

FULLY COUPLED DYNAMIC SOIL-STRUCTURE INTERACTION ANALYSES OF PILE FOUNDATIONS IN WEAK SOILS

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ABSTRACT

Dynamic soil-structure interaction analyses of several single pile foundations in a soft clay during seismic loading are presented. While one foundation was in the unimproved soil, the soil surrounding three other foundations is improved to varying extents. The analyses are performed using a framework-based finite element computer code TeraDysac. TeraDysac solves the coupled differential equations governing the behavior of the solid skeleton, pore water, and the structural elements using the TeraScale finite element framework. A framework represents a collection of common software components for building different computer codes and is an efficient way to build large parallel codes. The analyses reveal that lateral displacements of the piles can indeed be controlled by improving the ground around the piles to a sufficient extent.

Keywords: Finite element framework, fully coupled analysis, soft clay, soil-structure interaction

INTRODUCTION

Dynamic soil-structure interaction during seismic events is a complex problem. Soil, the embedded structural foundation, and the above ground structure undergo a series of complex interactions during earthquakes. Soils are nonlinear materials and in general consist of a solid skeleton, pore liquid (generally water), and pore gas (generally air). Any rigorous soil-structure interaction analyses should not only capture the complex interaction between the soil and the structure, but also capture the interactions between the solid skeleton and the pore fluids.

Pile foundations are an integral part of many civil engineering structures such as highway bridges, port wharves and tall buildings. As described above, the behavior of pile foundations during seismic loading is a complex problem. This complexity is further increased when weak soils such as soft clays and liquefiable loose sands surround the foundation. The seismic behavior of a pile foundation is dictated by its structural properties, pile head fixity, and the stiffness and strength of the soil surrounding the upper portion of the pile(s). The current philosophy for seismic design of bridges in U.S.A. is that pile foundations should be inhibited from experiencing inelastic behavior under earthquake loads. This is achieved in the design process by forcing the plastic action to occur in the columns and limiting the lateral displacements of pile foundations (e.g., Priestley et al., 1996; Caltrans, 2003). The reason behind this approach is that any failure of piles below ground will be difficult to detect and repair after an earthquake. Limiting the lateral displacement of a pile foundation is relatively easy to achieve in competent soils. In case of weak soils (e.g. soft clay or liquefiable loose sand), the current design practice is to use increased number of more ductile larger diameter piles,

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which are difficult and expensive to design and construct (see Zelinski et al., 1995). An innovative, more cost-efficient solution to this problem, which has not found wide usage due to lack of knowledge under seismic conditions, is to improve the soil surrounding the bridge foundation and thereby increasing its lateral stiffness. For example, Ohtsuka et al. (2004) analytically showed that soil improvement around a pile foundation in a weak soil can reduce the foundation cost by 28%. For structures undergoing seismic retrofit with existing pile foundations in weak soils, improving the soils may be the only option to improve the seismic behavior of the foundation.

In this paper we investigate the seismic behavior of several pile foundations with varying degrees of soil improvement around them using a fully coupled finite element computer code TeraDysac (Muraleetharan et al., 2003; Ravichandran, 2005). TeraDysac is a framework based finite element computer code. A finite element framework is an efficient way to develop extensible parallel computing computer programs. Following a brief description of the finite element framework (TeraScale, 2001) and TeraDysac an example fully coupled analysis of pile foundations in weak and improved soils using TeraDysac is presented.

SIMULATION TOOL: TERADYSAC

The 3-dimensional (3-D), fully coupled, parallel computer code TeraDysac (Muraleetharan et al., 2003; Ravichandran, 2005) used in this paper was developed using the TeraScale finite element framework (TeraScale, 2001). Brief descriptions of TeraScale framework and TeraDysac are presented in this section.

