Simulation of a Centrifuge Model Test of Pile Foundations in CDSM Improved Soft Clays

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ABSTRACT

A fully coupled finite element computer code, TeraDysac, was used to study the influence of ground improvement around piles in a planned centrifuge model test. TeraDysac considers the coupled differential equations governing the behavior of the soil skeleton, pore water, and the piles. Bounding surface elastoplastic constitutive models are used to simulate the stress-strain behavior of soils in TeraDysac. The prototype of the centrifuge model consisted of 10 m of soft clay underlain by 8 m of dense sand. Four 0.36 m diameter single piles were simulated with various extents of CDSM around the piles. The simulations using TeraDysac involved base shaking of the entire deposit. Static lateral loading of slightly different piles using the computer code LPILE is presented in a companion paper (Sritharan and Huang, 2010). It was shown that CDSM around the piles is effective in reducing the lateral displacements of the piles during static and dynamic loading.

INTRODUCTION

Dynamic soil-structure interaction during seismic events is an important and complex phenomenon. A series of complex nonlinear interactions take place in soil, embedded structural foundation, and the above ground structure during earthquakes. In general soil consists of a solid skeleton, pore fluid (generally water), and pore gas (generally air). It is very important to consider the interactions between the solid skeleton and the pore fluid while analyzing the complex interactions between soil, foundation and above ground structure.

Many important structures such as bridges, port wharves and tall buildings are built on pile foundations and their behavior during a seismic excitation is highly dependent on the soil supporting them. When the supporting soils are weak, the problem becomes more complex and weak soils such as soft clays and liquefiable loose sands need more attention. The behavior of pile foundations in liquefiable sands has been studied extensively, but not in soft clays and investigations for seismic response of piles in improved soils have been rarely performed.

As mentioned above, the behavior of a pile foundation under earthquake loads is very complex and depends on pile structural properties, pile head fixity, and the stiffness and strength of the soil surrounding the upper portion of the pile. The capacity design philosophy that is now commonly adopted in seismic design of bridges requires that pile foundations be inhibited from experiencing inelastic behavior under earthquake loads. To satisfy this design philosophy, the plastic hinge locations are chosen at the column ends and the superstructure and the pile foundations are designed for the column overstrength flexural moments (e.g., Priestley et al., 1996; Caltrans, 2003). The main motivation for using this approach is that any pile damage below ground will be difficult to detect and repair after an earthquake. Furthermore, in order for columns and the bridge to achieve a dependable plastic mechanism under earthquake loading, lateral displacement of a pile foundation should be limited, which 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 larger diameter piles, which are difficult and expensive to design and construct (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 weak soil can reduce the foundation cost by 28%. For structures undergoing seismic retrofit with existing pile foundations in weak soils, improving the soil may be the only option to improve the seismic behavior of the foundation. Therefore investigations for seismic response of piles in improved soils are really needed.

Soft clays (undrained shear strength < 25 kPa, Peak et al., 1974) are common in earthquake prone areas of the U.S. For example, San Francisco Younger (Holocene) Bay Mud, sepiolite-rich playas and bentonite deposits of southern Nevada, residual kaolinitic Kanasket Clays of Washington and the fire clays in Eastern Missouri and Arkansas within the New Madrid fault zone are all soft clays. It is important to investigate the behavior of pile foundations in soft clays using sophisticated fully-coupled simulation tools such as TeraDysac (Muraleetharan et al., 2003; Ravichandran, 2005) in order to understand the seismic behavior of pile foundations in improved soft clays. The Cement Deep Soil Mixing (CDSM) technique is very useful in soil improvement and can be used to enhance the behavior of soft clays. The CDSM method has become an increasingly popular method to improve the weak soils as there is sufficient increase in strength and stiffness to fulfill the intended functions. Lorenzo and Bergado (2006) showed that strength and stiffness of the CDSM improved soft Bangkok Clay increased dramatically.

In this paper, the seismic behavior of pile foundations with varying degrees of CDSM improvement around them is investigated using a fully coupled finite element computer code TeraDysac. Static lateral loading analyses of slightly different piles in improved and unimproved soils can be found in a companion paper (Sritharan and Huang, 2010).

