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NONLINEAR MODELING OF LARGE-SCALE GROUND-FOUNDATION-STRUCTURE SEISMIC RESPONSE

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ABSTRACT

Numerical modeling of ground deformation effects on structural systems remains an area of major challenges. Effective and efficient nonlinear soil and structural models are needed. Furthermore, calibration of the employed numerical procedures requires significant effort and judgment. In this regard, large one-*g* shake table and centrifuge testing facilities worldwide are generating valuable datasets and insights for geotechnical earthquake engineering applications. In each experiment, hundreds of sensors record salient features of the involved response, providing new horizons for the development and calibration of high-fidelity computational simulation tools. Such datasets along with high-performance parallel computing environments are increasingly permitting the evolution of insights, gained from analyses of entire ground-foundation-structural systems. The studies presented herein address these issues through recently conducted representative research efforts. Results are shown for situations of ground modification as a liquefaction countermeasure, and for a ground-foundation-structure seismic response scenario. A user interface for lateral pile response simulations is also discussed in order to facilitate such studies by interested researchers and engineers.

KEYWORDS: Finite Element, Liquefaction, Soil-Structure Interaction, Shake Table, Parallel Computing

INTRODUCTION

Seismically-induced permanent deformation of the ground may impose excessive loads on the foundations and supported structural systems. Research efforts worldwide continue to address this challenge with simplified empirical procedures as well as increasingly realistic elaborate finite element (FE) approaches.

For large systems, parallel computing is gradually becoming a main-stream tool in geotechnical simulations (e.g., Bielak et al., 2000; Yang, 2002). Recently a new parallel nonlinear FE formulation with an implicit time-integration scheme has been developed (Lu et al., 2004; Peng et al., 2004; Lu, 2006). This parallel-computing approach extends the original serial code, which is a nonlinear finite element program for the analysis of liquefaction-induced seismic response (Parra, 1996; Yang and Elgamal, 2002).

In this paper, recent research to develop such a nonlinear FE analysis framework is presented. Emphasis is placed throughout on the important scenario of seismically induced lateral ground deformation.

In the following sections a brief description of the numerical framework is presented. Representative calibration efforts based on large-scale experimental simulations are discussed. A user-interface for conducting routine analyses is shown to be a useful tool for practical applications. To illustrate the significance of combined ground-foundation structural response, results from a three-dimensional (3D) simulation of an idealized pile-supported wharf structure are discussed.

NUMERICAL FRAMEWORK AND CONSTITUTIVE MODEL

The numerical framework employs a two-phase (fluid and solid) fully-coupled FE formulation (Parra, 1996; Yang and Elgamal, 2002) based on Biot's theory (Biot, 1962). In this framework, the saturated soil system is modeled as a two-phase material. A simplified numerical framework of this theory (Chan, 1988), known as the *u-p* formulation (in which displacement of the soil skeleton, *u*, and pore pressure *p* are the primary unknowns), was implemented for the simulation of two-dimensional (2D) and 3D response scenarios (Parra, 1996; Yang, 2000; Yang and Elgamal, 2002; Lu, 2006).

The *u-p* formulation is defined by (1) equation of motion for the solid-fluid mixture, and (2) equation of mass conservation for the fluid phase that incorporates equation of motion for the fluid phase and Darcy's law (Chan, 1988). These two governing equations are expressed in the following finite element matrix form (Chan, 1988):

$$[M]\{\ddot{U}\}+\int_{\Omega}[B]^T\{\sigma'\}d\Omega+[Q]\{p\}-\{f^s\}=\{0\} \tag{1a}$$

$$[Q]^T\{\dot{U}\}+[S]\{\dot{p}\}+[H]\{p\}-\{f^p\}=\{0\} \tag{1b}$$

where $[M]$ is the total mass matrix, $\{U\}$ the displacement vector, $[B]$ the strain-displacement matrix, $\{\sigma'\}$ the effective stress tensor, $[Q]$ the discrete gradient operator coupling the solid and fluid phases, $\{p\}$ the pore pressure vector, $[S]$ the compressibility matrix, and $[H]$ the permeability matrix. The vectors $\{f^s\}$ and $\{f^p\}$ represent the effects of body forces and prescribed boundary conditions for the solid-fluid mixture and the fluid phase, respectively. Equations (1a) and (1b) are integrated in the time domain using a single-step predictor multi-corrector scheme of the Newmark type (Chan, 1988; Parra, 1996).

Soil Constitutive Model: For cyclic and seismic loading scenarios, multi-surface plasticity pressure-independent (Von-Mises) as well as pressure-dependent models are capable of reproducing the desired cyclic shear stress-strain response characteristics. For (pressure-dependent) frictional soils, a soil constitutive model (Parra, 1996; Yang, 2000; Yang and Elgamal, 2002) was developed based on the original framework of Prevost (1985). In this model (see Figures 1 and 2), emphasis was placed on simulating the liquefaction-induced shear strain accumulation mechanism in clean medium-dense sands (Yang and Elgamal, 2002; Elgamal et al., 2003). Special attention was given to the deviatoric-volumetric strain coupling (dilatancy) under cyclic loading, which causes increased shear stiffness and strength at large cyclic shear strain excursions (i.e., cyclic mobility). The main modeling parameters (Yang et al., 2003) include standard dynamic soil properties such as low-strain shear modulus and friction angle, as well as parameters to control the dilatancy effects (phase transformation angle, contraction, and dilation), and the level of liquefaction-induced yield strain (γ_y).

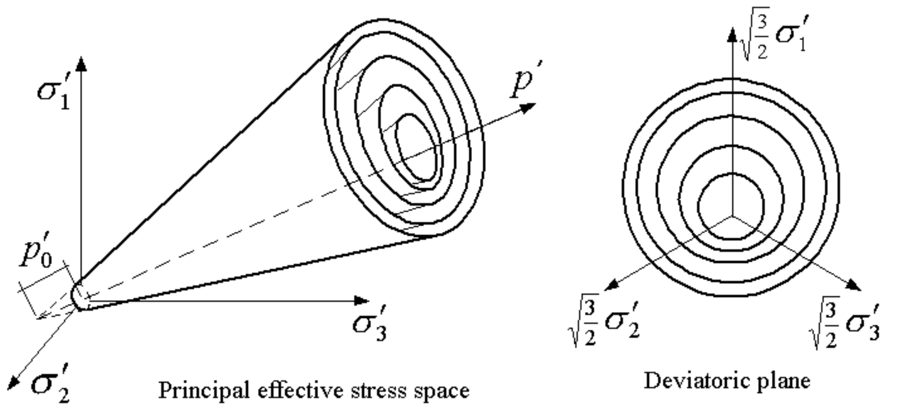


Fig. 1 Conical yield surfaces for granular soils in principal stress space and deviatoric plane (after Prevost, 1985; Yang et al., 2003)

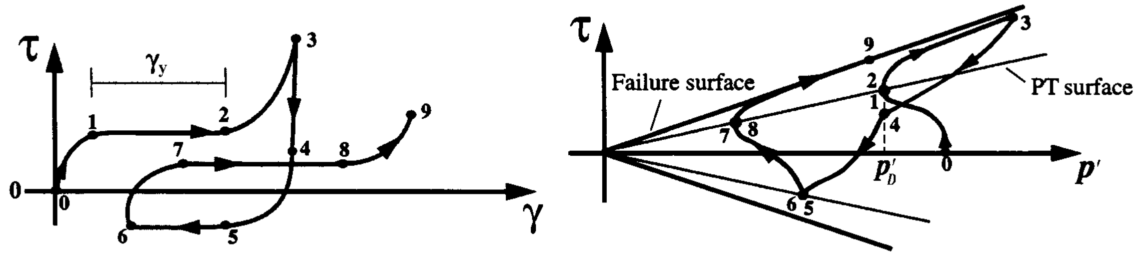


Fig. 2 Shear stress-strain and effective stress path under undrained shear loading conditions (Yang et al., 2003)

CALIBRATION AND VALIDATION OF NUMERICAL FRAMEWORK

Calibration and validation has always been an integral part of the numerical framework developments. Experimental programs conducted on the Rensselaer Centrifuge have been a major source of calibration over the years (Dobry et al., 1995; Elgamal et al., 1996; Dobry and Abdoun, 1998). For instance, a broad-based 2D embankment liquefaction-countermeasure centrifuge investigation has been a key component (Adalier, 1996; Parra, 1996; Adalier et al., 1998).