TeraScale Framework

A framework based finite element approach is one of the powerful and efficient methods for developing extensible finite element applications. A framework represents a collection of common software components for building different finite element codes. The basic premise behind the use of a framework is the recognition of a common set of tasks that must be accomplished in writing any finite element application code. These tasks can be factored out of the application codes and collected into a single tool kit. The goal is to separate the physics aspects from the computer science aspects of writing a computer code and thereby making the code development more efficient. A framework also provides an efficient way to develop a parallel computer code that is essential for analyzing large problems such as 3-D dynamic soil-structure interaction problems. Some of the key components of the TeraScale framework are:

- TeraScale Mesh Tool (Mesher): First a recipe that contains information such as coordinates of the vertices, straight edges, and number of elements along each edge is created. Then this recipe is used to create the required finite element mesh. The graphical user interface (GUI) used for creating a mesh recipe is shown in Figure 1(a).
- Data Model Object: This object is used to provide the required data such as the material properties, boundary conditions, and analysis control data to the finite element code. The GUI for the data model is shown in Figure 1(b). TeraScale's flexible data model makes it easy to add new analysis information such as a new material model or a boundary condition to this GUI.
- Grok: A flexible data reader/writer that recognizes the data being read and presents itself within the appropriate GUI. For example, the Grok is used to create the mesh recipe and the TeraDysac data model as shown in Figures 1(a) and 1(b).
- Finite Element Procedural Abstractions: The TeraScale framework provides predefined set of abstractions for the procedural flow of algorithms in the finite element application. These abstractions can be used to create any finite element code with any physics, including tightly coupled multiphysics applications such as TeraDysac.
- Parallel Mesh Object (PMO): The PMO is fundamentally structured to support parallel computation in a SPMD (Single Program Multiple Data) manner. It contains all the

information about shared nodes and/or elements and the communication lists required by the finite element algorithms.

- Math Library: A collection of methods for manipulating vectors, tensors, and matrices.
- Scalable Linear Equation Solver: A service that provides a common interface to linear solver services for scalable solution of sparse systems of equations on distributed and shared memory architecture.

