Development of a numerical nonlinear soil module to expand the capabilities of the SCEC BroadBand Platform

Project 1803

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Abstract

Numerical modeling of seismic wave propagation in inelastic soils is an important task in seismic hazard studies. Taking into account inelastic soil behavior is difficult and demands special attention. In this project, we use a rheological constitutive model that requires a small number of material parameters to capture stiffness degradation and can be calibrated using laboratory or in-situ tests. The model is implemented in a 1D-3C soil column developed using existing finite element libraries. The site response tool is integrated into the SCEC Broad Band Platform. In this phase of the project all necessary computational tools were implemented and basic verification analyses were completed.

1 Introduction

Propagation of seismic waves in soils is a complex phenomenon that requires advanced models to capture the response of harder geological units and advanced material models to represent the inelastic response of the upper soft soil layers. Extensive work has been – and continues to be – carried out in the development and validation of numerical tools for the simulation of synthetic motions in hard geological units; including different rupture generation models and high-and-low frequency seismogram generation. Full utilization of such tools by the broader earthquake engineering community is not possible unless their capabilities are extended to include wave propagation in soft inelastic soil layers. This requires the use of finite element/difference platforms featuring advanced constitutive models to represent the wave propagation in inelastic soils and coupling of these modules to existing broadband earthquake generation tools. In this context, this project aims to extend the capabilities of the SCEC Broad Band Platform (BBP) (Goulet et al. [2015]) to include the nonlinear response of soft soil layers near the surface. For this purpose, BBP is coupled with a finite element (FE) tool that incorporates robust nonlinear constitutive models for soils (OpenSees [2007]). Existing OpenSees FE libraries are used to represent the soft soil layers, and the Borja-Amies bounding surface constitutive model is used to represent the inelastic/hysteretic behavior of surface soils (Borja and Amies [1994]). The model is based on sound mechanics principles, and is well described mathematically and algorithmically. The required model parameters can be calibrated using field or laboratory data, as well as empirical relations that are deemed to have sound physical meanings both for engineers and seismologists (Zhang et al. [2017]). The resulting finite element soil column is added to the BBP workflow and an option is included into its standard operation mode allowing the user to perform a nonlinear analysis with minimal additional input data.

This project adheres to the initiative for a Technical Activity Group to coordinate SCEC research on nonlinear shallow crust effects and complements project 18020 by Asimaki et al., which aims to use the same constitutive model in the Hercules numerical platform.

2 Research tasks

During this phase of the project the research group concentrated on three tasks as described below:

- Implementation of constitutive model. The J2 bounding surface constitutive model proposed by Borja and Amies (Borja and Amies [1994]) is chosen due to its simplicity and robustness. The research team has experience using this model and early in the project a series of implementations existed in C++, fortran, MATLAB and Python. The main objective of this task is to evaluate the capabilities of the model to capture shear stiffness degradation with shear strain (i.e., G_i/G curves) and shear strength, s_u.

- Implementation of a 1D-3C finite element soil column. To resolve the wave equation in the nonlinear regime the constitutive model is implemented into a finite element platform capable of solving nonlinear systems of equations and a customized 1D model for a vertically propagating wave was created. The OpenSees framework OpenSees [2007] is chosen due to its flexibility and possibility to couple with BBP.

- Development of a coupling interface between the FE soil column and BBP. This coupling requires the development of appropriate application interfaces between these two disparate tools. For this purpose a hybrid approach is used to combine rock motions computed with BBP and and the nonlinear soil column model.

3 Soil Constitutive model

Taking into account the inelastic behavior of soils is a difficult task with dozens of rheological models available; ranging from simple to complex, and needing few or dozens of parameters to describe the nonlinear soil behavior. Furthermore, there is a lack of validated constitutive models to address soil nonlinearity and stiffness degradation in 3D. Indeed, most existing soil models have been created to perform site-specific studies. In this project, we are interested in ground motion computation at a regional scale. In this sense, we need to use rheological models that are robust enough and uses a minimum number of parameters describing soil inelasticiy, either from laboratory or in-situ tests as well as published data in the literature. This is the case for the Borja and Amies (Borja and Amies [1994]) model. Additionally, the question of validation of the simulated ground motion arises. Current practice compares the computed response spectra with observed data. Response spectra do not give information on the development of nonlinearity. In this context, once completed this phase, we need to investigate time histories, e.g., using non-stationary time-frequency analyses (i.e. Bonilla et al. [2011]). In this sense, there is also a need to investigate if the computational tools capture the physics of what is observed on real data.

