Project Report – SCEC Award 17-140

Workshop on Nonlinear Shallow Crust Effects

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1 Summary

The SCEC Workshop on Nonlinear Shallow Crust Effects was held on September 9 at the Hilton Hotel in Palm Springs, California, as a prelude to the 2017 SCEC Annual Meeting. The event brought together a group of 27 earthquake engineers, earth scientists, and computational scientists (with and without prior connections to SCEC), all of whom shared an interest in nonlinear effects in the context of regional ground motion simulation. The workshop activities comprised a series of presentations, and several group discussions. (The agenda and list of participants are enclosed at the end.)

The workshop started with a review of the conclusions of a related workshop held in May 2015 at the SCEC USC headquarters; continued with an explanation of the subject within the framework of SCEC's simulation efforts, the SCEC5 Science Plan and its *beyond elasticity* theme; continued with specific topics related to current practices in physics-based ground motion simulation for including site effects and other related phenomena of nonlinear nature, including the characterization of shallow crust media (in terms of scattering and attenuation effects), the use of different material and constitutive models to represent heterogeneities and plastic deformations; touched on the influence plastic deformation has on damping, the importance of other aspects such as pore pressure, the synthesis of observations with evidence of nonlinear behavior; and put all this in perspective with respect to SCEC's ground motion simulation objectives.

The discussions held throughout the workshop and towards the end of it focused on a few key aspects described in detail below, and made evident the interest of the group to start a collaboration, and possibly conform a Technical Activity Group to work on subjects related to the effects that the shallow crust has on the earthquake ground motion simulation. Identified topics of interest included but were not limited to: characterizing the material properties in the upper (300–500 m) crust, including rock and sedimentary deposits, and their variability; understanding of the range and extent to which nonlinearity affects a wide spectrum of frequencies in ground motion; identifying (alternative) constitutive models suitable to simulate nonlinear effects at regional scales; and advancing verification and validation efforts that can help narrow the options of models and approaches that are suitable for implementation in SCEC simulation platforms (Broadband, CyberShake, High-F), and adequate for obtaining realistic results (qualitatively) comparable to observations.

In closing, the group agreed to hold follow-up conference calls in October and November to coordinate the submission of a TAG proposal in response to the 2018 SCEC Science Plan (RFP), and to cross-reference this with other individual proposals.

2 Background, Objectives, and Scope

For over two decades, SCEC has promoted a physics-based approach to ground motion simulation for hazard mapping and engineering applications. Over the same period of time, simulations have advanced considerably thanks to increasing access to high-performance computing (HPC) resources and improvements in software tools, allowing SCEC scientists to target more complex problems, both in terms of higher frequencies and finer spatial resolutions. In turn, this has accelerated a transition from the hybrid simulation approaches (combining deterministic- and stochastic-based methods) to fully-deterministic broad-band simulations. In light of this, we are called upon to develop capabilities for the SCEC simulation frameworks to capture the physics of the processes that dominate the high frequency (> 1 Hz) regime of earthquake problems and earthquake ground motion, and this includes in good measure those aspects of earthquake related to nonlinearities, and in particular, those related to the characteristics and mechanical properties of shallow crustal materials (weathered rock and sedimentary soils).

In response to this, a workshop was organized in 2015 to identify the major topics of interest in terms of site effects and nonlinear soil behavior and how these could be incorporated into SCEC ground motion simulation frameworks (Broadband, CyberShake, High-F). That first workshop produced a report that served as input to the SCEC leadership in the preparation of the SCEC5 proposal to NSF and the USGS. Now in the first year of SCEC5, we organized a second workshop on nonlinear effects with the broader theme of "shallow crust effects". The goals of this second 2017 workshop were: (i) to foster collaboration between geotechnical engineers, geo-material scientists, and computational seismologists, bridging the scale between site-specific and region-specific simulations of nonlinear response; (ii) to collectively develop a road-map of research milestones to integrate nonlinear effects in physics-based broadband simulations within SCEC5; and (iii) to reach the consensus required to translate such road-map into a Technical Activity Group (TAG) charged with coordinating and supporting our collaborative research on the subject of integrating nonlinear models in broadband physics-based simulations.

