Experimental Testing of a Full-Scale Pile Group Under Lateral Loading

Anne Lemnitzer[1], Eric R. Ahlberg[2], Payman Khalili-Tehrani[3], Changsoon Rha[4]
Ertugrul Taciroglu[5], Jonathan P. Stewart[6], John W. Wallace[7]

[1] *PhD Candidate, Dept. of Civil Engineering, University of California Los Angeles, USA,*
email: alemnitz@gmx.de
[2] *Engineer, Exponent, Irvine, CA, USA*
[3] *PhD Candidate, Dept. of Civil Engineering, University of California Los Angeles, USA*
[4] *Assistant Professor, School of Architecture, Kookmin University, Seoul, Korea*
[5] *Associate Professor, Dept. of Civil Engineering, University of California Los Angeles, USA*
[6] *Professor and Vice Chair, Dept. of Civil Engineering, University of California Los Angeles, USA*
[7] *Professor, Dept. of Civil Engineering, University of California Los Angeles, USA*

ABSTRACT :

Full-Scale cyclic field testing was performed on a 3x3 pile group and a separate single fixed-head pile to evaluate group interaction effects. The piles in each experiment were constructed as 0.6 m diameter reinforced concrete shafts with reinforcement extending into caps at the ground surface. The piles were designed as CIDH (Cast-in-drilled-hole) piles and were embedded in predominantly clayey soil. The single pile and three piles within the group were instrumented internally; external instrumentation was used to for controlling the lateral displacement and to monitor cap rotation. Lateral loading was applied using four hydraulic actuators mounted between the pile caps and a reaction block. The single pile was loaded cyclically over the full range of displacements and achieved a maximum lateral capacity of 1210 kN at a displacement amplitude of 7.6 cm. The group specimen reached its maximum lateral capacity of 10.2 MN at a lateral displacement of 10.2 cm and was tested to a maximum displacement of 25 cm. Analytical studies have been performed to account for differing reinforcement ratios of 2% in the single pile shaft and 1% in the group shafts. Group efficiency factors were calculated using the measured group pile results and an analytically developed load deflection relationship for the single pile. Group factors varied from approximately 0.6 – 0.65 at small displacements (0.3 and 0.9 cm) to values near unity at the point of structural failure.

KEYWORDS: **Piles, pile group, lateral load, full scale test, group factors**

1. INTRODUCTION

Common foundation support systems for bridge structures consist of single shafts or shafts in group configurations constructed as Cast-In-Drilled-Hole (CIDH) shafts. The lateral resistance of these shafts is provided by the strength of the surrounding soil and the structural stiffness of the pile. The interaction of the soil and stiffness parameters is of particular importance when piles in a group are spaced at distances less than six pile diameters on center (Cox et al. 1984, Rollins et al. 1998). Shadowing effects reduce the capacity of the pile group versus the capacity of a single pile multiplied by the number of piles in the group. The introduction of group efficiency factors accounts for this reduction and in some cases are expressed as a function of pile position within the group (Brown *et al*. 1987, Ruesta and Townsend 1997, Rollins *et al*. 1998, 2002, 2006). These factors have been investigated principally through laboratory and field testing. Most previous tests have applied to free-head conditions at the top of the shaft (zero moment) and for conditions corresponding to (assumed) linear behavior of the pile section. Original features of the present test include the use of a fixed head boundary condition and significantly nonlinear pile section behavior.

2. TEST DESCRIPTION

This paper provides an overview of the test results for a 0.6 m (2 ft) diameter fixed head shaft and the nine pile group and addresses three overriding issues with respect to previous experimental studies: (1) Testing of reinforced concrete columns instead of structural steel columns or concrete filled hollow steel sections, (2) testing under reversed cyclic loading to large deformations, including inelastic behavior, and (3) deriving group efficiency factors. An overview of the test program is provided, followed by a discussion of test results and analytical studies.