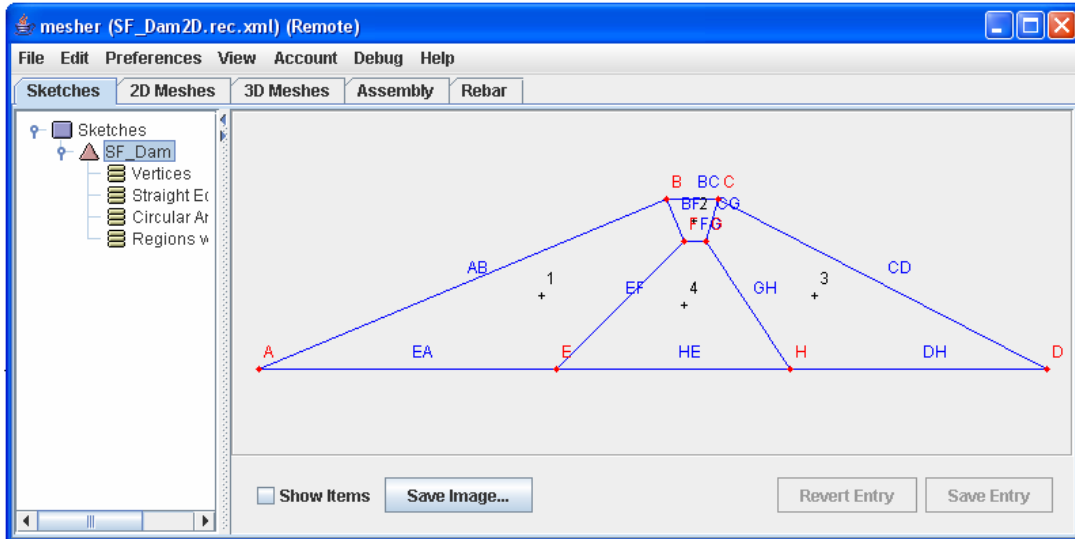


Figure 1(a): A TeraScale mesh recipe

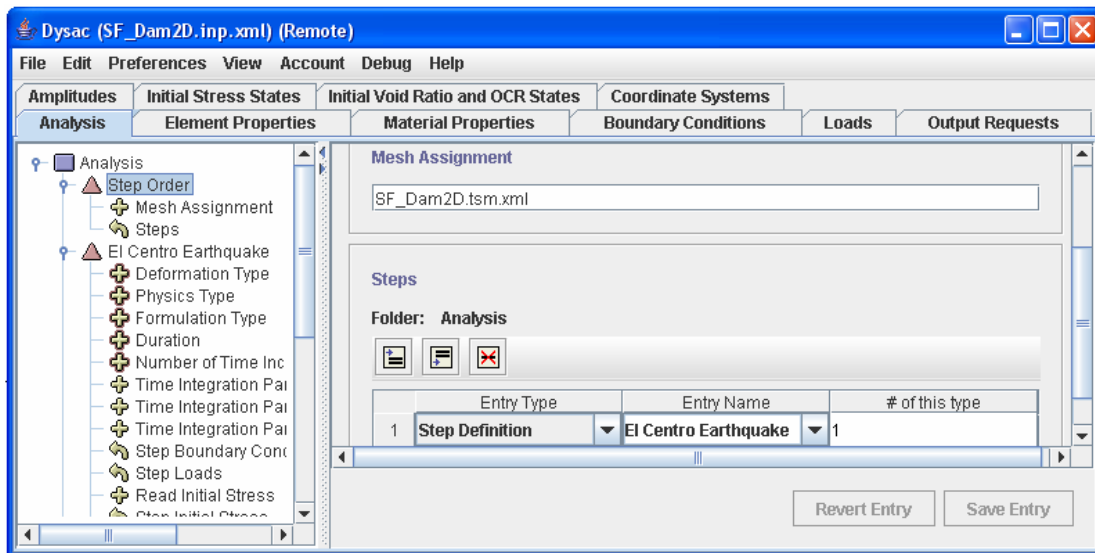


Figure 1(b): Data model for TeraDysac

TeraDysac

TeraDysac solves the fully coupled dynamic governing equations for saturated soils presented by Muraleetharan et al. (1994) and unsaturated soils given by Ravichandran (2005) within the TeraScale framework described above. TeraDysac is also capable of simulating large deformation problems and uses Timoshenko beam elements to model the structures. Displacements and rotations are used as nodal unknowns for Timoshenko beam elements. Four-noded quadrilateral (2-D) and eight-noded brick (3-D) isoparametric elements are used to model the soil. Solid and fluid displacements are used

as nodal unknowns for the soil elements. Therefore, when a beam element is connected to a soil element without an interface, at the common node, the beam element and the soil element will share the solid displacements. The rotations will only belong to the beam element and the fluid displacements will only belong to the soil element. This also means that the presence of beam elements within the soil will not impede fluid flow. Full Gauss quadrature and uniform gradient element formulation with hourglass control integration techniques are available to model compressible and incompressible materials. Both static and dynamic analyses can be performed using TeraDysac.

PILE FOUNDATIONS IN WEAK SOILS

The example problem selected for analysis using TeraDysac represents a centrifuge model test of 4 single pile foundations in a saturated clay as shown in Figure 2. The centrifuge model test is yet to be carried out and the TeraDysac results presented here are being used to design the centrifuge test. The soil profile consists of 10 m of soft clay underlain by 5 m of stiff clay. The improved ground around the piles is also simulated using the stiff clay. Simulated triaxial test results for these two clays are shown in Figure 3. A bounding surface elastoplastic constitutive model (Dafalias and Herrmann, 1986) is used to simulate the triaxial test results and is also used in TeraDysac. The model parameters are listed in Tables 1 and 2. As given in Table 1, the values of parameters λ , κ , and M_c are varied to obtain different stiffness and strength values for different clays. The values chosen for the stiff (and improved) clay are only initial estimates. The values of all the other parameters (Table 2) are kept the same for both clays. The model parameters used for the soft clay is same as those of Speswhite kaolin reported by Muraleetharan et al. (1994). An overconsolidation ratio of 3 was used for all clay layers.

