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PRELIMINARY TEST RESULTS FOR FULL SCALE DRILLED SHAFT UNDER CYCLIC LATERAL LOADING

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ABSTRACT

Preliminary results are presented of a field testing program for a full-scale, large diameter cast-in-drilled-hole (CIDH) shaft/column under cyclic lateral loading. The shaft was extensively instrumented to enable high precision, redundant section curvature measurements, measurements of pressure at the soil-shaft interface around the shaft perimeter, and in situ measurements of concrete quality. The principal objective of the testing was to characterize the soil-shaft interaction across a wide displacement range to gain insight into the adequacy of existing design guidelines (which are based principally on the testing of small diameter piles) for the large diameter shafts commonly used to support highway bridges in California. Also of interest is the failure mechanism of the shaft-column, since most previous tests of large-diameter shaft-columns do not test the column to large levels of ductility. This testing was only recently completed, and reduction and interpretation of the data is ongoing as of this writing. This paper presents preliminary results of the overall specimen performance across the full range of tested displacements. Details of the soil-shaft interaction remain under study, and are not presented here.

INTRODUCTION

Cast-in-drilled-hole (CIDH) shaft/columns have been widely used for the support of highway bridges in California and elsewhere. These structural elements consist of a column section with similar diameters above-ground and below-ground. Typical design guidelines allow variable ductility levels depending on the bridge importance and the redundancy in the structural system, and also seek to limit deck displacements (*Caltrans*, 1999).

The maximum moment in a CIDH shaft/column occurs below the ground line, and thus inelastic flexural hinging is expected below grade. Critical design issues affecting the design process are the hinge length and depth below ground line, and the soil reaction against the shaft. These issues, in turn, are directly related to the nonlinear and depth dependant distribution of the soil reaction. This reaction is commonly modeled using so-called Winkler springs described by nonlinear *p-y* curves (Focht and Koch, 1973). The *p-y* curves used commonly in practice (e.g., API, 1993) are derived from lateral load testing of small diameter piles, as indicated below:

- Soft clays: d=12.75 inches (Matlock, 1970)
- Stiff clays: d=6 and 24 inches (Reese et al., 1975)
- Sands: d = 24 inches (Reese et al., 1974)

A concern in design practice is the degree to which these curves represent the response of large diameter pile sections. Some researchers have found commonly used *p-y* curves to significantly overpredict the deflections and underpredict the bending moments in large diameter piles (Stevens and Audibert, 1979).

This paper presents preliminary results of a field testing program designed to provide insight into the depth dependant soil reactions against a 6-foot diameter shaft section across a wide range of displacements. Also investigated is the failure mechanism of the shaft/column. This testing was only recently completed, and reduction and interpretation of the data is ongoing as of this writing. This paper presents preliminary results of the overall specimen performance across the full range of tested displacements. Details of the soil-shaft interaction remain under study, and are not presented here.

SPECIMEN CHARACTERISTICS & TESTING PROTOCOL

The test site is at the interchange of Interstate Highways 105 and 405 in Hawthorne, California, just southeast of the Los Angeles International Airport. The soil conditions consist of deep alluvial sediments containing interbedded silty sandy clay and silty sand. The CPT tip resistance across most of the 48-foot embedment depth was consistently $q_c \approx$ 50-75 tsf, with a ratio of sleeve friction to tip resistance of $f_s/q_c \approx 4\%$. After drilling the shaft excavation, the soil had sufficient cohesion to stand unsupported for several hours before concrete placement. The groundwater table at the site is at a depth of approximately 48 feet.

The CIDH shaft-column was designed according to standard Caltrans' Bridge Design Specifications using their Seismic Design Criteria. The test specimen is six feet in diameter and extends 48 feet below ground line and 40 feet above. As shown in Figure 1, steel reinforcement is comprised of 36-#14 longitudinal bars and shop-welded #8 hoops at 6-inch spacing.

