Experimental Investigation of soil confinement impact on RC-pile nonlinearity

Conference Paper · September 2013

Ahmed Youssef
The University of Tokyo

Koichi Maekawa
The University of Tokyo

GEO MONTRÉAL 2013

Experimental Investigation of soil confinement impact on RC-pile nonlinearity

Ahmed Mohammed Youssef MOHAMMED[1], Koichi MAEKAWA[2]
[1.] *Post-doctoral Researcher, Department of Civil Engineering, The University of Tokyo, Japan*
E-mail: mohammed@concrete.t.u-tokyo .ac.jp
[2.] *Professor, Department of Civil Engineering, The University of Tokyo, Japan*

ABSTRACT

Small-scale RC-circular piles with 5 cm diameter were produced as an alternative of real ones and loaded by combined shear and flexure under the soil confinement of different magnitudes. In order to identify the lateral confinement, SNAP-PINS were newly utilized as a replacement of stirrups for miniature RC members. The experimental results show that soil confinement improves the RC-pile ductility by suppressing the spalling of concrete cover and local buckling of reinforcement, and that the magnitude of soil confinement may reach the level produced by the stirrups inside members. But at the same time, the greater soil confinement was experimentally confirmed to increase in shear forces to RC piles and simultaneously become a risk factor of shear failure, too. This small scale RC-pile is newly proposed to be used in the future small-scale experiment instead of common elastic material ones, while it enjoys the full features of RC nonlinearity. The flexural and shear failures of RC piles under soil confinement could be successfully simulated by using a full three-dimensional finite element program called COM3D, which was developed at the University of Tokyo. This analysis has been used in practice for seismic performance assessment of underground ducts, RC piles, and in-ground LNG storage tanks in consideration of soil-structure interaction under static and dynamic loading.

1 INTRODUCTION

The serious damage caused by the Hyogoken-Nanbu Earthquake of 1995 to both on-ground and underground structures provided impetus for experimental and analytical studies on the seismic performance of pile foundations as a pressing issue of concern. A series of variant scale experiments were carried out (Tamura *et al*. 1999; Shirato *et al*. 2007; Towhata 2008). As large-scale experiments are generally difficult to execute for parametric studies, small-scale ones have been conducted. Elastic piles (steel, aluminum, plastics) have been used in rather small-scale experiments where the structural nonlinearity of piles may not be explicitly taken into account (Matsumoto *et al*. 2010; Wilson 2000).

The main function of RC piles and columns is to sustain gravitational axial loads, but other straining actions of combined flexure and shear may hardly be avoided because of the lateral actions of seismic loads and constraints by soil foundation. The current design concept is to make structures safe by properly evaluating deformability under a precondition to allow damage to some extent during an intense earthquake (Takase *et al*. 1999), and avoiding occurrence of shear failure to axially loaded RC members in compression by increasing the member-inherent ductility, which is practically designated with the index denoted by JSCE 2002 as illustrated in Figures 1 and 2.The comparatively greater stiffness of soil may induce shortened shear span length in piles, resulting in higher shear forces as shown in Figures 1.

The Load carrying mechanism of the rafted pile foundation is proportionally divided between the raft and piles depending on the relative stiffness between raft, and piles as shown in Figure 3. While the piled raft foundations have the potential to provide economical foundation systems, under the appropriate geotechnical conditions (Poulos 2001), the raft load-share may increase in the confining pressure on the pile head and it may cause short shear span (shear failure potential) close to the RC piles heads. Accordingly, investigating the positive and negative effects of soil confinement on the RC-piles nonlinearity is a key factor for future rational design of RC-structures.

