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PRECAST PILE TESTS INDICATE HIGH DUCTILITY

Preliminary Report on Prestressed Pile Shaft Test Units PS7-PS10

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0. ABSTRACT

Lateral loading of prestressed piles under seismic attack can, under a variety of circustances, result in the formation of a plastic hinge in the pile shaft, 3-5 pile diameters below grade level. A series of four tests was performed on fullscale 0.61 m diameter piles to investigate the influence of internally provided transverse steel, and the confining effect of soil about the pile shaft. Both factors were found to play an important role in pile shaft performance; soil remaining sufficiently coherent to contrain the cover concrete after spalling may considerably increase the pile's post-spalling strength and ductility capacity. If the cover is unconstrained, adequate levels of internal reinforcement can provide significant post-spalling strength up to relatively high levels of ductility.

1. INTRODUCTION

This is a summary report on the testing of pile shaft test units PS7 - PS 10, performed to help characterize the subgrade plastic hinge which may form when the full capacity of the pile-pile cap of prestressed piles is mobilized, and to investigate the confining effect of soil on the structure's performance. These tests were performed March-May 1996.PS1-PS6 were cast-in-place pile shaft test, and thus fall outside the scope of this report.

The test apparatus was designed to simulate the moment pattern found about the subgrade hinge (point of maximum subgrade moment) in the lateral loading of a prestressed pile. The testing of PS7 and PS8 (March 1996) left the central 0.61 m (1 diameter D) of the test unit's plastic hinge region without simulation of external confinement (i.e., that provided by the soil surrounding the pile shaft). PS9 and PS 10 (April 1996) did have external confinement of the middle of the plastic hinge region. Predicted prototype and test unit moment patterns (PS7 shown) are shown in figs. 1 and 2.

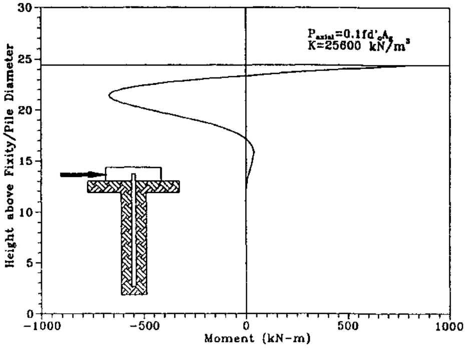

FIG. 1: PROTOTYPE PILE MOMENT VS. HEIGHT

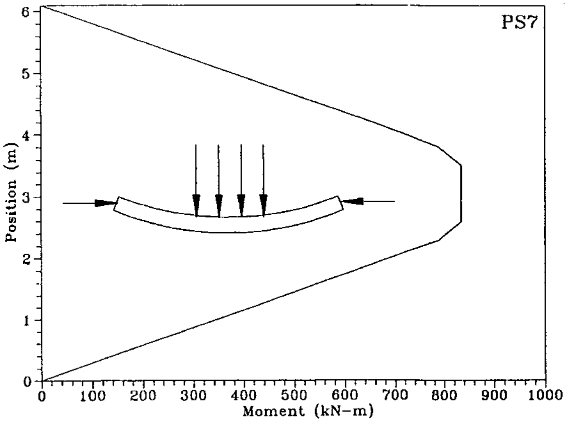

FIG. 2: TEST UNIT PS7 THEORETICAL MOMENT PATTERN AT MAXIMUM STRENGTH

The prototype analyzed was a 0.61 m diameter section with 24 prestressing tendons of 13.2 mm diameter (1860 MPa ultimate, 1302 MPa yield) prestressed at 1061 MPa, to give a nominal section prestress of 9.3 MPa. Transverse reinforcement was provided by W11 A82 spiral (D9.5, 565 MPa nominal) with a pitch of 63.5 mm, for a transverse reinforcement ratio of ρ_t=0.011 . Subgrade depth was 24.3 m. Assumed concrete strength for the model was 41.3 MPa.

The test unit was designed to full scale in physical dimensions, and retained a similar configuration of prestressing tendons; transverse reinforcement and method of loading were varied in this series. Parameter variations are outlined in table 1.

