17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

PHYSICS-BASED EARTHQUAKE SIMULATIONS WITH SOIL ELASTOPLASTICITY AT A STRONG MOTION ARRAY SITE IN CALIFORNIA

D. Asimaki(1), E. Seylabi(2), D. Restrepo(3), R. Taborda(4)

(1) *Professor, California Institute of Technology, domniki@caltech.edu*
(2) *Assistant Professor, University of Nevada Reno, elnaze@unr.edu*
(3) *Professor, Universidad EAFIT, Colombia, drestre6@eafit.edi.co*
(4) *Dean of Engineering, Universidad EAFIT, Colombia, rtaborda@eafit.edu.co*

Abstract

We present earthquake scenario simulations that account for elastoplastic constitutive behavior of basin sediments in the shallow crust. Our goal is to quantitatively assess the extent to which sediment nonlinearities influence strong ground motions in broadband earthquake simulations. We use as test-case the Garner Valley strong motion downhole array site in California. We model sediment elastoplasticity using a multi-axial constitutive model formulated within the framework of bounding surface plasticity in terms of total stress, and implemented in the high-performance finite element code Hercules. A major advantage of this model is the small number of free parameters that can be fully calibrated given a shear modulus reduction curve. This, in turn, makes the model a suitable choice for regional-scale simulations where geotechnical data in the shallow crust are scarce. In this paper, we first describe a series of numerical experiments designed to verify the model implementation in Hercules. This is followed by a series of idealized regional simulations in a 35 x 26 x 4.5 km3 domain that encompasses the Garner Valley – an instrumented and well-characterized site in Southern California. Material properties were extracted from the Southern California Earthquake Center (SCEC) velocity model CVM-S4.26 with optional geotechnical layer, while the modulus reduction curves were selected empirically to constrain the nonlinear soil model parameters. Our nonlinear simulations so far suggest that peak ground displacements within the valley increase relative to the linear case, while peak ground accelerations can increase or decrease, depending on the frequency content of the excitation.

Keywords: Ground motion simulations; Nonlinear soil behavior; Domain reduction method; Garner Valley.

1. Introduction

Three-dimensional (3D) earthquake ground motion simulations have been constrained, until recently, to low frequencies. However, over the last decade, the continuous growth of high-performance computing systems made higher frequency simulations an increasingly realistic target. It is expected, in fact, that deterministic broadband simulations will be possible over the next decade – complementing, and potentially replacing, current hybrid approaches that combine deterministic simulations at low frequencies with stochastic approaches at high frequencies. These advances, nonetheless, have brought with them new challenges, which have in turn motivated studies in source physics, energy scattering, intrinsic attenuation and subsurface imaging–all relevant to high frequency generation and propagation. Examples include the effects of fault roughness, on-fault rock damage and off-fault plasticity, as well as the effects of small-scale heterogeneities, frequency dependent attenuation, and shallow crust material nonlinearities.

In this work, we focus on the problem of nonlinear effects in the shallow crust, especially on a regional scale. Up until recently, the most feasible approach to tackle this problem was through the combination of 3D anelastic simulations and one-dimensional (1D) nonlinear analysis of the incident motion at the interface between the bedrock and sedimentary deposits [1,2]. Hybrid simulations, however, cannot capture the complexity of fully 3D effects. Xu et al. [3] demonstrated the deficiencies of hybrid simulations with one of the first 3D analyses of an idealized basin comprising elastic-perfectly plastic sediments using the Drucker-Prager yield criterion. Since then, 3D simulations using Drucker-Prager and Mohr Coulomb criteria to represent nonlinearities in sedimentary media have been employed in larger regional simulations [4,5] and have further expanded to consider weathered rock plasticity in the crust and in the proximity of damaged fault zones [6].

The progress made in recent years using elastic-perfectly plastic constitutive models has been remarkable and has helped understand the 3D nature of nonlinear wave propagation in heterogeneous media. However, it is well known that these constitutive models do not accurately reproduce the behavior of most geomaterials. This is partially because their bilinear stress-strain representation leads to artificially large hysteresis loops, which in turn may result in artificially large permanent deformations [5] and artificially large intrinsic attenuation over time. In response to the need for incorporating more realistic constitutive models on the Southern California Earthquake Center (SCEC) wave propagation simulation platforms, we implement, verify and test a multi-axial bounding surface plasticity model in Hercules [7], one of SCEC's High Performance Computing (HPC) software packages for high frequency regional ground motion simulations.

In this paper, we first describe the main characteristics of the plasticity model in Section 2. Then, in Section 3, we provide details of two valley structures in Southern California that we use as testbeds for the model implementation and validation. In Section 4, we use results to quantitatively assess the effects of shallow crust nonlinearity coupled with the frequency content of the simulations and 3D scattering effects. We provide our concluding remarks in Section 5.