SIMULATION TOOL TERADYSAC

TeraDysac is a 3-dimensional, fully coupled, parallel computer code and was developed using the TeraScale finite element framework (ANATECH, 2001). A framework is used for building different finite element codes and framework based finite element approach is one of the powerful and efficient methods for developing extensible finite element applications. It is also useful in developing parallel computer codes that are essential for analyzing complex problems such as 3-dimensional dynamic soil-structure interaction problems. TeraDysac solves the fully coupled dynamic governing equations for saturated soils presented by Muraleetharan et al. (1994) and unsaturated soils by Ravichandran (2005) within the TeraScale framework. Large deformation problems can be simulated in TeraDysac and both static and dynamic problems can be solved using TeraDysac. In TeraDysac, the soil can be modeled using four-noded quadrilateral (2-D) and eight-noded brick (3-D) isoparametric elements and the piles with Timoshenko beam elements. Solid and fluid displacements are the nodal unknowns for the soil elements, and displacements and rotations are the nodal unknowns for the pile elements. Therefore a pile element and a soil element will share the solid displacements when a pile element is connected to a soil element without an interface at a common node. The rotations will only belong to the pile element and the fluid displacements will only belong to the soil element and therefore the fluid flow will not be impeded due to the presence of piles within the soil.

PILE FOUNDATIONS IN CDSM IMPROVED CLAYS

A planned centrifuge model test of 4 single pile foundations with varying degrees of CDSM improvement around them in a saturated soft clay was selected for the analysis in TeraDysac. The centrifuge test was recently completed and the results are still being analyzed and hence no comparisons with the test results are presented in this paper. Figure 1 shows the centrifuge model with the prototype dimensions in meters.

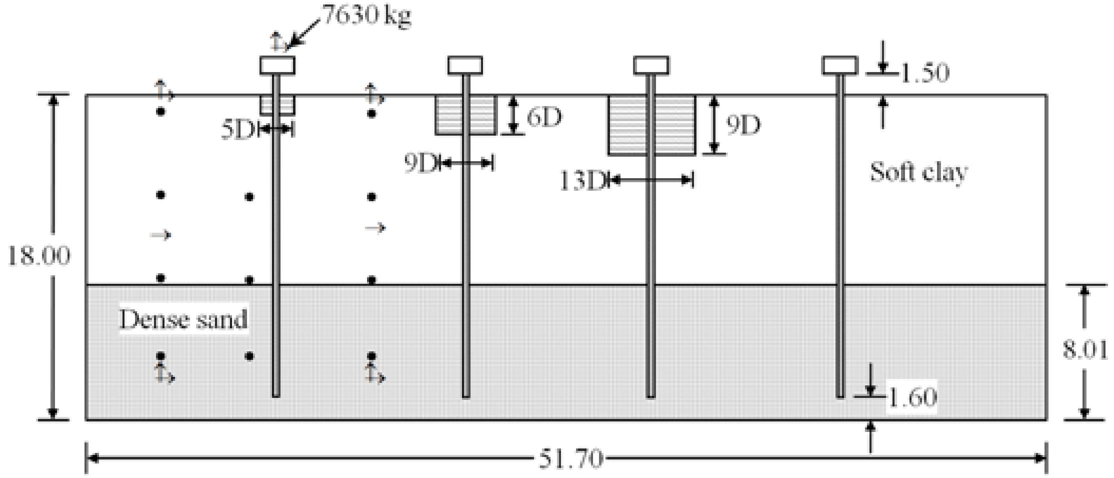

Figure 1. Centrifuge model (D= 0.36 m).

The soil profile consists of approximately 10 m of soft clay underlain by 8 m of dense sand. Four 0.36 m diameter single piles were simulated with various extents of CDSM around the piles as shown in Figure 1. All the pile foundations are 16.4 m in length and have a density of 2500 kg/m^3. The above ground piers are 1.5 m long and have the same diameter and density of the piles. A mass of 7630 kg is used to simulate the superstructures on top of the piers. All the structural elements have a Young's modulus of 24.1 GPa.

The simulated triaxial test results for these two clays are shown in Figure 2. A single element computer code (EVALK) which utilizes a bounding surface elastoplastic constitutive model (Dafalias and Herrmann, 1986) is used to simulate the triaxial test results. The same constitutive model is also used in TeraDysac. The parameters used for the analysis are listed in Tables 1 and 2. The parameters for the soft clay given in Table 1 were measured in the laboratory. The parameters λ, κ, and M_c,and the overconsolidation ratio (OCR) for the improved soil were inferred from Lorenzo and Bergado (2006) and the permeability of the improved soil was estimated. The soft clay mixed with 10% cement at a water:cement ratio of 1:1 yielded an unconfined compression strength of approximately 750 kPa. The stiffness and strength of the improved soil shown in Fig. 2 reasonably matches those shown by Lorenzo and Bergado (2006).