Sample laboratory data were also used (Arulmoli et al., 1992; Parra et al., 1996; Yang, 2000). In addition, valuable downhole-array earthquake datasets were employed. The downhole-array calibration efforts started in the early 1990s and have been based on (i) low (linear) and moderate (nonlinear) amplitude earthquake datasets from Lotung (i.e., a major set of 18 different earthquakes) and Hualien, Taiwan, as well as Treasure Island, California (Elgamal et al., 1996; Gunturi et al., 1998), and (ii) liquefaction response data from Imperial County, California and Port Island, Kobe, Japan (Elgamal et al., 1996).

Current ongoing research includes calibration and validation based on a series of one-*g* shake-table experiments recently conducted at the University of California, San Diego (UCSD) and the National Research Institute for Earth Science and Disaster Prevention (NIED) in Japan (He, 2005). To study the response of single piles and pile groups under liquefaction-induced lateral spreading conditions, these experiments employed a slightly inclined laminar box patterned after the work of Abdoun et al. (2003) and Dobry et al. (2003) to simulate lateral spreading in mild infinite slopes. Single piles of 0.1 to 0.3 m in diameter as well as 2×2 pile groups were tested in soil layers of up to 5.5 m depth with and without an upper non-liquefiable crust (He, 2005). In the following section, the scope of this large-scale experimental program will be presented.

1. One-*g* Shake Table Experiments

In this series of tests, a total of seven shake table experiments were conducted (He, 2005). Among these experiments, four (for Models 1–4) were conducted using a large-size laminar box (see Figure 3) at the NIED laboratory in Tsukuba, Japan, and three (for Models 5–7) were conducted using a medium-size laminar box (see Figure 4) at UCSD.

The sand stratum in these models was constructed by the sedimentation method (involving sand deposition in water). Relative density was about 40–50% and saturated density was about 1940 kg/m^3. Each model was instrumented with accelerometers and pore pressure sensors within the soil, and LVDTs were mounted on the exterior wall of the laminar box to measure free-field lateral displacements. The piles were instrumented with strain gages and displacement transducers to measure bending moment and deformation during the shaking event.

The piles in all experiments were rigidly attached to the base in an attempt to mimic a fixed-cantilever boundary condition. Static pushover tests were conducted before the soil layer construction to obtain the bending stiffness *EI* and the actual base fixity condition of the piles. In the following, attention is given to Model 4, noting that detailed information about the entire experimental program can be found in He (2005).

Model 4 Test: This experiment was conducted at NIED employing a large laminar box (see Figure 3) inclined at 2° to the horizontal, patterned after Abdoun et al. (2003) and Dobry et al. (2003). The employed laminar box is about 12 m long, 6 m high and 3.5 m wide (Tokimatsu and Suzuki, 2004).

Figure 5 shows the test setup (He, 2005), consisting of a 5.0 m sand layer with a water table at the up-slope ground surface. In this model, two separate single piles of different stiffness were tested (see Table 1). Base dynamic excitation was imparted along the sloping direction. Input motion was mainly at a frequency of 2 Hz, 0.2*g* amplitude, and with 44 s duration.

Fig. 3 The NIED large size laminar box (Tokimatsu and Suzuki, 2004)

Fig. 4 The UCSD medium size laminar box (Jakrapiyanun, 2002)

Table 1: Summary of the Soil Profile and Pile Foundations for Model 4 (He, 2005)

Soil Profile		Pile Properties				
Height (m)	**Water Table**	**Embedded Length (m)**	**Diameter (m)**	**Wall Thickness (mm)**	**Bending Stiffness *EI* (kN-m^2)**	**Base Fixity* (kN-m/rad)**
5	Covers the entire soil layer	5.0	0.318	6	14320	18500
		5.0	0.318	3	7360	8500

*Pile base fixity condition is characterized by a rotational spring with constant stiffness

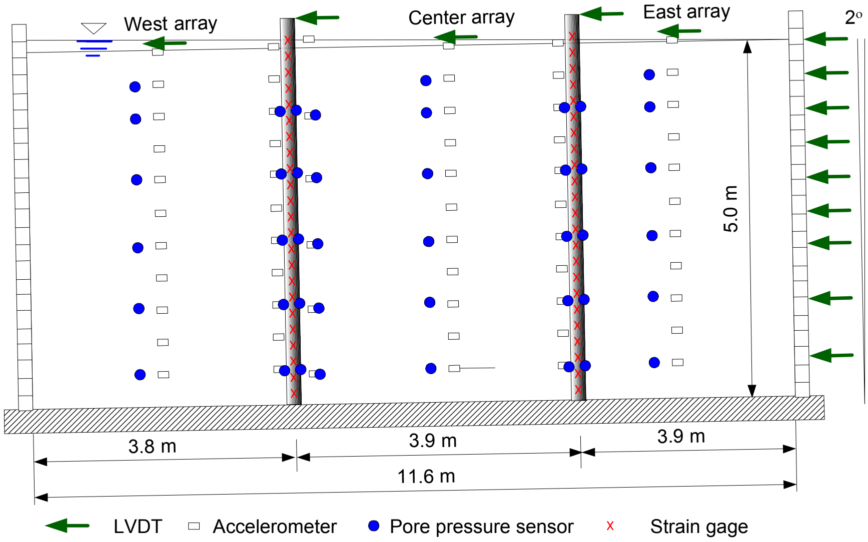


Fig. 5 Model 4 test setup (He, 2005)

2. Test Results and Finite Element Calibration

The computational platform OpenSees was employed for numerical simulation. OpenSees[1] is an open-source platform under development at the University of California, Berkeley. The soil developments described earlier are implemented by the author and co-workers in OpenSees, and are available for use within this open-source platform.

Soil response (acceleration, displacement, and excess pore pressure) and pile behavior (pile head displacement and strains along the pile) were measured. This data was employed (He, 2005) to assess the possible ranges and significance of the soil model parameters through finite element simulations (see Figure 6). The main calibrated modeling parameters include typical dynamic soil properties such as low-strain shear modulus, friction angle, and permeability, as well as calibration constants to control pore-pressure buildup rate, dilation tendency, and the level of liquefaction-induced cyclic shear strain γ_y (as in Figure 2).

The experimental and computed responses of Model 4 are shown in Figures 7–11. An effort is made to match acceleration (in Figure 7), permanent displacement (in Figure 8), and the observed pile response (in Figure 9). In general terms, the experimental data of Model 4 along with the finite element simulation (see Figures 7–11) currently suggest a low liquefied soil strength (about 2 kPa), an apparent pinning effect of the two piles in the container (see Figure 11), little dilative tendency (during this shaking event), and lower overall excess pore pressure near the pile compared to the free-field (He, 2005).

