the SCEC CVM-S4.26+GTL and constrain the nonlinear soil model parameters using empirical modulus reduction curves and ultimate shear strength.

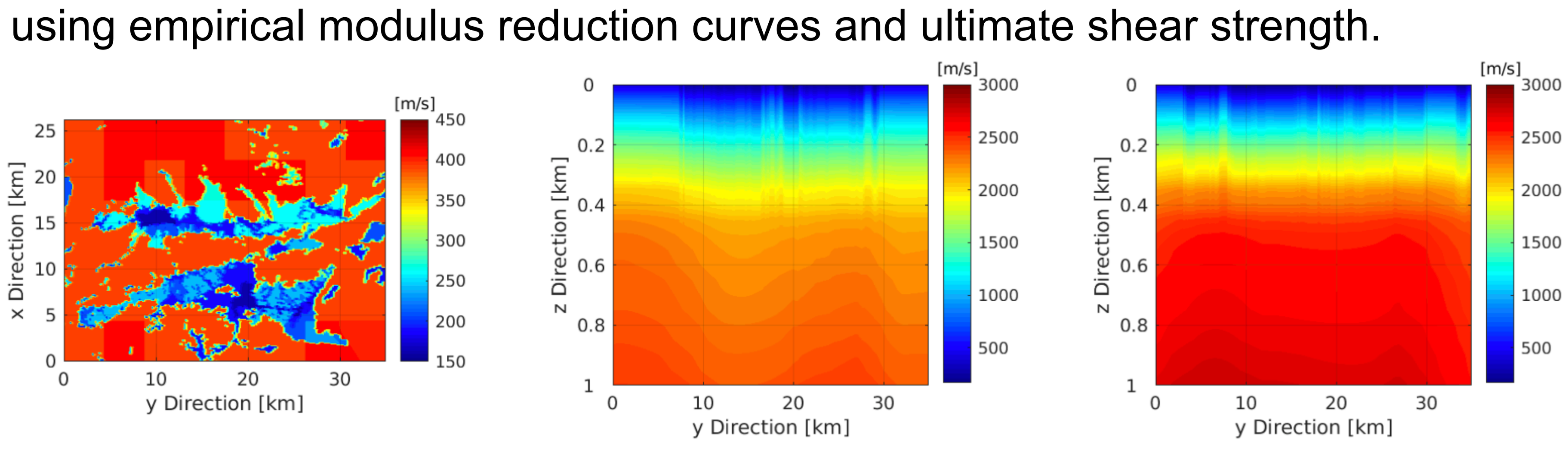

Figure 3: Velocity structure of the region: (a) at surface (z = 0); (b) at x = 7.5 km; (c) at x = 15 km.

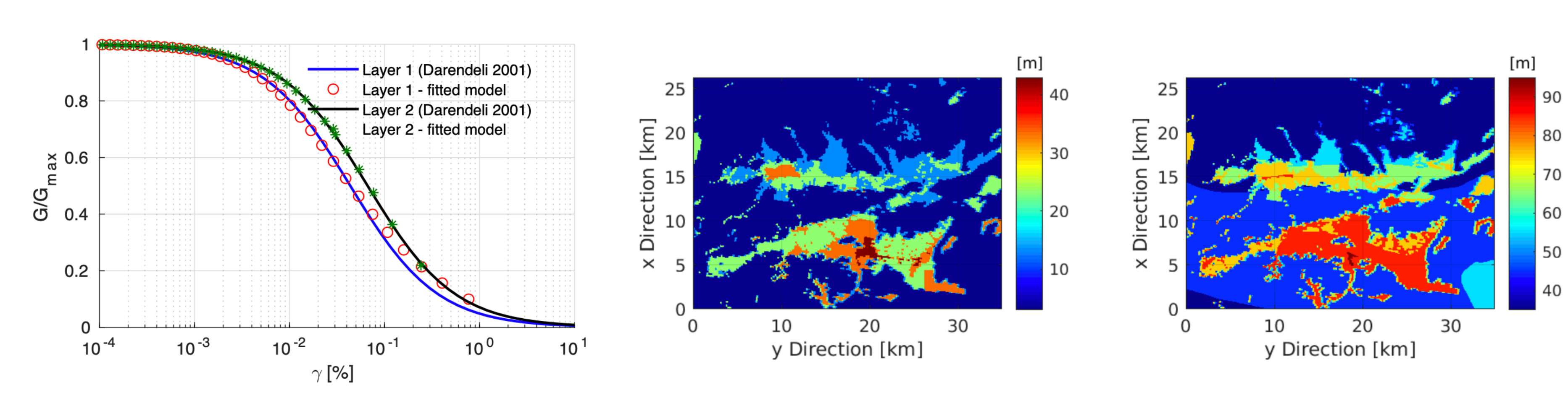

Figure 4: (a) Fitted G/Gmax curves for each layer; (b) Depth [m] to Vs = 450 m/s; (c) Depth to Vs = 800 m/s.