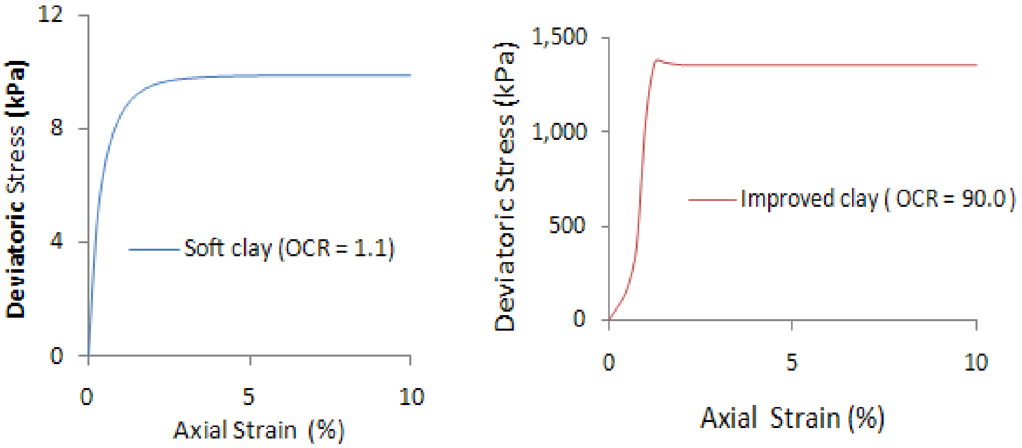

Figure 2. Simulated isotropically consolidated undrained compression triaxial test results for soft and improved clays (initial confining pressure = 40 kPa)

Table 1. Model parameters for soft and improved clays

Parameter	Soft Clay	Improved Clay
Slope of the isotropic consolidation line on e - ℓn p' plot (λ)	0.182	0.015
Slope of an elastic rebound line on e - ℓn p' plot (κ)	0.026	0.002
Slope of the critical state line in q - p' space (compression) (M_c)	0.984	2.952
Permeability (m/s)	9.26x10^{-10}	1.85x10^{-10}

Table 2. Other model parameters and soil properties

Parameter	Value
Initial void ratio (e_0)	1.20
Specific gravity	2.70
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$_o$)	2.00

The finite element mesh and the base motion used for the analysis are shown in Figures 3 and 4, respectively. Interface elements were not used between the piles and the soil. A level ground boundary condition is simulated in the analysis.

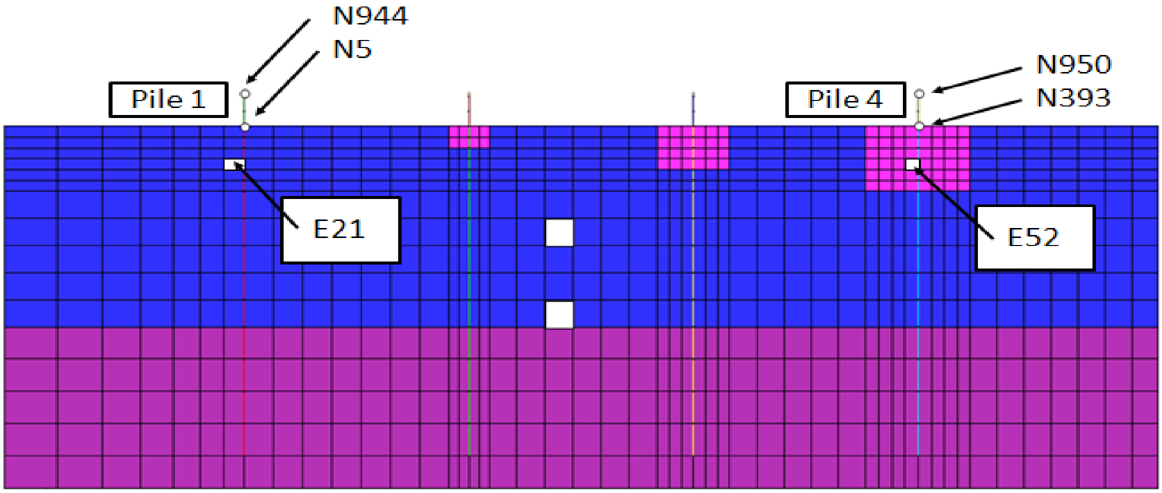

Figure 3. Finite element mesh.