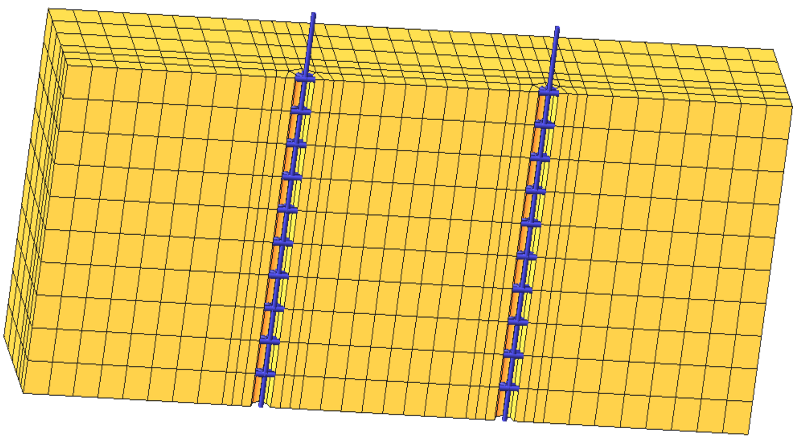


Fig. 6 Model 4 FE model, with a ½ mesh configuration in view of symmetry (He, 2005)

[1] Website of OpenSees, http://opensees.berkeley.edu

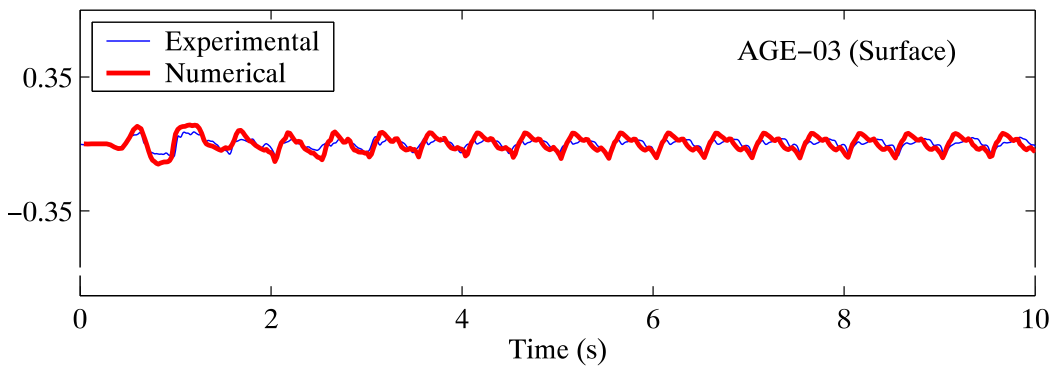


Fig. 7 Free-field acceleration time histories in Model 4 (He, 2005)

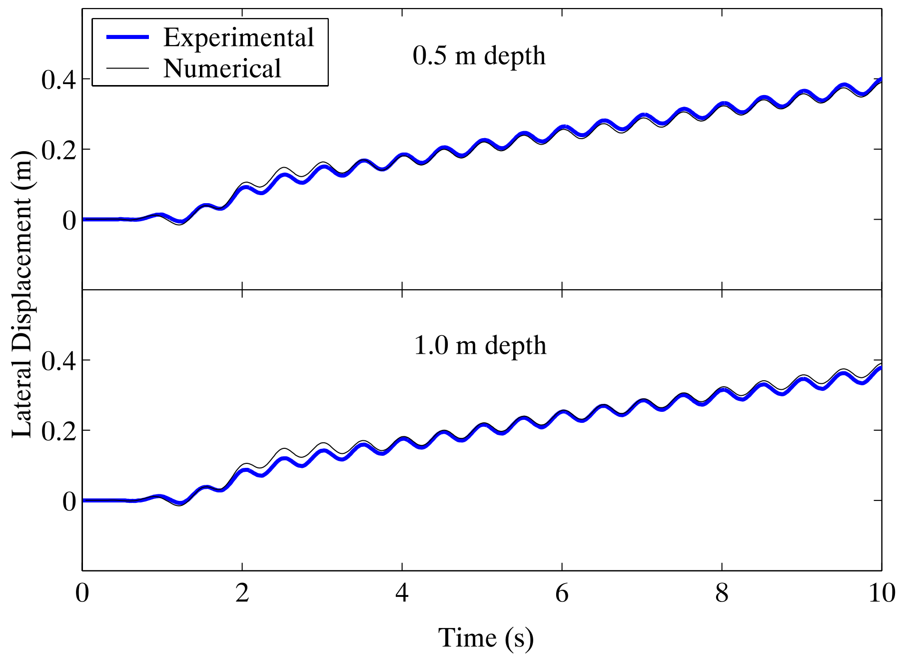


Fig. 8 Recorded and computed free-field displacement time histories (He, 2005)

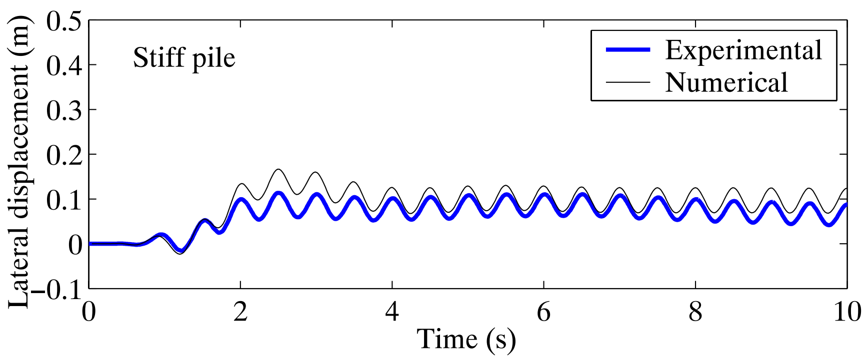


Fig. 9 Recorded and computed pile-head displacement time histories (He, 2005)

USER-INTERFACE FOR NONLINEAR GROUND-FOUNDATION ANALYSIS

As may be inferred from the above simulations, much effort and experience is required to conduct such studies. In particular, preparation of the FE data file is a step that requires careful attention to detail. A minor oversight might go undetected leading to erroneous results. Numerous opportunities for such small errors abound, and a user-friendly interface can significantly alleviate this problem and allow for high efficiency and much increased confidence.

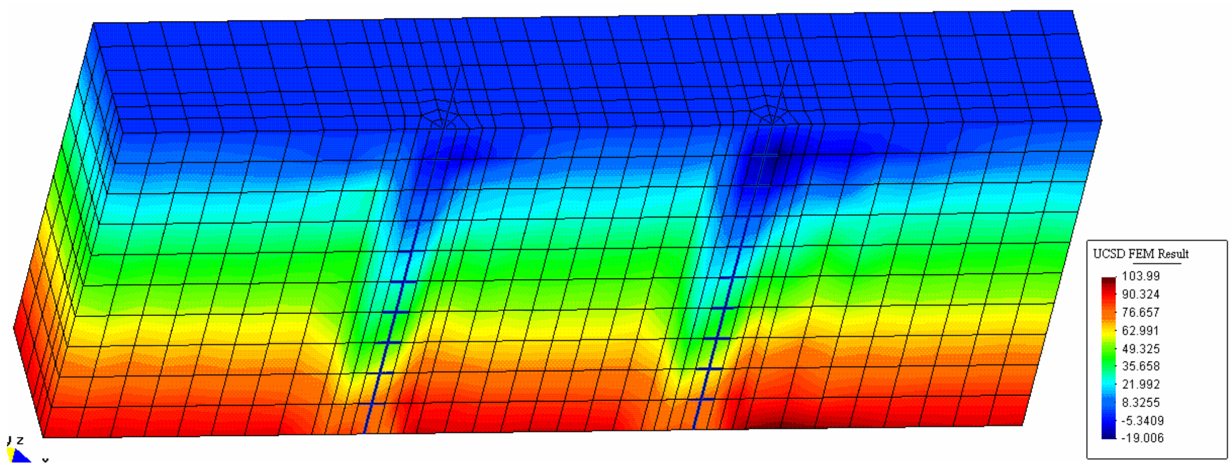


Fig. 10 Sketch of excess pore pressure (in kPa) at 10 s (He, 2005)