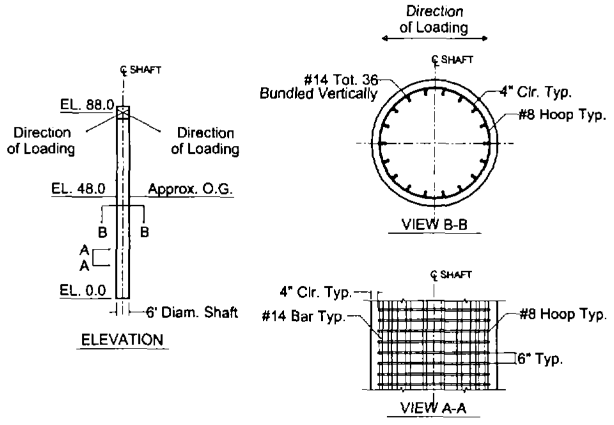

Fig. 1. Reinforcement details

A schematic illustration of the loading system is shown in Figure 2. Lateral loads were imposed on the column using tension cables reacting against soil anchors. A yoke system installed near the soil anchors imparts tension to the cables. The yoke system consists of four 100-kip jacks installed between a top beam rigidly connected to screw rods, and a moveable bottom beam to which the cables are connected through a load cell. The jacks have roughly 14 inches of useable stroke, but by resetting the position of the top beam on the screw rods, the yoke system allows movements of +/- 12 feet from the original shaft position. Figure 3 shows a photo of the completed loading system.

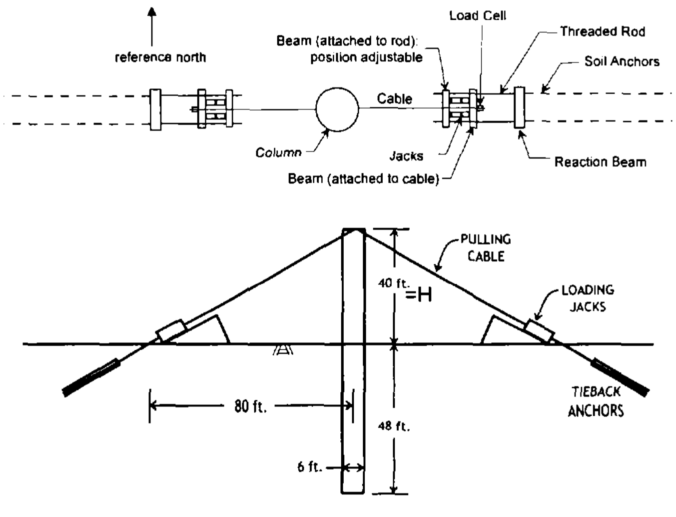

Fig. 2. Schematic plan and profile views of loading system

Testing of the shaft/column was displacement controlled. Cyclic lateral loading was applied across an amplitude range of 2 to108 inches (approximately 0.4% to 22.5% of the shaft height above ground line, H). Two loading cycles were performed at most displacement levels; however, 12 loading cycles were performed at two displacement amplitudes (6 and 18 inches) to investigate the effects of cyclic degradation.

INSTRUMENTATION

High precision instrumentation was employed to provide detailed data on shaft bending deformations, soil-shaft interaction pressures, and reinforcement bar strains.

Shaft bending deformations were measured with a redundant system of extensometers and inclinometers. Both high precision fiber-optic extensometers and conventional extensometers were installed. Extensometers were generally installed just inside of the reinforcing cage. However, in the region within a few shaft diameters of the ground line where the inelastic bending deformations were expected to concentrate (commonly referred to as the "plastic hinge" region), a second set was installed mid-way between the shaft centroid and reinforcing cage. A total of 64 extensometers were used, 32 fiber-optic (4-foot length) and 32 conventional (2-foot length). The fiber-optic instruments have very high resolution, but operate within a limited strain range of 1% in tension and 0.5% in compression. The conventional extensometers were used in the plastic hinge region where large deformations were expected. These extensometers consisted of potentiometers encased in PVC pipe with a working range of 10% in tension and 4% in compression. Inclinometers were installed down the middle of the shaft to obtain relative rotation values over the shaft height to compare with integrated curvature data, as well as to monitor the rotation at the base. The expected uses of the extensometer and inclinometer data (i.e., average concrete strains, curvatures, and rotations) include evaluation of the plastic hinge location and length, evaluation of nonlinear and depth-dependant soil-shaft interaction resultant forces (i.e., *p-y* spring reactions), and evaluation of moment-curvature/rotation relations for the shaft.

Non-displacement soil pressure cells (i.e. cells with the approximate stiffness of concrete) were installed at the interface between the concrete and soil. A total of 26 cells were installed at seven depths along the shaft both in the line of loading, and at several depths, at 30 and 60 degrees from the line of loading. Each cell was installed by hand on the excavation wall after the cage had been placed and immediately prior to concrete placement. We intend to use the soil pressure cell data to infer the contribution of normal stresses to resultant soil-shaft interaction forces.

Reinforcement bar strains were measured using 60 strain gauges installed on longitudinal bars and 16 gauges on transverse bars. Strain gauge data will be used to assess the extent of longitudinal reinforcing bar yielding as well as the effectiveness of the hoops in confining the concrete within the column core. Strain gauge data will also be used to assess the reliability of the overall load-displacement relation and concentration of damage within the plastic hinge region.

