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A Brief Overview of the NEESgrid Simulation Platform OpenSees: Application to the Soil–Foundation–Structure Interaction Problems

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Presented here is an overview of our recent work in the area of soil–structure interaction. The overview is centered around NEESgrid simulation platform OpenSees. In particular described are simulation tools available for soil–foundation–structure (SFS) interaction analysis. Illustration of available tools is described through examples related to the widely accepted idea (or ideal) that the SFS interaction is beneficial to the behavior of the structural system under earthquake loading. The beneficial role of SFS interaction has been essentially turned into dogma for many structural engineers. For Example the NEHRP-94 seismic code states that: *”These [seismic] forces therefore can be evaluated conservatively without the adjustments recommended in Sec. 2.5 [i.e. for SFS interaction effects]”*. Even though design spectra are derived on a conservative basis, and the above statement may hold for a large class of structures, there are case histories that show that the perceived role of SFS interaction is an over–simplification and may lead to unsafe design.

OpenSees: the NEESgrid Simulation Platform

Motivation

There exists a need of the structural/geotechnical engineers for a set of simulation tools to be used in assessing future performance of infrastructure (bridges, buildings, port structures, dams...). The tools need to be hierarchical in nature, from very simplistic ones, usually used in initial phases of the design, to very sophisticated ones that are used to assess performance

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of structures during extreme loads. This set of hierarchical models will exist concurrently with the physical system they represent. Moreover, available models (of different sophistication) will provide designers, owners and operators with the capability to assess future performance. This seems to be very important as it will empower designers, owners and operators to make educated decisions on the current state or future performance of structures. The hierarchical set of models should be able to foretell the state of the structure (deformations, safety, limit loads...) for both service and extreme loads. In addition to that, the observed performance can (and should) be used to update and validate models through simulations. This additional benefit of being able to validate models goes along well with a much wider goal of verification and validation of the developed simulations tools (c.f. [8] and [9]).

In this paper, a brief overview of some of the tools available in the OpenSees NEESgrid computational platform is presented. The described tools are mostly developed and implemented by the UC Davis Computational Geomechanics group. The descriptions are fairly brief in nature and references to relevant published work are provided for the more interested readers. Interested readers are also welcome to visit the author's web site which features links to related projects and publications (http://sokocalo.engr.ucdavis.edu/˜ jeremic/)

Template Elasto–Plasticity

The standard incremental theory of elasto–plasticity was used to develop and implement a template constitutive driver. The separation of elastic models, yield function, plastic flow directions and evolution laws (hardening and/or softening) was achieved using the object oriented paradigm. The implementation into OpenSees finite element platform allows use of existing and development of new elasto–plastic material models by simply combining yield functions, plastic flow directions (or plastic potential functions) and evolution laws into a working elastic–plastic models. Examples of such combinations (and more details on the approach) are given in a recent paper [6].

The next few examples show various capabilities (from very simplistic to sophisticated ones) of the approach. One of the simplest models to be tried first is obtained by combining Drucker–Prager yield surface, Drucker–Prager flow directions and the perfectly plastic hardening rule. Figures 1 shows results from a monotonic triaxial loading on one such sample. As expected the load displacement response is bilinear. The volumetric response is at first compressive (within the elastic limits) and then becomes dilative when the material becomes elastic–plastic.

Figure 2 shows results for cyclic triaxial loading of a normally consolidated sand specimen using the Manzari and Dafalias ([7]) elastic–plastic material model. The load displacement curve shows near saturation after few cycles while the volumetric response is compressive.