All the pile foundations are 13.3 m long and have a diameter of 0.36 m and a density of 2500 kg/m³. The above ground piers are 1.5 m long and have the same diameter and density of the piles. Superstructures are simulated using a mass of 7630 kg on top of the piers. All the structural elements have a Young's modulus of 24.1 GPa. The finite element mesh used for the analysis is shown in Figure 4. The base motion applied is shown in Figure 5. A level ground boundary condition is simulated by constraining the displacements of the right boundary nodes to be same as those of the corresponding left boundary nodes (see Figure 4). No interface elements are used between the structure and the soil.

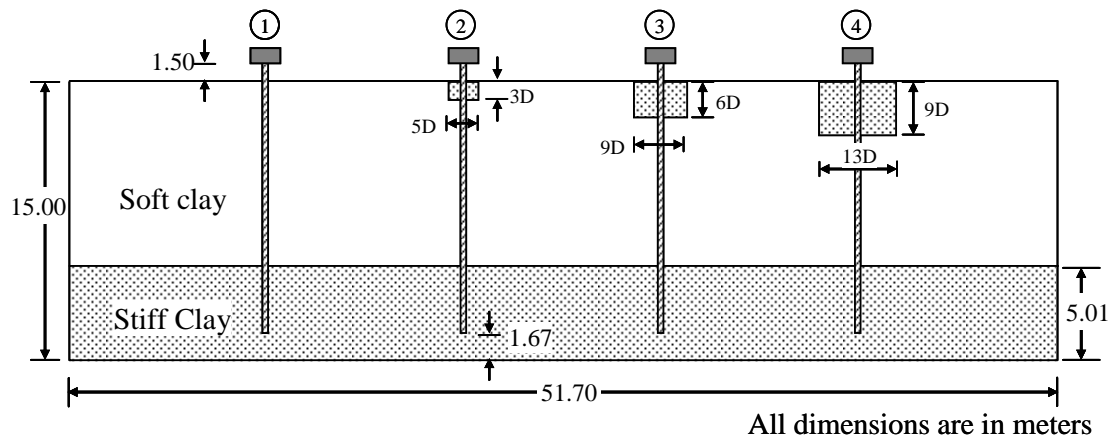


Figure 2: Single pile foundations in soft and improved clay ($D = 0.36$ m)

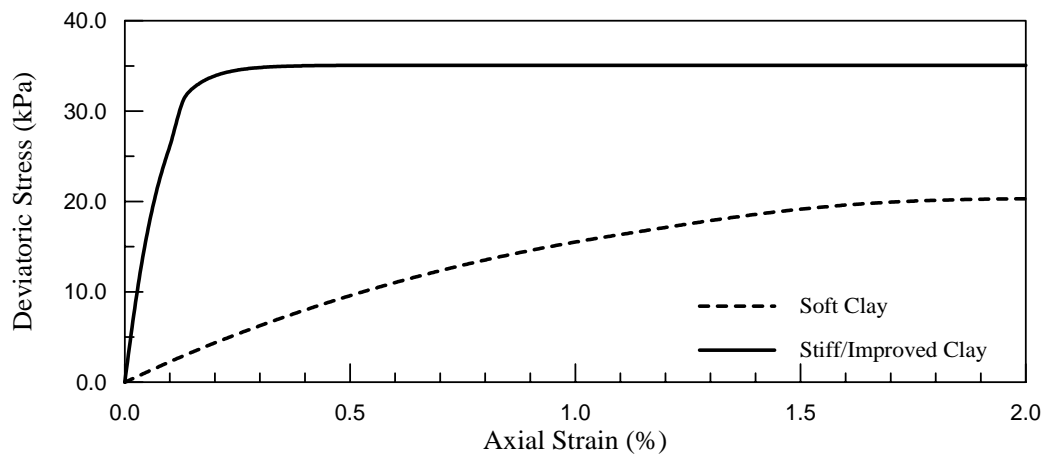


Figure 3: Simulated isotropically consolidated undrained compression triaxial test results for soft and stiff clays (consolidation pressure = 19.2 kPa)