TABLE 1: PRESTRESSED PILE SHAFT TEST UNITS AND LOADING

Test Unit	Method of Loading	ρ_t (reinforcement details)
PS7	Plastic hinge unconfined	0.015 (W11 A82 @ 41.3 mm)
PS8	Plastic hinge unconfined	0.010 (W11 A82 @ 63.5 mm)
PS9	Plastic hinge confined	0.010 (W11 A82 @ 63.5 mm)
PS10	Plastic hinge confined	0.005 (W6.5 A82 @ 70 mm)

2. THEORETICAL BACKGROUND

The prototype pile and the test units were analyzed using a purpose-designed inelastic finite-element code. The basic model for the prototype was that of a beam on an elastic foundation, with the pile-column's stiffness reduced after first yield in accordance with discretized moment-curvature data (theoretical moment-curvature data for the test unit is shown in fig. 10). The same code was used for analysis of the test unit, with suitable modifications for the different physical configuration.

3. EXPERIMENTAL APPARATUS AND TEST UNIT

A general view of the test apparatus is shown in fig. 3. It was designed to load the test unit in a way that would as closely as possible simulate the moment pattern produced by the lateral pressure of soil on a pile shaft. Basically a whiffle tree, the loading mechanism distributed the applied force from three (or two) 980 kN MTS actuators through five (or four) symmetrically arrayed load points. The force was applied to the test unit via sets of 'saddles', lined with rubber, which covered 100° of the test unit's circumference, top and bottom. The placement of the saddles, and the stiffness of the rubber used, were chosen to model the lateral bearing properties of the soil surrounding the pile shaft.

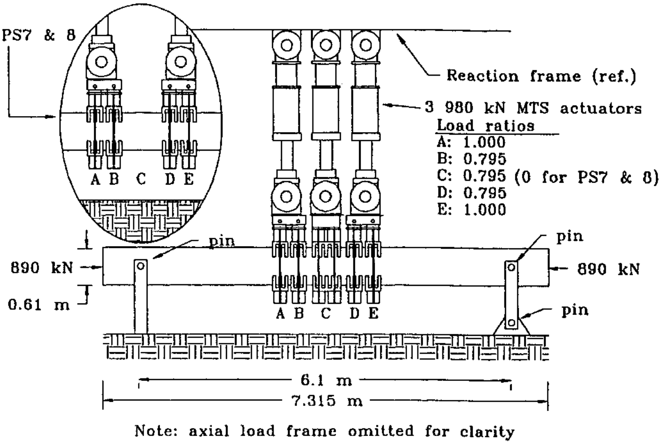

FIG. 5: GENERAL VIEW OF EXPERIMENTAL APPARATUS USED TO TEST PILE SHAFT TEST UNITS PS7 - PS10

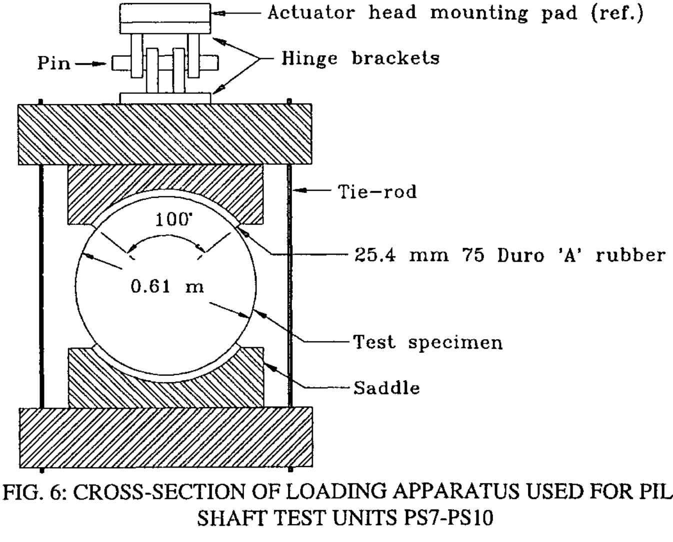

FIG. 6: CROSS-SECTION OF LOADING APPARATUS USED FOR PILE SHAFT TEST UNITS PS7-PS10

An axial load of 890 kN was maintained during the test to give a nominal $P_{ax}=0.074f'_cA_g$ (actual axial load ratio averaged about 10% less, based on day-of-test concrete strengths). Axial load was applied by strongbacks at either end of the test unit, connected by high strength steel rods running down either side (fig. 7). Load was applied via hollow-core jacks, and monitored by load cells. The strongbacks were kept level through the test by a manually-controlled system of jacks (fig. 8). A significant P-Δ effect was expected.

