2010 SCEC Research Report

A Nonlinear Site Response Computer Application for the SCEC Broadband Ground Motion Simulation Platform

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ABSTRACT

We have developed a computer application that integrates our findings on nonlinear site response into the SCEC Broadband Ground Motion Simulation Platform, thus allowing dissemination of our results to the broader SCEC community. The computational tool was developed in coordination with the SCEC Ground Motion Prediction Focus Group. Within the science objectives of SCEC, the proposed research contributes to the representation of high frequency components for broadband ground motion simulations, the incorporation of nonlinear soil models in ground motion predictions, and the development of physics-based predictive models for engineering applications.

1. INTRODUCTION

The advancements in the representation of dynamic source rupture simulations and the development of detailed 3D crustal velocity and fault system models for seismically active regions have enabled the high spatio-temporal resolution of design-level ground motion predictions through physics-based simulations. Among these efforts, the SCEC broadband platform (http://scec.usc.edu/scecpedia/Broadband_Platform) is a collaborative software development project involving SCEC researchers, graduate students, and the SCEC/CME software development group, with the goal of generating broadband (0-10 Hz) ground motions via deterministic low frequency and stochastic high frequency simulations. As a result, broadband synthetic ground motions may nowadays be used by the engineering community in the aseismic design of civil infrastructure, either supplementing the existing database of recorded ground motions, or providing a more sophisticated method of developing artificial seismograms than alternative methodologies such as stochastic simulation and design spectrum compatible time histories.

Physics-based ground motion simulations for engineering applications require realistic predictions of the so-called high frequency components at the source, propagation of these frequencies through the lithosphere, and interaction of the incident seismic waves at the engineering bedrock with the near-surface soil layers. Specifically for the latter, the recent expansion of international ground motion records databases since the 1990's including –but not limited to- the US, Japan, Europe, Taiwan and Turkey, provide abundance of data to the seismological and engineering communities alike that highlight the significance of the near-surface sediment nonlinearity during strong ground motion (Chin and Aki, 1991; Field et al., 1997; Cramer, 2008); among these recordings, perhaps the most reliable source of information came from downhole arrays. Field and laboratory experiments have shown that nonlinear effects dominate the propagation of seismic waves through the soft soil layers during strong ground motion, and therefore, when high frequency ground motion components (i.e. wavelengths comparable to the thickness of soft soil layers) are simulated as part of seismological model predictions, nonlinear site effects need to be accounted for to ensure accuracy of the ground surface motions. As an example of a recent study, Assimaki et al. (2008) used downhole array recordings in the Los Angeles basin to show that insufficient consideration of nonlinear site effects may cause up to 60% relative error in spectral acceleration prediction.

The spatial and temporal resolution required for the simulation of soil nonlinearity in seismological models, however, implies excessively large computational time and effort. Therefore, efficient integration of nonlinear site response analyses in ground motion models may only be achieved by developing quantitative criteria that will indicate when nonlinear effects are anticipated to be important and need to be accounted for. In the past five years, we have conducted extensive studies funded by SCEC towards the efficient integration of nonlinear site response models into broadband ground motion simulations, The corresponding tools developed -now integrated as a SCEC Broadband Ground Motion Platform component- are reviewed in the following section.

2. NONLINEAR SITE EFFECTS – NEW DEVELOPMENTS vs FIELD OBSERVATIONS

A new site response model (Li and Assimaki, 2010) was developed for nonlinear site response analyses based on the viscoelastic formulation for frequency-independent Q proposed by Liu and Archuleta (2006) and the hysteretic scheme proposed by Muravskii (2005). The model can simulate close to frequency-independent viscous damping in the strain range below the linear threshold, and match the nonlinear dynamic soil properties of soils (G/G_{max} and damping, §) in the intermediate to high strain range ($\gamma > 10^{-3}$). The model was implemented into the 1D site response computational tool "Site1D" for the purpose of this work, and is briefly described in the Appendix of this report.

The low-strain frequency-independent damping feature of the model is approximated by means of generalized Maxwell bodies comprising 8 standard Maxwell elements (denoted as GMB8). The low strain damping behavior of GMB8 is compared with alternative viscous damping models frequently used in geotechnical earthquake engineering in **Figure 1**. The damping variation as a function of strain beyond the elastic range is implemented by the hysteretic concept of Muraviskii (2005). The comparison of the hysteric loop predicted by the Li and Assimaki (2010) model and by the extended Masing criteria (abundantly implemented in 1D site response analyses) is shown in **Figure 2**. Note that narrower hysteretic loop translates in lower damping in the high strain range, a much more realistic representation than the overestimated damping values systematically predicted by extended Masing criteria hysteretic models.