3. Numerical Results & Discussion

Case 1: Linear, Low Frequency Input
Case 2: Linear, High Frequency Input
Case 3: Nonlinear, Low Frequency Input
Case 4: Nonlinear High Frequency Input

3D: 3D simulation
3D-1D: Coupled 3D-1D simulation

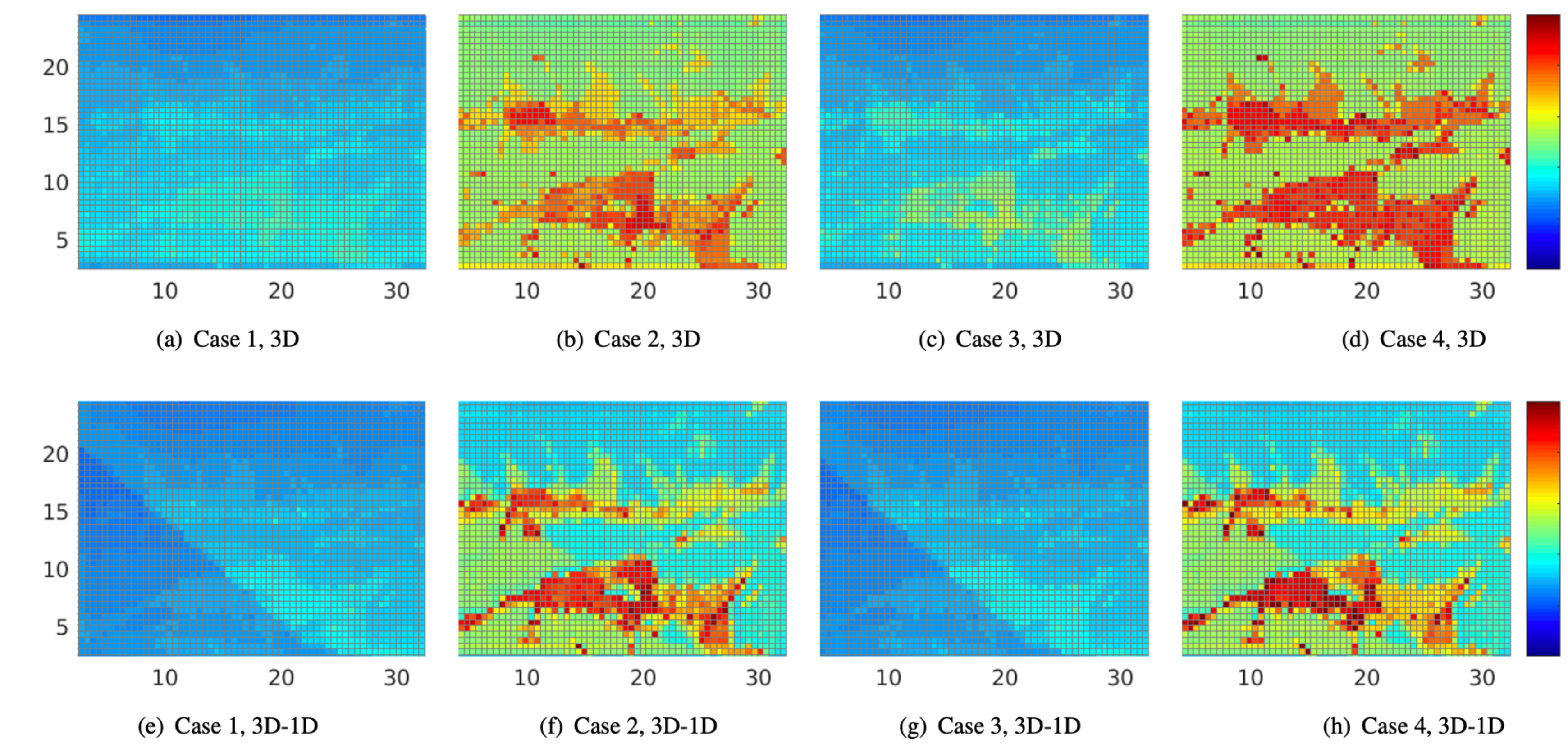

Figure 5: x direction PGD normalized by outcrop PGD obtained from 3D and hybrid 3D-1D simulations.