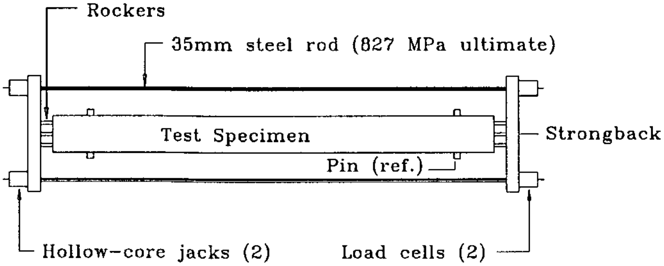

FIG. 7: AXIAL LOAD MECHANISM - PLAN VIEW

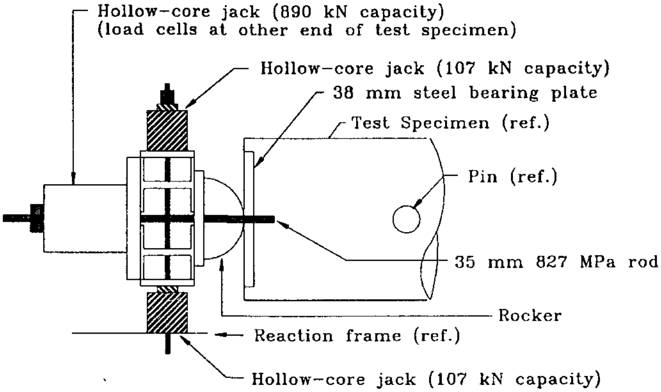

FIG. 8: SIDE VIEW OF AXIAL LOAD STRONGBACK AND LEVELING MECHANISM

The test units were circular-section prestressed piles of 0.6096 m diameter, with 76.2 mm cover to the tendons (fig. 9). Transverse reinforcement details are given in table 1. The test unit was 6.096 m between pins, and 7.315 m overall. Moment-curvature data for this section is shown in fig. 10.

The test units were cast on November 17, 1995. Concrete strength at transfer (i.e., cutting of the tendons at the pile ends) was 27.7 MPa.

Actual material properties are shown in table 2.

TABLE 2: PRESTRESSED PILE SHAFT TEST UNIT MATERIAL PROPERTIES

Test Unit	f'_c (Mpa)	transverse steel yield strength f_{yt}
PS7	**47.1**	**599**
PS8	**53.4**	**599**
PS9	**49.9**	**599**
PS10	**49.3**	**599**

The prestressing tendons could not be tested because of equipment limitations.

Actual cover thickness was 86 mm.