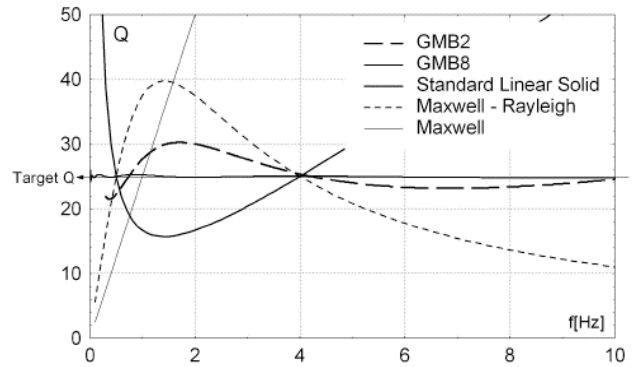

Figure 1 Comparison of the performance of various viscous damping models

The new model was implemented in the computational tool "Site 1D" for integration in the SCEC Broadband Ground Motion Simulation platform. A simplified version of the program user manual is attached in the appendix of this report. Note that a nonlinear time-domain analysis with the Li and Assimaki (2010) model requires exactly the same input parameters as the equivalent linear method, by and large used for site response analyses by the geotechnical engineering research, practice, and seismological communities alike, at the sole expense of increased computational time.

Funded by SCEC, the effectiveness of the Site1D for strong motion site response predictions has been previously evaluated by comparison with recordings at downhole array sites in the Los Angeles Basin (Assimaki et al., 2008). For this purpose, we first collected downhole and suspension logging measurements, and laboratory G/G_{max} and damping (ξ) curves available at these locations. We next estimated the attenuation (Q) and density (ρ) profiles by inversion of low-amplitude seismogram recordings using the waveform inversion algorithm by Assimaki et al (2006). We compiled shear wave velocity (V_s), attenuation (Q) and density profiles (ρ), and used generic G/G_{max} and damping (ξ) curves where site-specific nonlinear properties were not available. We then conducted site response analyses using linear elastic, equivalent linear and multiple nonlinear models and compared the ground surface predictions with the observed time histories. We concluded that the modified hyperbolic constitutive law by Matasovic (1995) coupled with the new hysteretic model described above yielded the minimum average error and this model was implemented in the computational tool for nonlinear site response simulations.

To illustrate the role of site response model selection in earthquake scenario simulations, we compute a series of synthetic motions over a 100 x100km^2 grid of surface stations using 1D crustal profiles from the SCEC CVM IV (http://www.data.scec.org/3Dvelocity, and the hybrid low-/high-frequency dynamic rupture source model by Liu et al (2006). The synthetic motions correspond to strike-slip rupture scenarios of medium to large magnitude events (M_w = 3.5~7.5) at distances R = 2.0~75km. The soil profiles are then subjected to various combinations of seismic excitations to investigate how the selection of different categories of site response models affects the accuracy of ground motion prediction in these scenarios.

For each scenario, we estimate the site response using each of the following: (i) empirical amplification factors multiplying the reference site ground motion; (ii) linear elastic site-specific analyses; and (iii) nonlinear simulations with the new hysteretic model.

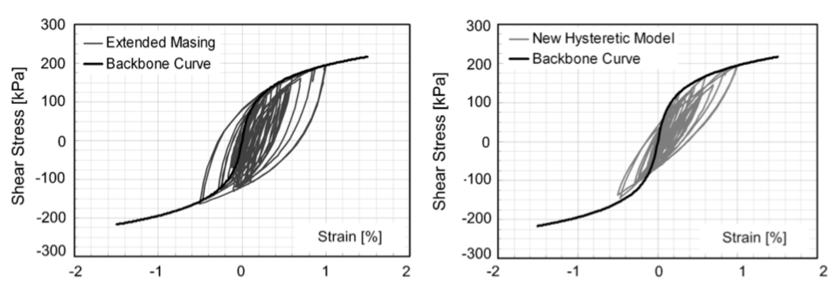

Figure 2 Comparison of hysteretic loops (left) extended Masing rules, and (right) Li & Assimaki (2010) hysteretic model

