SCEC Site Effects Workshop Report

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1. Introduction

The SCEC Site Effects Workshop on May 5, 2015, brought together engineers and earth scientists with expertise in ground motion simulations, geotechnical earthquake engineering, constitutive soil modeling, regional soil characterization and structural geology (see agenda and participants in appendix). The goal of the workshop was to promote discussion and develop consensus among the participants on the research priorities that SCEC should consider to integrate nonlinear near-surface[1] path effects in ground motion simulations.

The research challenges and priorities in the realm of ground motion simulations with nonlinear site effects were discussed in the context of three short-, mid- and long-term goals, aligned with the three primary simulation applications within SCEC: *one-dimensional* (1D) *broadband* ground motion simulation techniques in flat-layered structures (as implemented in the SCEC Broadband Platform, or BBP); *three-dimensional* (3D) regional-scale wave propagation simulation techniques (as implemented in SCEC simulation codes such as AWP-ODC and Hercules); and *simulation-based seismic hazard mapping* (as implemented through the CyberShake simulation activities).

Despite the diversity of expertise and interests reflected in the presentations, invited participants—earth scientists and engineers representing both academia and industry—unanimously recognized that the near-surface geology (stratigraphy) and rheology (nonlinearity) significantly affect the amplitude, frequency content and duration of ground motions. As such, simulations intended for engineering applications should reflect realistic rheology including nonlinear site effects not only in the amplitude, but also in the organization of phase arrivals, polarization, and dispersion that are characteristic of real ground motions (comprising body and surface waves). The participants' consensus was that SCEC5 should include a plan to advance the science needed to incorporate nonlinear effects in ground motion simulations. This can be achieved through incorporation and testing of physical rheology models of various complexity into simulations, study of efficient ways to measure or estimate all of the necessary stratigraphic and rheological parameters needed for the calculations, dealing with computational challenges, and validating measurement techniques and models—possibly by including a focus on a natural laboratory the size of a small basin.

The following sections summarize the workshop discussions and the participants' feedback. We should note here that in the context of this workshop summary, intact rock, fractured rock and soil were considered as three different materials. The workshop focused on soil and intact rock (to a lesser extent), so the subsequent discussion primarily reflects our consensus on modeling these materials. In some circumstances, fractured rock in the near surface may also have important effects on strong motion, but this problem is (perhaps) a lower priority.

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[1] Heretofore referred to as *site effects*.

2. Nonlinear constitutive models

2.1 Physics-based models

Although there exist numerous sophisticated constitutive soil and rock models that have been developed on the basis of site-specific field and laboratory testing, the scale of the problem at hand presently prohibits their use in regional simulations. This is due to the computational constraints in space and time imposed by these models, but most important because of the many unknown or sparsely measured input parameters, which make the task of quantifying their parametric uncertainty practically impossible.

Nonetheless, this section applies to the admittedly small subset of sites where velocity profiles and other required site information are known so that 1D physics-based wave propagation modeling can be applied. For the common case where that information is not available and more approximate methods are needed, the reader is referred to the class of methods in Section 2.2. This section also applies to 3D physics-based wave propagation models where available near-surface material proxies (e.g., Vs30) have been translated into idealized velocity profiles (e.g., the CVM-H geotechnical layer, GTL), and empirical correlations have been thereafter employed to estimate soil and rock nonlinear parameters for implementation in ground motions simulations.

In these situations, it is sensible to begin with the development (if necessary) and implementation of simplified constitutive models based on very few physical parameters, with the obvious caveat that their predictive capabilities will also be limited. To that end, a series of models with increasing complexity should be tested, and both the epistemic and parametric uncertainties of these models should be quantified. Each step in this process should be accompanied with mapping of the material proxies (e.g., Vs30, or velocity profiles where available) and the empirical estimates of the nonlinear soil and rock parameters (e.g., friction angle as a function of confining pressure); with a systematic verification procedure to assess the tradeoffs between the accuracy of models, their implementation and their parametric uncertainties; and wherever possible, with a continuous validation of the simulated ground motions against observations. In this regard, four levels of model complexity are suggested:

i. The first level of constitutive model complexity should be *elastic-perfectly plastic*, such as the Drucker-Prager pressure-dependent model that has already been implemented in High-F simulations (e.g., Taborda et al., 2012; Roten et al., 2014). These models capture the elastic stiffness and strength of the material, but ignore the transition regime between the two. One important point here is that soils and intact rocks are different materials, and exhibit different behavior when subjected, for example, to the same level of confining pressure. In turn, when elastic perfectly-plastic models are integrated in ground motion simulations to capture the response of soils and rocks, the input parameters such as stiffness and strength should be selected on the basis of empirical correlations and published data that reflect the distinct behavior of each material.