2. Methodology

A wide range of models exist for describing multi-axial cyclic plasticity behavior of geomaterials. Among them, rigorous models are usually defined in terms of a large number of parameters devised to make them well-behaved for a wide range of strains, including post-liquefaction and cyclic mobility. However, due to the scarcity of geotechnical data, use of such models is often impractical, even for small scale problems such as site-specific response and soil-structure interaction analyses. This has motivated the development of more practical, yet still effective constitutive models that can reproduce the main features of dynamic soil behavior using only a small number of parameters.

We decide to use a bounding surface multiaxial cyclic plasticity model introduced by Borja and Amies [8]. This model has been extensively tested and consistently shown good performance [e.g., 9-11]. It is based on the J2-bounding surface plasticity theory with a vanished elastic region, where a mapping rule is used to ensure smooth transition of the hardening modulus within the bounding surface. Using the exponential form to define the hardening modulus, Chao and Borja [12] showed that under a simple shear test condition, the relationship between the normalized shear modulus G/G_{max} and shear strain γ can be approximated as:

$$\frac{G}{G_{max}} = 1 - \frac{3}{2h\gamma}\int_0^{2\tau}\left(\frac{\xi}{\tau_f + \tau - \xi}\right)^m d\xi$$

where τ is the shear stress and h and m are the unknown hardening parameters that can be obtained through curve fitting for a given G/G_{max} curve and ultimate soil strength τ_f.

Finite element implementation of this model in Hercules – which uses an explicit time integration method – calls for solving a nonlinear equation at each Gauss point to compute the hardening modulus. After implementation, we first performed a series of numerical experiments to verify the model. In all experiments, we modeled the same problem in OpenSEES – the open system for earthquake engineering simulation [13] – where a similar implementation of the plasticity model by [10] is available. Results from the Hercules and OpenSEES implementations were in good agreement across the range of numerical experiments. More information can be found at https://www.scec.org/proposal/report/18020.

3. Garner Valley Downhole Array site in Southern California

The well-documented Garner Valley Downhole Array (GVDA) site has been characterized for over 20 years, resulting in a wealth of geotechnical data ideal for validation purposes. Although strong ground motion records are scarcely recorded, multiple events are reported at the site with peak ground accelerations (PGAs) ranging from 0.1 to 0.2g, a PGA range in which nonlinear effects are frequently triggered. Fig. 1 shows the region of interest which encapsulates the Garner Valley and the installed downhole array, which denoted as GVDA inside the domain. The geometry of the computational domain presented below on the ground surface as well as its vertical cross section are shown in Fig. 1.

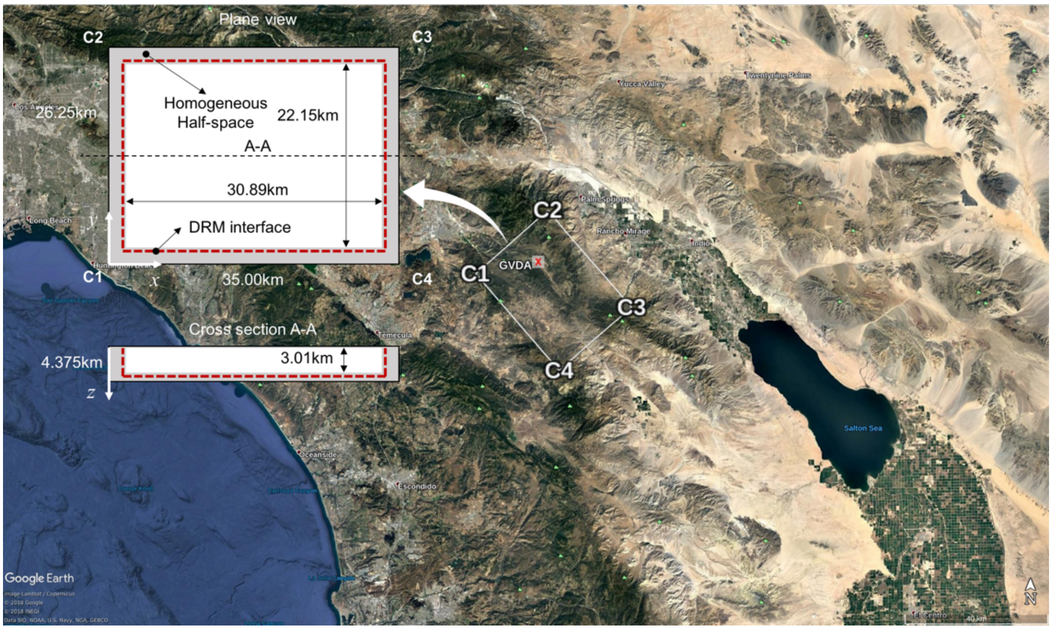


Fig. 1 – Region of interest including the Garner Valley Downhole Array (GVDA).