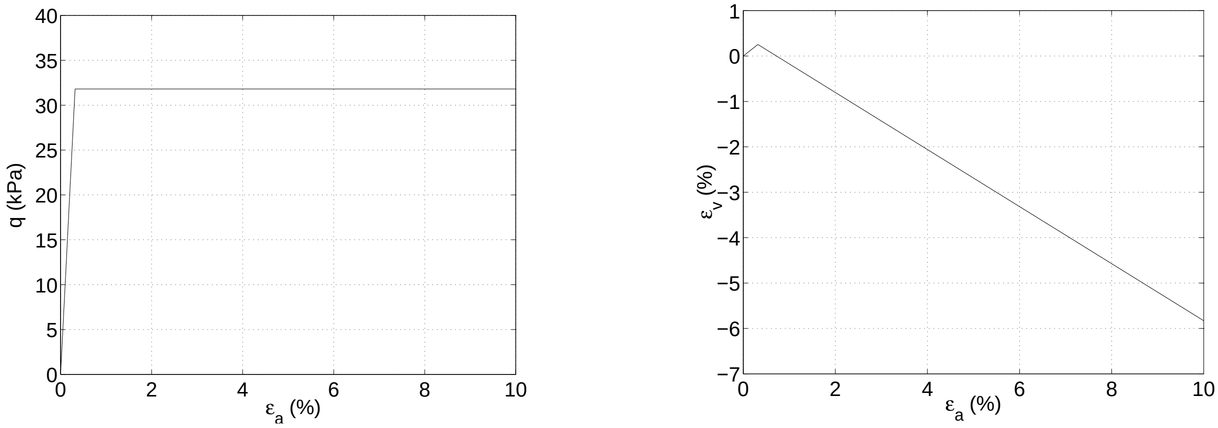


Figure 1: Monotonic triaxial loading on a soil sample modeled using Drucker-Prager yield surface, Drucker-Prager flow direction, perfectly plastic hardening rule.

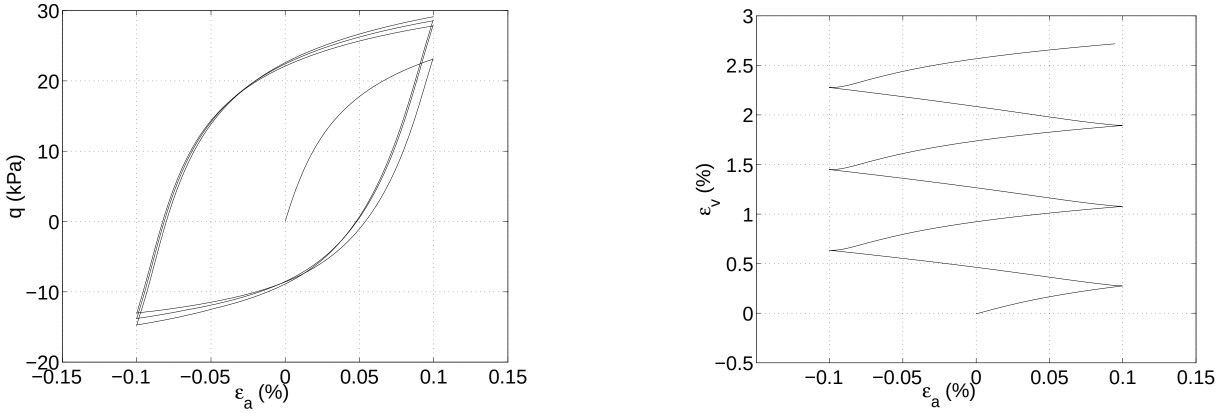


Figure 2: Cyclic triaxial loading results for normally consolidated soil sample modeled using Drucker-Prager yield surface, Manzari-Dafalias flow direction, bounding surface hardening rule.

Full Coupling of Solid and Fluid

The full coupling of solid and fluid in computational geomechanics is a necessary part of the computational formulation if one expects to obtain realistic results. This is particularly important for problems involving soil structure interaction, where a stiff structure interacts with soft soil (that might become even softer after the buildup of pore pressure and the reduction of effective stresses). A formulation originally proposed in [16] is used as a basis. Few changes and improvements are described in some more details in [5]. It proves beneficial to treat the problem using mixed unknown field consisting of $\bar{u}_{Lj} \rightarrow$ solid displacements $\bar{p}_L \rightarrow$ fluid pressures $\bar{U}_{Lj} \rightarrow$ fluid displacements. After finite element discretization of the governing equations, one obtains the following system of equations that needs to be solved using some time stepping scheme:

