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Transfer Length of Strands in Prestressed Concrete Piles

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Transfer Length of Strands in Prestressed Concrete Piles

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A top bar effect has been identified in prestressed concrete piles. The effect that this top bar effect has on the development of the prestressing strand is investigated. Strand transfer length is found to be proportional to the observed end slip. While the average transfer length of all strands in a section may satisfy the assumptions inherent in the ACI transfer length equation, due to the top bar effect, top-cast strand transfer lengths are considerably in excess of the ACI-calculated value. The flexural behavior of the pile, accounting for varying transfer lengths through its section, is investigated. Finally, recommendations for in-plant testing and acceptance criteria for prestressed strand bond quality are proposed.

Keywords: development length; pile; prestressed concrete; slip; strand; transfer length.

INTRODUCTION

Prestressed concrete piles are used in a variety of structures and loading conditions. Although primarily compression members, piles may be subjected to tensile forces induced during handling, placement, and in service.

Service tensile forces are likely to be developed during a seismic event. A pile may be subject to direct tension, as is the case when it is resisting uplift forces. More likely, however, is that a pile will be subject to flexural stresses while resisting lateral forces. Piles, particularly those in soft soils, may be subjected to large lateral deflections in the event of an earthquake. The lateral deflections can result in high local curvature and moment demands at various locations along the pile length, as shown in Fig. 1.[1] Of particular concern is the pile-to-pile cap interface. At this location, very high moment demands result from the assumed fixity of pile-to-pile cap connection. For this behavior to occur as assumed, the connection must be able to transmit lateral forces to the pile and remain essentially rigid. It has been demonstrated that the pile-to-pile cap connection can be easily designed to provide this assumed fixity and to develop the entire moment capacity of the pile.[2] Determining the flexural capacity, and thus the lateral load resistance of the pile foundation, therefore becomes a question of determining the flexural capacity of the pile at its critical section, the pile-to-pile cap interface.

The capacity of the pile at this location is affected by the transfer length of the strands. Although it has been suggested that the pile-to-pile cap embedment be made longer than the strand transfer length,[3] this is generally viewed as impractical,[2] resulting in very deep pile caps. Typically, the pile embedment will be shorter than the strand transfer length.[1,2,4] In this case, the theoretical, fully prestressed capacity of the pile is not available at the critical section. To account for the reduction in pile capacity at this partially prestressed location, the transfer length of the strand and other prestressing losses must be taken into account.

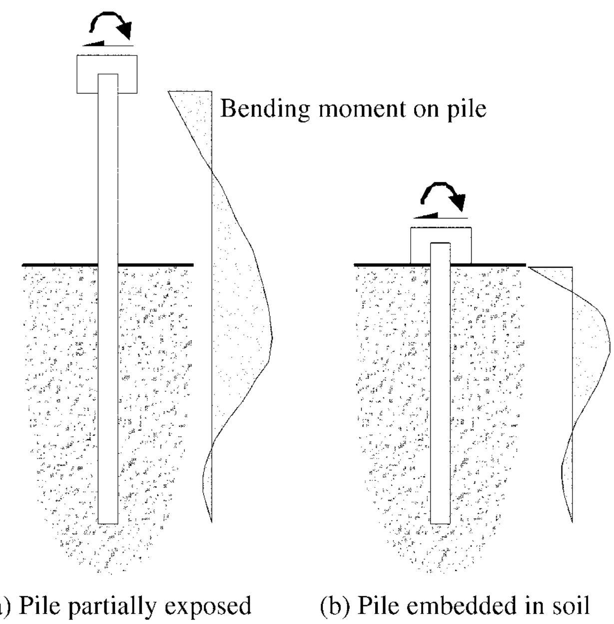

Fig. 1—Bending of long piles due to horizontal ground motion (adapted from Joen and Park 1990).

PRESTRESSING LOSSES

Prestressing losses in prestressed concrete may be classified into two categories based on their time of occurrence. The first category consists of initial losses, which occur immediately after the transfer of the prestressing force. The second type of losses are time-dependent and occur over time after the prestressing force is transferred. Initial losses include elastic shortening of the concrete and initial strand end slip, while time-dependent losses include creep and shrinkage of concrete, and relaxation of the steel strands. Total expected losses are specified by both ACI-ASCE[5] and by AASHTO.[6] The ACI-ASCE Joint Committee suggested losses to be approximately 35 ksi (241 MPa), which does not include strand end slip losses. AASHTO recommends keeping total losses under 45 ksi (310 MPa) for concrete with f_c' = 5000 psi (34.5 MPa).

Strand end slip losses

A realistic method of calculating prestressing loss due to strand end slip is based on a strand slip theory discussed in papers by Brooks, Gerstle, and Logan[7] and Anderson and Anderson.[8] The theory is based on the premise that the initial slip is a direct indication of the bond quality of the concrete. The slip, therefore, is directly related to the transfer length of the strand.