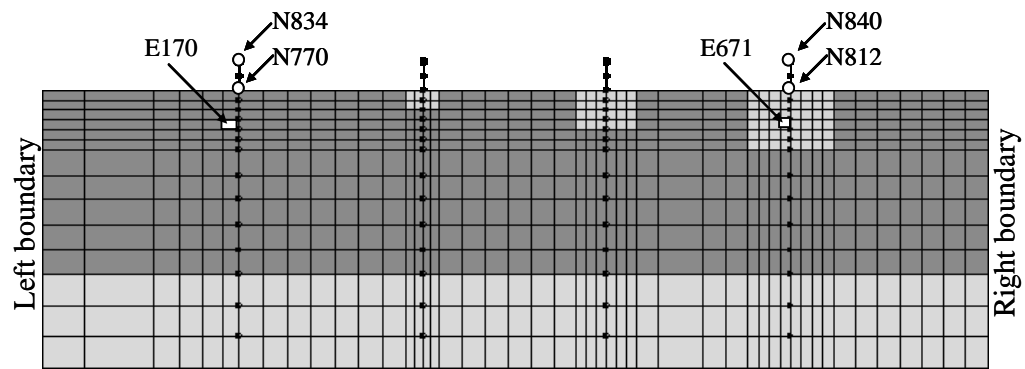


Figure 4: Finite element mesh

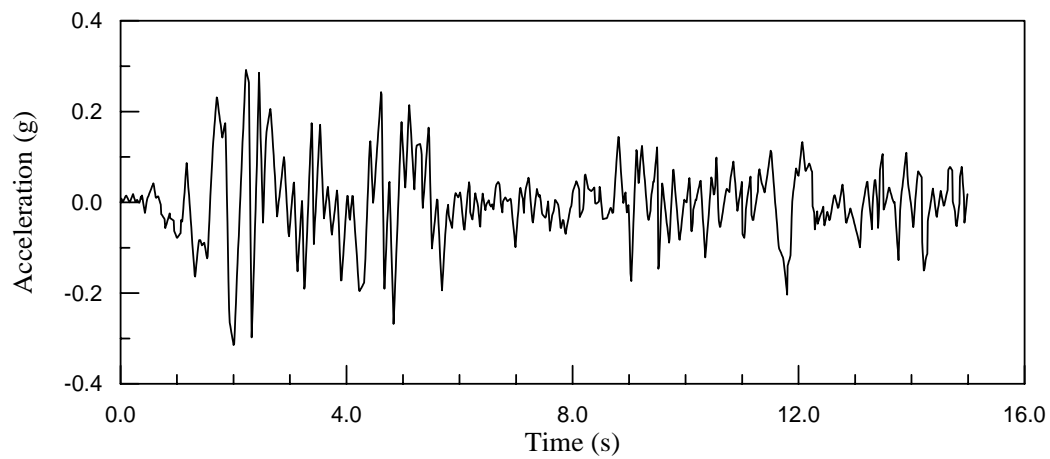


Figure 5: Horizontal base motion

Table 1: Model parameters for soft and stiff clays

Parameter	Soft Clay	Stiff/ Improved Clay
Slope of the isotropic consolidation line on $e - \ell n p'$ plot (λ)	0.250	0.017
Slope of an elastic rebound line on $e - \ell n p'$ plot (κ)	0.050	0.003
Slope of the critical state line in $q - p'$ space (compression) (M_c)	0.880	1.500

Table 2: Soil properties and other model parameters

Parameter	Value
Initial void ratio (e_0)	1.48
Specific gravity	2.62
Coefficient of earth pressure at rest (K_0)	0.69
Permeability (m/s)	1.7×10^{-9}
Traditional Model Parameters	
Poisson's ratio (ν)	0.30
Ratio of extension to compression value of M (M_e / M_c)	1.00
Bounding Surface Configuration Parameters	
Value of parameter defining the ellipse1 in compression (R_c)	2.40
Value of parameter defining the hyperbola in compression (A_c)	0.01
Parameter defining the ellipse 2 (tension zone) (T)	0.01
Projection center parameter (C)	0.00
Elastic nucleus parameter (S)	1.00
Ratio of triaxial extension to compression value of R (R_e / R_c)	0.92
Ratio of triaxial extension to compression value of A (A_e / A_c)	1.20
Hardening Parameters	
Hardening parameter (m)	0.02
Shape hardening parameter in triaxial compression (h_c)	3.00
Ratio of triaxial extension to compression value of h (h_e / h_c)	1.00
Hardening parameter on I-Axis (h_0)	2.00