$$\begin{bmatrix} (M_s)_{KijL} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & (M_f)_{KijL} \end{bmatrix} \begin{bmatrix} \ddot{\bar{u}}_{Lj} \\ \ddot{\bar{p}}_L \\ \ddot{\bar{U}}_{Lj} \end{bmatrix} + \begin{bmatrix} (C_1)_{KijL} & 0 & -(C_2)_{KijL} \\ 0 & 0 & 0 \\ -(C_2)_{LjiK} & 0 & (C_3)_{KijL} \end{bmatrix} \begin{bmatrix} \dot{\bar{u}}_{Lj} \\ \dot{\bar{p}}_L \\ \dot{\bar{U}}_{Lj} \end{bmatrix}$$
$$+ \begin{bmatrix} (K^{EP})_{KijL} & -(G_1)_{KiL} & 0 \\ -(G_1)_{LjK} & -(P)_{KL} & -(G_2)_{LjK} \\ 0 & -(G_2)_{KiL} & 0 \end{bmatrix} \begin{bmatrix} \bar{u}_{Lj} \\ \bar{p}_L \\ \bar{U}_{Lj} \end{bmatrix} = \begin{bmatrix} (\bar{f}_s)_{Ki} \\ 0 \\ (\bar{f}_f)_{Ki} \end{bmatrix}$$

It is interesting to note that damping terms for this coupled system are only present if the subtensor $(C_1)_{KijL} = (C_2)_{KijL} = (C_3)_{KijL}$ are present, and that is the case only if the fluid displaces relative to the solid, as shown in the equation below:

$$(C_1)_{KijL} = (C_2)_{KijL} = (C_3)_{KijL} = \int_\Omega N_K^{u,U} n^2 k_{ij}^{-1} N_L^{u,U} d\Omega$$

The consequence is that the basic energy dissipating mechanism in geomaterials are stemming from either (a) inelastic deformation or (b) from coupling of the fluid (can also be air) and the solid matrix.

Simulation of coupled problems, like wave propagation in fully saturated soils, are challenging, yet of great practical significance. For example, Figure 3 shows results of viscous coupling for a vertically propagating wave in fully saturated porous medium (saturated soil) for different values of permeability. It is obvious that the permeability will greatly affect the response (given in terms of soil displacements, pore fluid pressures and fluid displacements).

Single Pile in Layered Soils

Numerical modeling of behavior or piles in layered soils has not received much attention due to the large computational and modeling efforts required. The problem is quite interesting and of great practical importance as soils are mostly layered, particularly close to bodies of water, where piles are used. As an example, figure 4 shows moment, shear force and pressure (c.f [12, 14]). Pressure here relates to the integral of all the forces acting on a pile, and it has dimension force per length. In particular, the first set of figures, shows results for a pile with a sand layer sandwiched between two soft clay layers, while the other set of figures shows results for a pile in layers of sand–clay–sand. The effects of soft layers (clay) on stiff layers (sand) are obvious.

Pile Group Simulations

In addition to modeling of single piles, pile groups pose some significant simulations challenges. Both the computational and modeling aspects need to be tackled, but the benefit of simulation