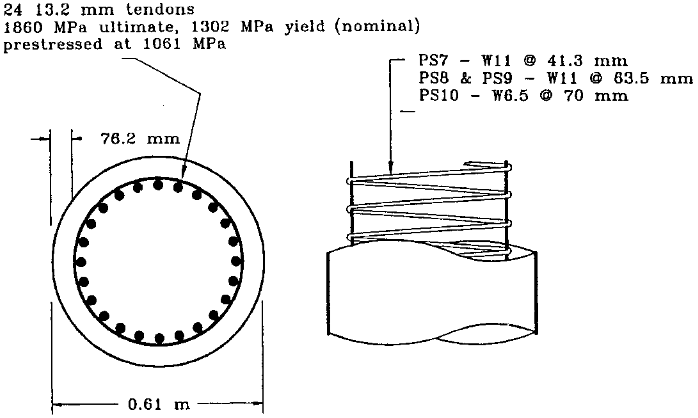

FIG. 9: DIMENSIONAL AND REINFORCEMENT DETAILS OF PILE SHAFT TEST UNITS PS7-10

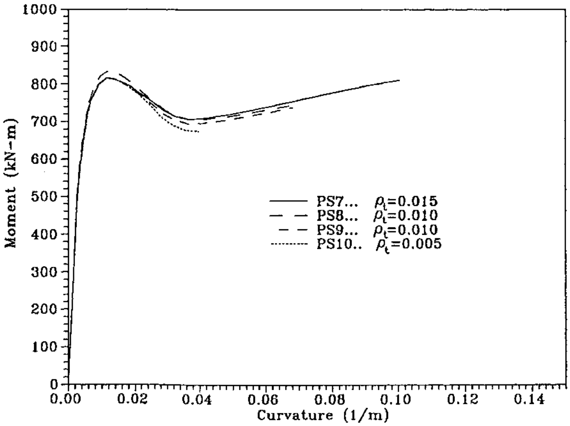

FIG. 10: THEORETICAL MOMENT-CURVATURE DATA FOR PILE SHAFT TEST UNITS PS7-10, USING ACTUAL MATERIAL PROPERTIES (AXIAL LOAD OF 890 KN)

4. EXPERIMENTAL PROCEDURE

The actuators were initially zeroed to compensate for the self-weight of the test unit, and the dead load of the loading apparatus. The following loading program was then followed. Forces given are half-loads of the sum of the actuator forces.

(1) +/- 50 kN, 1 cycle
(2) +/-100 kN, 1 cycle
(3) +/- 150 kN, 1 cycle
(4) +/- 200 kN, 1 cycle

Displacement at ductility μ=1 was then defined (for PS8, the first unit tested) as

$$\mu_1 = \Delta_{200kN}\frac{M_{ideal}}{M_{200kN}} = 18.7 \text{ mm}$$

in which first-yield and ideal moments were obtained by through moment-curvature analysis using the Mander model for confined concrete. Similar displacements corresponding to multiples of the above value of $\mu=1$ were used for all four test units, to provide a 'level' basis for comparison.

Loading was then continued as follows (test unit failure levels included):

(6) 3 cycles at $\mu=1$
(7) 3 cycles at $\mu=1.5$
(8) 3 cycles at $\mu=2$
(9) 3 cycles at $\mu=3$
(10) 3 cycles at $\mu=4$
(11) 3 cycles at $\mu=6$ (PS8)
(12) 3 cycles at $\mu=8$ (PS9; PS7 two cycles)
(13) 1 cycle at $\mu=10$ (PS10)

5. RESULTS

A comparison of PS7 and PS8 yields the direct effect of internal transverse reinforcement on plastic behavior in the absence of external confinement. It may be seen that PS7 maintained a relatively stable post-spalling strength plateau until the first push cycle at $\mu=8$, when a transverse spiral was observed to fracture. The post spalling strength of PS8 shows a generally downward trend to $\mu=5$, after which there is a sharp decline in performance. Both test units showed extensive damage in the plastic hinge region; the cover was destroyed over virtually the entire circumference. PS7 susteained fractures of spiral steel; necking of spiral steel was observed in PS8 (the test was terminated ay $\mu=6$; both saw buckling of tendons. Both test units slightly exceeded displacement ductility predictions (which are inherently conservative), albeit at a slightly lower post-spalling strength than predicted.