Results and Discussion

The horizontal displacement-time histories of the superstructure mass for Piles 1 and 4 (see Figure 2) are shown in Figure 6. The horizontal displacement-time histories at the ground surface for these piles are shown in Figure 7. The deformed mesh at 6 s is shown in Figure 8. Excess pore water pressure-time histories for elements E170 and E671 are shown in Figure 9. The response of Piles 2 and 3 are in between those of Piles 1 and 4. Based on these results following observations can be made.

- Compared to the unimproved case, the improved ground around Pile 4 reduces the maximum displacement of the superstructure by about 0.12 m and the ground surface displacement by about 0.07 m (Figures 6 and 7).

- Ground improvement to a sufficient extent alters the deformed shape of the pile and therefore the shear stress and bending moment distributions (not shown here) within the piles (compare the deformed shapes of Piles 1 and 4 in Figure 8).
- Excess pore pressure increases are predicted by the fully coupled computer code TeraDysac, but there is no significant difference in pore pressure response within improved and unimproved clays near the piles.

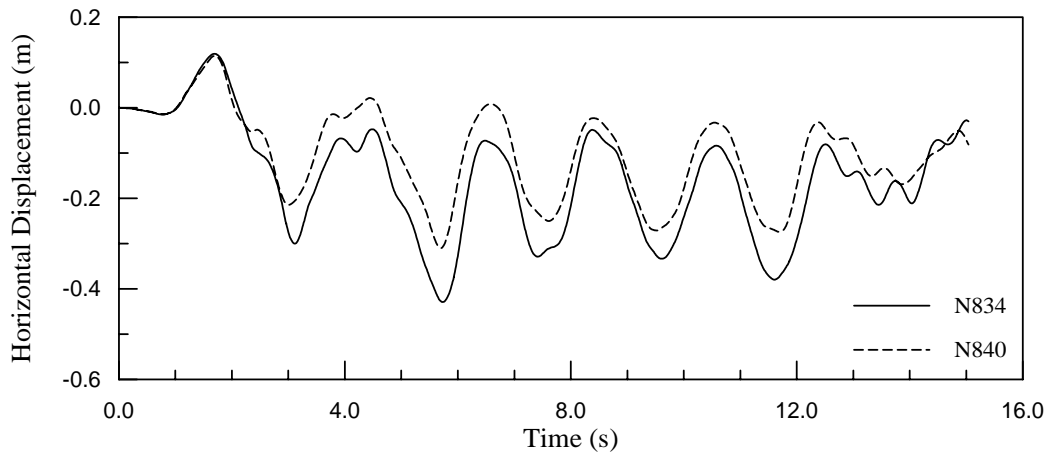


Figure 6: Horizontal displacement-time histories of the superstructure

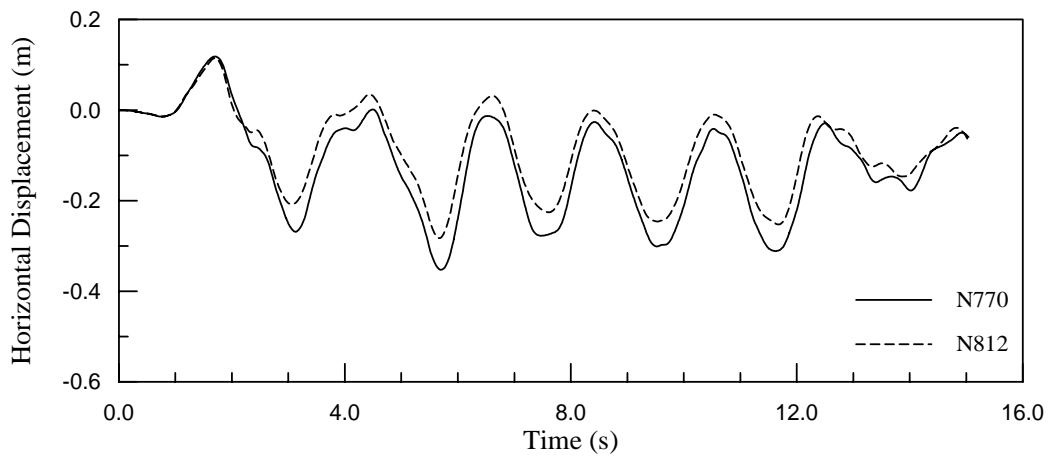


Figure 7: Horizontal displacement-time histories at the ground surface

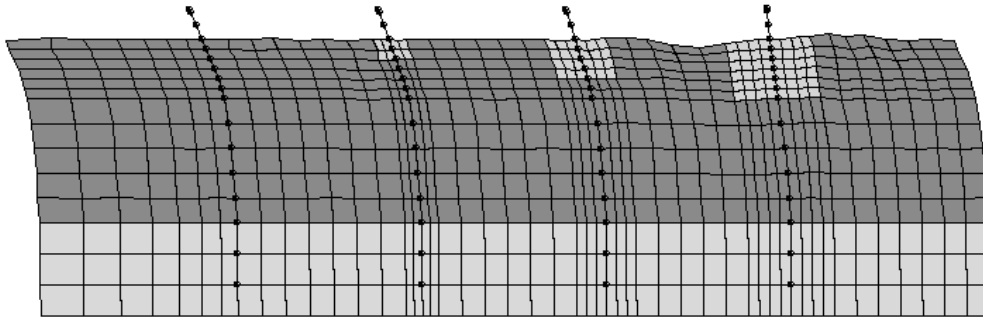


Figure 8: Deformed mesh at $t = 6.0$ seconds (displacements magnified by a factor of 8)

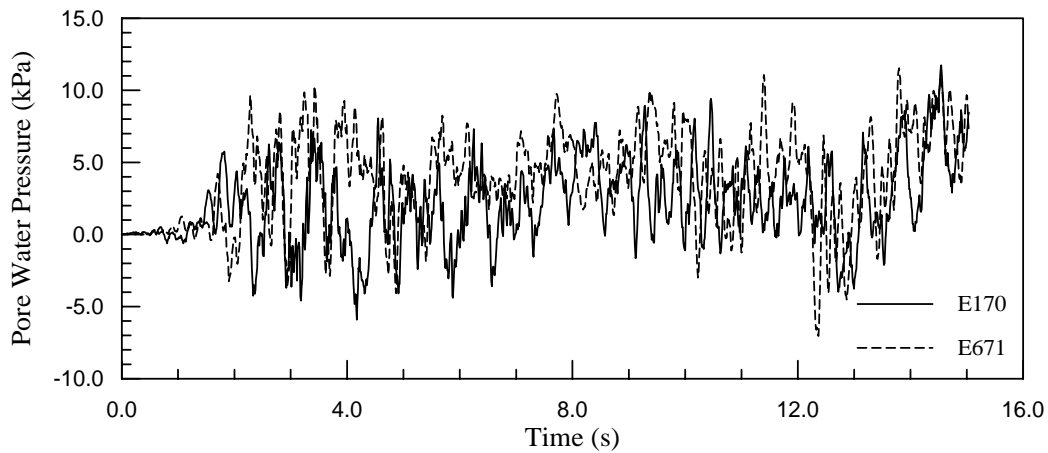


Figure 9: Excess pore pressure-time histories

SUMMARY AND CONCLUSIONS

A fully coupled finite element computer code, TeraDysac, is used to simulate the seismic response of pile foundations in soft and improved clays. TeraDysac is developed using the TeraScale finite element framework. A finite element framework is an efficient way to develop extensible parallel computing computer codes. The example problem used in this study reveals that lateral displacements of the superstructure and the ground around the piles can be controlled by improving the ground around the piles to sufficient extent.

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