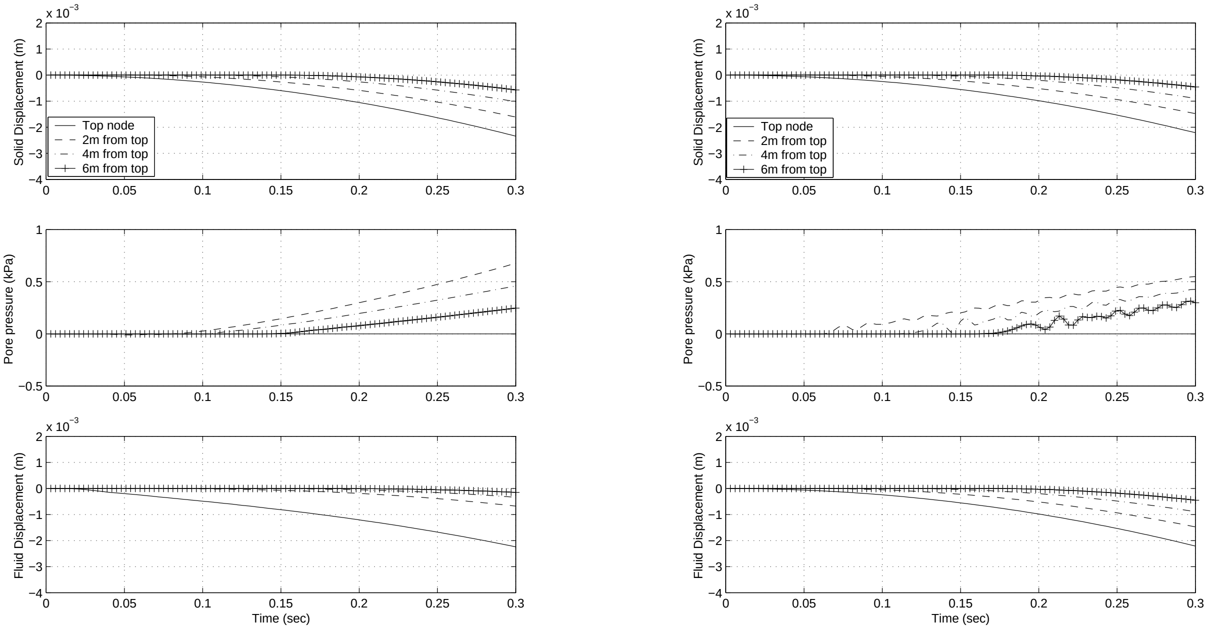


Figure 3: Viscous coupling for a vertically propagating wave in two soils with different permeability, left soil has $k = 10^{-3} m/s$ while the one of the right has $k = 10^{-5} m/s$.

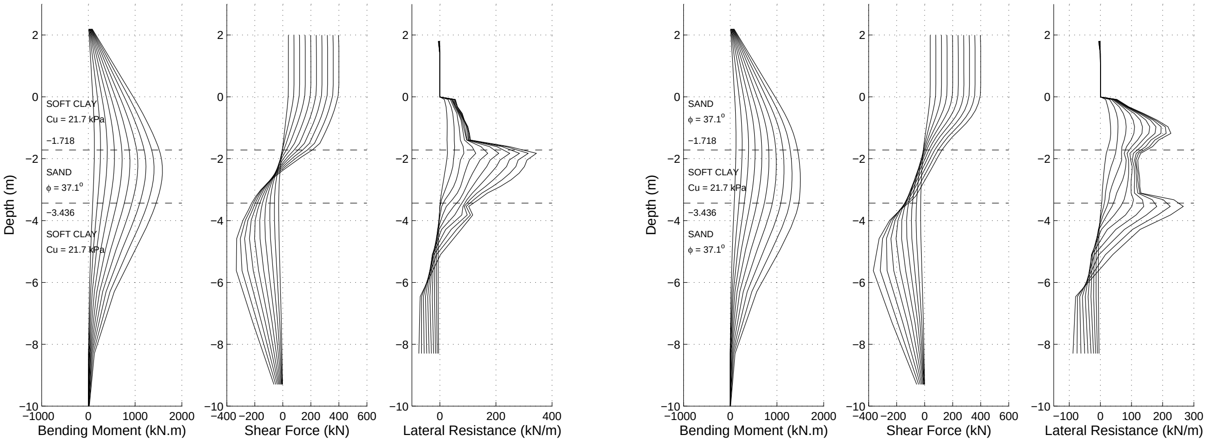


Figure 4: Moment, shear force and pressure for a single pile in layered soils, left figures, clay–sand–clay layers, right figures, sand–clay–sand layers.

results to practical problems can be significant. For example, Figure 5 shows the numerically generated interaction P-Y curves for piles in a 4x3 pile group (c.f [13]). It is obvious from this picture that one cannot simply scale back the single pile load deformation response to analyze pile groups.