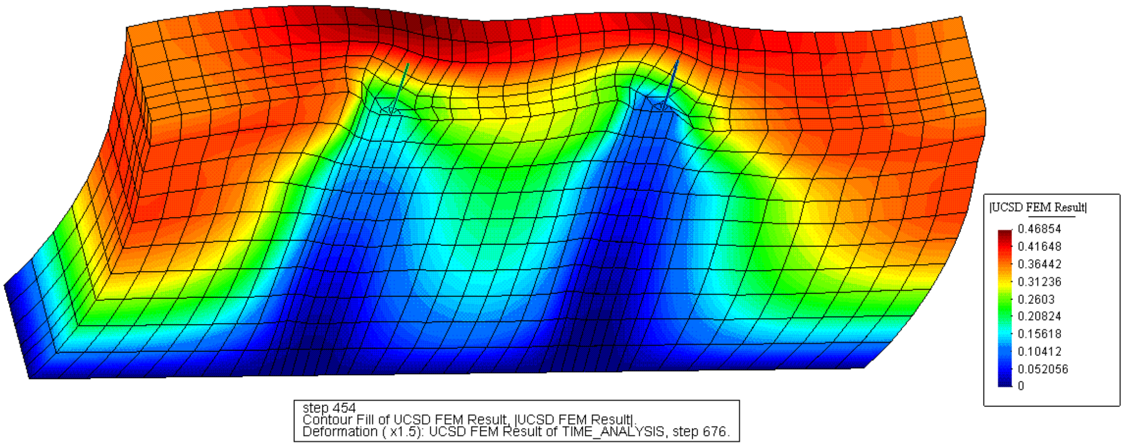


Fig. 11 Sketch of deformed mesh (factor of 1.5; color map shows longitudinal displacement in meters) at 10 s (He, 2005), clearly showing significant reduction in lateral displacement around the piles (the pile-pinning effect)

On this basis, a user-interface OpenSeesPL[2] is under development (see Figure 12), to allow for the execution of push-over and seismic single-pile ground simulations (Lu et al., 2006). Through this interface, OpenSees[1] is employed to conduct the specified FE analyses, with soil materials represented by the solid-fluid formulation and constitutive modelling procedures as described earlier.

The OpenSeesPL graphical interface (pre- and post-processor) is focused on facilitating a wide class of 3D studies (with additional capabilities yet under development). In the current version, OpenSeesPL may be employed to study a number of geometries and configurations of interest including

- linear and nonlinear (incremental-plasticity based) 3D ground seismic response with capabilities for 3D excitation, and layered soil strata. Multi-yield surface cohesionless (Drucker-Prager cone model), and cohesive (Mises or J2) soil models are available. The coupled solid-fluid analysis option allows for conducting liquefaction studies.
- inclusion of a pile or shaft in the above-described 3D ground mesh (e.g., circular or square pile in a soil island). For the pile response, linear, elastic-perfectly-plastic, or nonlinear fiber elements are available in OpenSees[1]. The pile may extend above ground, and may support a bridge deck or a point mass at the top. This bridge deck can be specified to only translate longitudinally, or to undergo both lateral translation and transversal rotation. In addition to the seismic excitation option, the pile system may be subjected to monotonic or cyclic lateral push-over loading (in prescribed displacement, or in prescribed force modes).

[2] Website of OpenSeesPL, https://neesforge.nees.org/projects/openseespl/

- soil properties within the zone occupied by the pile (as specified by the pile diameter). Those can be specified independently, allowing for a variety of practical modeling scenarios. For instance, various ground modification scenarios may be studied by appropriate specification of the material within the pile zone. Among other options, liquefaction countermeasures in the form of gravel drains, stone columns, and solidification/cementation may all be analyzed. Of particular importance and significance in these scenarios is the ability to simulate the presence of a mild infinite-slope configuration, thus allowing estimates of accumulated ground deformation, efficacy of a deployed liquefaction countermeasure, pile-pinning effects, and liquefaction-induced lateral pile loads and resulting moments/stresses.
- slopes and pile embedded in sloping ground that can also be simulated within this interface.

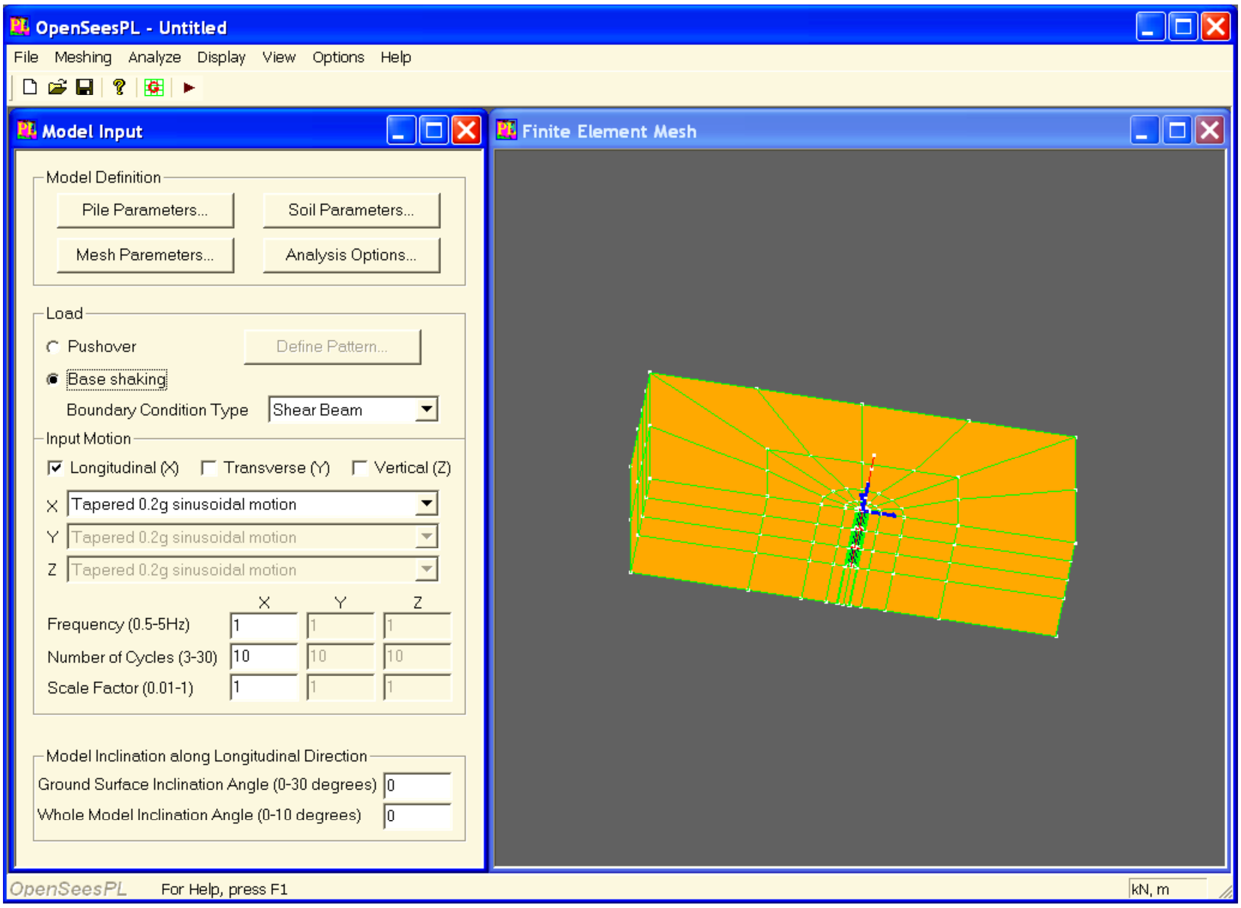


Fig. 12 OpenSeesPL user interface with mesh showing a circular pile in level ground (view of ½ mesh shown due to symmetry under uni-directional lateral loading)

1. Pre- and Post-Processing

OpenSeesPL includes a point-and-click pre-processor for (i) definition of the pile geometry (i.e., circular or square pile) and material properties (i.e., linear or nonlinear), (ii) definition of the 3D spatial soil domain, (iii) definition of the boundary conditions and input excitation or push-over analysis parameters, and for (iv) selection of the soil materials from an available menu of cohesionless and cohesive soil materials. The menu of soil materials includes a complementary set of soil modeling parameters representing loose, medium and dense cohesionless soils (in the cyclic Drucker-Prager model with silt, sand, or gravel permeability), and soft, medium, and stiff clay (in the J2 plasticity cyclic model).

OpenSeesPL also allows convenient post-processing and graphical visualization of the analysis results including the deformed mesh (see Figure 13), ground response time histories, and pile response. As such, OpenSeesPL makes it possible for the geotechnical and structural engineers/researchers to rapidly build a model, run the FE analysis, and to evaluate performance of the pile-ground system (Lu et al., 2006). As an example of OpenSeesPL capabilities, a mitigation scenario of seismically induced lateral spreading is included below.