ii. A second level of complexity should incorporate *nonlinear elastic* (small-strain nonlinearity and anelastic attenuation) models with smooth transitions from the elastic to the plastic regimes. For soils, the parameters required to capture this behavior are the so-called modulus reduction and damping curves, which reflect the material stiffness degradation and intrinsic attenuation increase with cyclic shear strain amplitude. There is a large body of literature on these properties, and a widely used set of empirical correlations that can estimate the pressure-dependent nonlinear dynamic soil behavior using information as crude as a clay/sand distinction (Darendeli, 2001). Interestingly, laboratory and vibroseis field tests by Johnson and co-workers at LANL have shown that the low to intermediate strain regime of rocks subjected to dynamic loading compares well, qualitatively, with the dynamic soil behavior described above. In turn, the constitutive model selected to capture the nonlinear soil behavior could in theory be used to capture the response of rocks as well, provided that each material were calibrated separately on the basis of the corresponding laboratory and field data. Constitutive models such as those proposed by Iwan (1966, 1967), where the hysteretic material behavior is captured using assemblies of elastic springs and plastic sliders, would be good first candidates.

iii. On a third level of complexity, constitutive models formulated in the framework of *elastoplasticity* should be considered. These models can consider dilation, kinematic hardening, and soil-water phase coupling using multi-yield plasticity, bounding surface plasticity, generalized plasticity or hypo-plasticity formulations. An example of a simplified elastoplastic formulation that would be a good candidate to consider on this level is the recently published work by Pisanò and Jeremic (2014). In this work, the authors combined an effective stress, elastic-perfectly plastic frictional model with kinematic hardening with a viscous model to reproduce 3D nonlinear dynamic soil behavior. The 7 parameters of the Pisanò and Jeremic model can be calibrated from the modulus reduction and damping curves and the material strength, at the expense of increasing parametric uncertainty compared to the simpler models described before. On the other hand, the Pisanò and Jeremic model can simulate strain-induced anisotropy and coupling between shear and volumetric strains, which are important features of soil behavior, particularly for saturated cohesionless soils susceptible to liquefaction.

iv. Beyond that level, elastoplastic models formulated in the framework of *critical state soil mechanics* are also available. In these models, the coupling between volumetric and shear deformation is formalized by means of a state parameter (typically void ratio). Depending on the state of the material at the onset of loading, these models can thus capture the effects of strain hardening and softening with increasing strain. Examples include the work by Dafalias and co-workers (see Dafalias, 1986 and references therein). For rock formations with distinct planes of in-plane anisotropy, additional levels of constitutive modeling complexity should include elastic transverse anisotropy. The number of parameters associated with models in this class, however, might be prohibitive for implementation in regional scale models. They can be considered, however, as means to identify the important soil and rock behavior trends that the simplified models should be capturing.

2.2 Stochastic and Semi-stochastic models

Most broadband ground motion models simulate high-frequency (>1Hz) components using non-deterministic (e.g., stochastic) methods that capture the waveform amplitude and phase in terms of trends, or semi-deterministic methods that make approximations to favor computational efficiency. Since the contribution to site effects from shallow geotechnical layers is primarily at high frequencies (>1 Hz), the analysis of site effects has been traditionally performed separately from the source and path components. When the velocity profile is known in the near surface, ground response is usually evaluated through 1D fully deterministic analyses referred to as site-specific ground response analyses. Since more frequently than not, however, only the general site conditions are known through an estimate of parameters such as Vs30, the effects of nonlinear site response are frequently added to the simulated motions *post facto*, by means of empirical site amplification factors.

Modern Vs30-based site amplification methods (e.g., Choi and Stewart, 2005; Kamai et al., 2014; Seyhan and Stewart, 2014), however, are based on response spectra, which are not designed to correct ground motion time-series for site response. Additionally, these methods only adjust the frequency-dependent amplitudes and cannot account for the effects of nonlinear site response on the phase. There have been a few studies that have included site effects in the analysis of Fourier amplitudes (e.g., Trifunac, 1976; McGuire 1978; Atkinson and Mereu, 1992), but these studies do not consider the effects of phase or the effects of nonlinear site response.