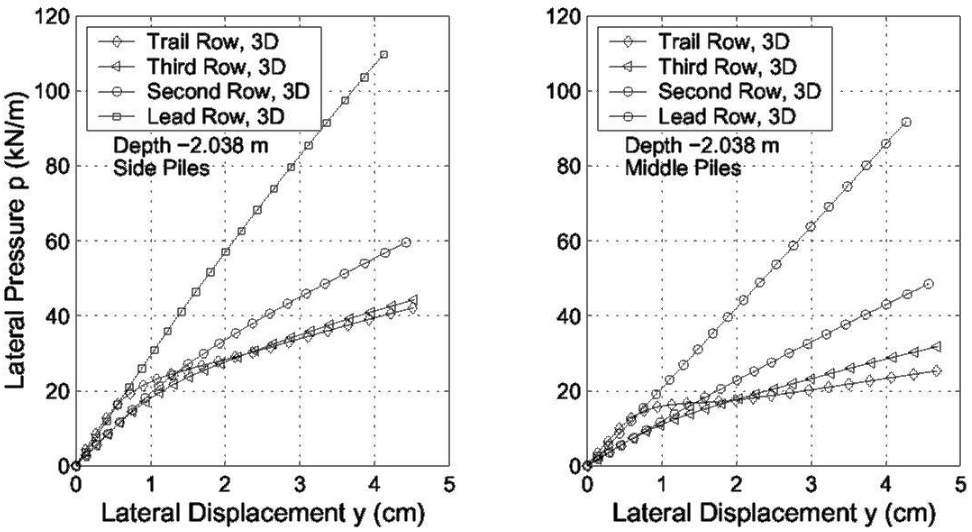


Figure 5: Load displacement interaction diagrams for piles in a pile group.

Dynamic SFS Interaction Modeling

One of the basis for seismic analysis of soil–foundation–structure (SFS) system is appropriate formulation and implementation. The finite size of finite element models introduces many problems, including the input of seismic motions, trapping of wave energy in the finite size model to list just a few. The recently developed Domain Reduction Method (DRM) for elastic problems [2, 15] is used and adapted for SFS interaction problems. One of the best features of the DRM is that in addition to being applicable to elastic problems, close inspection of the formulation shows that it can be applied to inelastic problems as well. Formulation and implementation details are given in [4]. Figure 6 shows the application of the DRM to SFS problems. The seismic wave field (free field) obtained using some of the available methods, including closed form solutions (Green's functions or large scale geophysical simulations), are used to provide input for the DRM. The input requires displacements and accelerations on a single layer of elements that completely encompasses the inelastic domain with the SFS system. The effective forces that are used to load the system are then

$$\left\{ \begin{array}{c} P_i^{eff} \\ P_b^{eff} \\ P_e^{eff} \end{array} \right\} = \left\{ \begin{array}{c} 0 \\ -M_{be}^{\Omega+} \ddot{u}_e^0 - K_{be}^{\Omega+} u_e^0 \\ M_{eb}^{\Omega+} \ddot{u}_b^0 + K_{eb}^{\Omega+} u_b^0 \end{array} \right\}$$

Seismic amplification of local, soft soil sites has been reported many times, yet robust and accurate 3D simulation techniques have not been fully developed to help analyze SFS interaction problems. For example, Figure 7, obtained by using our DRM implementation in OpenSees,

