A Technical Activity Group for the coordination of SCEC5 research on nonlinear effects in the shallow crust

1. Mission Statement

To develop, verify and validate a robust family of computational tools that will advance the capabilities of SCEC ground motion simulation frameworks to capture anelastic effects in the shallow crust. More specifically, our Technical Activity Group will coordinate efforts in: (i) constitutive modeling and simulation of nonlinear effects; (ii) development and validation of semi-empirical nonlinear site factors; and (iii) heterogeneity characterization and scattering attenuation modeling. Our efforts will focus on extending the capabilities of the SCEC Broadband Platform and the High-F ground motion simulation frameworks.

2. Definition and Scope

Significant advances in physics-based earthquake ground motion simulations have allowed us to move towards higher frequencies and finer resolution scales. This, however, has brought to light complex phenomena arising from the source physics, the path properties and their coupling in seismic wave propagation, which were not *visible* by previously coarser models. Some of the most prominent features that higher resolution models are called to account for are the spatial variability and the anelastic behavior of geomaterials in the shallow crust, which include scattering, diffraction, focusing, hysteresis, and permanent or transient ground deformation. These effects, hereupon referred to as *nonlinear shallow crust effects*, span a wide range of scales, affect the amplitude and duration of ground motions over a broad range of frequencies, and are highlighted among the research priorities of SCEC5.

Under the umbrella theme of SCEC5 *Beyond Elasticity*, nonlinearities have been associated with three processes: (i) the geodynamic evolution of faults; (ii) the fault rupture itself, and the deformation in its immediate vicinity, both at depth and in near-surface plastic fault zones; and (iii) the anelastic effects along the path, including the effects of plastic deformations in sedimentary deposits, scattering effects due to small-scale heterogeneities, and energy attenuation due to internal friction. Our TAG will focus on understanding, modeling, implementing and testing models that will enhance the capabilities of SCEC ground motion simulation frameworks to capture anelastic path effects in the upper 300–600 m of local and regional basins, where the crustal structure is mainly composed of sedimentary deposits and weathered rock with typical shear wave velocities under 1 km/s. On the temporal scale, we will focus our attention on localized transient phenomena occurring during, or as a consequence of, strong earthquake ground motions.

Within SCEC5, this TAG is complementary to—but not overlapping with—research activities carried out in earthquake geology (focused on much deeper structures), fault and rupture mechanics (where nonlinearities are related to rupture dynamics), stress evolution and geodynamic modeling (focused on much longer time scales), and in developing the Community Rheology Model (focused on larger and deeper geologic scales). The TAG will facilitate research initiatives at the intersection of seismology, ground motion, and computational science; will feed into the CXM initiative on matters related to the characterization of small scale heterogeneities, sedimentary velocity structures, and constitutive behavior of shallow geomaterials; and will support the activities of the Earthquake Engineering Implementation Interface Focus Group by developing products intended for the engineering community, such as BBP computational modules and empirical site factors.

3. Technical Activity Group Research and Coordination Plan

3.1. Goals

Although the term nonlinear effects is often conflated with the inelastic behavior of geomaterials, we wish to clarify that by nonlinear effects, we refer to the ensemble of wave propagation phenomena in the shallow crust—scattering due to small-scale heterogeneities, attenuation due to internal friction, and viscous and plastic deformations simulated via nonlinear constitutive laws—which are coupled and cannot be separated without loss of predictive accuracy. In this context, the main goals for the proposed TAG will be:

- To develop, verify and validate two categories of nonlinear site response computational modules for the SCEC Broadband Platform: i) site-specific, namely discretized solutions of the wave PDE, conditioned on velocity profiles and nonlinear material parameters; ii) semi-empirical, based on ground motion records complemented by numerical simulations. The latter will be developed in the Fourier domain, and will be conditioned on generic site properties such as V_{s30}, and ground motion intensity measures, such as PGA.
- To characterize material properties contributing to scattering effects in the shallow crust; synthesize data that can be coupled with the SCEC community velocity models used in three-dimensional physics-based simulations; and validate the resulting parameterized, queryable models to capture observed trends of spatial variability of surface ground motions and frequency-dependent scattering attenuation.
- To implement, verify and validate nonlinear constitutive models in the SCEC three-dimensional physics-based ground motion simulation frameworks. Validation of these models will focus on an instrumented and well-characterized basin structure in Southern California (e.g. Garner Valley) to constrain the modeling and parametric uncertainty of the simulated problem, and allow linking of discrepancies between simulations and observations to the regional material characterization and constitutive model behavior.