3.1 Input excitation

In this study, the main focus was to quantitatively assess 3D shallow crust nonlinearity effects using more realistic constitutive models. Therefore, to exclude source and path effects, we assume that the region is encapsulated within a homogeneous half-space and the incoming waves are vertically propagating shear waves polarized in the y direction. We used the domain reduction method (DRM) proposed by Bielak and co-workers

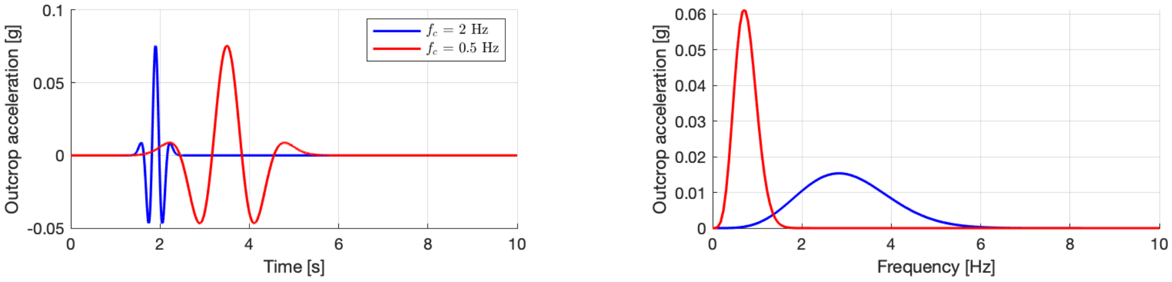
[14] to prescribe the driving forces along the DRM interface, shown as red dashed lines in Fig. 1. We selected the properties of the homogeneous region as V_s = 3050 m/s, V_p = 5250m/s, and ρ = 2800kg/m^3 [15]. Since the computational domain of interest was embedded in a homogeneous halfspace, the DRM wavefield could be computed analytically at any point [16]. We define the outcrop displacement motion as:

$$u(t) = A[2\pi^2 f_c^2 (t - t_s)^2 - 1] \exp[-\pi^2 f_c^2 (t - t_s)^2]$$

where A, t_s and f_c are the maximum displacement amplitude, time at which maximum displacement occurs, and central frequency of the Ricker wavelet. In this study, we considered two central frequencies and defined A such that both outcrop motions have the same PGA (see Table 1 and Fig. 2). The parameters A, t_s and f_c for the two motions are tabulated in Table 1, and the acceleration time histories and Fourier amplitude of the corresponding outcrop motions are shown in Fig. 2.

Table 1 – Characteristics of the outcrop displacement response in the homogeneous half-space.

Input	A	t_s	f_c
Low Frequency	0.05	3.5	0.5
High Frequency	0.003125	1.9	2.0



(a) (b)

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

3.1 Velocity structure and plasticity model parameters

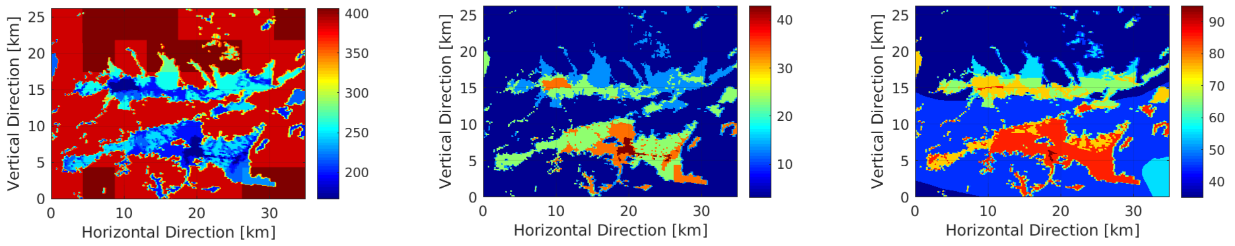
SCEC has a catalogue of registered velocity models intended for physics-based ground motion simulations. Taborda and co-workers [17] studied how different velocity models affect the predictive capabilities of the simulation platforms by reproducing recent events in greater Los Angeles area and comparing simulations with observations. They concluded that CVM-S4.26 velocity model consistently yields better results, and on the basis of their conclusions, we also use the same velocity model for the characterization of deep crustal layers. To model near-surface soft layers, we use the optional geotechnical layer[1] (GTL) [18]. Fig. 3a shows the velocity structure at the surface and Fig. 3b and 3c show depths to V_s = 450 m/s and 800 m/s respectively. It is worth mentioning that we will use these two values to define the two layers for the plasticity model parametrization. Fig. 4a and 4b on the other hand show two vertical cross sections at y = 7.5 km and y = 15 km illustrating the shallow depth of the two valleys in the region of interest.