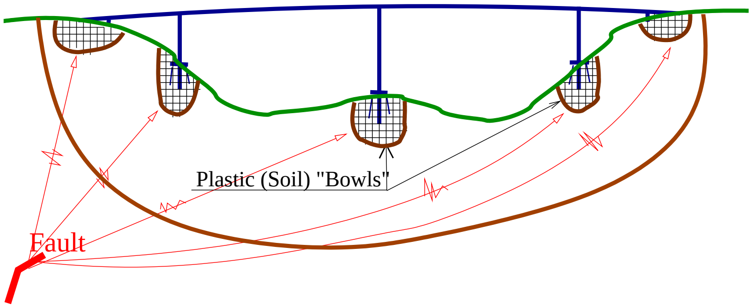


Figure 6: Seismic SFS interaction using large scale geophysical wave propagation and the DRM (soil islands) to assess the behavior of a bridge during an earthquake.

shows vertical wave propagation through stiff (dense sand) and soft (soft clay) soils subject to the same earthquake. The result shows that the soft soil site has an increase in surface deformation of 3.5 times than that one of the stiff site.

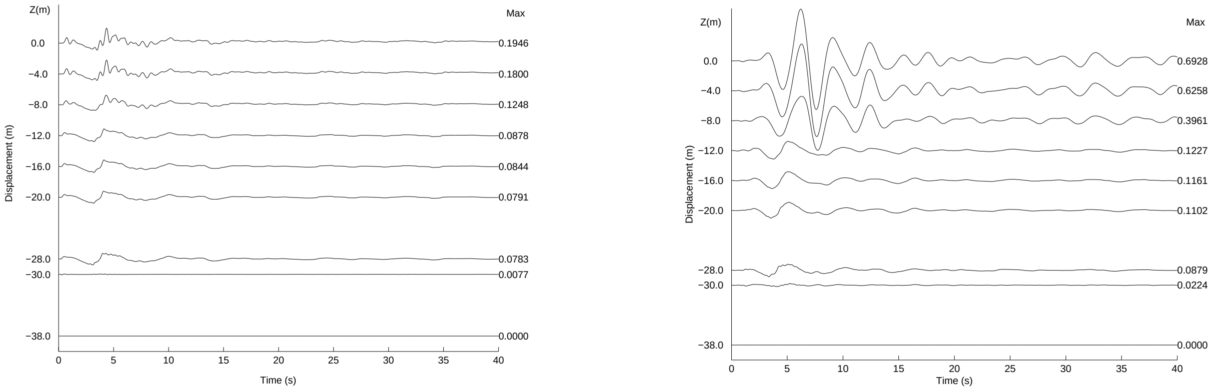


Figure 7: Seismic wave propagation resulting from the same earthquake acting on a stiff and soft soil site.

SFS Case Study

A simple case study was performed in order to investigate SFS interaction effects during earthquakes (eg. Jeremić et al. [3]). A simplified SFS model, using soil springs was used to illustrate beneficial and detrimental effects of SFS interaction on performance of the structure. The prototype structure is a typical bent of the I–880 highway structure in Oakland, CA. The model consists of inelastic fiber column–beams to represent the bridge piers where much of the inelastic behavior is expected to occur, elastic column–beams to represent the deck and equivalent zero-length foundation springs to represent the soil-foundation system. Figure 8 shows the frame models, one without and one with the SFS interaction. Foundation springs were obtained from

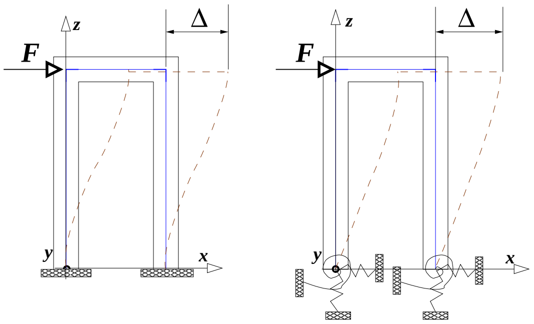


Figure 8: Two frame models for the Bent #16,fully fixed and the model with soil springs.

a detailed 3D finite element model of the pile group foundation system using elastic soil properties. It is noted that the inelastic analysis of soil–foundation system was also performed for a limited number of load cases and it was shown that, at least for small deformations expected here, the response can be very well approximated with elastic soil behavior. The foundation system consists of a 5×5 pile groups connected with a massive pile cap. The piles are made of reinforced concrete and reside in a steel shell with a diameter of 0.6m. The schematic figure of the pile cap, the piles and the finite element mesh for the soil–foundation system is show in Figure 9.