2.1. Test Setup

The single pile test consisted of a 0.6 m (2ft) diameter reinforced concrete shaft extending 7.6 m (25ft) below ground with reinforcement extending 1.8 m (6ft) above ground into a load application cap with dimensions of 1.5 m x 2.1 m x 1.8 m (5ft x 7ft x 6ft). A schematic test layout is shown in Figure 1. The pile was reinforced with 8#9 (28 mm) bars, providing a vertical reinforcement ratio of ~ 2% and spiral reinforcement of #4 (13 mm) bars at a 11 cm (4.5 inch) pitch. Maximum concrete strengths f'_c were measured between 30 MPa and 36 MPa (4.4 ksi and 5.2 ksi) (ASTM C39) and testing of longitudinal rebar samples indicated a yield stress f_y of approximately 483 MPa (70 ksi).
The group specimen consisted of nine 0.6 (2 ft) diameter shaft spaced 1.8 m (6 ft) on center in each plane direction. The piles extended into a cap with dimensions of 4.9 m x 5.5 m x 1.8 m (16 ft x 18 ft x 6 ft). All piles extended about 7.6 m (25 ft) below ground and are reinforced with 8#7 (22 mm) bars, resulting in a longitudinal reinforcement ratio of 1%. Transverse reinforcement was provided by #4 (13 mm) spirals spaced at a 10 cm (4 inch) pitch. Maximum concrete compressive strengths f'_c were measured to range between 28 MPa and 34 MPa (4.1 ksi and 4.9 ksi).
A gap existed underneath both test specimens to avoid the contribution of cap-soil friction to lateral load resistance. The field reaction system for both tests consisted of a pile cap with dimensions of 7.3 m x 3.65 m x 1.8 m (24 ft x 12 ft x 6 ft) cast on top of two 1.8 m (6 ft) diameter, 15 m (48 ft) deep drilled shafts. Actuators were installed between the reaction system and the test specimen to apply loads/displacements to the test specimen (Figure 1).

2.2. Instrumentation

Both test specimens were equipped with internal and external sensors, including strain gauges, LVDTs, fiber-optic Fiber-Bragg gratings. The single pile, and three of the piles within the nine-pile group (shaded in Figure 1), were densely instrumented (102 sensors were used for each instrumented pile). External sensors were installed between external reference frames and the pile caps to measure lateral displacement and to monitor the cap rotation. The test protocol for the single pile included restraining the cap rotation to zero using three sensors mounted between an external reference frame and a vertical face of the pile cap. A zero rotation boundary condition could not be achieved for the group specimen due to equipment and test geometry limitations; therefore, the pile cap rotation was monitored using 3 LVDTs installed between an external reference frame and the top surface of the pile cap. All data were recorded using a National Instruments data acquisition system.