Overall, our results suggest that nonlinear effects at soil sites are both a function of the soil stratigraphy in the near-surface, and the ground motion characteristics: the site conditions define which layers are susceptible to nonlinear effects, and the ground motion amplitude and frequency determine whether the seismic waves will "see" the soft layers and whether they "carry" adequate energy at the corresponding wavelengths to impose large strains. Based on this concept, we developed in the past a set of quantitative criteria to determine when site-specific analyses should be employed in ground motion simulations (Assimaki et al., 2008). For each site and ground motion scenario, these criteria can be summarized as follows: (i) the rock outcrop peak ground acceleration (PGA_{ROCK}) is used to represent the motion intensity, and (ii) the so-called frequency index (FI) is a dimensionless quantity that describes how aligned the site response peaks are to the incident ground motion frequency content. Note that as FI approaches unity, the amplification potential of a seismic wave incident at a site increases, and if this seismic wave has a high PGA_{ROCK}, the motion will be further amplified causing strong nonlinear effects. **Figure 3** shows the deviation of linear elastic prediction from site-specific nonlinear predictions (denoted as $e_{SA(LIE)}$) as a function of (PGA_{ROCK}, FI) for three sites in the LA Basin: a stiff (Class C), a medium stiff (Class D) and a soft (Class E) site. As can be seen, the trend is the same for all three sites. Large PGA_{ROCK} and FI close to unity imply that empirical amplification factors do not adequately describe the site response, and site-specific analyses should be employed.

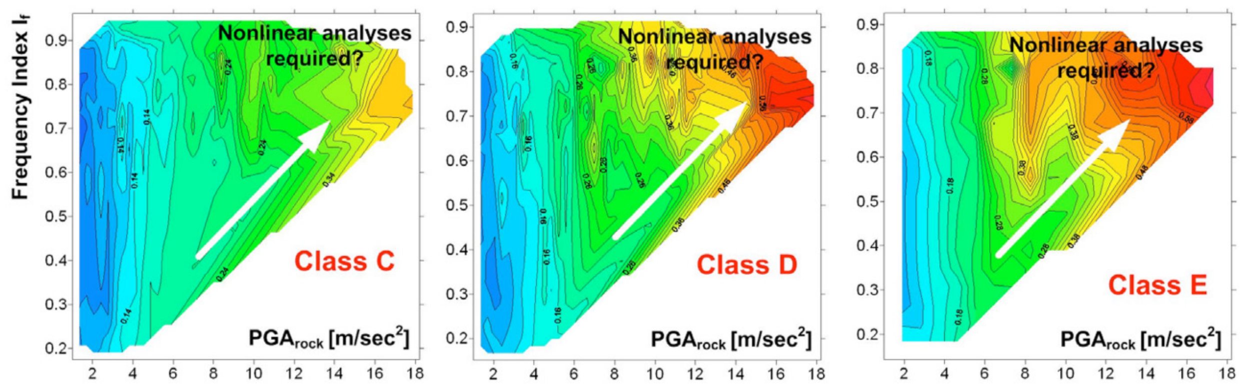

Figure 3. (PGA, FI) criteria implementation at three sites (Class C-E) in the LA basin for a series of broadband ground motion synthetics. The contour plots indicate the deviation of linear elastic predictions from nonlinear site-specific response predictions.

3. GENERALIZED RELATIONSHIP FOR SITE RESPONSE PREDCITIONS

As part of a subsequent proposal funded by SCEC, we quantified the criteria above using explicit regression models for each site, and generalized them to site independent functions that estimate the deviation of predictions from nonlinear analyses by incorporating the site dependency of the regression coefficient. The establishment of the quantitative correlation relation will be described in this section.

Considering the clear PGA_{ROCK} and FI dependency of $e_{SA(LIE)}$ revealed by **Figure 3**, $e_{SA(LIE)}$ can be expressed as a linear function of PGA_{ROCK} and FI, i.e. $e_{SA(LIE)} = a \cdot PGA_{ROCK} + b \cdot FI$, where "a" and "b" are regression coefficient. "a" and "b" are clearly site property dependent, and the two site parameters selected here to express this dependency are V_{S30} and first mode amplification (Amp). The correlation analysis between coefficient "a" and site parameters shows that the V_{S30} dependency of "a" is much stronger than its Amp dependency. Therefore, "a" can be expressed solely as function of V_{S30}. Correlation analysis between coefficient "b" and site parameters shows that the Amp dependency of "b" is slightly higher that its V_{S30} dependency. However, to keep the final formulation of $e_{SA(LIE)}$ as simplified as possible, we still express "b"