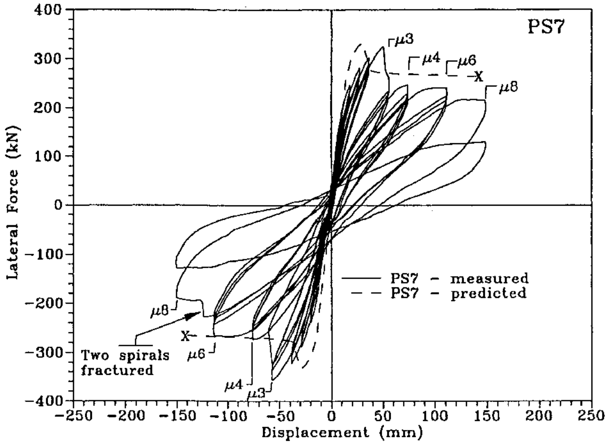

FIG. 11: FORCE-DISPLACEMENT HYSTERESIS LOOPS FOR PILE SHAFT TEST UNIT PS7

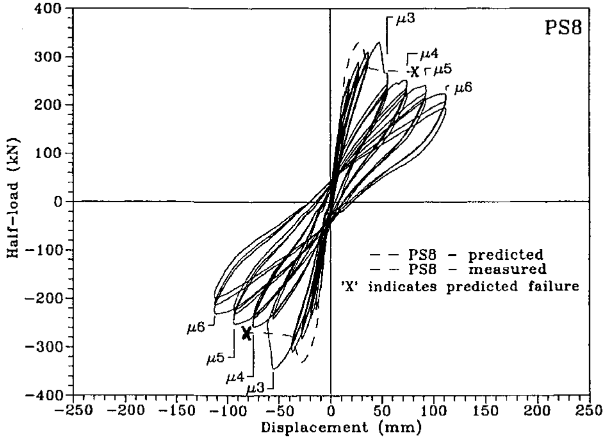

FIG. 12: FORCE-DISPLACEMENT HYSTERESIS LOOPS FOR PILE SHAFT TEST UNIT PS8

PS9 and PS10 were tested with external confinement about the center of the plastic hinge region. The salient feature of this data is the extent to which the cover, though cracked and somewhat degraded, was able, by virtue of its being constrained by the central saddles to remain in place, to preserve a considerably higher level of post-spalling strength and ductility than could be maintained by the unaided core. Through μ=8, the level of internally provided transverse reinforcement does not affect the pile shafts' performance. (As the testing of PS9 was halted at μ=8, this is all that may definitely be said.) It is of interest that none of the transverse steel failed in either test unit; PS10 had failures of individual strands in prestressing tendons at μ=10; PS9 showed evidence of tendon buckling, but not failure. Both test units considerably outlasted their predicted lives; comparison with PS7 and PS8 strongly suggests that the constraint of the cover concrete was the main contributory factor in this enhancement of performance.

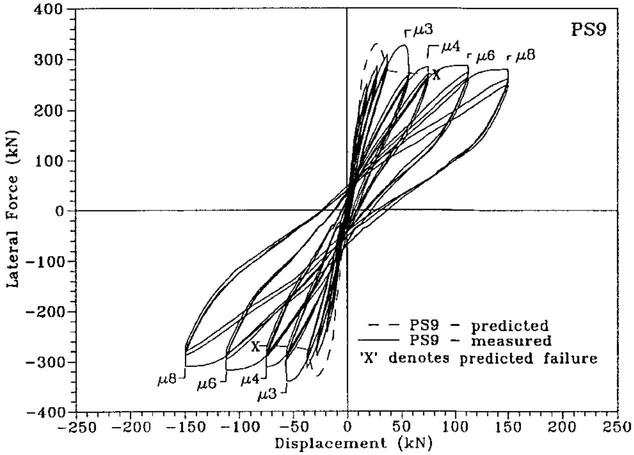

FIG. 13: FORCE-DISPLACEMENT HYSTERESIS LOOPS FOR PILE SHAFT TEST UNIT PS9

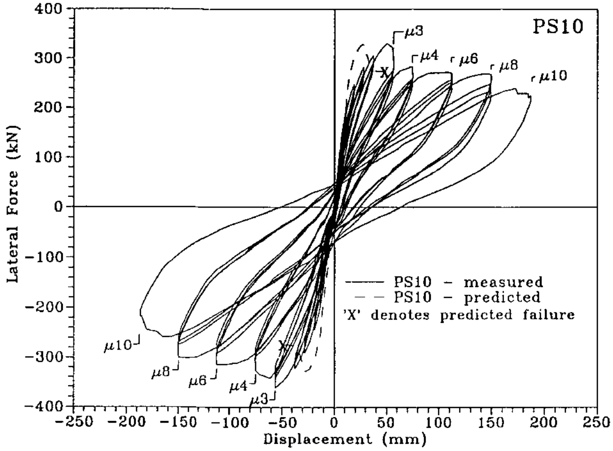

FIG. 14: FORCE-DISPLACEMENT HYSTERESIS LOOPS FOR PILE SHAFT TEST UNIT PS10

6. CONCLUSIONS

This series of tests reinforces the main conclusion drawn from the testing of cast-in-place pile shaft test units PS1-6; that is, that the external confinement provided by soil about the pile can greatly enhance the performance of the subgrade hinge. Also, the broadly-peaked moment pattern resulting from certain soil profiles can serve to spread plasticity over a fairly broad front, delaying the occurrence of localized, fatal damage.

ACKNOWLEDGMENTS

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We would like to thank Utility Vault Co., in Fontana, California, for the donation of prestressed pile test units PS7 through PS10.