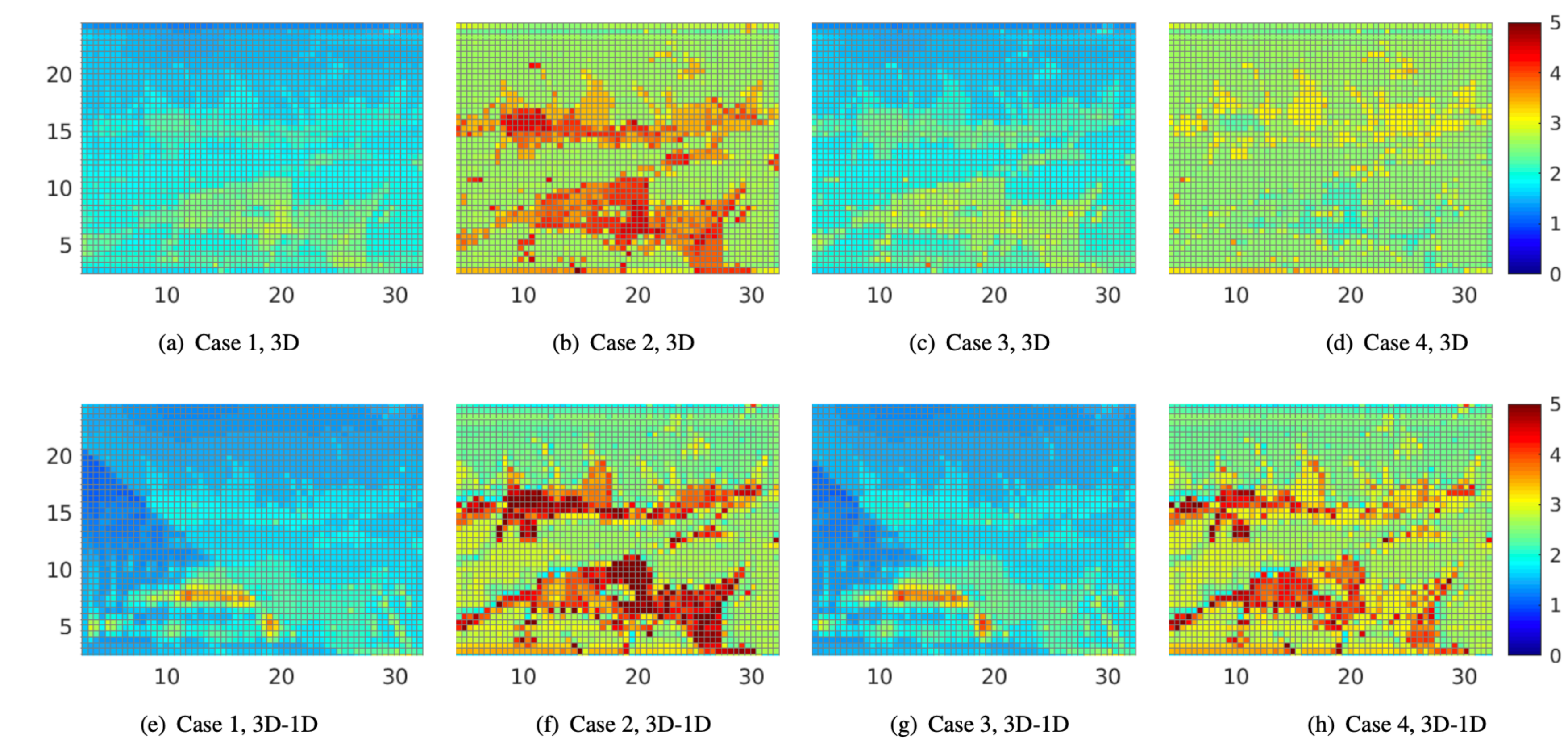

Figure 6: x direction PGA normalized by outcrop PGA obtained from 3D and hybrid 3D-1D simulations.