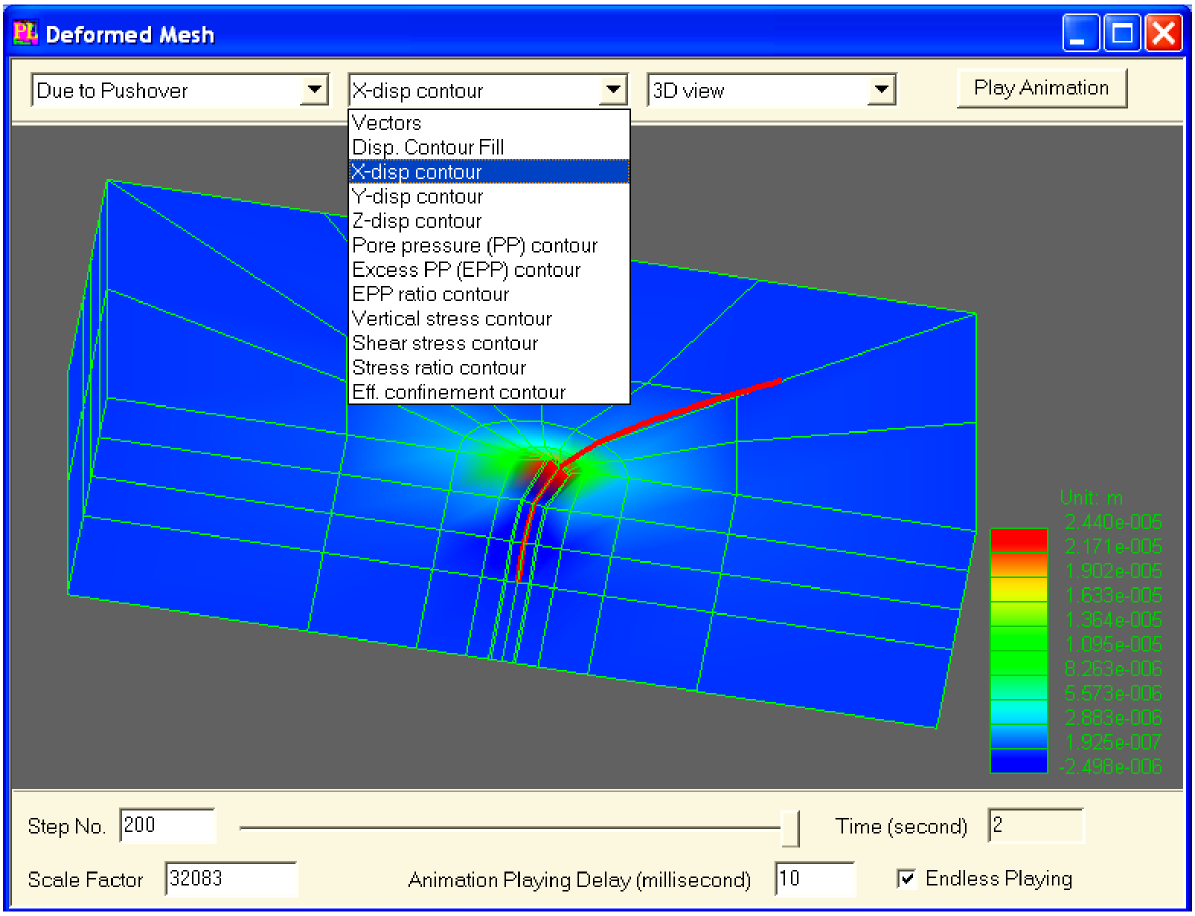
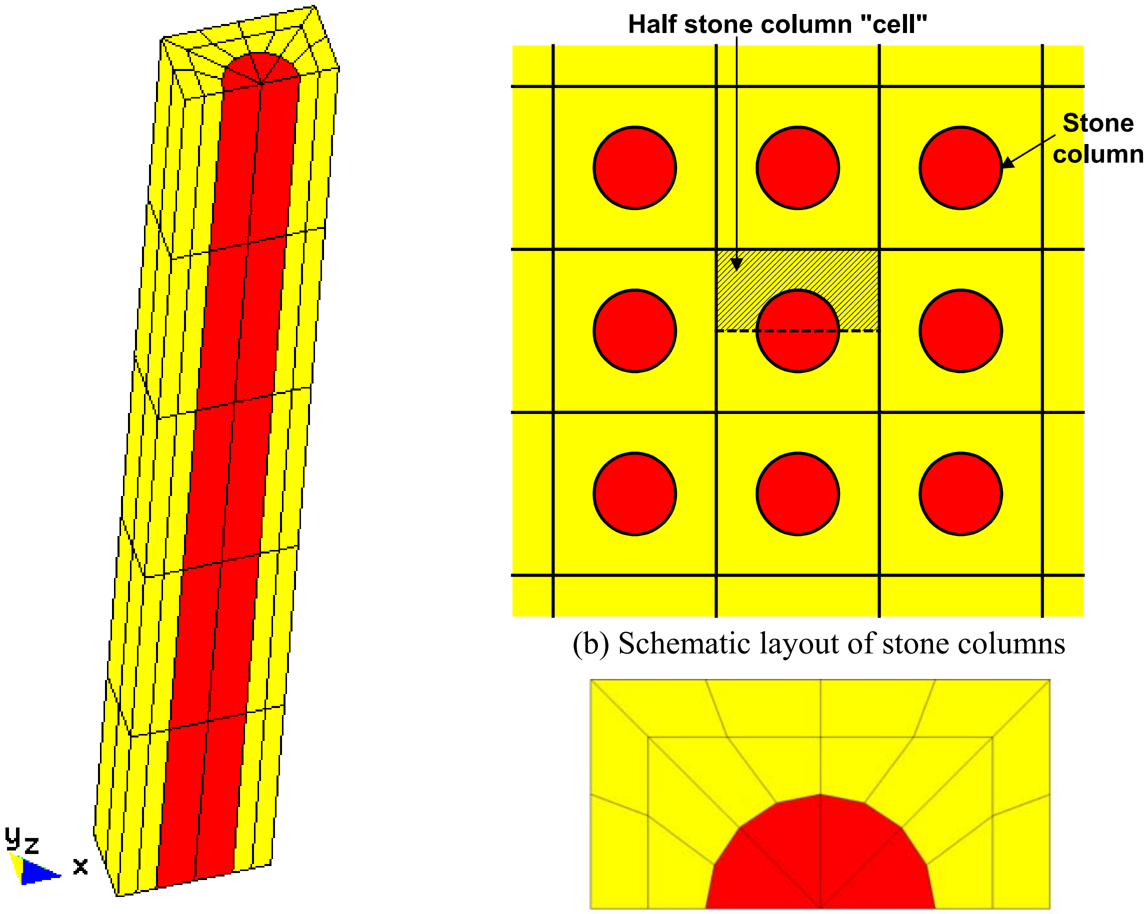


Fig. 13 Push-over analysis and deformed mesh window in OpenSeesPL (Lu et al., 2006)

2. Lateral Spreading Countermeasures

This section presents an example of 3D seismic ground simulation using OpenSeesPL (see Figure 14). Motivated by the earlier experimental setups (as in Figures 3 and 4), a 10-m depth, mildly inclined (at 4 degrees), saturated medium sand layer (of permeability $k = 6.6\times10^{-5}$ m/s, with Nevada sand properties at a D_r of about 40% according to Elgamal et al. (2003) and Yang et al. (2003)) was studied. Remediation by stone columns (with an area replacement ratio of 20%) and by the pile-pinning effect was investigated for reducing the extent of liquefaction-induced lateral deformation. The stone column properties were represented by dense cohesionless soil properties and by the permeability $k = 1.0\times10^{-2}$ m/s. In the above, the area replacement ratio is defined as the area of the stone column to the tributary area per stone column (see Figure 14(b)). For the pile-pinning scenario, the same geometric configuration was used with the pile bending stiffness $EI = 1.27\times10^5$ kN-m^2.