3.2. Research Thrust Areas

Based on a series of previous workshops and subsequent in-person and remote group discussions, we have identified the following research problems as priorities to be coordinated by this TAG over the next three years:

BBP Modules for Nonlinear Site Response: Two families of nonlinear site response modules are proposed to be developed and implemented on the BBP. The goals and proposed research steps are described below. Upon completion of the implementation, the TAG will also coordinate a BBP validation for the same earthquake scenaria as in Goulet et al. (2014), but will use ground motion records on all site conditions as reference, and the said modules as nonlinear site response correction factors. Results will be compared with previous efforts of BBP validation.

Fourier-based nonlinear site amplification:

Jeff Bayless, Andreas Skarlatoudis (AECOM); Jon Stewart, Scott Brandenburg, Chukwuebuka C Nweke (UCLA); Domniki Asimaki, Jian Shi (Caltech)

Develop appropriate models for frequency-dependent amplification of Fourier amplitude ordinates, using earthquake recordings and/or ground response simulations. The product will be a Southern CA region-specific nonlinear amplification model for the horizontal components of the Fourier amplitude spectrum. This topic will comprise of the following tasks: i) combine NGA-W2 and ground motions recorded in Southern CA since the completion of the database, with multiple recordings per site for many sites, allowing for a partially non-ergodic site response analysis; ii) get reference condition residuals; iii) use non-ergodic site response procedures to infer site-specific site amplification at multiple locations inside and outside of basins in Southern CA; iv) combine with numerical simulations to gain insight into large strain range site response; v) Use results to develop empirical and possibly semi-empirical (using simulations) site amplification models that account for VS30, basin depth, and potentially basin tag information (i.e., LA basin, SF valley, etc.); vi) Test how well the region-specific model compares to existing ones.

Nonlinear site-specific amplification:

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Two site-specific nonlinear wave propagation codes, a finite difference based on Shi and Asimaki (2017) and a finite element based on Borja and Amies (1994), will be implemented on the BBP. The generic velocity model for Southern California, SVM (Shi and Asimaki, 2018), conditioned on V_{s30}, will also be implemented. A workflow will be designed to modify the BBP simulated ground motions on reference site conditions by generating soil profile realizations using SVM, and prescribing the BBP output as rock outcrop input motion. Most components of this work have already been developed, so the team will focus on repeating the validation exercise of the BBP as per Goulet et al. (2014).

Parameterization of Stochastic Media: Develop methods for better representation of wave propagation scattering due to structural complexities in deterministic broadband ground motion simulations. This topic will comprise of the following tasks: i) parameterization of correlation functions used in statistical representation of small-scale velocity variations. The method should be fast and adoptable to parallel computing and capable of being applied to velocity models on a regional scale; ii) validation of the stochastic models using recorded data, with emphasis on estimating properties of the correlation functions, in particular correlation lengths in horizontal and vertical directions in basin and rock settings; iii) efficiency assessment of the stochastic models using wave propagation modeling for recorded small earthquakes (¡ M5). Simulations will also be used to separate intrinsic attenuation from wave scattering attenuation; and to estimate the relative contributions and nature of scattering from topography and crustal small-scale heterogeneities.

Arben Pitarka (LLNL), Nori Nakata (UO) and Kim Olsen (SDSU)

Verification and Validation of Nonlinear Constitutive Models in 3D Simulations: Develop a verification test plan of the plasticity models implemented in physics-based SCEC ground motion simulation platforms using canonical problems with analytical or numerical published solutions. Develop a validation plan for a small-scale basin testbed at various levels of strong ground motion. Among the sites that the TAG has considered, Garner Valley was identified as a well-documented, and well-characterized candidate for a local 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—albeit weak—are frequently triggered (Kaklamanos et al., 2013). The TAG will also seek alternative non-local validation datasets and sites that can be used as proxies for importing insight useful to southern California. To ensure the feasibility of nonlinear ground motion simulations on a regional scale, following the recommendations from previous workshop discussions (Asimaki et al., 2015; Asimaki and Taborda, 2017), constitutive models with only a small number of input parameters have been prioritized.

Domniki Asimaki, Elnaz Esmaeilzadeh Seylabi (Caltech); Daniel Roten, Kim Olsen (SDSU); Doriam Restrepo, Ricardo Taborda (EAFIT)

3.3. Coordination Efforts (2018-2019)

The TAG organized an in-person meeting at the 2018 Annual SCEC Meeting in September 2018. Participants included members of the SCEC funded research community with interest in contributing to the TAG activities, USGS researchers who provided insight in the architecture of the BBP and the site characterization data availability across Southern California, and interested users of the Community Modeling Environment software relevant to the developments planned by the TAG. The TAG participants narrowed the goals of the group to the three research thrust areas summarized above, and outlined research plans to reach these goals through concretely identified milestones through the end of SCEC5. These plans are expected to be materialized through proposals planned to be submitted in response to the SCEC 2019 call for proposals.

4. References

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