We should note that the problem of earthquake simulation involves nonlinearities in various forms. There are nonlinearities associated with the fault rupture, the material in the immediate vicinity of the fault, and the path along which seismic waves travel, which in turns include the upper (shallow) crust and its sedimentary deposits. In discussions leading to and during the workshop, it became important that we broaden our interest in material nonlinearities (i.e., nonlinearities associated with plastic deformations due to the mechanical properties of the material) to also include other aspects of the shallow crust influencing the surface ground motion in the range of frequencies where nonlinearities are more prominent. This is why the workshop—and by extension, a future TAG—contemplated presentations related to scattering due to small-scale heterogeneities heterogeneities, surface topography, attenuation, and near-surface plastic fault zones. Other nonlinear phenomena out of the scope of the workshop (and the TAG) are nonlinear fault rupture and off-fault plasticity in dynamic rupture simulation (which we assume of the tenure of the dynamic rupture simulation and earthquake simulators groups), and rheology of the deep crust (which we assume of the tenure of the CRM group). We recognize, however, that there are areas of overlap and we will try to coordinate with other group leaders within SCEC to address such areas in the future.

3 Main Discussion Topics

During the workshop, the participants agreed that incorporating nonlinear effects in SCEC ground motion simulations involves the selection and validation of appropriate models to represent plasticity effects in near-surface fault damaged zones, shallow crust weathered rocks, and basin sedimentary structures, as well as localized areas prone to strong site effects. Each of these models will be further accompanied by a set of input parameters, which will need to be retrieved either as function of the linear viscoelastic material properties, or as part of the Community Models (CXM), such as the Community Rheology Model. Also, the participants agreed that appropriate methodologies will need to be devised to incorporate nonlinearity in physics-based ground motion simulations in a computationally efficient manner (for example, multi-scale or domain reduction methods to limit the computational domain where nonlinear time-domain analyses will be conducted); as well as to incorporate nonlinear effects (or proxies thereof) in CyberShake while retaining the reciprocity principle that for now renders the development of synthetic hazard maps feasible. A brief summary of the topics discussed in the workshop is provided below, followed by an outline of action items and research activities that the PIs and members of the SCEC community interested in conducting research in the field of nonlinear ground motion simulations will need to undertake in the remaining 4 years of SCEC5.

3.1 Fault zone plasticity modeling

Results of a SCEC funded research (Roten et al., 2017) depicted the sensitivity of ground motions to the presence of a fault damage zone—characterized by laterally varying degrees of fracturing—, demonstrating the need to characterize and quantify the strength of crustal and sedimentary rocks. Results from simulations with plasticity in the Los Angeles basin showed that nonlinearity in the fault damage zone and in the near-surface deposits could reduce peak ground velocities by 15-50%, depending on the strength of crustal rocks and shallow sediments. Simulations presented in this work were performed for three rock strength models representing good, average, and poor quality rocks, using HoekBrown failure criterion to account for the reduction of rock strength. The simulations suggested that non-linear effects may be relevant at frequencies below 1 Hz, and at magnitudes as low as 6.5. Moreover, simulations of a high stress drop M 7.8 scenario earthquake on the southern San Andreas fault for a realistic earth structure, including a low-velocity shallow crustal zone demonstrated that plastic effects can be relevant at periods of 2 and 3 s, especially on soft soils. Spectral accelerations at 2 and 3 s obtained in these studies were consistent with two recent GMPEs for rock and soil sites. Moreover, the agreement between long-period simulated ground motions in the Los Angeles basin and GMPEs improved when plasticity was considered.

We should note here, however, that GMPEs do not account explicitly for 3D basin effects (i.e., the distance of the site to the basin edge, and the resonant modes of the basin structure), so the effects of plasticity on the long period ground motions are not accounted for in GMPEs and are unlikely the source of the above improvement.

3.2 Integrating nonlinear effects in CyberShake

Discussions on incorporating nonlinear effects in CyberShake were centered around the fact that the synthetic hazard maps are computationally feasible by employing the principle of seismic reciprocity when post-processing the strain Green tensors to obtain synthetic seismograms, and successively spectral acceleration hazard curves (Graves et al., 2011). Clearly, nonlinear effects cannot be explicitly integrated in Cybershake. On the other hand, synthetic hazard maps are ideally estimating events at long return periods, where the ground shaking is expected to be strong and the effects of nonlinearity will most likely affect the ground surface response. Among others, viable strategies that were identified to circumvent the problem included: (1) devising event classification algorithms to identify (small) subsets of events that dominate the hazard and trigger nonlinear effects; performing forward nonlinear simulations for the selected events; and using reciprocity for all other scenarios; and (2) developing and incorporating pseudo-nonlinear simulation approximations, such as kinematic rupture models with reduced stiffness and quality factor to approximate nonlinear source effects, calibrated using a set of nonlinear forward simulations.