The SCEC velocity model provides us with small strain soil properties. To approximate nonlinear soil properties, we decide to use the empirical equations by [19] to define G/G$_{max}$ curves. To limit the number of nonlinear elements and therefore reduce simulation time, we only allow elements with Vs less than 800 m/s to behave nonlinearly. The fitted parameters for the modulus reduction (G/G$_{max}$) curves that we used to calibrate the plasticity model are listed in Table 2 and the resulting fitted and 'target' curves are shown in Fig. 4c. We note that for all elements with Vs less than 450 m/s we use Layer 1 properties and for all elements with Vs

---

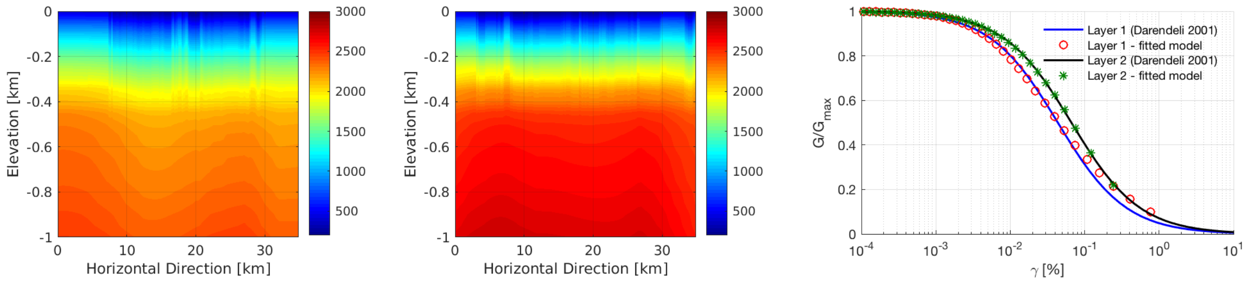
[1] GTL overwrites the properties up to depth of 350m.

between 450 m/s and 800 m/s we use Layer 2 properties. It is worth mentioning that for modeling small strain attenuation we use stiffness proportional Rayleigh damping where 2% damping is defined at 10Hz for all elements.



(a) (b) (c)

Fig. 3 – (a) Vs at surface; (b) depth to Vs = 450 m/s; (c) depth to Vs = 800 m/s.



(a) (b) (c)

Fig. 4 – (a) Vs at y = 7.5 km; (b) Vs at y = 15 km; (c) Fitted G/G$_{max}$ curves for each layer.

Table 2 – Fitted plasticity model parameters.

Layer	**V_s Range [m/s]**	**h [MPa]**	**m**	**τ_f [kPa]**
1	0.0 - 450	70.44	1.18	98.40
2	450 - 800	2244.04	1.00	426.6

4. Results

Using the input excitations defined in Section 3.1, we consider four 3D simulation cases: (1) linear simulation using low frequency input excitation, (2) linear simulation using high frequency input excitation, (3) nonlinear simulation using low frequency input excitation and (4) nonlinear simulation using high frequency input excitation. Table 3 provides details of the simulation parameters that we considered for each case as well as the number of processors and the resulting simulation wall-clock time[2]. In all simulations, the minimum Vs was set to 200 m/s and we use at least 10 points per wavelength to define the element size.

4.1 Spatial variation of peak ground responses in 3D simulations

First, we studied the effects of shallow crust nonlinearity on PGA and peak ground displacement (PGD). Fig. 5 and Fig. 6 show respectively the spatial variations of PGA and PGD normalized by the outcrop PGA and PGD. Fig. 7, next, shows the PGA and PGD amplification of the nonlinear simulations relative to the linear simulations with the same excitation. We observe that the response of the valleys highly depends on the

---

[2] TACC's Stampede2 supercomuter is used to run all simulations.

frequency content of the input excitation. As shown in Fig. 3b and 3c, the maximum first layer depth is 40 m while the maximum depth of the second layer is 100m. Therefore, the maximum discernible frequency in Case 1 and Case 3 is not high enough to translate the effects of near-surface soft soil layers on the computed responses. In turn, performing nonlinear simulations only results in slight increase in PGA and PGD compare to their linear counterparts. On the other hand, in high frequency simulations, the wavelengths are small enough to make results more sensitive to the behavior of the shallow crust. In Case 4, as expected, PGD increases due to cyclic softening effects of near-surface layers. This is while PGA is significantly deamplified within the valley. It is worth mentioning that the (de)amplification patterns of PGA and PGD in low/high frequency simulations are correlated with the velocity structure of the two valleys (see Fig. 7 and Fig. 3b and 3c).

Table 3 – Simulation parameters for different models considered in this study.

Simulation Parameters	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Maximum Frequency [Hz]	1.5	5.0	1.5	5.0
Δt [s]	0.001	0.0004	0.001	0.0004
Simulation Time [s]	10	10	10	10
Minimum Element Size [m]	8.54	2.14	8.54	2.14
Maximum Element Size [m]	136.72	68.36	136.72	68.36
Total Number of Elements	12,229,531	328,397,558	12,229,531	328,397,558
Nonlinear Elements [%]	--	--	74	60
Processors	84	840	840	4200
Simulation Wall-clock Time [hr:mm:ss]	00:09:46	01:08:31	00:41:43	04:53:34