The Borja and Amies model is a J2 model with nonlinear kinematic hardening. Kinematic hardening is accounted for using conventional bounding surface concepts which for the undrained case and an infinitely small yield locus, reduce to a state of stress moving inside a bounding surface described by a circle of radius, R in a deviatoric space. This is schematically shown in Figure 1. This substantially simplifies the model formulation, benefits robust implementations, and allows to investigate different function to represent kinematic hardening. In this context, it is common to use exponential hardening functions, H, of the form

$$H = h\kappa^m \tag{1}$$

where h and m are material parameters, and κ maps the current deviatoric stress $\boldsymbol{\sigma}'$ to an image deviatoric stress $\hat{\boldsymbol{\sigma}}'$ on the bounding surface defined by

$$\hat{\boldsymbol{\sigma}}' = \boldsymbol{\sigma}' + \kappa(\boldsymbol{\sigma}' - \boldsymbol{\sigma}'_o) \tag{2}$$

and is schematically shown in Figure 1(a).
Most importantly, these concepts result in a deviatoric stress increment that is in the same direction as the deviatoric strain increment, i.e., $\Delta\boldsymbol{\sigma}' = \psi\Delta\boldsymbol{\epsilon}'$. Operating, a simple algorithmic expression emerges for the updated state of stress,

$$\boldsymbol{\sigma}_{n+1} = \boldsymbol{\sigma}_n + Ktr(\Delta\boldsymbol{\epsilon})1 + \psi\Delta\boldsymbol{\epsilon}', \tag{3}$$

where ψ can be obtained by solving a 2×2 system of nonlinear equations that ensures the new state of stress satisfies Equation: 2 and remains inside the bounding surface. That is,

$$\psi + 3G\psi\frac{1}{H} = 2G, \tag{4}$$

and

$$R = ||\boldsymbol{\sigma}' + \psi\Delta\boldsymbol{\epsilon}' + \kappa_{n+1}(\boldsymbol{\sigma}' + \psi\Delta\boldsymbol{\epsilon}' - \boldsymbol{\sigma}'_0||. \tag{5}$$

Moreover, performing a few additional steps a close form expression for the stiffness degradation G_i/G can be obtained of the form,

$$(G/G_i)^{-1} = 1 + \frac{3G}{2h\sigma_i}\int_{-\sigma_i}^{\sigma_i}\left(\frac{\xi}{R + \sigma_i - \xi}\right)^m d\xi, \tag{6}$$

which can be used to calibrate/optimize the parameters h and m to capture experimental or empirical shear modulus degradation curves (e.g. Darendeli [2001] and Menq [2003]). Figure 1(b) and (c) shows typical stress-strain loops for a cyclic simple shear test and the backbone modulus degradation curve for a material with $h = 0.1Su$, $m = 1$, and $s_u = 0.6MPa$.

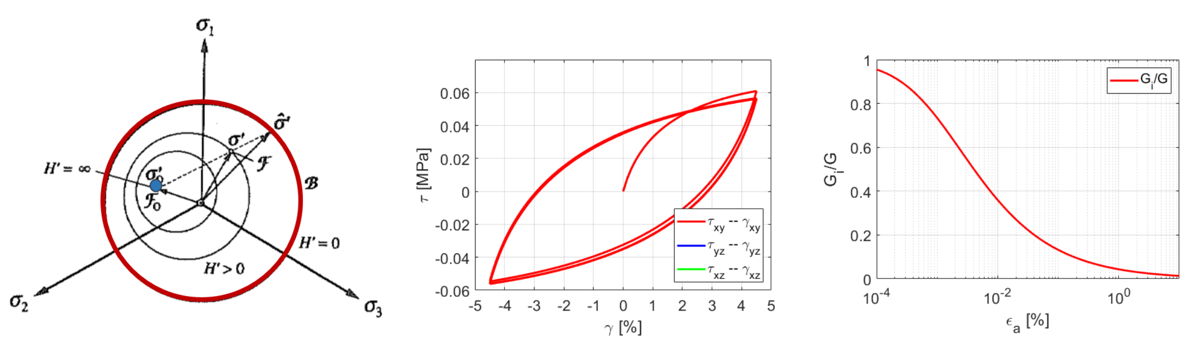

Figure 1: (a) J2 Bounding surface model in deviatoric space, (b) shear stress-strain hysteresis loops, (c) G_i/G stiffness degradation curve