Because recordings of large magnitude earthquakes at short distances on soft soils are scarce, empirical site amplification factors are often complemented with numerical simulations to constrain the effects of nonlinear response for large peak ground accelerations (PGA) (e.g., Kamai et al., 2014). These simulations, however, are frequently conducted using the so-called equivalent linear method (Schnabel et al., 1972). While the equivalent linear method offers a widely used approximation to the solution of the nonlinear wave equation, it is not reliable for very strong ground motion analyses or very deep sediments. It is therefore important to ensure that these synthetic site amplification factors are computed using soil models that properly capture the physics of nonlinear site response.

With the above considerations in mind, and in the context of SCEC applications, it is recommended that the site amplification parameters currently implemented in the BBP be revised. Future versions of the SCEC BBP should adopt formulations in the complex Fourier amplitude domain (including both amplitude and phase) parameterized in terms of simple site parameters such as Vs30, basin depth, and/or the near surface soil-velocity gradient. The proposed complex amplification factors should be developed on the basis of an exhaustive set of analyses with 1D site response models that capture soil behavior in the linear elastic, nonlinear elastic and plastic strain regimes. Examples of available codes for the latter include SEISMOSOIL (by Asimaki and co-workers); DeepSoil v7.0 (by Hashash and co-workers); D-MOD (by Matasovic and co-workers); and NOAH (by Bonilla and co-workers). Multiple models should ideally be used to capture the epistemic uncertainty and modeling variability of the nonlinear site response simulations. Last, because the equivalent linear method is widely implemented in engineering practice and in regional hazard mapping applications, we recommend it to also be considered as one of the candidate models in this task, albeit only in the strain range where it is most reliable (typically <0.1%).

In addition, a number of the above site-specific response models should be also made available on the BBP, to enable correction of the simulated time series by users in the engineering research and practice communities at sites with known velocity profiles. This implementation should be accompanied by a systematic verification and validation effort, with the latter preferably based on downhole array recordings in Southern California and beyond, to minimize the epistemic uncertainty of source and path conditions in the performance assessment of the nonlinear models. Last, validation of the BBP simulations has to this point focused on matching response spectra, but should be extended to Fourier spectra for these purposes.

3. Material Parameter Characterization and Mapping

The ingredients of wave propagation in nonlinear media are the spatial distribution of the elastic parameters (Vp, Vs, density), the anelastic parameters (Qp and Qs), and the nonlinear parameters (selected on the basis of the corresponding rheology). The significance of nonlinear site effects notwithstanding, any plans to map and constrain, regionally, nonlinear material properties in the near surface should be coupled with a systematic effort to also map the elastic and anelastic soil properties of the geotechnical layers in the upper few hundred meters.

For example, when Assimaki et al. (2008) used inversion of KIK-net downhole array recordings to estimate low-strain velocity and attenuation profiles, they found that the Qs-Vs relationship in the near surface (0-30m) was very different than in the deeper soil layers (30-100m), which in the geologic setting of Japan frequently qualify as rocks. Specifically, Qs appeared to almost saturate in the very shallow soil layers, albeit at values much lower than the ones measured in laboratory experiments of dynamic soil behavior. The very low Qs values in the near surface were explained as a combination of intrinsic and scattering attenuation. The results obtained by Assimaki et al. (2008) were recently found in agreement with the Qs-Vs ambient noise inversions by Kawase et al. (2015, in preparation) for the same region. In the Los Angeles basin, there are numerous strong motion stations that have been characterized by Yong et al (2013) using passive geophysical techniques. Ambient noise measurements at these stations could thus be used to better characterize Qs in the GTL, and accordingly update its implementation in the SCEC Unified Community Velocity Model (UCVM) software framework.

The velocity profiles at the same stations could be also used to develop improved parameterizations of the currently employed geotechnical layer (GTL) in community velocity models, or CVMs. Assimaki et al. (2013), who used profiles collected by Yong et al. (2013) to compute site-specific nonlinear amplification factors at strong motion stations in Southern California, showed that near surface profiles with similar Vs30 had a similar velocity gradient. This is not surprising since most of the stations examined in that study were on sedimentary deposits with various levels of overburden stress history. On the same time, Taborda and Bielak (2014) found that the GTL currently employed in the model CVM-H, which follows the formulation proposed by Ely et al. (2010), can significantly alter the basin's shape (depth and width) and thus change the impedance contrast between basement rock and sedimentary deposits. This can introduce errors in the ground motions, especially in areas and frequency ranges strongly influenced by basin edge effects.