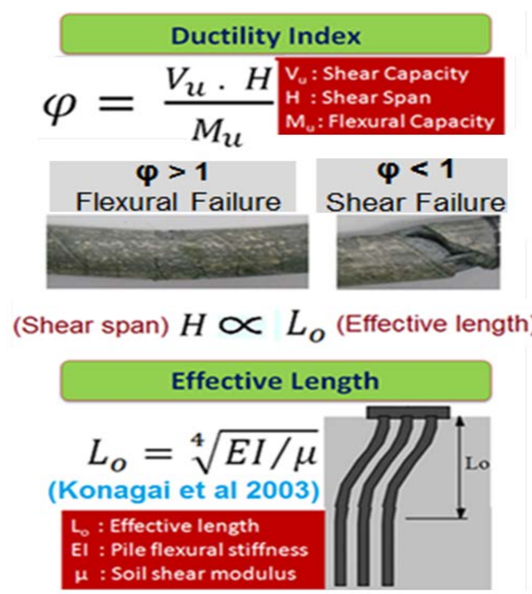

Figure 1. RC piles failure modes

Figure 2. Ductility of RC piles

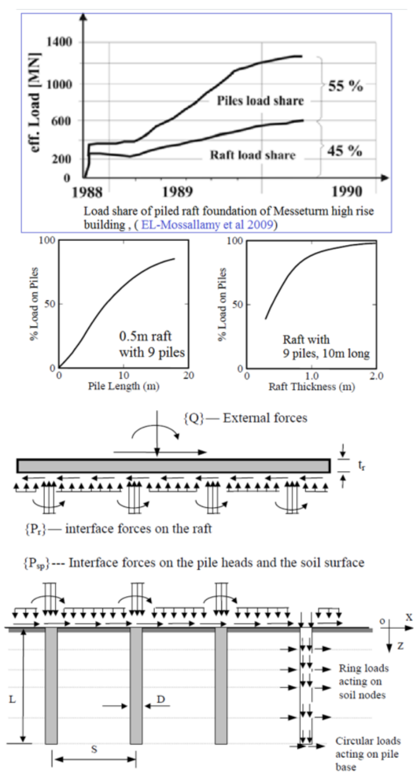

Figure 3. Rafted pile foundation load carrying mechanism (Poulos 2001)

2 CONSTITUTIVE MODELING

A reinforced concrete material model has been constructed by combining constitutive laws for cracked concrete and those for reinforcement. The fixed multi-directional smeared crack constitutive equations (Maekawa *et al*. 2003) are used as summarized in Figure 4. Crack spacing and diameters of reinforcing bars are implicitly taken into account in smeared and joint interface elements no matter how large they are.

The constitutive equations of structural concrete satisfy uniqueness for compression, tension and shear transfer along crack planes. The bond between concrete and reinforcing bars is taken into account in the form of tension stiffening model, and the space-averaged stress-strain relation of reinforcement is assumed to represent the localized plasticity of steel around concrete cracks. The hysteresis rule of reinforcement is formulated based upon the Kato's model (1979) for a single bar under reversed cyclic loads. This RC in-plane constitutive modeling has been verified by member-based and structural-oriented experiments. Herein, the authors skip the details of the RC material modeling by referring to Maekawa et al. (2003).

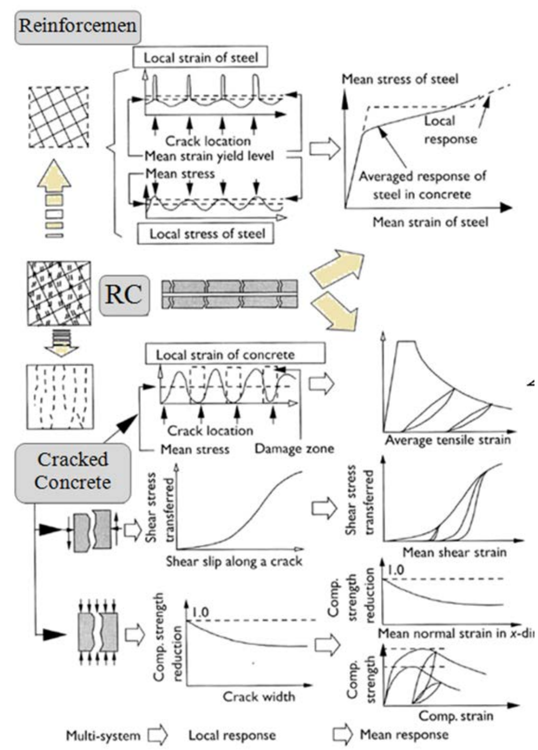

Figure 4. RC constitutive modeling (Maekawa et al. 2003)