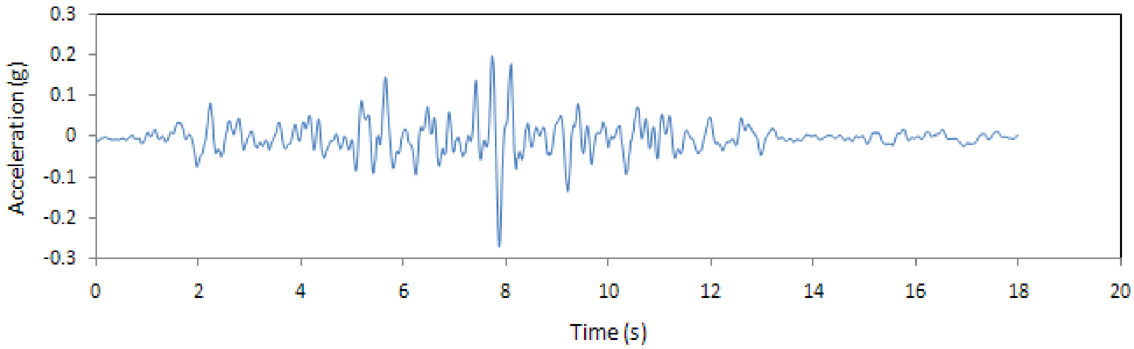

Figure 4. Horizontal base motion.

RESULTS AND DISCUSSION

The deformed mesh at 8.2 s is shown in Figure 5. The horizontal displacement-time histories of the ground surface and the superstructure for Piles 1 and 4 are shown in Figures 6 and 7, respectively. Excess pore water pressure-time histories for elements E21 (unimproved clay) and E52 (improved clay) are shown in Figure 8. The bending moment distribution within Piles 1 and 4 are shown in Figure 9. TeraDysac simulation results show that the response of Piles 2 and 3 are in between those of Piles 1 and 4.

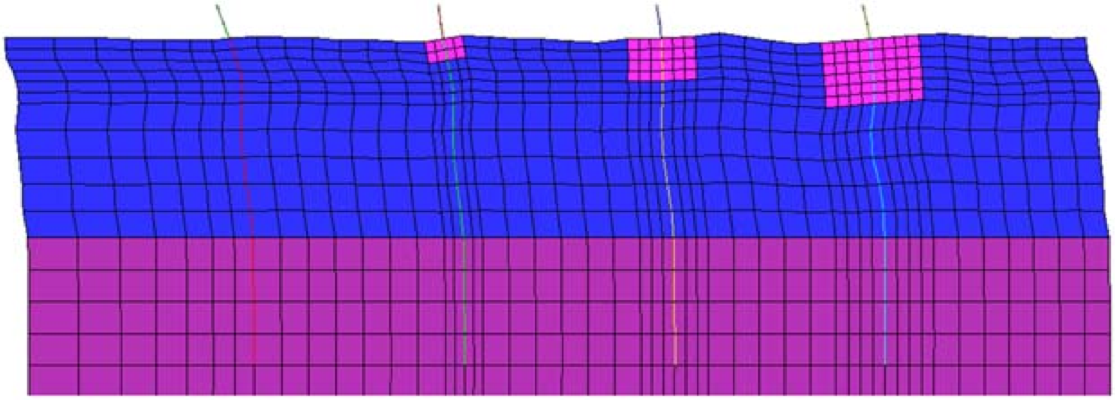

Figure 5: Deformed mesh at t = 8.2 s (displacements magnified by a factor of 20).

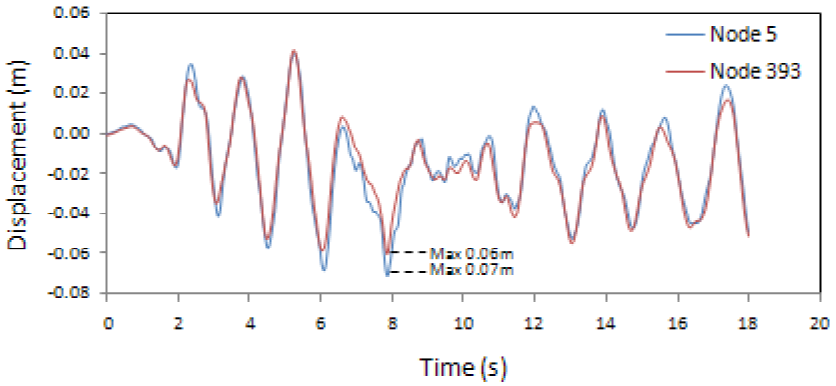

Figure 6. Horizontal displacement-time histories at the ground surface.