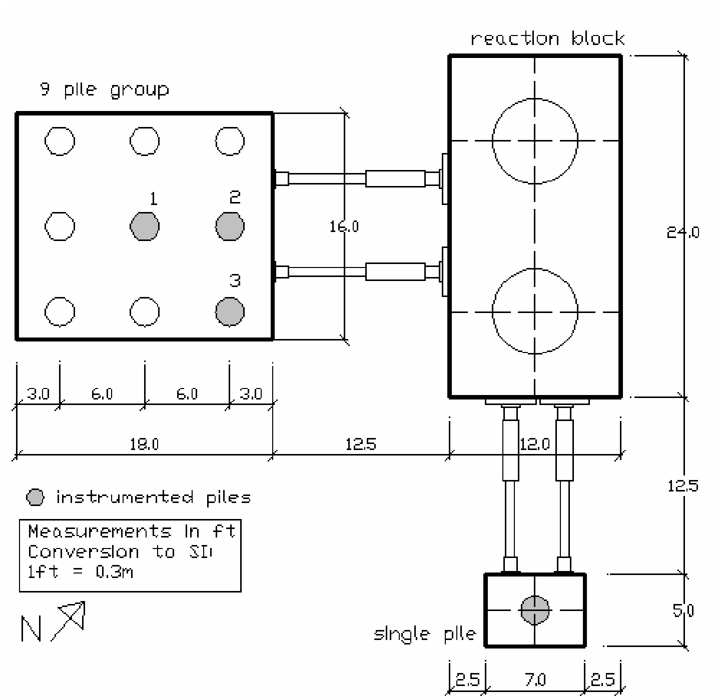

Figure 1: Plan view of Test setup for single pile and pile group test

2.3. Geotechnical Site Conditions

Several suites of geotechnical testing were performed in 2001 and 2006 to investigate the soil properties of the site (Janoyan *et al*., 2006, Stewart *et al*. 2007). Work performed included seismic cone penetration testing (SCPT), rotary-wash borings with standard penetration testing (SPT), down-hole suspension logging of shear wave velocities, pressuremeter testing (PMT), and test pit excavation mapping. Laboratory testing of soil samples provided information of shear strengths and soil classifications. The soil conditions at the test site were determined to consist of deep alluvial sediments. The upper 15 m (50 ft) are mostly silty clays interspersed with relatively thin layers of silty sand. The soil profile can be described in more detail as follows:

- 0 – 1.5 m: Rubble and fill including asphalt and concrete debris (this layer was removed before testing)
- 1.5 – 6.4 m: Silty clay, moderate plasticity (PI~15), 60% fines, OCR = 3.5-5.9, I_c = 2.6-3.0, thin sand interbed with a thickness of ~ 2 ft at approximately 10 ft depth.
- 6.4 – 7.3 m: Medium to fine grained silty sands, PI~12, 30% fines, I_c = 2.1-2.5
- 7.3 – 14.6 m: Silty Clay, PI ~ 13-14, I_c = 2.8 – 3.2
- > 14.6 m: Medium sand, groundwater table

2.4. Test Conduction

Lateral loads were applied to the specimens using four 2 MN (450 kip) actuators installed between the reaction block and the pile caps. The hydraulic actuators were controlled by an MTS Flextest GT Controller, which was able to independently operate actuators under displacement or load control. Three cycles of lateral displacement were applied at monotonically increasing peak values up to a maximum of 2.5 and 10 cm (1.0 and 4.0 in.) for the pile group and single pile, respectively. The load capacity of the four actuators was reached at a lateral displacement of 2.5 cm (1.0 in.) for the pile group; therefore, thee additional actuators were installed and the test was continued under monotonic loading to a lateral displacement of 25 cm (10 inches). Photographs of the two tests are shown in Figure 2 and 3.

Figure 2: Single pile specimen at the test site

Figure 3: Nine pile group specimen before testing

3. TEST RESULTS

3.1. Recorded Displacements and Pile Cap Rotations versus Lateral Load

Figures 4 and 5 present the measured load displacement backbone curves of the single pile and the group specimen, respectively. A maximum capacity of 1214 kN (273 kip) was reached for the single pile at a horizontal displacement of 7.6 cm (3 inch) in north direction. The group specimen achieved its maximum lateral resistance of 10.2 MN (2300 kip) at 10.2 cm (4 inch) lateral displacement (during the monotonic push). Whereas data points for the backbone curve are generally taken as the peaks of the first cycle of loading, due to problems encountered with the data acquisition system during the group test, some points at low displacement levels were derived from subsequent cycles; these are shown in Figure 5 as individual points.