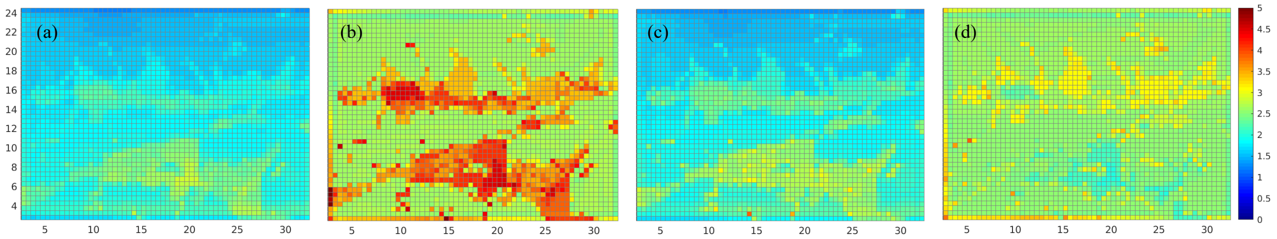


Fig. 5 – PGA normalized by outcrop PGA: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

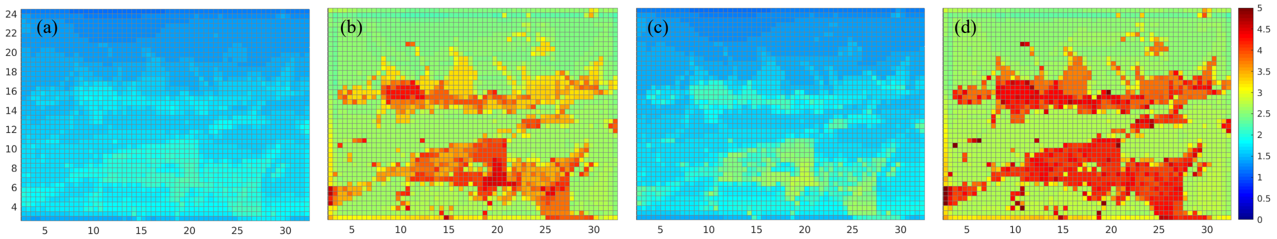


Fig. 6 – PGD normalized by outcrop PGD: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

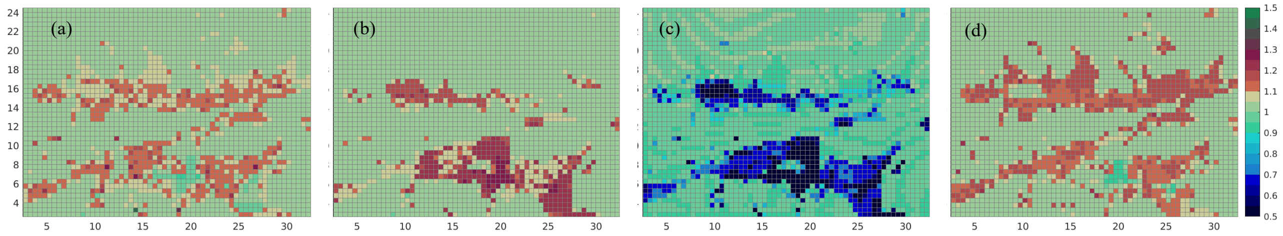


Fig. 7 – Nonlinear-to-linear amplification of peak ground responses: (a) $\text{PGA}^{\text{Case 3}}/\text{PGA}^{\text{Case 1}}$; (b) $\text{PGD}^{\text{Case 3}}/\text{PGD}^{\text{Case 1}}$; (c) $\text{PGA}^{\text{Case 4}}/\text{PGA}^{\text{Case 2}}$; (d) $\text{PGD}^{\text{Case 4}}$ / $\text{PGD}^{\text{Case 2}}$.

4.2 Assessment of 3D scattering effects

To assess the effects of shallow crust nonlinearity and frequency content of incident waves on 3D scattering, we perform 1D analysis at 3640 stations over a uniform grid points 500 m apart within the Garner Valley region of study. Each 1D site response analysis considers a soil column of height 3km over an elastic bedrock with properties the same as the homogeneous half-space defined in Section 3. We use the CVM-S4.26 to query the small strain properties at each station and use the outcrop motion to define the velocity of the incident wave in the elastic half-space. Figs. 8 and 9 show the ratio of PGA and PGD in 3D simulations divided by their 1D counterpart. It is obvious that 1D simulations are incapable of reproducing the 3D wavefields that give rise to the spatially distributed PGA and PGD results. This is especially true in Case 2 and Case 4. We observe that 1D simulations underpredict the PGA in high frequency nonlinear simulation and overpredict the PGD. It is worth mentioning that the triangular patterns observed in Case 1 and Case 3 (i.e., low frequency simulations) are highly correlated with the crustal properties used to define the velocity structure of the region (see Fig. 10 showing the crustal Vs values (i.e., CVM-S4.26 without GTL) at the surface).