3.3 Integrating near-surface basin sediments in community velocity model

The workshop included presentations on a multi-institutional effort (led by Jon Stewart at UCLA) to develop an open-source database for shear wave velocity profiles across the United States. Currently, 5200 V_s profiles have been collected to be integrated in the database, for which the prototype data model has been developed. In addition to V_s, the database will include upon availability, information such as geotechnical logs, penetration resistance, laboratory test data, ground water elevation and P-wave velocity profiles. Access to such a database of geotechnical site characterization data will clearly benefit the development and calibration of nonlinear models in the shallow layers of basin sediments.

At the same time, Domniki Asimaki and her group at Caltech have been developing data-driven, V_{s30}-dependent, stochastic velocity model, referred to as Sediment Velocity Model (SVM), for Southern California. This effort was motivated by the need to improve and refine existing SCEC CVM models for broadband physics-based ground motion simulations. SVM is intended to replace its predecessor, the GTL model currently implemented in UCVM, which has been shown to distort the shape of the basement rock-soil interface of shallow basins due to its use of a smooth geometric function with fixed depth. SVM has been developed using data from geotechnical site-specific characterization studies (1D) and thus includes statistical properties that are data driven only in the vertical direction; future extensions will likely include the statistical analysis of high-resolution 3D seismic surveys in Southern California, such as Long Beach, to derive the correlation structure, correlation distance and material anisotropy in the horizontal directions.

3.4 Soil constitutive models and physics-based ground motion simulations

To ensure the feasibility of nonlinear ground motion simulations on a regional scale, selected constitutive models should require only a small number of input parameters (Asimaki et al., 2015). Two presentations described a number of alternative constitutive soil models that one could consider for this purpose, including Iwan‘s series-parallel and parallel-series models, and a bounding surface model with vanishing elastic region by Borja and Amies (1994), all of which can be calibrated using shear wave velocity profiles and shear modulus reduction curves. Results from these models were juxtaposed with simulated data from elastic-plastic models such as Drucker-Prager, which was shown to yield excessively large damping and artificially low ground shaking amplitude. Fabian Bonilla lastly highlighted the role of pore water pressures in nonlinear site response predictions for saturated cohesionless soils, and the effects of incorporating pressure dependent shear wave velocity profiles (Oral et al., 2017; Roten et al., 2009).

3.5 Nonlinear response of complex basins

Presentations continued with illustrations of the spectral cell method (SCM)—which combines fictitious-domain concepts with the spectral-version of the finite element method to solve the wave equations in heterogeneous geophysical domains—for nonlinear earthquake response modeling in complex basin structures (Giraldo and Restrepo, 2017). In this case, elastic-plastic models with Mohr-Coulomb and Drucker-Prager yielding criteria were used to account for soil nonlinearity.

Lastly, through a quantitative case study on site amplification effects (Jeong and Bradley, 2017), it was shown that site specific simulations that account for realistic basin geometry and soil nonlinear response performed significantly better than both empirical GMPEs and physics-based regional-scale ground-motion simulations with empirical site amplification factors. In this case, the pressure dependent multi-yield surface model was used to take soil nonlinearities into account, which was calibrated using modulus reduction curves and shear wave velocity profiles. Results showed that the linear-elastic assumption severely overestimates ground motions in high frequencies for strong earthquakes, and the effect of pressure-dependent soil velocities on the high-frequency ground motions is as significant as the amplification caused by the basin-edge-generated Rayleigh waves.

4 Discussion Outcomes and Action Items

Subjects that merit further investigation, ideas that should be explored and immediate action items —such as submitting a TAG proposal to coordinate the efforts of the various SCEC research groups that wish to be involved in the integration, optimization, verification and validation of nonlinear effects in broadband ground motion simulations— were identified in the closing session of the workshop. The summary of the discussion is outlined below:

- Considering that CyberShake is already a computationally intensive platform, adding more complexity, in the form of nonlinear effects, should be well justified. Identifying the range of frequencies where soil nonlinearity is important would be an essential first step in this direction. The question of whether long period surface waves can induce, or can be affected by nonlinear effects or not is of particular interest because a positive answer would offer a strong argument towards investing time and effort in incorporating these effects in CyberShake.

- Thorough verification and validation studies should be performed prior to investing resources to integrate nonlinear effects in SCEC regional simulations. Such studies should be ideally performed in small-scale basin testbeds. Among the ones discussed during the workshop, Garner Valley was considered as one option that is well-documented, and well-characterized to serve for case study. Although very strong ground motion records are rare at this site, several ground surface records exist with PGAs ranging from 0.1 to 0.2g in which nonlinear effects are shown to be triggered.

- Verification and validation efforts should start from simple problems similar to the approach that was used in previous successful BBP and rupture dynamics projects, and focus on matching selected ground motion metrics such as spectral acceleration.