A nonlinear path-dependent constitutive model of soil is essential to simulate the entire RC-soil system. Here, the multi-yield surface plasticity concept (Towhata *et al.* 1985; Towhata 2008) is applied to formulate the shear stress-shear strain relation of the soil which may follow hysteresis Masing's rule (1926) for example. The basic idea of this integral scheme is actualized to sum up component stresses that may represent microscopic events of particles' mechanics. First, the total stress applied on the soil particle assembly, denoted by σ_{ij}, can be decomposed into the deviatoric shear stresses (s_{ij}) and the mean confining stress (p) as,

$$\sigma_{ij} = s_{ij} + p\delta_{ij} \quad [1]$$

where δ_{ij} is Kronecker's delta symbol.

Soil is idealized as an assembly of finite numbers of elasto-perfectly plastic components, which are conceptually connected in parallel as shown in Figure 5 .The shear strength is dependent on the confinement developing in finite elements (Figure 6).

As each component is given different strengths, all components subsequently begin to yield at different total shear strains, which results in a gradual increase of entire nonlinearity. The nonlinear behavior appears naturally as a combined response of all components.

The multi-yield surface plasticity model has been used to simulate the static and seismic behaviors of nonlinear soil-structure systems (An *et al*. 1997, and Nam *et al*. 2006). Regarding the soil-RC interaction, the applicability of the models used in this paper was examined and verified by Maki *et al.* (2005).

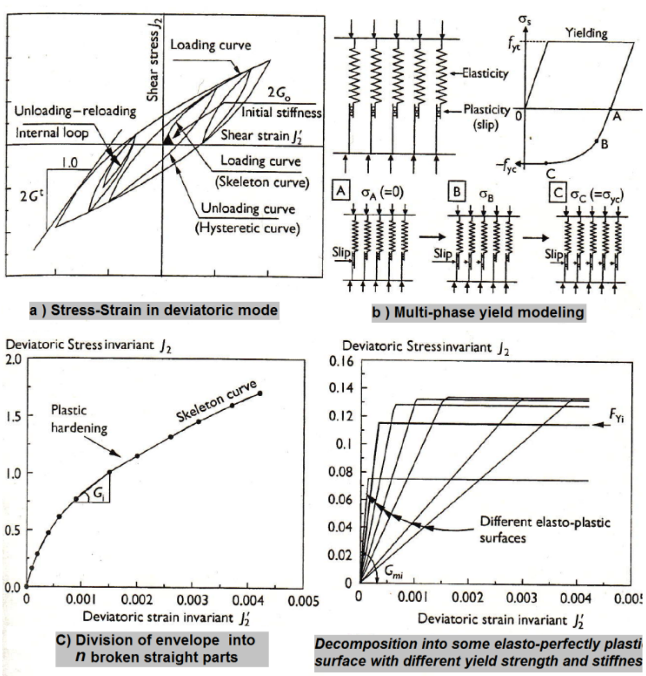

Figure 5. Multi-component plasticity modeling for soil used (Maekawa et al. 2003)

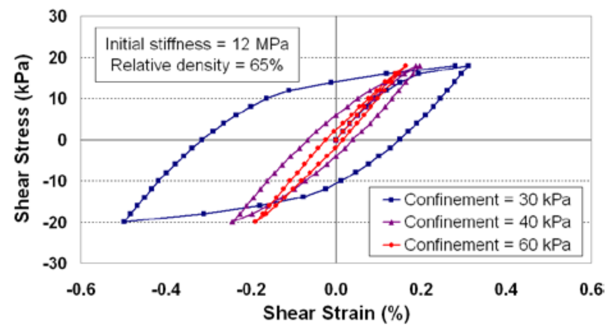

Figure 6. Confinement dependent soil model (Okhovat, et al. 2009)