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Using an assumed linear variation of stress from the free end of the member to the transfer length ℓ_t, the average strand force over the transfer length can be set to the initial force immediately after transfer, F_i, divided by 2. The initial strand end slip δ can be related to the average force by the steel strains

$$\delta = \frac{F_i \ell_t}{2A_{ps}E_s} \quad (1)$$

Substituting the steel stress, $f_{si} = F_i/A_{ps}$, and solving for the transfer length ℓ_t yields the following

$$\ell_t = \frac{2E_s}{f_{si}}\delta \quad (2)$$

By setting Eq. (2) equal to the transfer length specified by ACI 318-99[9], $0.33f_{se}d_b$ ($0.048f_{se}d_b$ in MPa units), an implied allowable end slip δ_{all} can be calculated

$$\delta_{all} = 0.165\frac{f_{se}f_{si}d_b}{E_s} \text{ (ksi units) or} \quad (3)$$

$$\delta_{all} = 0.024\frac{f_{se}f_{si}d_b}{E_s} \text{ (MPa units)}$$

As was stated previously, the flexural capacity of the pile is affected by the stress developed in the strand at the location of interest along the length of the pile. Manipulating the equations for flexural bond length given in ACI 318-99,[9] it is possible to determine the stress that is developed in the strand at a distance x from the free end of the pile as a function of the transfer length ℓ_t and thus, through Eq. (2) as a function of the strand end slip δ.[10]

$$f_{dev} = \frac{x}{\ell_t}f_{se} \qquad x < \ell_t \quad (4)$$

$$f_{dev} = f_{se} + \frac{x - \ell_t}{\ell_b}(f_{ps} - f_{se}) \qquad \ell_t < x < (\ell_t + \ell_b)$$

$$f_{dev} = f_{ps} \qquad x > (\ell_t + \ell_b)$$

where the development length is found by rearranging the ACI 318-99[9] equations for flexural bond and development length

$$\ell_b = 3.0\frac{(f_{ps} - f_{se})}{f_{se}}\ell_t \quad (5)$$

For 1/2-in. (12.7 mm), 270 Grade prestressing strand having $f_{si} = 0.75f_{pu}$ and additional losses of 30 ksi (207 MPa) making $f_{se} = 0.64f_{pu}$, the transfer length and flexural bond length are determined from ACI 318-99 to be 28.5 and 21.6 in. (724 and 550 mm), respectively. The development length is therefore 50.1 in. (1274 mm). Implicit in these calculations is a bond strength of 750 psi (5.2 MPa) over the transfer length and 250 psi (1.7 MPa) over the interior portion of the strand. Furthermore, based on these calculations, the theoretical allowable strand end slip (Eq. (3)) is 0.1 in. (2.54 mm).

As can be seen, the transfer length and flexural bond length are proportional to the strand end slip. Thus the capacity of the pile, is directly affected by the strand end slip.

Top bar effect

According to ACI 318-99[9] and AASHTO[6] provisions, a top bar is any reinforcement having more than 12 in. of concrete below it. The top bar effect is the most important factor contributing to the excessive end slip of top strands.[10,11] Measurements of prestressed strand end slip consistently show higher end slip in the top of a cross section, regardless of cross-sectional shape or strand arrangement.[10-14] In reinforced concrete design, the importance of top bar effects has been accounted for in the ACI 318 Code since 1951. The development length of top cast bars in reinforced concrete is increased by a factor of 1.3 (ACI 318-99[9]) or 1.4 (AASHTO[6]). The bond between prestressing strands and concrete is even more important in prestressed concrete because the prestressing force is transferred to the concrete by this bond. It is reasonable, therefore, to increase the development length of strands used in pretensioned members by a factor similar to that used for reinforced concrete elements.[11]

Field observations of strand end slip and top bar effect

In a previous paper,[10] the authors reported a series of strand end slip measurements taken from various piles at various precast plants in the Southeastern United States. Observed strand end slip measurements of 1/2 in. (12.7 mm) strand ranged from 0.13 to 1.5 in. (3.3 to 38.1 mm), all greater than the implied allowable strand end slip of 0.1 in. (2.54 mm). Furthermore, a large difference in end slip was observed between top- and bottom-cast strands. The ratio of top- to bottom-strand end slip t/b varied from 1.15 to 5.15 for the piles observed.

Strand pullout tests conducted on 144 and 52 in. (3660 and 1320 mm) prestressed pile specimens routinely resulted in bond failures, despite the embedment being greater than the development length in both instances.[10]

Finally, and most significantly, it was shown[10] that due to the observed end slip values, the flexural capacity of a prestressed pile was reduced between 17 and 39% from that calculated using ACI 318-99[9] methods, depending on the flexural axis considered. This reduction is due to the large observed end slips and the directional variability is due to the observed top bar effect.