- Similarly, a wide range of nonlinear models should be tested, first on a local (valley testbed) and then on a regional scale. In addition, the added complexity of input parameters, calibration and computational complexity should be juxtaposed to the improvements offered by each alternative model. New nonlinear models or improvements of existing ones should be considered if they reduce the number of input parameters and/or the computational effort without sacrificing the prediction accuracy.
- Lastly, computationally efficient approaches such as multi-scale analyses, domain reduction methods, and techniques to identify a-priori scenarios likely to trigger nonlinear effects—which merit consideration for forward nonlinear simulations as part of CyberShake calculations—should be a priority for the coming 4 years.

References

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D. Roten, K. Olsen, S. Day, and Y. Cui. Quantification of fault-zone plasticity effects with spontaneous rupture simulations. *Pure and Applied Geophysics*, pages 1–23, 2017.

Workshop Agenda

09:00 – 09:05	Welcome, agenda, objectives	Domniki Asimaki
09:05 – 09:15	Overview of SCEC's modeling and simulation software family	Ricardo Taborda
09:15 – 09:30	Current leading efforts in SCEC's 3D regional simulations including plasticity and small scale heterogeneities	Kim Olsen
09:30 – 09:40	The long-run computational challenges for using 3D simulations in seismic hazard analysis	Scott Callaghan
09:40 – 09:55	Datasets and data analysis for geotechnical site (profiles) characterization	Sean Ahdi
09:55 – 10:10	SVM – A stochastic velocity model of the shallow crust based on geotechnical site characterization data	Domniki Asimaki
10:10 – 10:20	Break	
10:20 – 10:30	Short catch-up Q&A and discussion	All
10:30 – 10:45	Characterization of the Earth's shallow crust	Oliver Boyd
10:45 – 11:00	Physical properties of damaged rock zones as inferred from observations	Yehuda Ben-Zion
11:00 – 11:15	Soil mechanics, constitutive models used in 1D/2D/3D geotechnical modeling	Fabian Bonilla
11:15 – 11:30	Simple soil constitutive models for wave propagation problems and their potential integration in 3D simulations	Elnaz Seylabi
11:30 – 12:00	Discussion	All
12:00 – 13:00	Lunch	
13:00 – 13:05	Re-cap and afternoon plan	Domniki Asimaki
13:05 – 13:15	Short catch-up Q&A and discussion	All
13:15 – 13:30	2D nonlinear and topography effects at local scales	Seokho Jeong
13:30 – 13:45	2D nonlinear and 3D topography effects at regional scales	Dorian Restrepo
13:45 – 14:00	Implications for SCEC modeling tools	Phil Maechling
14:00 – 14:15	Implications for SCEC special projects	Christine Goulet
14:15 – 14:30	Break	
14:30 – 15:50	Open Q&A and discussion about topics covered and other relevant, related issues	All
15:50 – 16:50	Open discussion about plans for a TAG and suggestions of language to be included in the RFP	All
16:50 – 17:00	Closing remarks	Domniki Asimaki

Workshop Participants

(In alphabetical order)

1.	Sean Ahdi	UCLA	(P)
2.	Domniki Asimaki	Caltech	(P,O)
3.	Peyman Ayoubi	Caltech	
4.	Yehuda Ben-Zion	USC	(P)
5.	Fabian Bonilla	IFSTTAR, France	(P)
6.	Oliver Boyd	USGS	(P)
7.	Brendon Bradley	U. of Canterbury	
8.	Alexander Breuer	SDSC/UCSD	
9.	Scott Callaghan	SCEC/USC	(P)
10.	Elnaz Esmaeilzadeh Seylabi	Caltech	(P)
11.	Christine Goulet	SCEC/USC	(P)
12.	Zhifeng Hu	SDSU	
13.	Seokho Jeong	U. of Canterbury	(P)
14.	Hiroko Kitajima	Texas A&M	
15.	Naeem Khoshnevis	U. of Memphis	
16.	Robin Lee	U. of Canterbury	
17.	Phil Maechling	SCEC/USC	(P)
18.	Dawei Mu	SDSC/UCSD	(P)
19.	Kim Olsen	SDSU	(P)
20.	Dorian Restrepo	EAFIT, Colombia	(P)
21.	Hamid Sana	IIT, India	
22.	Norm Sleep	Stanford	
23.	Ricardo Taborda	U. of Memphis	(P,O)
24.	Nan Wang	SDSU	
25.	Kyle Withers	USGS	
26.	Te-Yang Yeh	SDSU	
27.	Alan Yong	USGS	

P: Presenter
O: Organizer