Using OpenSeesPL, symmetry (as in Figure 14) allows the investigation of a representative stone column "cell". As such, a half-mesh (with 100 elements in total) of a typical cell within a large remediated ground zone was studied (see Figure 14). Thus, the following (solid and fluid) boundary conditions were implemented: (i) excitation was defined along the base in the longitudinal direction (x-axis), (ii) at any spatial location, displacement degrees of freedom of the left and right boundary nodes were tied together (both longitudinally and vertically by using the penalty method) in view of the symmetry, (iii) the soil surface was traction-free, with zero prescribed pore pressure, and (iv) the base and lateral boundaries were impervious (due to the symmetry). For illustration, the downhole acceleration record (in the NS direction, at 7.5 m depth) from the Wildlife site during the 1987 Superstition Hills earthquake (as shown in Figure 15) was employed as base excitation along the x-axis.



(a) 3D isomeric view

(b) Schematic layout of stone columns

(c) Plan view (or lateral cross-section of 3D mesh)

Fig. 14 FE mesh for the ground modification study (dark zone represents remediated domain), with the plan view depicting a typical cell (½ mesh due to symmetry) within the remediated ground

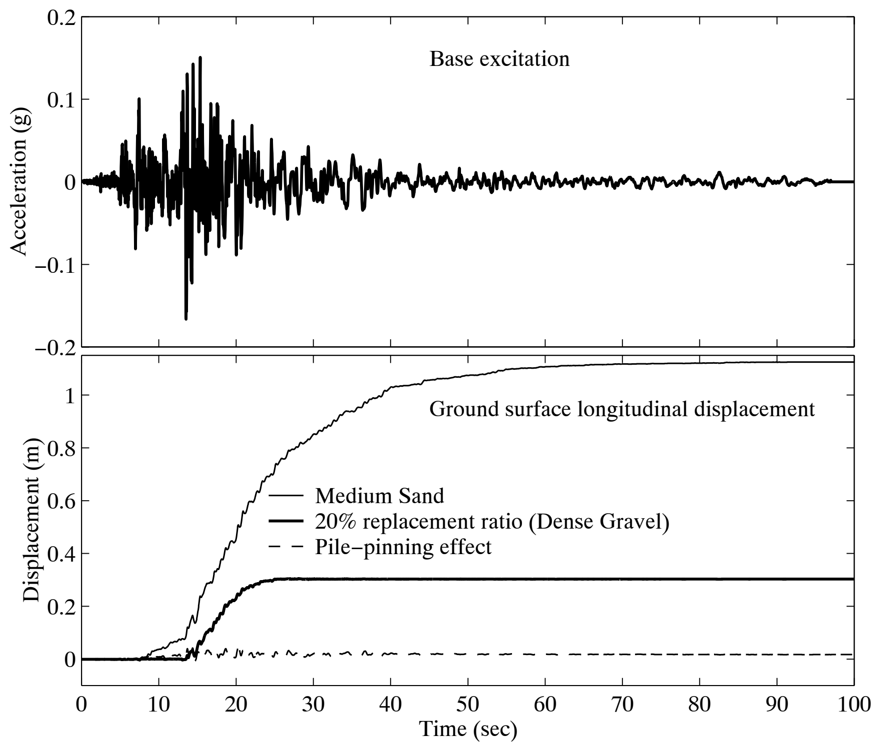
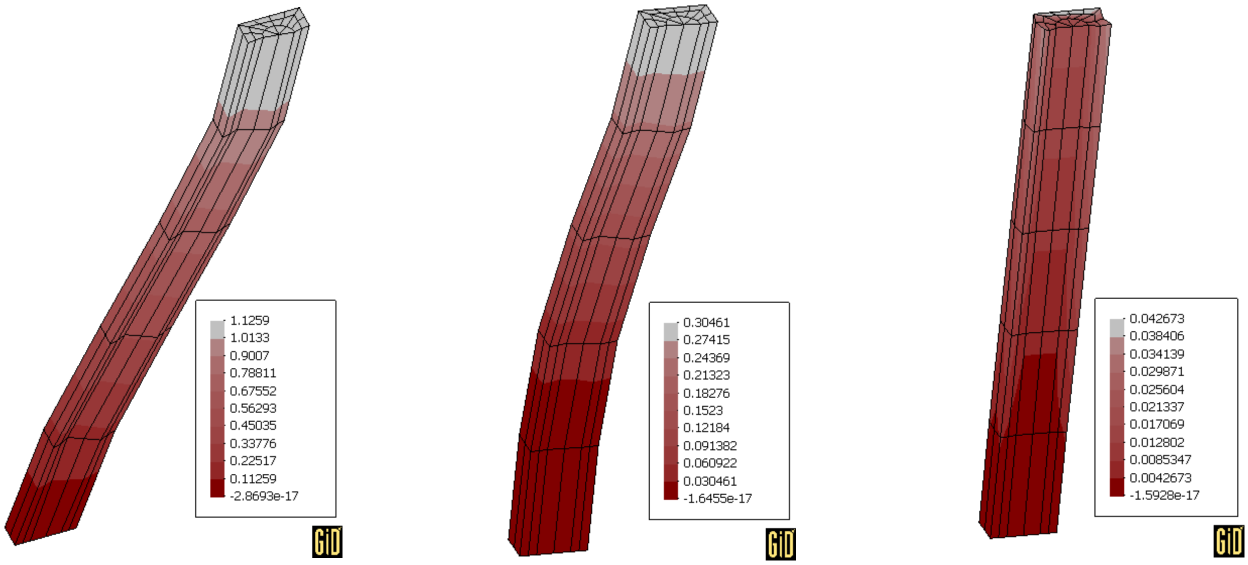


Fig. 15 Base input motion and ground surface longitudinal displacement time histories

Figure 16 compares the final deformed mesh for the three investigated cases. The longitudinal displacement time histories at the ground surface are displayed in Figure 15. As can be seen from Figures 15 and 16, the longitudinal displacement is reduced by more than half in the stone column model, compared to the original medium-sand site situation. It is also seen that pile-pinning has been particularly effective in reducing the extent of lateral spreading.



(a) Medium sand (b) 20% stone-column replacement ratio (c) Pile-pinning effect

Fig. 16 Final deformed mesh (factor of 5; color map shows longitudinal displacement in meters) for the investigated scenarios

LARGE-SCALE PARALLEL COMPUTING

In many situations of practical interest, the need for modeling large ground-structure systems exists. Utilization of parallel computers that combine the resources of multiple processing and memory units, can allow simulations of large and complex models. Execution time can also be significantly reduced.

Currently, parallel computing is gradually becoming a mainstream tool in geotechnical simulations. The need for high fidelity and for modeling of large 3D spatial configurations is motivating this direction of research. In this regard, a new program ParCYCLIC for seismic geotechnical applications has been recently developed (Lu et al., 2004; Peng et al., 2004; Lu, 2006), based on the original CYCLIC code (Parra, 1996; Yang and Elgamal, 2002). ParCYCLIC handles symmetric systems of linear equations (resulting from the employed implicit time-integration scheme) using a parallel sparse solver (Law and Mackay, 1993). This solver is based on a row-oriented storage scheme that takes full advantage of the sparsity of the stiffness matrix.

Key elements of the computational strategy employed in ParCYCLIC, designed for the distributed-memory message-passing parallel computer systems, include (Lu et al., 2004; Peng et al., 2004; Lu, 2006) (a) the parallel sparse direct solver (Law and Mackay, 1993), in which LDL^T factorization is performed (where L is a unit lower triangular matrix and D is a diagonal matrix), (b) nodal ordering strategies to minimize storage space for the matrix coefficients, (c) an efficient scheme for the allocation of sparse matrix coefficients among the processors, and (d) an automatic domain decomposer, where METIS (Karypis and Kumar, 1998) is used to partition the FE mesh.