It is therefore recommended for a new velocity parameterization of the GTL to precede the integration of nonlinear site effects in SCEC ground motion simulation models. Based on near-surface velocity measurements and constrained by the deeper CVM basement structure, the new GTL should preserve the basin's geometry and at the same time, should avoid artificial amplification of high frequencies that can take place by introducing sharp fictitious interfaces in the near-surface profiles.

Next, empirical correlations of nonlinear model parameters and available in-situ and laboratory measurements in the region of interest should be collected, evaluated, and thoroughly documented. Soil and rock parameters from field and laboratory measurements, as well as from empirical correlations based on material proxies such as Vs30, should be separately evaluated and quantified in terms of the sensitivity of the various nonlinear models to their variations. Necessary parameters in this category include friction angle, cohesion, and generalized modulus reduction and damping curves as a function of Vs30 and of overburden pressure.

Last, the elastic, anelastic and nonlinear parameters should be synthesized in the form of a community model, building upon SCEC's previous experience in the development, for example, of the UCVM software framework. Building a CVM-like model that evolves with time and includes near-surface rock and soil parameters for the simulation of nonlinear site effects should be a long-term commitment by SCEC.

4. Computational Challenges

The above recommendations on the modeling and integration of nonlinear site effects in ground motion simulations pose significant computational challenges, particularly to SCEC physics-based applications. For example, weakening of the near-surface soft soils during strong motion will require adaptive meshing techniques to accommodate the reduced spatiotemporal discretization associated with wave propagation in progressively slower velocity layers.

To address this complexity, multi-step and/or multi-scale simulations techniques could be implemented to separate the near surface analyses from the simulation of the stiffer—and less prone to nonlinear effects—rock basement. An example of this approach is the Domain Reduction Method (DRM) proposed by Bielak et al., (2005), which has been used in ground motion simulations with site effects by Isbiliroglu et al. (2015) among others. This approach would require criteria to decide which computational regions are most likely to experience strong nonlinearity during a given event. Based on a forward viscoelastic simulation, for example, such criteria could be based on the level of simulated maximum strain or on measures typically used to evaluate the susceptibility of geotechnical systems to ground failure such as: number of loading cycles or ground motion duration; estimated strain proxies (e.g., PGV/Vs30); PGA in low Vs30 regions; or ratio between shear stress and effective overburden pressure.

Another approach would be to determine, and accordingly limit, the depth of sediments for which material nonlinearity is important. This is a very key question, not only for computational purposes but also related to the media characterization. The shallower the phenomena are, the better they will be constrained either by in situ or laboratory data. The cost of characterizing nonlinear behavior increases proportionally with the exploration depth.

Of course, the preferred approach to mitigate the computational challenges posed by near-surface material yielding is to be controlled, to a large extent, by the target maximum simulated frequency. While maximum frequencies of about 4 Hz are presently a reasonable target for source to ground surface simulations with nonlinear site effects, and targets of about 8 Hz may seem feasible within the next 5-year period; 25 Hz would be prohibitive in terms of spatiotemporal resolution. It is therefore recommended that SCEC promotes the use of multi-scale and/or multi-physics simulation strategies (the latter in the case of liquefaction) in the future.

5. Verification and Validation

To assess the adequacy of the proposed 1D and 3D nonlinear models compared to the currently employed empirical approximations of nonlinear site effects, and to quantify the tradeoffs between modeling complexity and parametric uncertainty, the SCEC5 science plan should systematically integrate the implementation of these models with the development of a cyber-infrastructure for verification of the simulated ground motions. This infrastructure should be similar to that put in practice by the SCEC Community Modeling Environment (SCEC/CME) group or the SCEC/USGS Spontaneous Rupture Code Verification Project in past efforts (e.g., Day et al., 2001, 2003; Bielak et al., 2010). This effort should be also coordinated with the SCEC Ground Motion Simulation Validation technical activity group to identify metrics that are relevant to the end users of time-series, namely the engineering community.