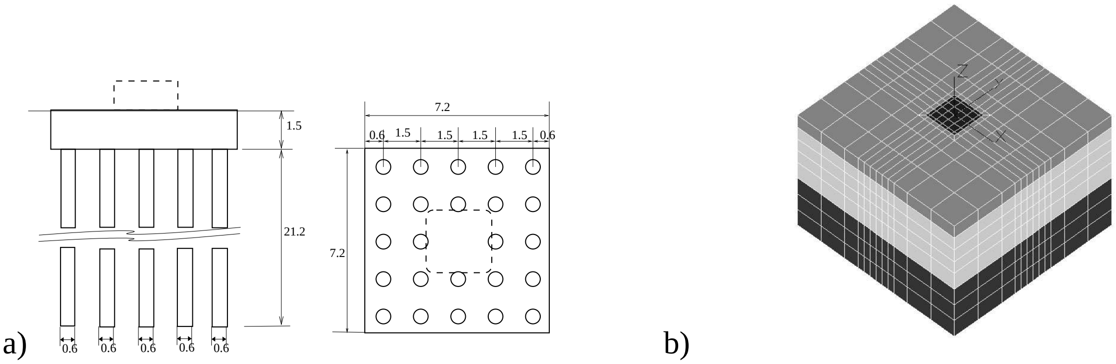


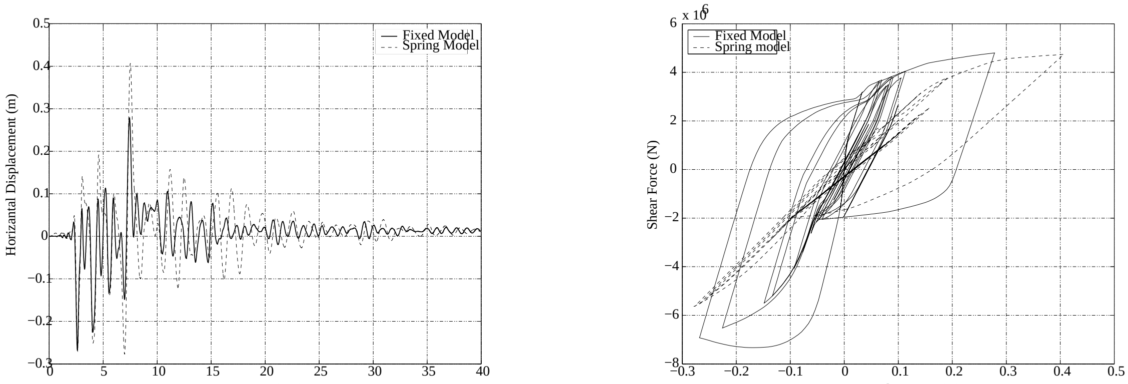
Figure 9: (a) Schematics of the pile cap and the piles. (b) Finite element mesh for soil foundation system.

A uniform hazard spectra for SD (soil) site conditions was derived for a site in Oakland which represents an event with a 10 % probability of exceedance in 50 years. The hazard is dominated by earthquakes on the Hayward fault which is located about 7 km east of the I–880 site. The ground motion model of Abrahamson and Silva [1] was used in generating the spectra (Somerville and Collins [10]). The spectra contains rupture directivity effects which were represented in the probabilistic hazard analysis using the empirical model proposed by Somerville et al. [11]. The spectra were generated for both fault-parallel (FP) and fault-normal (FN) directions. Three time histories were selected: two from the modified suite of Loma Prieta motions (recorded at Gilroy and Corralitos) and one from Kobe. Detailed description of ground motion generation is given by Jeremić et al. [3]

The main feature in evaluation of the two bent models is in different behavior of the same bent for chosen input motions. Presented here are result from two Loma Prieta motions (Corralitos and Gilroy). The effects of SFS interaction are considered to be beneficial to the structure under the following conditions:

- There are no significant permanent deformations in the structure resulting from yielding of the pier, or
- The energy dissipation (hysteretic loops) of the system with SFS interaction is smaller than that with fixed foundation, leading to the conclusion that there is less damage to the structure.