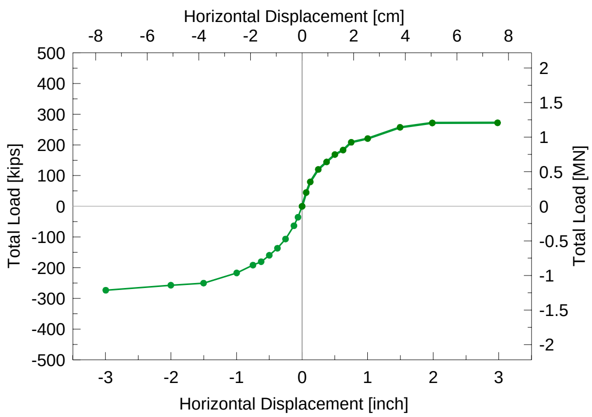

Figure 4: Load-displ. curve for the single pile

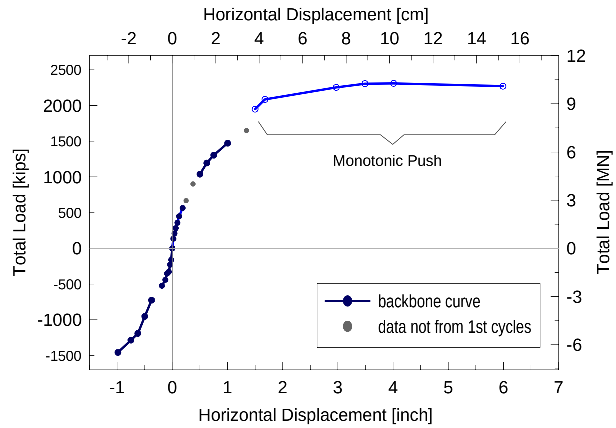

Figure 5: Load-displ. curve for the nine pile group

3.2. Rotation

The rotation of the nine-pile group cap was monitored and recorded using the external LVDT sensors installed at the top surface of the pile cap. Two sensors were located along the center of the cap and one sensor was located at distance in push direction to describe a triangular plane. Figure 6 shows the measured rotation of the pile cap and describes the linearly increasing cap rotation versus lateral top displacement.

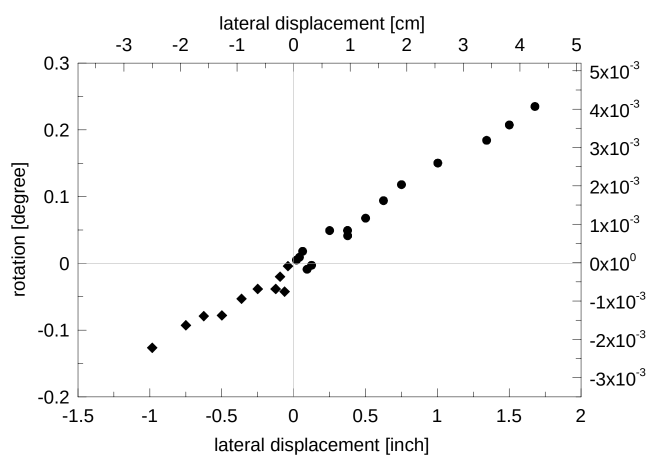

Figure 6: Measured cap rotations for the nine-pile group

4. DISCUSSION

4.1. Load Displacement Responses and Analytical Studies

Pre-test blind predictions using various analytical methods were performed for the fixed head single pile and are given in Rha (2006) and Stewart *et al.* (2007). Analytical studies included an experimental *p-y* model (with *p* being the lateral load per unit length and *y* being the lateral deflection) that was implemented in Frame Lab (Taciroglu, 2002).

Following testing of the fixed head single pile, the *p-y* curves implied by the test were evaluated (Stewart *et al.*, 2007), and those were used to produce the results in Figure 7 labeled as "calibrated *p-y* model 2%." The calibrated model was then applied with a smaller reinforcement ratio of 1% and results are presented along with the measured data in Figure 7.

Estimated load-deflection curves for the group with an efficiency factor of unity are presented in Figure 8. Those were obtained by multiplying the single pile loads for a given displacement by the number of piles in the group. This is done both for the measured load displacement curve and the calibrated single pile 1% p-y model results. Figure 8 shows that the expected specimen response for a 1% reinforcement ratio is almost identical to the measured response of the shaft with a 2% reinforcement ratio for displacement less than 1.6 cm (0.625 inches), implying that pile response (and hence the efficiency factors) are independent of the pile stiffness at small displacements.