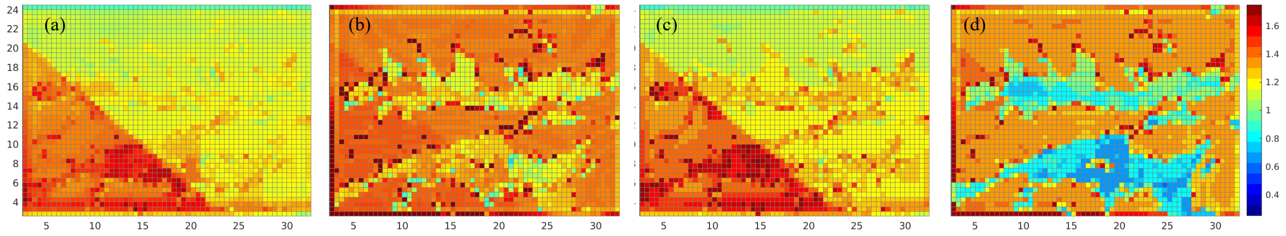


Fig. 8 – 3D to 1D amplification of PGA: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

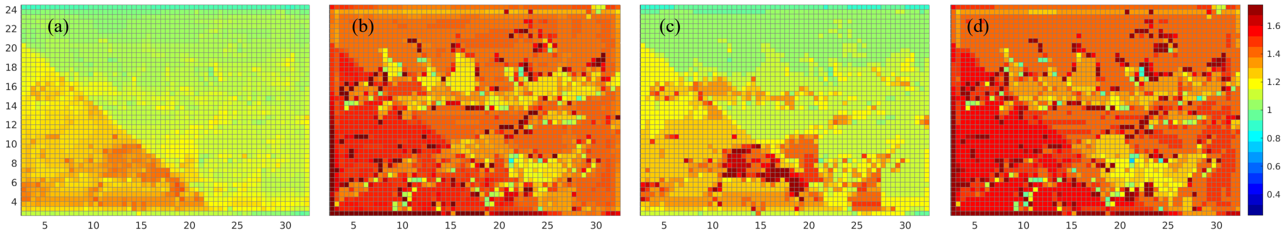


Fig. 9 – 3D to 1D amplification of PGD: (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4.

4.2 Response at the Garner Valley downhole array

The near-surface structure of the GVDA consists of an ancestral lakebed with soft alluvium down to 18-25 m depth, overlaying a layer of weathered granite. The competent granitic bedrock interface is located at 87-m depth [15]. Fig. 11a shows the velocity profile at the GVDA queried from the CVM-S4.26 velocity model compared to the one obtained from the joint inversion of dispersion and downhole array data [20]. By design, GTL can only vary smoothly with depth and therefore is not capable to capture sharp impedance contrasts in the shallow crust. This in turn may results in poor predictions of ground motions, especially at higher frequencies.

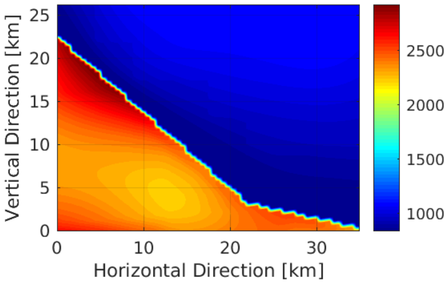
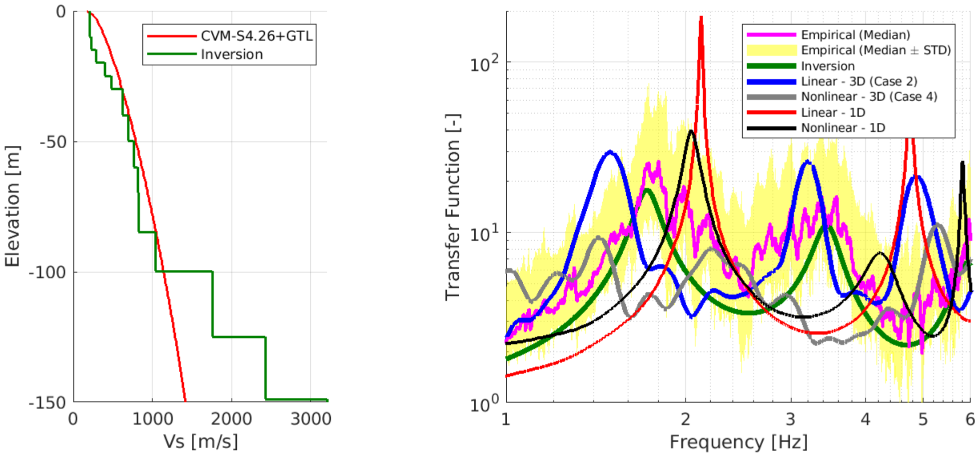


Fig. 10 – CVM-S4.26 without GTL at surface.