If any of the above criteria is not fulfilled, it is assumed that SFS interaction is detrimental to the structure behavior. Presented here are two examples of bent behavior, one representing beneficial effects and one for detrimental effects of SFS interaction. Figure 10 shows behavior of the bent subjected to the scaled Corralitos record. This record was scaled to match the hazard spectra at a period of 0.77 sec. As is evident from the spectra shown in Figure 10, the demands imposed by the earthquake are more significant in the short period range, hence the fixed base model experiences higher demands than the model with SFS interaction. Both SFS and non SFS interaction results show small permanent deformation (of the order of one to two centimeters). However, the hysteretic loops of the model considering SFS interaction effects are much smaller then those of the non SFS interaction model thus suggesting much smaller levels of damage for the SFS interaction model. The results in Figure 11, on the other hand, clearly indicate that the SFS interaction model subjected to scaled Gilroy earthquake is dissipating more energy and



a) b)

Figure 10: LP–Corralitos Record : a) displacement time history for fixed and spring supported models, b) horizontal displacement vs shear force for fixed and SFS interaction models.

also being subjected to larger deformations than the non–SFS interaction model. The spectral demands are initially higher in the short period range for this record, however, it is likely that the fixed base model moves into a region of slightly lower demands (just beyond 0.5 seconds) since the degree of inelasticity is not severe. The shift in the period from 1.24 seconds of the SFS interaction model takes it into a region of increased demand thus causing higher drifts.

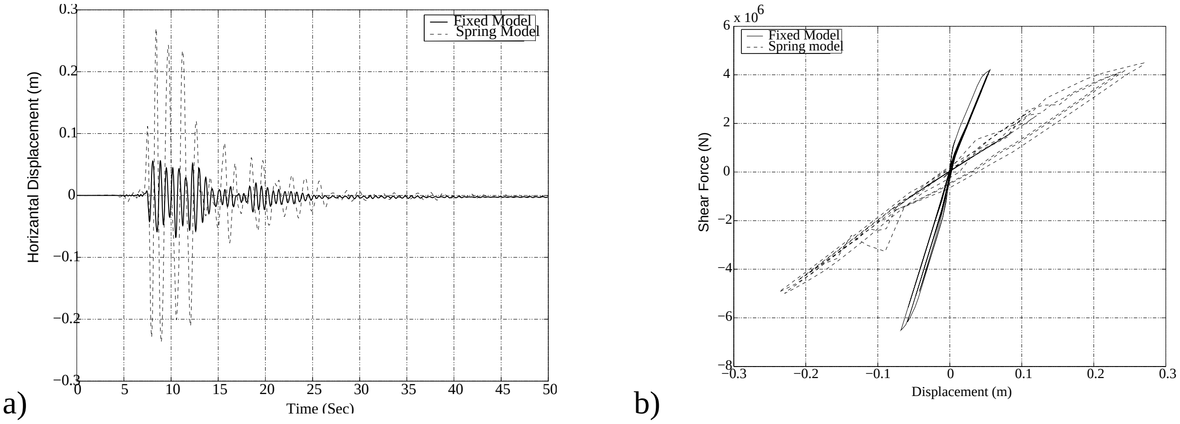


Figure 11: LP–Gilroy Record: a) displacement time history for fixed and SFS interaction models, b) horizontal displacement vs shear force for fixed and SFS interaction models.

Summary

The NEESgrid computational simulation platform OpenSees is a very versatile simulation tool. The selected examples, developed mostly within the computational geomechanics group at UCD show part of this versatility. In addition to that, OpenSees features a number of other models, elements, solutions procedures, making it one of the most useful simulations tools (platforms) available today.

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