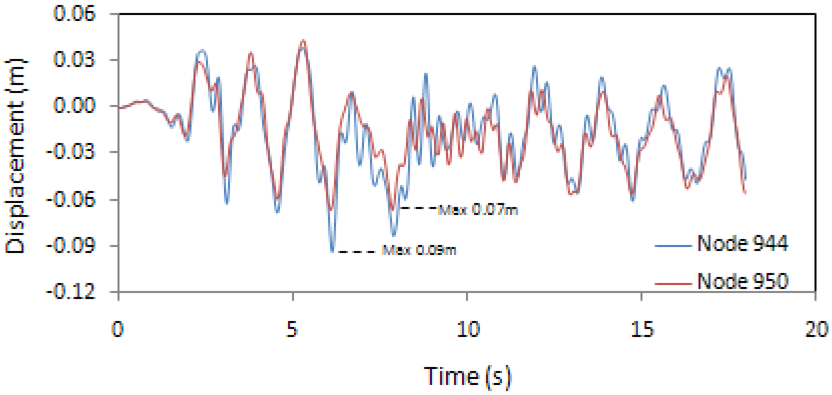

Figure 7. Horizontal displacement-time histories of the superstructure.

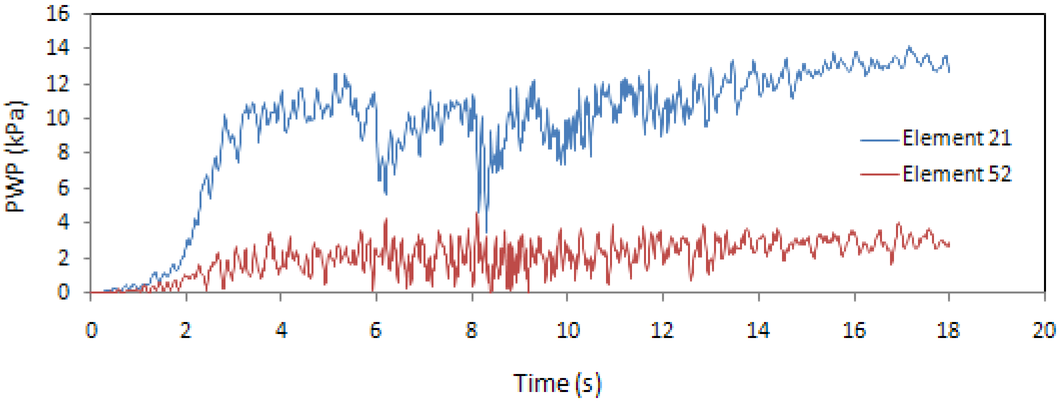

Figure 8: Excess pore pressure-time histories.

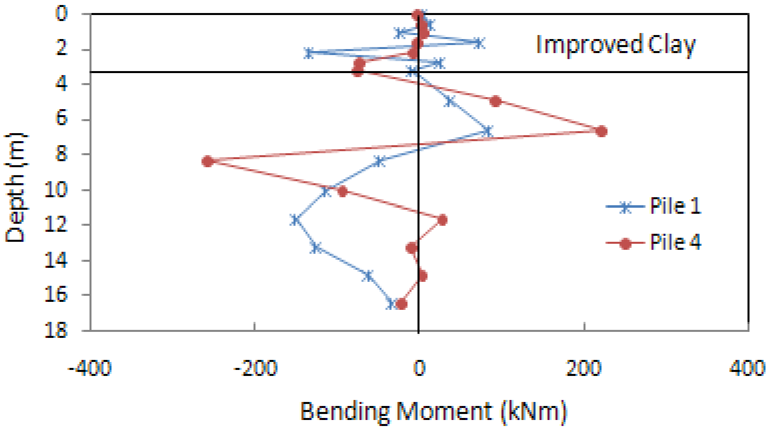

Figure 9: Bending moment distribution within piles.

The following observations can be made based on the TeraDysac simulations.

- Compared to the unimproved clay, the CDSM improved clay around Pile 4 reduces the maximum superstructure and ground surface displacements by about 2 cm and 1 cm, respectively.

- Excess pore pressure increases are predicted by the fully coupled computer code TeraDysac within the improved and unimproved clay. The pore pressure increases are, however, substantially larger within the unimproved clay.

- CDSM ground improvement increases the bending moments within the piles.

CONCLUSIONS

A fully coupled finite element computer code, TeraDysac, is used to simulate the seismic response of pile foundations in CDSM improved soft clays. The simulations show that CDSM around the piles is effective in reducing the lateral displacements of the piles during seismic events and pore pressure generated within the soil. CDSM around the piles, however, increases the bending moments within the piles and hence these piles have to be properly designed to carry the larger bending moments.

ACKNOWLEDGEMENTS

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