3 RC PILES BENDING TEST

Three RC piles 60 cm in span length were tested while being subjected to three different levels of soil pressure (indicated as low, medium and high) as shown in Figure 7. This static state of loading is thought to be similar to the pile tops subjected to horizontal actions. A rigid soil box (46.4 cm x 70.0 cm x 80 cm) was firmly fixed to the load-testing machine and first filled with Hamaoka sand to a depth of 10 cm. Afterwards, the miniature mockup pile was hanged horizontally by two vertical hangers (PC tendons). Every hanger was connected to the hydraulic jacks and the load cell placed on the rigid steel box beam. Two manual pumps were connected to both hydraulic jacks. After the setup, Hamaoka sand was poured up to a soil depth of 60 cm, and a set of two steel plates connected by a steel I-beam was placed on the soil top surface as shown in Figure 8.

After all the experiment apparatus was set up, two loading steps were carried out. First, the top ends of the hangers were released and the loading machine head was statically moved downward. The vertical force was transferred to the soil surfaces through the I-beam's upper flange (confining load level, 10 kN, 20 kN, and 40 kN). The vertical load was kept constant and uniformly distributed on the soil top surface through two rectangular bearing plates (64 cm x 18 cm x 2.2 cm) bolted to the I-beam's lower flange as shown in Figure 8. After setting a certain level of confinement, the top ends of the hangers were manually tied and lifted up using two sets of manually controlled hydraulic jacks. The load and displacement of every hanger were measured by using the load cells and the displacement transducers.