Recently, ParCYCLIC has been employed to perform simulations of centrifuge experiments, liquefaction-induced shallow foundation settlement and mitigation thereof, and a pile-supported wharf system (Lu, 2006). In the following, a representative pile-supported wharf system simulation is discussed.

1. Pile-Supported Wharf System

The idealized model configuration (see Figure 17) is based on typical geometries of pile-supported wharf structures (e.g., Berth 100 Container Wharf at the port of Los Angeles, California). Figure 17 depicts a 3D slice in this wharf structure (at the central section), exploiting symmetry of the supporting pile-system configuration (Lu, 2006).

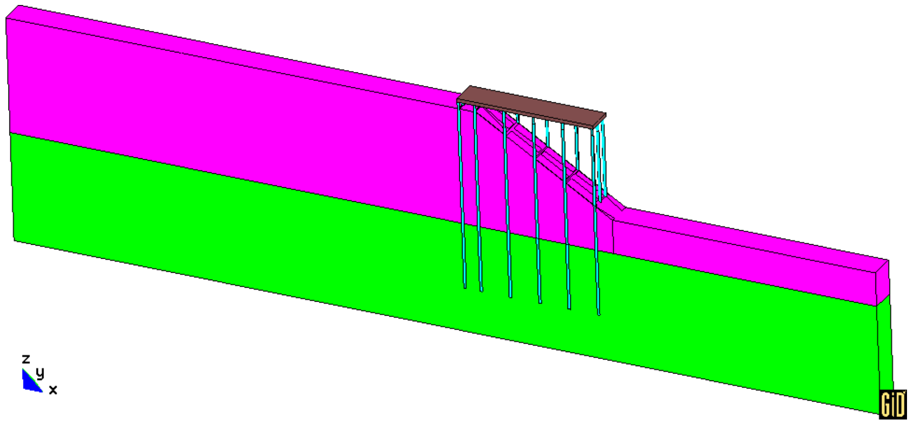


Fig. 17 Pile-supported wharf model (Lu, 2006)

In this idealized model, there are 16 (reinforced concrete) piles in 6 rows. Each pile is 0.6 m (24 inch) in diameter, and 43 m in length. The cracked flexural rigidity (*EI*) of each pile is 1.59×10^5 kN-m^2, with a moment of inertia (*I*) of 7.09×10^{-3} m^4. Relative to the piles, the wharf deck (with $E = 2.2 \times 10^9$ kPa and thickness of 0.8 m) was modeled to be essentially rigid.

Two soil layers were included in this idealized (cyclic Von-Mises) model. The lower layer (25 m in thickness) was modeled as stiff clay (having 255 kPa of cohesion), with the upper layer (28.5 m thick on the landside and 8 m thick on the waterside) being a weaker medium-strength clay (having 44 kPa of cohesion). Water table level was located at 16.6 m above the mud-line. The inclination angle of the slope was about 39 degrees.

The base of the FE model was assumed rigid (because the actual bedrock level is much deeper at this site), with the input seismic excitation prescribed uniformly at this level. A scaled Rinaldi Receiving Station record from the 1994 Northridge earthquake (see Figure 18) was employed as the base input motion (Lu, 2006). On the waterside and landside of the FE model, motion was specified as the computed accelerations from a 1D shear beam simulation (Yang et al., 2004) of the left and right soil columns. Symmetry along the 3D side boundaries was represented by the roller supports.

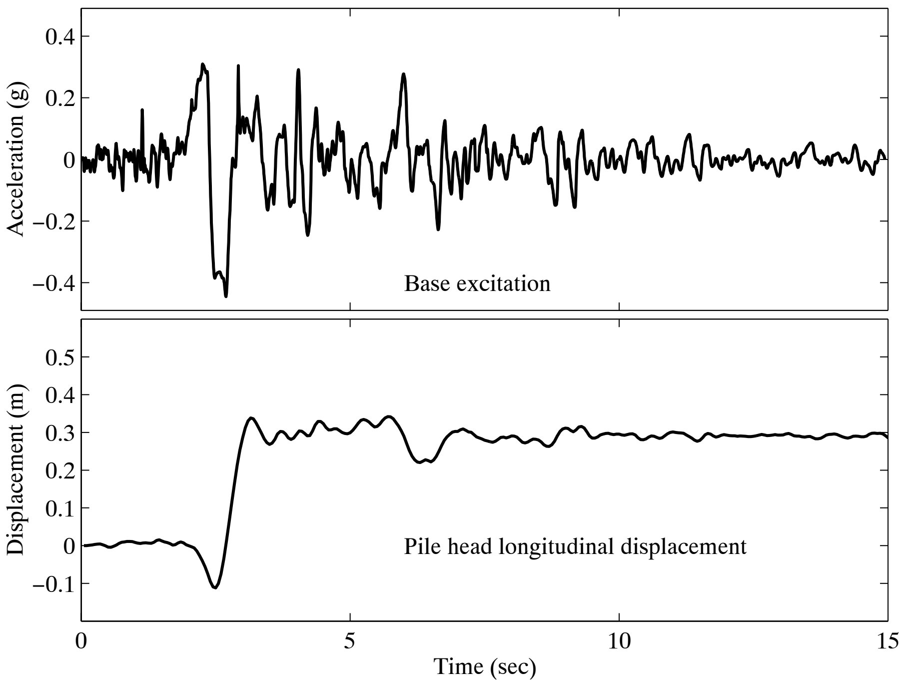


Fig. 18 Base excitation and deck longitudinal displacement time histories

Modeling of the above pile-supported wharf system was conducted on the machine Datastar at the San Diego Supercomputer Center (SDSC). Datastar is SDSC's largest IBM terascale machine, built in a configuration particularly suited to data-intensive computations. DataStar is composed of 272 (8-way) P655+ compute nodes, each with 8 POWER4 RISC-based processors and 16 GB of memory. The simulation reported herein consisted of 142,332 degrees-of-freedom, and 64 processors were employed (Lu, 2006).

2. Simulation Results

Figure 19 shows the final deformed mesh of the pile-supported wharf system. As can be seen, the large soil deformations occur mainly within the slope, while the lower layer shows a relatively low level of lateral displacement.

The computed wharf deck longitudinal displacement time history is included in Figure 18, with a permanent translation of about 0.3 m in this case. Most of this translation is associated with the large acceleration phase (due to the near-fault “fling motion”) in the employed base input motion (see the top graph in Figure 18).

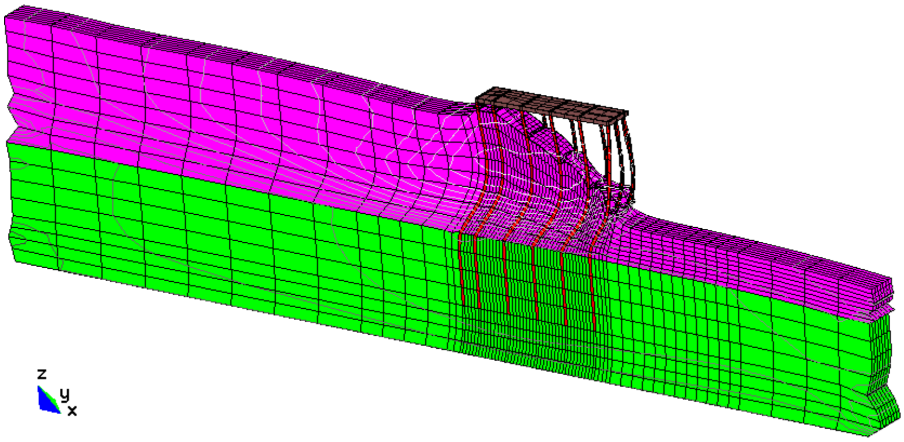


Fig. 19 Final deformed mesh with deformation shown at a factor of 30 (Lu, 2006)

SUMMARY AND CONCLUSIONS

Elements of a computational framework for conducting nonlinear studies of ground and ground-structure systems were presented. Cyclic plasticity constitutive models were employed within a coupled solid-fluid finite element formulation. Calibration through large-scale shake-table experiments was discussed. Recorded histories of permanent displacement, excess pore-water pressure, ground acceleration, and of pile response were employed to define the involved numerical modeling parameters.