4 1D-3C Finite element soil column

In this project the wave propagation problem is resolved using a one dimensional - three-computation (1D-3C) finite element (FE) soil column. The OpenSees FE framework is used for this purpose (OpenSees [2007]). OpenSees offers a flexible framework more suited for this project than other FE tools. In this context, OpenSees includes TCL and Phyton distributions, as well as, a complete set of static and dynamic libraries that can be linked to c++ codes. For this particular project two approaches were selected to define the soil column: i) a TCL script that encapsulates the complete inelastic wave propagation problem and is run from the OpenSees command line, and ii) an independent FE soil column tool using OpenSees libraries that can be called from any platform, independent of TCL or Python, and does not require the OpenSees command line. Both approaches require minimal (and identical) input parameters to define each soil layer. This data includes layer thickness, soil density, shear wave velocity and the two input parameters h and m defining G_i/G curves (see Table 1).

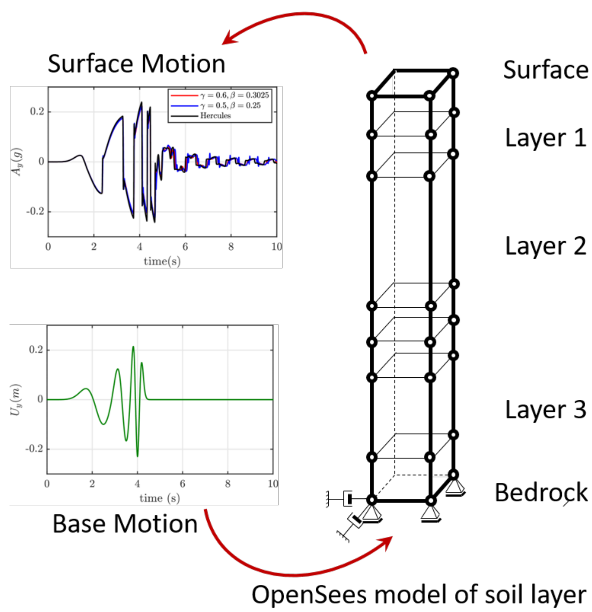

Figure 2: 1D-3C OpenSees finite element mesh and simulation results for simple wavelet signal

Figure 2 shows an schematic of the soil column. The FE model uses stabilized single Gauss point 3D quadrilateral elements (McGann et al. [2015]), referred as *sspBrick*, to represent the layers and the Borja and Amies J2Bounding model to represent the soil nonlinearity. During model generation the element size is automatically defined based on shear wave velocity and a minimum requirement of eight points to resolve the smallest wave length. Nodes at each elevation are slaved in the horizontal direction to capture the $1D$ propagation condition. Rock compliance is defined in terms of Lysmer dashpots in three directions defined in terms of rock shear and volumetric wave velocities and rock density. The input acceleration is transformed into a force time history that is applied between the rock dashpot and soil column. A 2% Rayleigh damping is added between the 1^{st} column natural period, T_n, and 5 times this value to account for small strain damping. Solvers, constraint handlers, and recorders are specified to maximize efficiency and accuracy. The input data format for both tools is identical and was designed to accommodate automatic generation of general soil profiles based on Vs_{30} and empirically based G_i/G curves like

Darendelli (e.g. Darendeli [2001] and Menq [2003]). Table 1 shows an example of the layer data that is required to perform the nonlinear analysis.