Validation of the ground motion simulations with nonlinear site effects should also be considered as part of the SCEC5 science plan. Ideally, the validation would take place on three levels: validation of the near surface stratigraphy; validation of the ground surface time series in terms of amplitude, frequency and duration; and validation of the nonlinear material response.

- On the first level, available velocity profiles would be compared to the Vs30-based GTL velocity gradient at the same sites, to ensure that the latter provides a realistic representation of the stratigraphy and the soil-rock interface at depth (to avoid spurious resonances).
- On the second level, simulated ground motions should be compared to observations at sites prone to nonlinear effects (e.g., very soft sites). Emphasis should be given to the metrics of ground motion prediction that are most relevant to the end users of the simulated ground motions, such as peak acceleration and velocity, pseudo-spectral acceleration over a range of oscillator periods, as well as Arias intensity, ground motion duration, and ground rotation. Observations should also be compared with data in the Fourier spectral domain, since this often tests the physical models in frequency bands that are masked by the asymptotic properties of response spectra. Although there exist very few sites in Southern California with recorded motions strongly affected by nonlinear effects, comparison of the recorded data to simulated ground motions at these sites would still provide valuable feedback on the predictive capabilities of the various models, albeit not statistically significant to draw more generalized conclusions.
- On the last validation level, in-situ nonlinear response recorded at downhole arrays (estimated at the midpoint between surface and downhole receiver, if available) should be compared to the computed stress-strain response.

Addressing these validation steps would imply gathering available near-surface velocity profiles and nonlinear soil properties in the region of interest; collecting additional geotechnical and geophysical data, particularly in areas with very soft sediments that are susceptible to large ground deformations; building simulation models where geomaterials are represented at various levels of complexity (see pertinent section above); and quantifying the epistemic and parametric uncertainty of these models, to assess the tradeoffs between modeling complexity and parametric variability of modeling nonlinear site effects in ground motion simulations.

This effort should start with available well-characterized downhole array sites, where the various nonlinear models could be evaluated in 1D, 3-component site response predictions prior to being extended in 3D (e.g. La Cienega geotechnical array, with multiple downhole instruments). Because such a validation goal would be nearly impossible to achieve in 3D on the scale of the Los Angeles basin, it is recommended that SCEC next selects and adopts a sub-region of interest within Southern California—as a *natural laboratory for site effects*—to test the elastic and anelastic soil property characterization in the near surface, and the performance of alternative nonlinear models, their epistemic uncertainty and their modeling variability. This laboratory should be a site that has experienced, or is highly likely to in the future, significant nonlinear effects and permanent ground deformation. Tentative candidates include but are not limited to the San Bernardino basin, the Oxnard plain and Ventura basin, Imperial Valley, Simi Valley, or Garner Valley. These suggestions are either based on prior work by SCEC collaborators and projects, or on their past and expected behavior during strong earthquakes.

Example of an extensive geotechnical and geophysical testing plan at the nonlinear laboratory site would include active (vibroseis) and passive ground motion inversion to reconstruct the 3D geometry, velocity and anelastic attenuation stratigraphy of the subsurface (see Kallivokas et al., 2013 and references therein); in-situ geotechnical testing such as Standard Penetration (SPT) and Cone Penetration tests (e.g., Mayne et al., 2007); and laboratory testing to estimate nonlinear dynamic soil properties (modulus reduction and damping curves via resonant column tests), material strength and compressibility (tri-axial and simple shear tests) and index properties such as plasticity index. Similar efforts have been undertaken by Chaljub et al. (2010) and Regnier et al. (2014) for validation of 3D valley effects and 1D nonlinear site response. Installing surface and possibly downhole instruments would also be recommended, to constraint the elastic and anelastic (low-strain) material parameters, and at the same time, set the infrastructure to capture strong nonlinear site effects in the future.