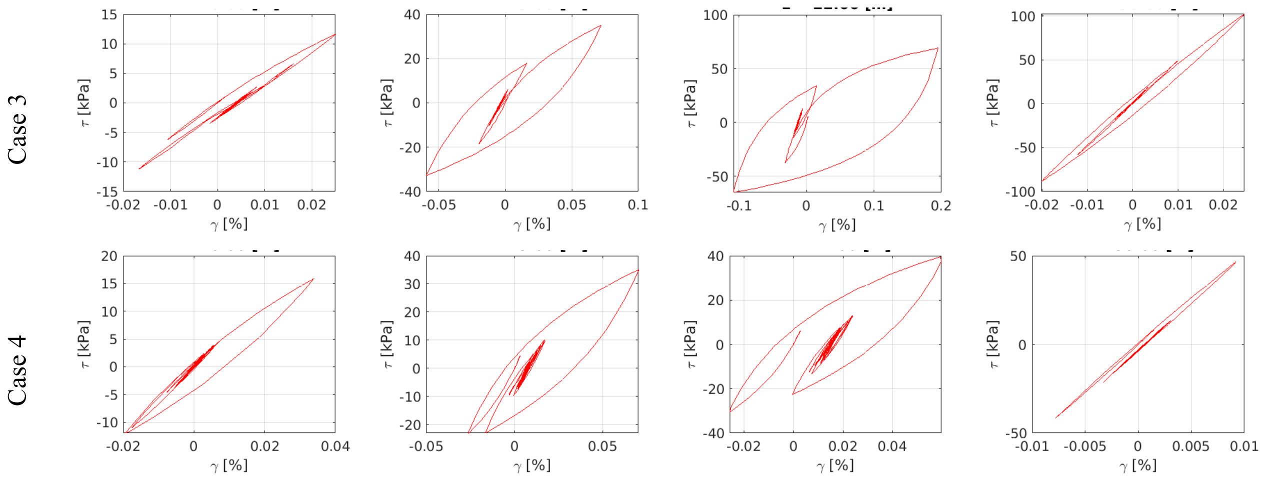
To assess the accuracy of the velocity models used in 1D and 3D simulations and the effects of shallow crust nonlinearity, we compute empirical and analytical transfer functions at the downhole array site. Fig. 12b shows the site transfer functions determined as the ratio of the surface to bedrock motion at depth of 150m. To compute the median empirical transfer function and its variation, we use 23 events from a curated dataset available at http://nees.ucsb.edu/curated-datasets with Mw less than 5 and ground surface PGAs greater than 10 gal. We use a second order Butterworth bandpass filter with corner frequencies of 1 and 5 Hz to filter the recorded acceleration time histories. To smooth the transfer functions of the 3D wave propagation simulations, we use Konno-Ohmachi algorithm [21] with smoothing parameter b = 50. Lastly, we use GTL to compute 1D transfer functions and, for completeness, we also compute the linear transfer function associated with the Vs profile obtained from inverse analysis. We observe that 1D simulations result in higher natural frequencies and amplification factors compared to the 3D simulation transfer functions. Aside from the fact that the definition of site response transfer functions implicitly assumes 1D effects and linear elastic material response, the mismatch of the analytical to empirical transfer functions likely arise from the idealized velocity distribution of GTL and from uncertainties associated with characterizing the shallow crust in numerical simulations.



(a) (b)

Fig. 11 – (a) velocity profile at the GVDA; (b) Empirically and analytically computed transfer functions at the GVDA.

Fig. 12 presents the strain-stress responses at different depth at the GVDA. We observe that the input excitations are not strong enough to trigger nonlinearity in elements with Vs greater than 450 m/s (i.e., stiff layer) and therefore shallow crust nonlinearity is only concentrated in near-surface layers with thickness less than 40m. Furthermore, the maximum strain levels suggest that the soil stiffness is reduced at least up to 30% in Case 3 and up to 50% in Case 4.



(a) (b) (c) (d)

Fig. 12 – xz component of the strain-stress responses at different depths at the GVDA: (a) z = 6m; (b) z = 15m; (c) z = 22m; (d) 50m.

5. Conclusions

We have presented a case study from a strong motion downhole array site in California where we tested the implementation of an elastoplastic nonlinear soil model. The model, introduced by Borja and Amies [8], was formulated on the basis of very few parameters, which renders it applicable for calibration of large scale ground motion simulations. Results show that nonlinear effects, at the region of interest yield reduced PGA and increased PGD on the order of ~20-30%. We also compare our 3D simulations to 1D site response analyses and conclude that the latter cannot capture the complexity of fully 3D simulations at high frequencies. We lastly illustrate that the hysteresis loops computed at depth in the 3D simulations are realistic and consistent with modulus reduction and damping of nonlinear sedimentary materials. Future extensions of the work will include more detailed comparison of time series and engineering intensity measures for linear and nonlinear analyses, as well as more complex broadband incident ground motions and realistic earthquake source models extracted from source inversion of the events that have been recorded at the GVDA. Results will also be compared with scenario simulations of the same events using J2 elastic-perfectly plastic models, which has been criticized in the past for yielding excessive reduction of PGA (~60%), likely associated with unrealistic modulus reduction and large intrinsic attenuation predictions of J2 models.