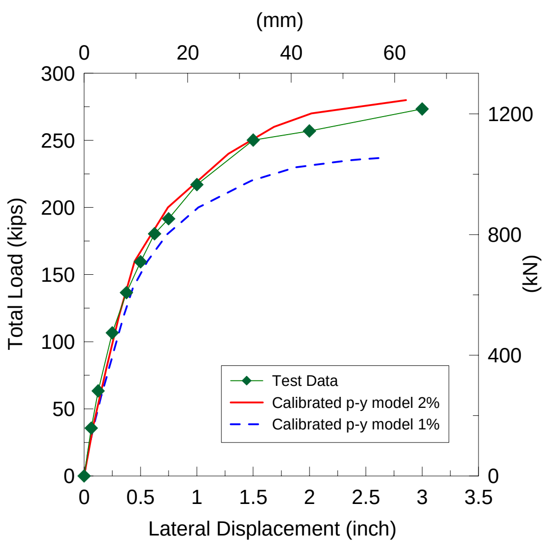

Figure 7: Measured,, predicted and fitted response for a 2% reinforcement ratio.

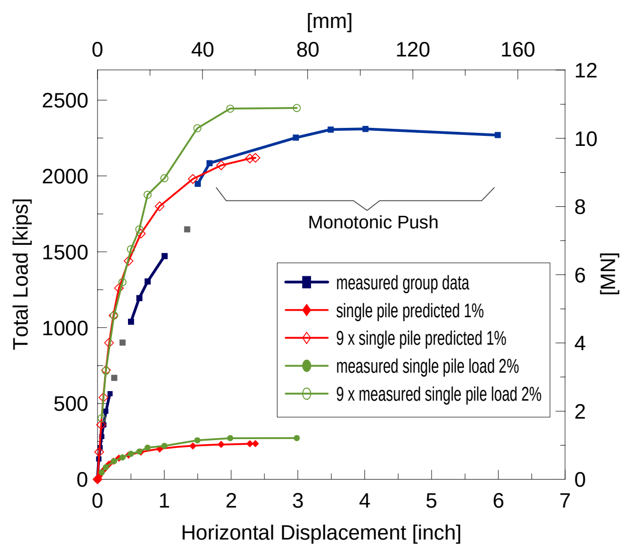

Figure 8: comparison of predicted response of a 1% reinforced specimen and the group data

The group efficiency factors were then derived using the following relationship:

$$\eta = \frac{P_g(y_0)}{N_g P_{sp}(y_0)} \qquad \text{(Eq. 4.1)}$$

where $P_g(y_0)$ is the lateral force applied to a pile group to reach a lateral deflection of y_0 at the pile cap, $P_{sp}(y_0)$ is the corresponding single-pile head load for pile deflection y_0, N_g is the number of piles in group, and η is the group efficiency factor.

Figure 9 presents two sets of group efficiency factors derived using Eq. 4.1. In both sets, the numerator of Eq. 4.1 is taken as the group test result for a given displacement y_0. The first set of results in Figure 9 is obtained by using the analytically determined load for the 1% reinforced shaft as P_{sp} in Eq. 4.1. The second set is obtained by using the measured response of the 2% reinforced shaft as P_{sp}.
The lowest group factors of 0.6 – 0.65 correspond to displacements between 0.3 and 0.9 cm (0.125 and 0.35 inch). Group efficiency factors then increase and reach maximum values near unity at displacements near structural failure.

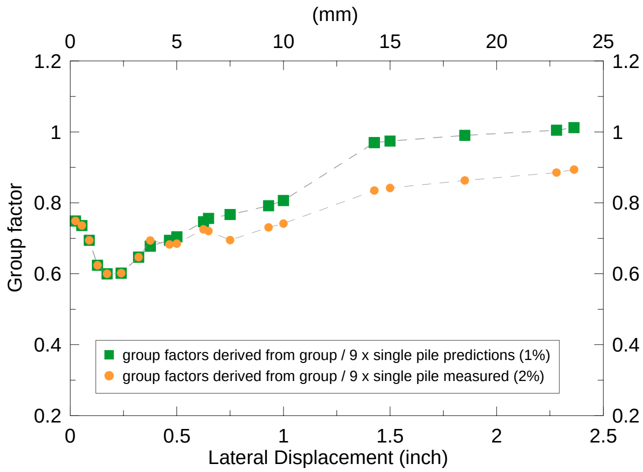

Figure 9. Group efficiency factors versus lateral displacement.