Representative numerical results were shown for the situations of ground modification as a liquefaction countermeasure, and for a ground-foundation-structure seismic response scenario. To facilitate such computations, a user interface was shown to be a useful tool for conducting 3D simulations of idealized ground and ground-pile systems. The reported simulations of a wharf structure were conducted on a supercomputer using ParCYCLIC, a parallel nonlinear finite element program. Key elements of the developed parallel-computing implicit-integration framework were discussed.

Overall, the presented studies illustrate the potential for further reliance on computer simulations for the assessment of seismic ground response. Challenges in calibration, and in high-fidelity modeling are being gradually overcome. With careful attention to the involved modeling details and necessary idealizations, effective insights may be gleaned for a wide range of practical applications.

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REFERENCES

1. Abdoun, T., Dobry, R., O'Rourke, T.D. and Goh, S.H. (2003). "Pile Response to Lateral Spreads: Centrifuge Modeling", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 129, No. 10, pp. 869–878.
2. Adalier, K. (1996). "Mitigation of Earthquake Induced Liquefaction Hazards", Ph.D. Dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, U.S.A.
3. Adalier, K., Elgamal, A.-W. and Martin, G.R. (1998). "Foundation Liquefaction Countermeasures for Earth Embankments", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 124, No. 6, pp. 500–517.
4. Arulmoli, K., Muraleetharan, K.K., Hossain, M.M. and Fruth, L.S. (1992). "VELACS: Verification of Liquefaction Analyses by Centrifuge Studies, Laboratory Testing Program, Soil Data Report", Earth Technology Project Report 90-0562 (prepared for National Science Foundation), The Earth Technology Corporation, Irvine, U.S.A.
5. Bielak, J., Hisada, Y., Bao, H., Xu, J. and Ghattas, O. (2000). "One- vs Two- or Three-Dimensional Effects in Sedimentary Valleys", Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, Paper No. 2689 (on CD).
6. Biot, M.A. (1962). "The Mechanics of Deformation and Acoustic Propagation in Porous Media", Journal of Applied Physics, Vol. 33, No. 4, pp. 1482–1498.
7. Chan, A.H.C. (1988). "A Unified Finite Element Solution to Static and Dynamic Problems in Geomechanics", Ph.D. Dissertation, University College of Swansea, Swansea, U.K.
8. Dobry, R. and Abdoun, T. (1998). "Post-Triggering Response of Liquefied Sand in the Free Field and near Foundations" in "Geotechnical Earthquake Engineering and Soil Dynamics III (edited by P. Dakoulas and M. Yegian)", Geotechnical Special Publication No. 75, American Society of Civil Engineers, Reston, U.S.A.
9. Dobry, R., Taboada, V. and Liu, L. (1995). "Centrifuge Modeling of Liquefaction Effects during Earthquakes", Proceedings of the First International Conference on Earthquake Geotechnical Engineering, Tokyo, Japan, Vol. 3, pp. 1291–1324.
10. Dobry, R., Abdoun, T., O'Rourke, T. and Goh, S.H. (2003). "Single Piles in Lateral Spreads: Field Bending Moment Evaluation", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 129, No. 10, pp. 879–889.
11. Elgamal, A., Zeghal, M. and Parra, E. (1996). "Liquefaction of Reclaimed Island in Kobe, Japan", Journal of Geotechnical Engineering, ASCE, Vol. 122, No. 1, pp. 39–49.
12. Elgamal, A., Yang, Z., Parra, E. and Ragheb, A. (2003). "Modeling of Cyclic Mobility in Saturated Cohesionless Soils", International Journal of Plasticity, Vol. 19, No. 6, pp. 883–905.
13. Gunturi, V.R., Elgamal, A.-W. and Tang, H.-T. (1998). "Hualien Seismic Downhole Data Analysis", Engineering Geology, Vol. 50, No. 1, pp. 9–29.
14. He, L. (2005). "Liquefaction-Induced Lateral Spreading and Its Effects on Pile Foundations", Ph.D. Dissertation, Department of Structural Engineering, University of California San Diego, La Jolla, U.S.A.

15. Jakrapiyanun, W. (2002). "Physical Modeling of Dynamic Soil-Foundation-Structure-Interaction Using a Laminar Container", Ph.D. Dissertation, Department of Structural Engineering, University of California San Diego, La Jolla, U.S.A.
16. Karypis, G. and Kumar, V. (1998). "METIS: A Software Package for Partitioning Unstructured Graphs, Partitioning Meshes and Computing Fill-Reducing Orderings of Sparse Matrices, Version 4.0", Technical Report, Department of Computer Science/Army HPC Research Center, University of Minnesota, Minneapolis, U.S.A.
17. Law, K.H. and Mackay, D.R. (1993). "A Parallel Row-Oriented Sparse Solution Method for Finite Element Structural Analysis", International Journal for Numerical Methods in Engineering, Vol. 36, No. 17, pp. 2895–2919.
18. Lu, J. (2006). "Parallel Finite Element Modeling of Earthquake Site Response and Liquefaction", Ph.D. Dissertation, Department of Structural Engineering, University of California San Diego, La Jolla, U.S.A.
19. Lu, J., Peng, J., Elgamal, A., Yang, Z. and Law, K.H. (2004). "Parallel Finite Element Modeling of Earthquake Ground Response and Liquefaction", Earthquake Engineering and Engineering Vibration, Vol. 3, No. 1, pp. 23–37.
20. Lu, J., Elgamal, A. and Yang, Z. (2006). "OpenSeesPL Three-Dimensional Lateral Pile-Ground Interaction Version 1.00 User's Manual", Report SSRP-06/04, Department of Structural Engineering, University of California San Diego, La Jolla, U.S.A.
21. Parra, E. (1996). "Numerical Modeling of Liquefaction and Lateral Ground Deformation Including Cyclic Mobility and Dilation Response in Soil Systems", Ph.D. Dissertation, Department of Civil Engineering, Rensselaer Polytechnic Institute, Troy, U.S.A.
22. Parra, E., Adalier, K., Elgamal, A.-W., Ragheb, A. and Zeghal, M. (1996). "Analyses of Site Liquefaction and Remediation", Proceedings of the Eleventh World Conference on Earthquake Engineering, Acapulco, Mexico, Paper No. 372 (on CD).
23. Peng, J., Lu, J., Law, K.H. and Elgamal, A. (2004). "ParCYCLIC: Finite Element Modelling of Earthquake Liquefaction Response on Parallel Computers", International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 28, No. 12, pp. 1207–1232.
24. Prevost, J.H. (1985). "A Simple Plasticity Theory for Frictional Cohesionless Soils", International Journal of Soil Dynamics and Earthquake Engineering, Vol. 4, No. 1, pp. 9–17.
25. Tokimatsu, K. and Suzuki, H. (2004). "Pore Water Pressure Response around Pile and Its Effects on *p-y* Behavior during Soil Liquefaction", Soils and Foundations, Vol. 44, No. 6, pp. 101–110.
26. Yang, Z. (2000). "Numerical Modeling of Earthquake Site Response Including Dilation and Liquefaction", Ph.D. Dissertation, Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, U.S.A.
27. Yang, Z. (2002). "Development of Geotechnical Capabilities into OpenSees Platform and Their Applications in Soil-Foundation-Structure Interaction Analyses", Ph.D. Dissertation, Department of Civil Engineering, University of California, Davis, U.S.A.
28. Yang, Z. and Elgamal, A. (2002). "Influence of Permeability on Liquefaction-Induced Shear Deformation", Journal of Engineering Mechanics, ASCE, Vol. 128, No. 7, pp. 720–729.
29. Yang, Z., Elgamal, A. and Parra, E. (2003). "A Computational Model for Cyclic Mobility and Associated Shear Deformation", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 129, No. 12, pp. 1119–1127.
30. Yang, Z., Lu, J. and Elgamal, A. (2004). "A Web-Based Platform for Computer Simulation of Seismic Ground Response", Advances in Engineering Software, Vol. 35, No. 5, pp. 249–259.