Additional instrumentation included total station survey instruments (to measure above-ground shaft displacements), load cells on the yoke system, and time-domain-reflectometry cables and gamma tubes (to measure the quality of the as-placed concrete).

PRELIMINARY RESULTS

The relationship between lateral-load and top-of-column lateral peak displacement is shown in Figure 4 for both the first and second cycle at each displacement amplitude. Despite minor soil gapping and typical concrete cracking, the shaft-soil system response was nearly bi-linear up to the yield displacement of approximately 12 inches (0.025H), where H = above ground line column height. Yielding of the reinforcement occurred between the 12 and 24 inch displacement cycles; however, a significant reduction of load capacity was not observed until shaft displacements reached approximately 108 inches (0.225H). Loss of capacity occurred due to fracture of the reinforcement bars approximately four to five feet (< 1.0d) below ground line.

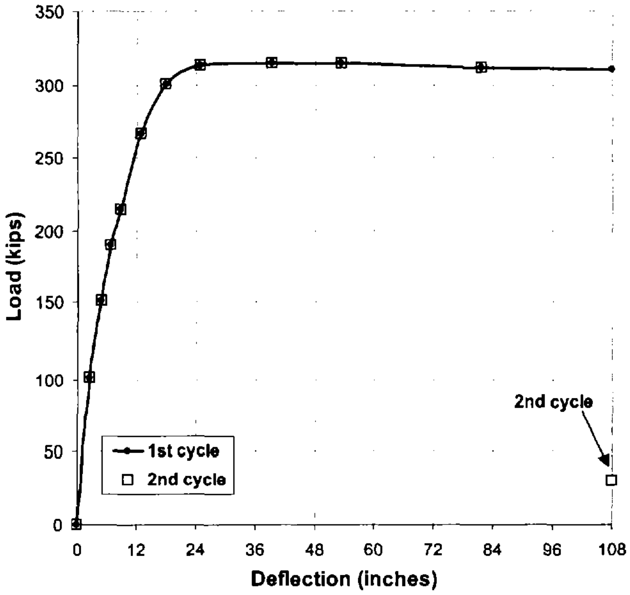

Fig. 4. Lateral load-deflection curve

As noted above, shaft/soil behavior prior to yield was nearly bi-linear. The cyclic relationship between shaft load and displacement (i.e., hysteresis loops) at 9 inch displacement amplitude are shown in Figure 5, and the deflected shape of the shaft-column is shown in Figure 6. [The diagrams in Figures 5 and 6 also indicate results for the 40- and 80-inch displacement amplitudes, which are discussed below.] Minor gapping between the shaft and soil was observed at the ground line for these displacements, and significant cracking occurred in the concrete under tension. At these small displacements, the maximum column rotations (calculated from inclinometer data as the derivative of column slope) in the shaft were near the ground line (Figure 7).

At displacements beyond yield, but prior to failure, soil-shaft gapping increased and passive wedges progressively formed on both sides of the shaft. The slip plane for the passive wedges was later traced to the depth of the plastic hinge. Concrete crack widths progressively increased and at displacements between 2 and 9 feet, spalling of cover concrete occurred. The nonlinearity of the lateral load response is demonstrated by the hysteresis loops for 40-inch displacement amplitude (Figure 5). After yielding, the location of maximum bending strains in the column migrated from the surface to a depth of about 4-5 feet. The plastic hinge that formed at this location is apparent from the deflected shape (Figure 6) and rotation profiles (Figure 7).