Table 1: Site layering input data

LayerName	Thickness	V_s	V_p	ρ_s	s_u	h	m
Clay1	2.0	98.78	184.79	2.05	200.0	1.0	1.0
Clay2	6.0	100.76	188.50	1.97	200.0	1.0	1.0
...	...	...	...	...	...	...	...
Rock	0.0	1000.0	3000.0	2.50	0.0	0.0	0.0

5 Soil column coupling with SCEC BBP

As indicated above the main objective of this project is to improve the SCEC BBP capabilities to include nonlinear response of surficial soils. This implies making changes to the existing BBP standard workflow. To accommodate the needs of different audiences, or user groups, two approaches were used. The first approach consists of creating a .bash script that runs outside BBP and executes BBP, modifies the output motions, runs OpenSees and performs pos-processing tasks using python scripts. The second, and more involved approach, consists of running the nonlinear FE analysis from within BBP. For this purpose the BBP tool was modified to accommodate new functionality including running nonlinear soil column analyses and pos-processing results. For this purpose it was necessary to understand the BBP workflow logic. Figure 3 (a) and (b) shows workflows for both approaches. Source codes and examples files for both cases are available at `https://github.com/UWGeotech/bbpUW`.

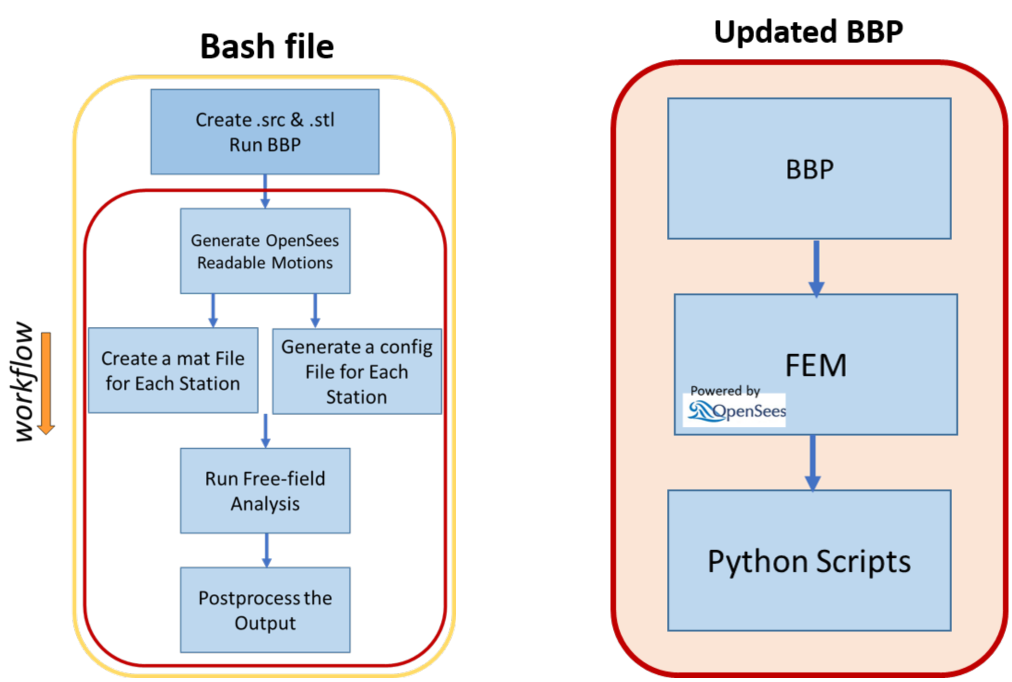

Figure 3: (a) workflow for BBP .bash script, (b) workflow for updated BBP tool

6 Conclusions and future work

An updated BBP tool was developed expanding the capabilities of SCEC BBP to include inelasticity in wave propagation analyses. For this purpose a robust 3D constitutive model was implemented in the OpenSees framework. The selected constitutive model provides enough functionality to represent the nonlinear response of soils during cyclic loads and G_i/G degradation curves. An OpenSees soil column FE tool was developed to improve efficiency maintaining accuracy. Basic validation studies were completed and results compared with equivalent simulations performed using the same constitutive model implemented in Hercules. A complete verification and validation study is required and it is planned for the next phase of this project. For this purpose general soil profiles based on Vs_{30} and automatic generation of G_i/G degradation curves will be used to expedite the analysis process.

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