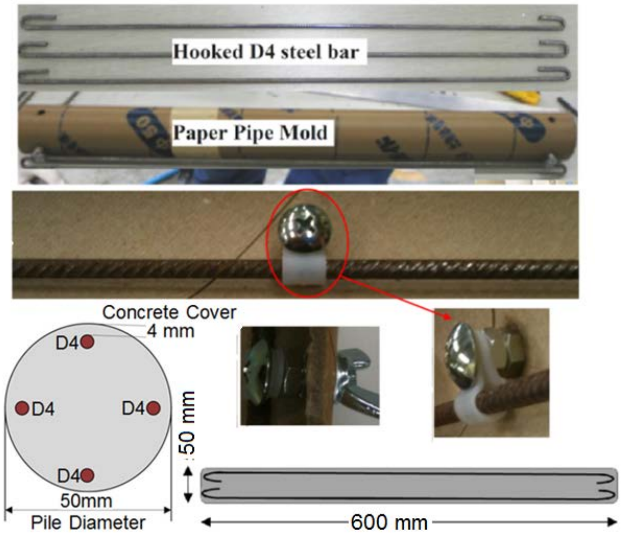

Figure 7. RC pile cross section

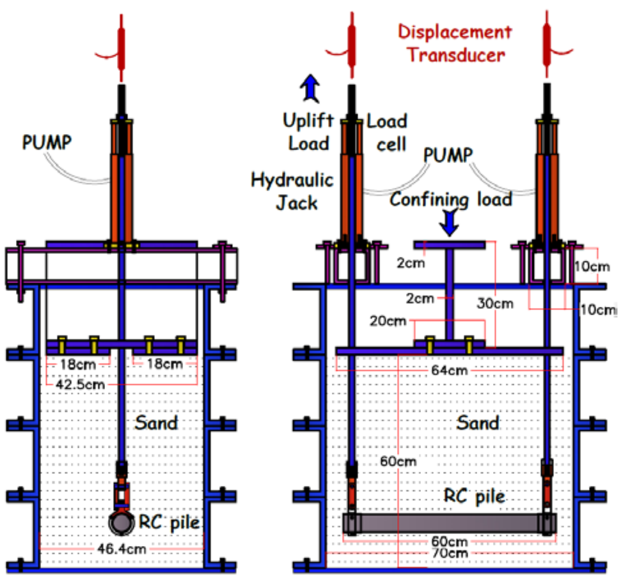

Figure 8. RC pile bending test under soil confinement

As the result of full symmetry in the vertical plane view of this experiment around two perpendicular axes (X-axis and Y-axis as shown in Figure 8), one quarter of the experimental model was analytically simulated to optimize the whole number of finite elements and to reduce the computational time, as shown in Figure 9. The friction between the hangers and the soil box with sandy soil was neglected in the simulation model. The set of two rectangular plates and I-beam was simulated by stiff rectangular plates, as shown in Figure 9. The initial stiffness of the soil was assumed to be 6 MPa as the result of low initial compaction and the small thickness of the soil layer.

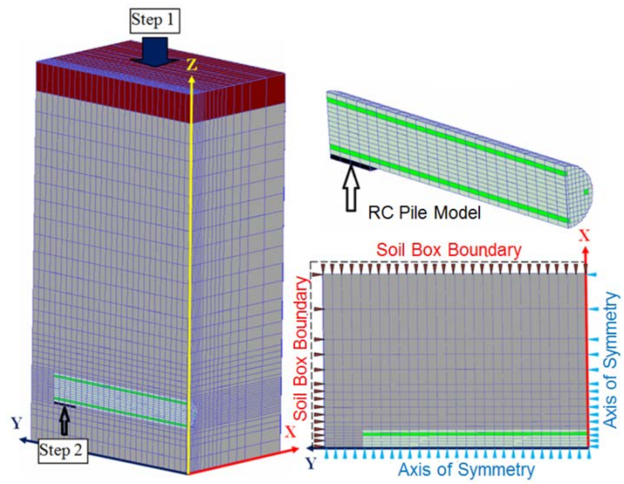

Figure 9. Analytical model of RC pile bending test

4 FAILURE MODES OF RC PILES

As for the overall soil-pile interaction, the uplifting force and the displacement of both left and right hangers were controlled to produce simultaneous movement to both ends of embedded piles in the soil foundation. The uplift forces of the two hangers are consistently controlled under different levels of soil confinement pressure. The analyzed uplift load-displacement diagrams are not so far from those of the experiments. Figure 10 shows the sensitivity of soil mean confining pressures on the uplift force-displacement relations.

Figure 11 shows the experimentally obtained failure mode in both flexure and shear. When greater soil confinement is applied, larger shear force may arise at the loading ends of the piles. Then, the impacts of soil can be experimentally detected by checking the mode of failure at the loading points. As a matter of fact, shear failure can be seen when the soil's overall confining pressure is large. The computational simulation of the mockup pile bending test shows consistency of different failure modes with the experimental results, as shown in Figure 11.