6. References

[1] Stephen Hartzell, Alena Leeds, Arthur Frankel, Robert A. Williams, Jack Odum, William Stephenson, and Walter Silva. Simulation of broadband ground motion including nonlinear soil effects for a magnitude 6.5 earthquake on the Seattle Fault, Seattle, Washington. Bull. Seis- mol. Soc. Am., 92(2):831–853, 2002.

[2] Ralph J. Archuleta, Pengcheng Liu, Jamison H. Steidl, L. Fabian Bonilla, Daniel Lavallee, and Francois E. Heuze. Finite-fault site-specific acceleration time histories that include nonlinear soil response. Phys. Earth Planet. In., 137(1-4):153–181, 2003.

[3] Jifeng Xu, Jacobo Bielak, Omar Ghattas, and Jianlin Wang. Three-dimensional nonlinear seismic ground motion modeling in basins. Physics of the earth and planetary interiors, 137(1):81– 95, 2003.

[4] Fabrice Dupros, Florent De Martin, Evelyne Foerster, Dimitri Komatitsch, and Jean Roman. High-performance finite-element simulations of seismic wave propagation in three-dimensional nonlinear inelastic geological media. Parallel Computing, 36(5):308–325, 2010.

[5] R Taborda, J Bielak, and D Restrepo. Earthquake ground-motion simulation including non- linear soil effects under idealized conditions with application to two case studies. Seismological Research Letters, 83(6):1047–1060, 2012.

[6] D. Roten, K. B. Olsen, S. M. Day, Y. Cui, and D F¨ah. Expected seismic shaking in Los Angeles reduced by San Andreas fault zone plasticity. Geophys. Res. Lett., 41(8):2769–2777, 2014.

[7] Taborda, R., J. López, H. Karaoglu, J. Urbanic, J. Bielak (2010). Speeding Up Finite Element Wave Propagation for Large-Scale Earthquake Simulations, Carnegie Mellon University, Parallel Data Lab, Technical Report No. CMU-PDL-10-109.

[8] Ronaldo I Borja and Alexander P Amies. Multiaxial cyclic plasticity model for clays. Journal of geotechnical engineering, 120(6):1051–1070, 1994.

[9] Near-fault seismic site response. PhD thesis, University of California, Berkeley, 2000.

[10] Gang Wang and Nicholas Sitar. Nonlinear analysis of a soil-drilled pier system under static and dynamic axial loading. Pacific Earthquake Engineering Research Center, College of Engineering, 2006.

[11] Wenyang Zhang, Elnaz Esmaeilzadeh Seylabi, and Ertugrul Taciroglu. Validation of a three- dimensional constitutive model for nonlinear site response and soil-structure interaction anal- yses using centrifuge test data. International Journal for Numerical and Analytical Methods in Geomechanics, doi:10.1002/nag.2702, 2017.

[12] Heng-Yih Chao and Ronaldo I Borja. Nonlinear dynamic soil-structure interaction analysis and application to Lotung problem. Technical Report J. A. Blume Earthquake Engrg. Ctr. Tech. Rep. 129, Stanford University, Stanford, CA, 1998.

[13] Silvia Mazzoni, Frank McKenna, Michael H Scott, Gregory L Fenves, et al. Opensees command language manual. Pacific Earthquake Engineering Research (PEER) Center, 264, 2006.

[14] Jacobo Bielak, Kostas Loukakis, Yoshiaki Hisada, and Chiaki Yoshimura. Domain reduction method for three-dimensional earthquake modeling in localized regions, part i: Theory. Bulletin of the Seismological Society of America, 93(2):817–824, 2003.

[15] Luis Fabian Bonilla, Jamison H Steidl, Jean-Christophe Gariel, and Ralph J Archuleta. Bore-hole response studies at the garner valley downhole array, southern california. Bulletin of the Seismological Society of America, 92(8):3165–3179, 2002.

[16] Karl F Graff. Wave motion in elastic solids. Courier Corporation, 2012.

[17] Ricardo Taborda, Shima Azizzadeh-Roodpish, Naeem Khoshnevis, and Keli Cheng. Evalua- tion of the southern california seismic velocity models through simulation of recorded events. Geophysical Journal International, 205(3):1342–1364, 2016.

[18] Geoffrey P Ely, TH Jordan, P Small, and Philip J Maechling. A vs30-derived nearsurface seismic velocity model. In Abstract S51A-1907, Fall Meeting. AGU San Francisco, CA, 2010.

[19] Mehmet Baris Darendeli. Development of a new family of normalized modulus reduction and material damping curves. PhD thesis, University of Texas at Austin, 2001.

[20] Elnaz Seylabi, Andrew Stuart, Domniki Asimaki, Site characterization at strong motion arrays by data fusion of non-destructive testing and ground motion records, Bulletin of the Seismological Society of America, Under Review.

[21] Konno, K. and Ohmachi, T. (1998). Ground-motion characteristics estimated from spec- tral ratio between horizontal and vertical components of microtremor. Bulletin of the Seismological Society of America, 88(1):228–241.