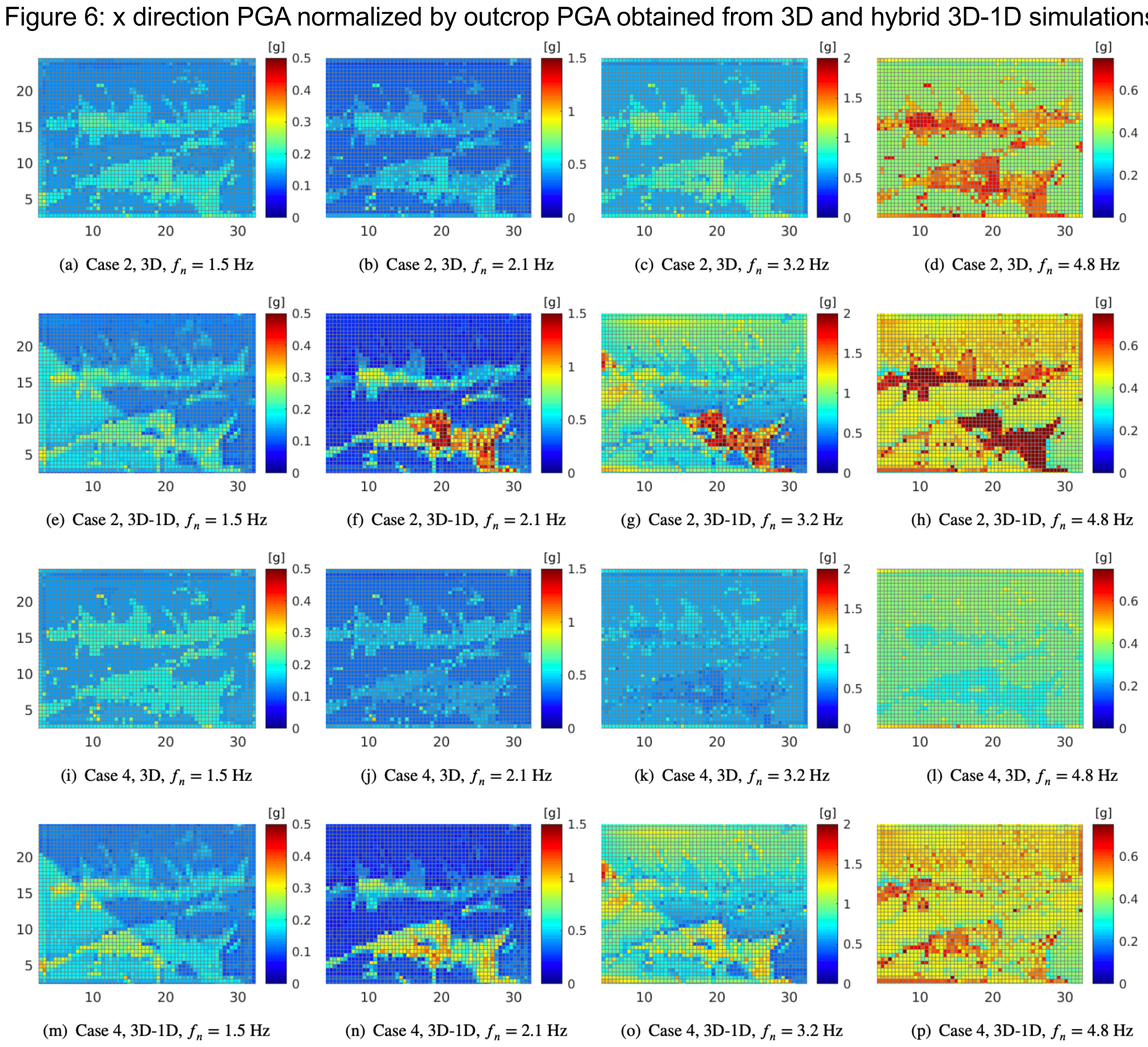

Figure 7: x direction SA [g] obtained from 3D and hybrid 3D-1D simulations.

Our results suggest that:

1) the considered level of excitation in 3D simulations could trigger nonlinearity in near surface soft layers, especially at higher frequencies, which resulted in decreased PGA and increased PGD within the two valleys in the region;
2) hybrid 3D-1D site response analyses were **incapable** to capture 3D scattering effects and resulted in over estimation of PGA and under estimation of PGD compared to the 3D simulation results; they also over-predicts SA responses, especially at deeper locations of the valleys.
3) using elastic perfectly plastic models with bilinear strain-stress relations reproduced anelastic simulation results because the stress states were not high enough to reach the soil strength and trigger nonlinearity.