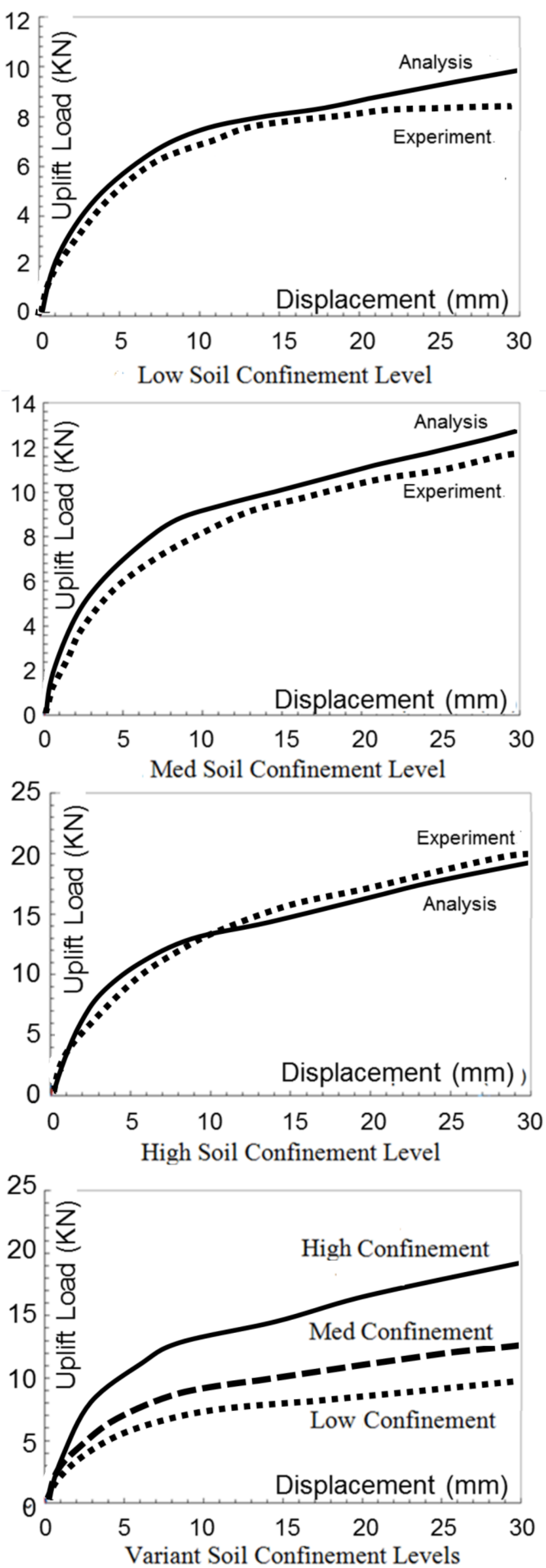

Figure 10. Uplift load-displacement of RC piles

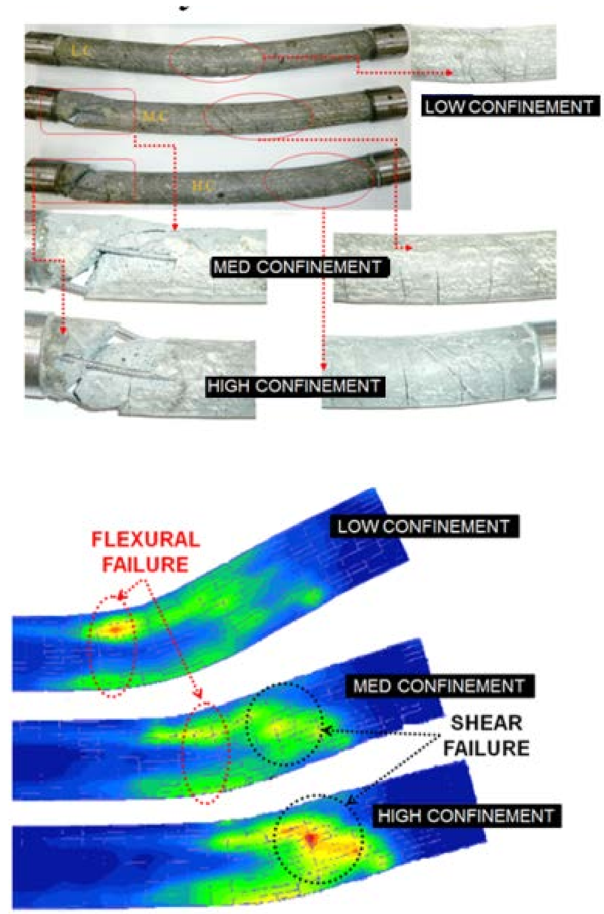

Figure 11. Damage mechanism of RC piles

5 CONCLUSION

Small-scale RC piles were newly produced for pile-structure interaction tests, and it was clearly shown that shear failure can be successfully reproduced in experiments using small-scale pile replicas made of mortar and featuring specially manufactured deformed reinforcing bars of small sizes.