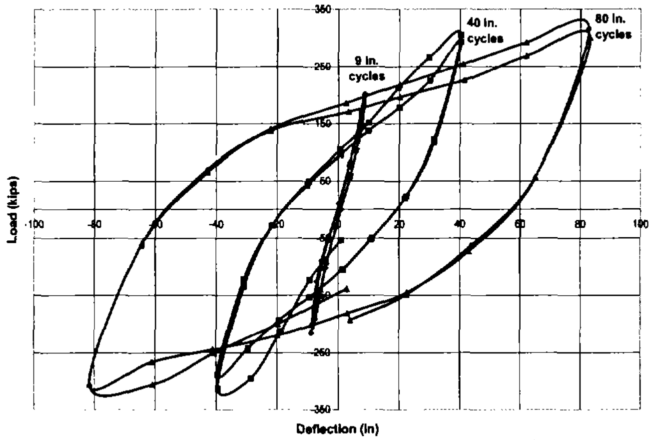

Fig. 5. Hysteresis loops

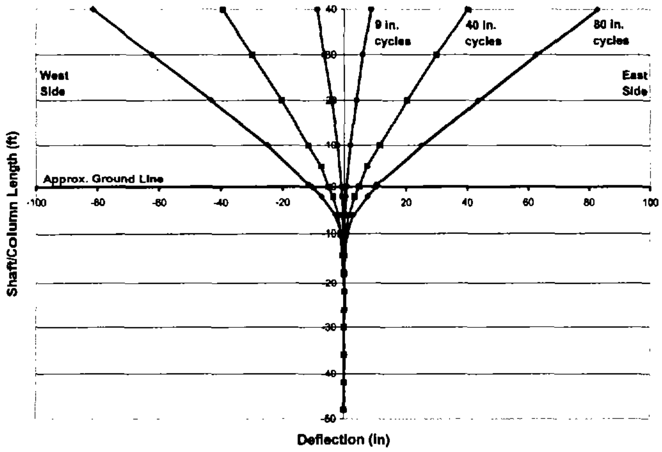

Fig. 6. Deflected shape at different displacement amplitudes

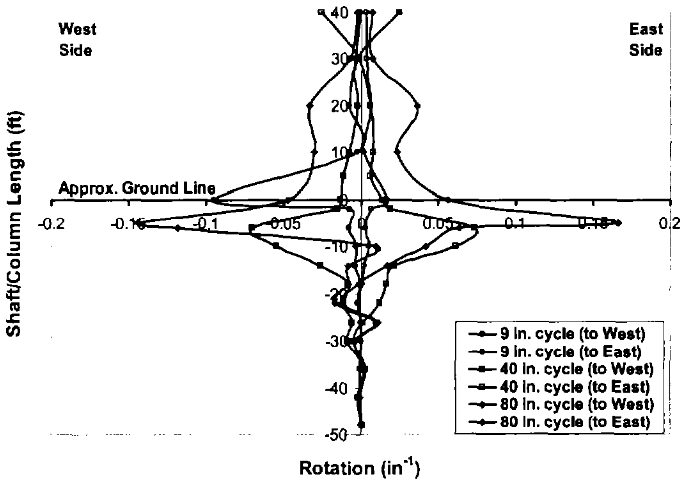

Fig. 7. Rotation (derivative of slope) along shaft/column

Failure of the shaft occurred in the second cycle at the 9-foot displacement level. During the first half-cycle, it appears that the pressure exerted on the hoops by the longitudinal bars trying to buckle resulted in fracture of one or two hoops. Fracture of the hoops allowed substantial buckling of the longitudinal bars to occur; however, the load capacity did not drop as compression in the longitudinal steel does not significantly affect the moment capacity of the cross section. In the subsequent half-cycle, when the buckled bars were placed in tension, they fractured and the load capacity dropped to approximately 30 kips from a peak value of approximately 320 kips measured in the previous half-cycle. An additional half-cycle was performed, resulting in fracture of the longitudinal bars on the other face of the column. Soil excavation revealed that 28 of the 36 longitudinal reinforcing bars had buckled and the concrete was crushed across a wedge-shaped zone as illustrated in Figure 8. Approximately 1.5 feet of intact concrete remained at the neutral axis.

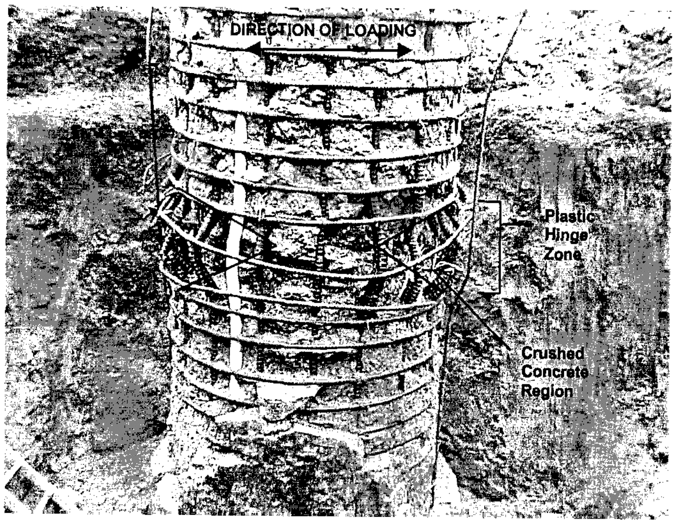

Fig. 8. Photograph of plastic hinge, showing zone of crushed concrete

The data resulting from this testing is still under review, and the results presented here are preliminary. From further examination of the data, we expect to develop *p-y* curves quantifying the nonlinear soil-shaft interaction and to more thoroughly document the nonlinear behavior of the reinforced concrete shaft/column. The results will also be compared to performance predictions made using standard Caltrans design procedures and other, more sophisticated, procedures.

ACKNOWLEDGEMENTS

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