6. Cybershake: Nonlinear effects & reciprocity

New strategies will need to be developed to incorporate site effects in the development of deterministic hazard simulations (CyberShake). Motivated by the discussions of the Committee for Utilization of Ground Motion Simulations, which took place on May 4, 2015, one possible avenue would be to use a reduced number of physics-based 3D simulations with nonlinear site effects to develop basin-specific nonlinear amplification factors that can be applied to the whole CyberShake simulations ensemble. Contrary to the proposed site amplification factors for the BBP, the Cybershake nonlinear basin amplification factors could be parameterized, for example, as a function of intensity, site, depth to basement, distance to basin edge and azimuth, allowing the phase of the complex factors to capture the organization of body and surface wave arrivals. The selection of the reduced number of simulations to be done in an end-to-end fashion, could be determined based on the disaggregation of event contribution to the final hazard estimates from previous CyberShake runs. This can be coupled with the *small-scale natural laboratory* for nonlinear effects described above, which would serve as a constrained region where to test how to best parameterize the coupled near-surface site and basin effects. Determining whether the effects of near surface nonlinearity translate into significant changes in the long period ground motions dominated by basin edge effects, would be key in deciding whether the latter could be treated as linear amplification factors, uncoupled from the intensity-dependent nonlinear site effects.

While it is unclear at this point how this will be accomplished, it is recognized that developments implemented in the BBP and High-F projects will in time need to be ported into CyberShake in some manner. It is therefore necessary to support research that will help answer the question of how to couple forward site effects simulation with the reciprocity-based approach used by CyberShake.

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APPENDIX

Agenda

09:00	Breakfast	Presenters
09:30	Introductions-Scope of Workshop	Domniki Asimaki (Caltech)
09:40	SCEC's broadband platform (BBP)	Phil Maechling (SCEC)
09:50	BBP ground motions: Verification and Validation against GMPE's	Christine Goulet (PEER)
10:00	1D site response in SCEC ground motion simulations: Present and future	Domniki Asimaki (Caltech)
10:10	Physics-based 3D ground motion simulations: CME High-F and SEISM projects	Ricardo Taborda (UMemphis)
10:20	CyberShake	Tom Jordan (SCEC)
10:30	SCEC Committee for the Utilization of Ground Motion Simulations: Summary of	John Anderson (UNR)
10:45	Break	
11:00	Earthquake Soil Structure Interaction Modeling and Simulation	Boris Jeremic (UC-Davis)
11:20	Numerical Simulations of Seismic Waves in Nonlinear Media	Daniel Roten (UCSD)
11:40	Challenges in Broad-Band Ground Motion Simulations	Arben Pitarka (LLNL)
12:00	Lunch	
13:00	Multiaxial Constitutive and Numerical Modeling in Geomechanics within Critical State Theory	Mahdi Taiebat (UBC)
13:20	Nonlinear Ground Response Analysis: Recent Experiments and Future Directions	Scott Bradenberg (UCLA)
13:40	Recent advances in 3D full-waveform inversion for site characterization - Challenges and open issues	Loukas Kallivokas (UT-Austin)
14:00	3D Numerical SSI Analysis: Some Current Practical Application Challenges and Opportunities	Ahmed Elgamal (UCSD)
14:20	Geophysical Site Characterization at Strong Motion Stations in Southern California	Alan Yong (USGS)
14:45	Break	
15:00	Discussions and short presentations by those interested in sharing 2-3 slides (5 min.) with key questions, challenges and ideas	All Participants
16:30	Adjourn	

Organizers

Domniki Asimaki (Caltech)
Ricardo Taborda (U of Memphis)
John Anderson (UNR)
Jon Stewart (UCLA)

Participants

In person:

John Anderson (UNR)
Pedro Arduino (U Washington)
Domniki Asimaki (Caltech)
Scott Bradenberg (UCLA)
Ahmed Elgamal (UCSD)
Rob Graves (USGS)
Liz Hearn (Capstone Geophysics)*
Tran Huynh (SCEC)
Boris Jeremic (UC Davis)
Tom Jordan (SCEC)
Loukas Kallivokas (UT Austin)
Ting Lin (Marquette)
Phil Maechling (SCEC)
Neven Matasovic (Geo-Logic)
Kim Olsen (SDSU)
Anders Petersson (LLNL)
Arben Pitarka (LLNL)
Arti Rodgers (LLNL)
Daniel Roten (SDSC)
Jon Stewart (UCLA)
Ricardo Taborda (U of Memphis)
Mahdi Taiebat (UBC)
Alan Yong (USGS)

Remotely:

Kioumars Afshari (UCLA)
Jacobo Bielak (CMU)
Fabian Bonilla (IFSTTAR)
Justin Coleman (INL)
Art Frankel (USGS)
Christine Goulet (PEER)
Kien Nguyen (Caltech)
Doriam Restrepo (EAFIT)
Jian Shi (Caltech)
Jamie Steidl (UCSB)

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* Representing the Community Rheology Model group.