4.2. Post Test Specimen Investigation

Post test excavations were performed for the group specimen to investigate the pile damage and monitor the crack layout (Figure 10). Extensive cracks with crack widths up to 5 cm (2 inches) were observed between ground line and a depth of 0.9 m (3 ft). At depths lower than 1.8 m (6 ft), no cracks were observed. Several piles experienced concrete spalling as shown in Figure 11. Most severe damage was observed to occur at front row piles. Only moderate cracks were found in piles located in the middle row.

Figure 10: Group specimen after soil excavation

Figure 11: Concrete spalling at a pile

5. ACKNOWLEDGEMENTS

The California Department of Transportation is greatly acknowledged for the support of this research under research contract No. 59A0247 (and amendments thereto). Particular acknowledgements are being addressed to Craig Whitten and Anoosh Shamsabadi (Caltrans), to George Cook (GB Cooke) and to Robert Nigbor, Steve Kang, Steve Keowen and Alberto Salamanca (NEES @ UCLA) for their collaborative efforts, their technical support and their continuous and indispensable assistance in test management during the time of preparation, test conduction and data evaluation.

6. REFERENCES

Brown, D.A., Reese, L.C., and O'Neill, M.W. (1987). "Behavior of a large scale pile group subjected to cyclic lateral loading," *J. Geotech. and Geoenv. Eng.*, ASCE, 113 (11), 1326-1343

Cox, W.R., Dixon, D.A., and Murphy, B.S. (1984). " Lateral load tests of 5.4 mm diameter piles in very soft clay in side-by-side and in-line groups." *Laterally loaded deep foundations: analysis and performance*, ASTM, West Conshohocken, Pa.

Janoyan, K.D, Wallace, J.W., Stewart, J.P. (2006). "Full-Scale Cyclic Lateral Load Test of Reinforced Concrete Pier-Column," ACI Structural Journal, March/April 2006, #103-S19, 178-187.

Rha, C. (2006). "Analytical studies of full-scale reinforced concrete shaft/column subject to cyclic lateral loads," Ph.D. Thesis, Department of Civil and Environmental Engineering, University of California, Los Angeles, Los Angeles, California

Rollins, K.M., Peterson, K.T. and Weaver, T.J. (1998). "Lateral load behavior of full-scale pile group in clay." *J. Geotech. and Geoenv. Eng.*, ASCE, 124 (6), 468-478

Rollins, K.M., Olsen,R.J., Egbert, J.J., Jensen, D.H., Olsen, K.G. and Garrett, B.H. (2006). " Pile spacing effects on lateral pile group behavior: Analysis," *J. Geotech. and Geoenv. Eng.*, ASCE, 132 (10), 1272-1283

Rollins, K.M., Olsen,R.J., Egbert, J.J., Jensen, D.H., Olsen, K.G. and Garrett, B.H. (2006). " Pile spacing effects on lateral pile group behavior: Load Tests," *J. Geotech. and Geoenv. Eng.*, ASCE, 132 (10), 1262-1271

Ruesta, P.F. and Townsend, F.C. (1997). "Evaluation of laterally loaded pile group at Roosevelt Bridge," *J. Geotech. and Geoenv. Eng.*, ASCE, 123 (12), 1153-1161

Stewart, J.P., Taciroglu, E., Wallace, J.W., Ahlberg, E.R., Lemnitzer, A., Rha, C., Khalili-Tehrani, P., Keowen, S., Nigbor, R., Salamanca, A. (2007) Full Scale Cyclic Large Deflection Testing of Foundation Support Systems for Highway Bridges. Part I: Drilled Shaft Foundations, *Research Report No. UCLA SGEL-01*, *http://repositories.cdlib.org/cee_ucla/geotechnical/*

Taciroglu, E., (2002). *A Matlab Package for Structural Analysis and Soil-Structure Interaction*. University of California, Los Angeles.

Taciroglu, E., Rha, C., Wallace, J.W. (2006). "A Robust Macroelement Model for Soil-Pile Interaction under Cyclic Loads," *J. Geotech. And Geoenv. Eng.*, ASCE, 132(10), 1304-1314.