Although soil confinement increases the RC pile ductility associated with crushing of cover concrete and the local buckling of steel, it may reduce the effective pile shear span length, which drastically increases the risk of shear failure. The authors propose that this trade-off confirmed by the analysis shall be explicitly considered in practical designs.

By using full three-dimensional simulation without degeneration of degree of freedom of strain fields, the flexural and shear failures of piles under soil confinement could be simulated.

REFERENCES

An, X., Shawky, A. A. and Maekawa, K. 1997. The Collapse mechanism of a subway station during the Great Hanshin earthquake, Cement and Concrete Composite, 19: 241-257.

EL-Mossallamy, Y.M. Lutz, B. and Duerrwang, R. 2009. Special aspects related to the behavior of piled raft foundation, Proceedings of the 17th international conference on soil mechanics and geotechnical engineering, Egypt, 1366-1369.

Japan Society of Civil Engineers. 2002. Recommended code and manual for seismic performance verification of out-door important structures of nuclear power plants, Concrete International Library.

Kato, B. 1979. Mechanical properties of steel under load cycles idealizing seismic action, CEB Bulletin D'Information, 131: 7-27.

Konagai, K., Yin, Y. and Murono, Y. 2003. Single beam analogy for describing soil–pile group interaction. Soil Dynamics and Earthquake Engineering, 23: 213-221.

Maekawa, K., Pimanmas, A. and Okamura, H. 2003. Nonlinear Mechanics of Reinforced Concrete, Spon Press, London.

Maki, T., Maekawa, K. and Mutsuyoshi, H. 2005. RC pile-soil interaction analysis using a 3D-finite element method with fiber theory-based beam elements. Earthquake Engineering and Structural Dynamics, 99: 1-26.

Masing, G. 1926. Eigenspannungen and verfestigung beim messing, Proc. of Second International Congress of Applied Mechanics, 332, Zurich.

Matsumoto, T., Nemoto, H., Mikami, H., Yaegashi, K. Arai, T. and Kitiyodom, P. 2010. Load tests of piled raft models with different pile head connection conditions and their analysis, Soil and Foundation, 50(1): 63-81.

Okhovat, M.R., Shang, F. and Maekawa, K. 2009. Nonlinear seismic response and damage of reinforced concrete ducts in liquefiable soils, Journal of Advanced Concrete Technology, 7(3).

Poulos, H.G. 2001. Methods of analysis of piled raft foundations, Report, Coffey Geosciences Pty. Ltd. & The University of Sydney, Australia.

Shirato, M. and Nakatani, S. 2007. Seismic design specifications for Japanese highway bridge deep foundations against large earthquakes. Advances in Deep Foundations, 397-402.

Takase, N., Ikegame, M., Tanamura, S., Nishimura, A. and Kondou, M. 1999. Seismic design of pile foundation. QR of RTRI, 40(3): 152-157.

Tamura, S., Minowa, C., Suzuki, Y., Sugimoto, M., Fujii, S. and Kagawa, T. 1999. Dynamic response and failure mechanism of pile foundation during soil liquefaction under shaking table test using a large scale laminar shear box, Proceedings of the Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resources Panel on Wind and Seismic Effects, 31: 252-257.

Towhata, I. and Ishihara, K. 1985. Modeling soil behaviors under principal stress axes rotation, 5th Int. Conf. on Numerical Method in Geomechanics, Nagoya, 523-530.

Towhata, I. 2008. Geotechnical Earthquake Engineering, Springer, Germany.

Wilson, D.W., Boulanger, R.W. and Kutter, B.L. 2000. Observed Seismic lateral resistance of liquefying sand, Journal of Geotech. and Geoenv. Engr, ASCE, 126(10): 898-906.