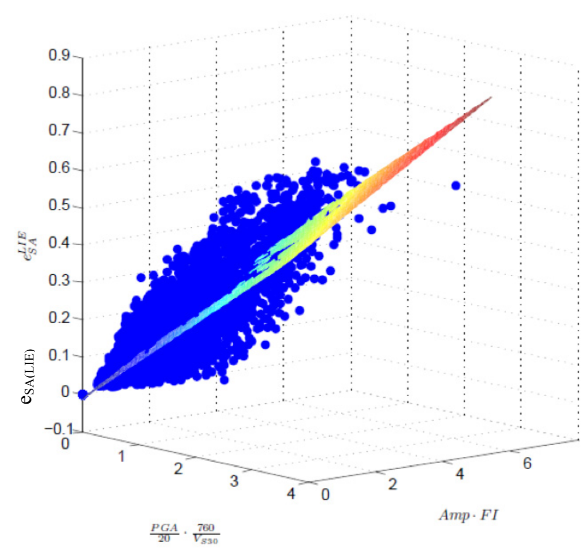

Figure 4 $e_{SA(LIE)}$ as a function of combined site and motion parameters

solely as function of Amp. The consequence of this hypothesis can be seen in the residual-predictors plot. Based on the previous discussion, the final formulation of $e_{SA(LIE)}$ can be expressed as: $e_{SA(LIE)} = \alpha \cdot (760 / V_{S30}) \cdot (PGA_{ROCK} / 20) + \beta \cdot Amp \cdot FI + \varepsilon$; where α and β are regression coefficients and ε is the residual, assumed to be normally distributed. Note that the unit of V_{S30} is [m/sec] and the unit of PGA_{ROCK} is [m/sec^2]. The relation between $e_{SA(LIE)}$ and site-motion parameters is depicted in **Figure 4.**

As can be seen, the residual ε is independent of both regression terms. The mean of residual is zero and the variance is assumed to be constant. It should be noted here that the linear response divergence from the nonlinear prediction, $e_{SA(LIE)}$, was defined above as the averaged error within the period interval [0.2 - 2.0sec]. Since this quantity is clearly period dependent, we also investigate the dependency of the divergence for a particular period. For this purpose, we use the same procedure to establish the relation between $e_{SA(LIE)}$ for and the site and ground motion parameters period T_i. **Table 1** summarizes the values of the regression coefficients α; β and the standard deviation of residual (denoted as σ) for representative periods of interest in earthquake engineering. In summary, the $e_{SA(LIE)}$ give an a priori estimation of level of divergence of linear ground motion prediction from nonlinear prediction, and can be used to determine whether nonlinear site response should be employed for given motion and site conditions before actual site response analysis.

Table 1 Regression coefficients in the final formation of $e_{SA(LIE)}$ for different periods

T	α	β	σ
[0.2 - 2.0]	0.1342	0.0587	0.0442
0.0	0.1878	0.0517	0.0689
0.2	0.1517	0.0591	0.0712
0.5	0.1505	0.0752	0.0777
1.0	0.0817	0.0406	0.0534

4. SIMPLIFIED ESTIMATION OF SITE AND GROUND MOTION PARAMETERS

While the parameters described in the previous section are shown to correlate well with the intensity of nonlinear effects at the sites investigated, the estimation of frequency index FI and first mode site amplification Amp requires detailed velocity and damping profiles, which may not be available for large scale seismological models or for implementation in engineering practice. As a result, a simplified procedure is necessary to estimate these parameters using the minimal available information at the site. Dobry et al. (2000) introduced the following empirical equation for the estimation of the first mode amplification (Amp): $Amp = 1 / (1 / I + \pi / 2 \cdot \xi)$, in which "I" is rock/soil impedance ratio and ξ is the soil damping ratio. Assuming $IC = V_{S100} / V_{S30}$ (V_{S100} corresponds to the shear wave velocity at depth of 100 m) and $\xi = 0.05$, Amp can be estimated using the above empirical relation. The comparison between the value of Amp extracted from the transfer function and Amp from the empirical relationship by Dobry et al. (2000) is shown in **figure 5**. It can be seen that the empirical equation yields a very good approximation of Amp for a wide range of impedance ratios.

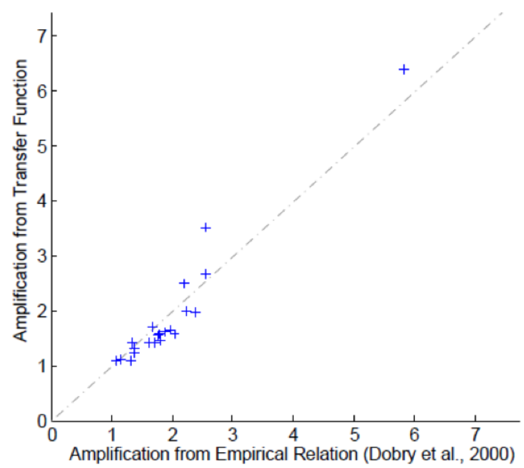

Figure 5 Comparison of Amp from empirical relation and Amp from calculated transfer function

For the approximate estimation of the frequency index, given the estimate of Amp above, the fundamental frequency of the site could be estimated using the H/V spectral ratio technique (Theodulidis et al., 1996). Admittedly, three-component ground motion records or ambient noise measurements are more widely available than detailed geotechnical information at soft sites. Successively, combining Amp with the fundamental frequency estimated via H/V, one can obtain an approximation of the transfer function at first mode, which can be next used to calculate the frequency index FI at the site for a given motion.

5. FUTURE WORK

The nonlinear model described above has been prepared for integration into the SCEC broadband platform, along with examples of implementation, validation and recommendations on the material input selection. We envision the criteria described above to be implemented in the neat future as part of an automated selection of site response analysis model for large scale simulations. Such incorporation is pending the following verifications: (a) the proposed criteria were established primarily through simulated ground motions and they require verification against independent data set of soil profiles and ground motions, ideally downhole array observations. The unprecedented volume of data from the 2011 M9.0 Japan earthquake will provide an ideal test bed for validation studies in nonlinear site response, among multitude other areas of seismology and earthquake engineering.

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APPENDIX

User Manual of Program Site1D

Program name:
Site1D

Software dependencies:
The source code compiled using Intel FORTRAN compiler. The compiled executable file tested in windows XP professional SP3.

Executable name:
Site1D.exe

Compilation Command:

```
ifort -o Site1D site1D.f90
```

Example how to call the program
"Site1D MasterInputFile" or "Site1D".
If no argument specified, the default file name of master input file should be "control.dat"

List of all required input files

name	dimension	description
'control.dat' or user-specified	n/a	Set parameters or files
User-specified	(nlayer+1) by 5	Site profile
User-specified	N_obs by (n_ma*4)	Soil parameters, i.e. Modulus reduction and material damping
User-specified	nt_out by 2	Input motion

Refer to master input file for meaning of variables

Master input file consists of a FORTRAN namelist with group name CONTROL, the list of variables shown as follows:

name	Type	description
f_max	real	Maximum frequency modeled, unit is Hz
ppw	integer	Point per wavelength
ndt	integer	Number of sub-steps in one time step
boundary	string	Boundary condition, can be 'elastic', 'rigid', or 'borehole'
nlayer	integer	Number of soil layers, not including bedrock
nt_out	integer	Number of input or output time steps
n_ma	integer	Number of material
N_obs	integer	Number of points in modulus reduction of damping curve

file_prof	string	Name of site profile file
file_soil	string	Name of modulus reduction and damping file
file_motion	string	Name of input motion file

Site profile contains a (nlayer+1) by 5 array.
1st column: thickness of layer with unit of meter.
2nd column: shear wave velocity with unit of m/sec.
3rd column: material damping ratio with unit of 1.
4th column: mass density with unit of 10^3 kg/m^3
5th column: material number

Soil parameter file contains an N_obs by (n_ma*4) array. Every four columns correspond to one material. For each material:
1st column: strain series with unit of %
2nd column: modulus reduction or G/Gmax corresponding to strain in column 1
3rd column: strain series with unit of %
4th column, material damping ratio corresponding to strain in column 3

Input motion file contains an nt_out by 2 array
1st column: time series with unit of sec, should have evenly distributed time step
2nd column: acceleration time history with unit of cm/sec^2

List of all output files

name	dimension	description	Unit
't.dat'	nt_out by 1	Time series	sec
'layer_depth.dat'	1 by nlayer	Depth of center of each layer	meter
'node_depth.dat'	1 by (nlayer+1)	Depth of each node	meter
max_v.dat	1 by (nlayer+1)	Maximum velocity of each node	meter/sec
max_d.dat	1 by (nlayer+1)	Maximum displacement of each node	meter
max_gamma.dat	1 by nlayer	Maximum strain of each layer	1
max_tau.dat	1 by nlayer	Maximum stress of each layer	Pa
out_a.dat	nt_out by (nlayer+1)	Acceleration time history of each node	m/sec^2
out_v.dat	nt_out by (nlayer+1)	Velocity time history of each node	m/sec
out_d.dat	nt_out by (nlayer+1)	Displacement time history of each node	meter
out_gamma.dat	nt_out by nlayer	Strain time history of each layer	1
out_tau.dat	nt_out by nlayer	Stress time history of each layer	Pa
para.dat	6 by n_ma	Model parameters of each material	1
Refer to master input file for meaning of variables			