Several factors were identified as contributing to the excessive strand end slip and the observed top bar phenomena.[10,11] These

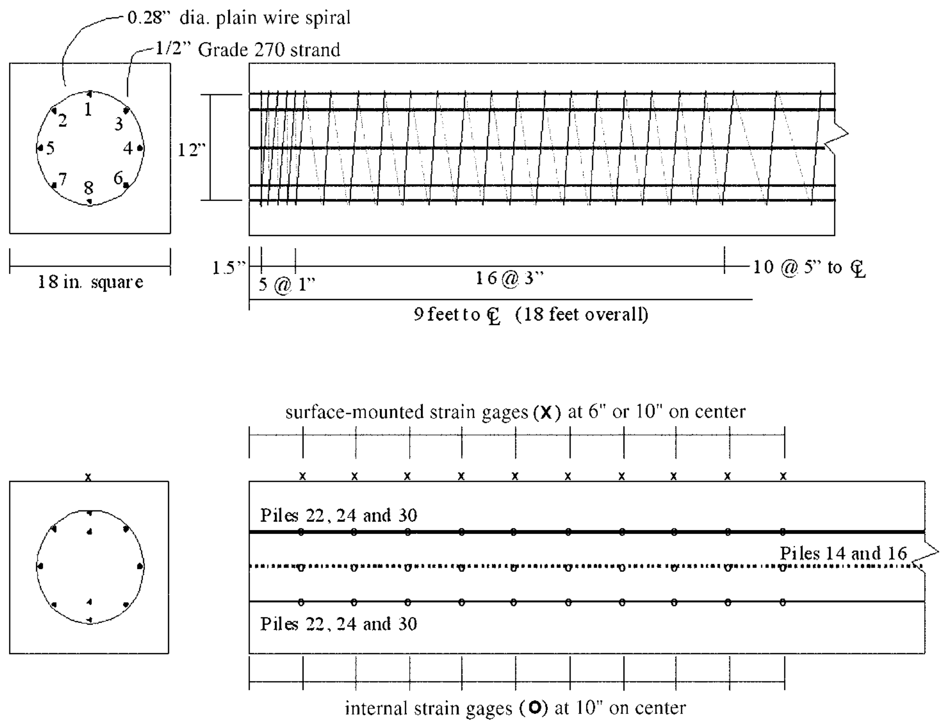

Fig. 2—Pile test specimen details, strand numbering, and instrumentation.

included concrete strength and consistency, transverse steel arrangement, and method of strand release.

RESEARCH SIGNIFICANCE

This paper demonstrates the presence of top bar effects in prestressed concrete members and demonstrates a proportional relationship between transfer length and strand end slip. The introduction of a top bar effect factor in prestressed concrete development length calculations similar to the one applied in reinforced concrete structural elements is recommended. Finally, the effects of strand end slip and the top bar effect are discussed in context of the behavior of the pile.

EXPERIMENTAL INVESTIGATION

This study and the previously mentioned study of Southeastern United States prestressing plants[10] focus on prestressed concrete piles. Piles have the simplest possible cross section and, when cast horizontally, they offer the clearest definition of top- and bottom-cast strand. Additionally, piles have only straight strand, theoretically resulting in no flexural stresses that may also affect strand slip measurements and development length determination. It is also important to note that the top bar effect is properly termed the top-cast bar effect. Precast piles, although vertical elements in a structure, are cast horizontally and thus have both top- and bottom-cast strands.

A laboratory investigation of full-scale prestressed concrete piles was carried out to investigate strand development and top bar behavior. The details of this study are reported by the authors elsewhere[11] and summarized as follows.

Pile test specimens

Details of the 18 ft (5.5 m) long, 18 in. (457 mm) square prestressed pile specimens used in this study are shown in Fig. 2. The left-hand columns of Table 1 summarize the variable parameters of the pile design and concrete mixes; these are discussed elsewhere.[11] These prestressed piles are typical of those used throughout the Southeastern U.S.

All piles were prestressed with 8-1/2 in. (cross sectional area = 0.153 in^2 [99 mm^2]) Grade 270 strands, except Piles 22 and 23, which had 3/8 in. (cross sectional area = 0.085 in^2 [55 mm^2]) Grade 270 strands. All strand used was provided by the same manufacturer and all strand of the same size came from the same roll of strand. All strands were prestressed to 203 ksi (1397 MPa) or 0.75f_{pu}. Confining spiral reinforcement was provided by smooth, 0.28 in. (7 mm) diameter wire having a yield strength of 82 ksi (565 MPa). Not all piles were provided with confining spirals, as indicated in Table 1. The South Carolina Department of Transportation (SCDOT) Highway Class X (now called Class 5000) or Class D (now called Class 4000) concrete was provided by a local ready-mix supplier. Class X concrete is a Type III mixture having a minimum specified 28-day compressive strength of 5000 psi (34.5 MPa) and is designed to achieve 3500 psi (24.1 MPa) within 72 h. Class D concrete is a Type I mixture having a minimum specified 28-day compressive strength of 4000 psi (27.6 MPa). Class D would not typically be used for prestressed piles but has been included herein for comparison. As indicated in Table 1, most batches easily achieved their design strengths. As shown in Table 1, concrete slump was varied from 3.5 to 5.5 in. (90 to 140 mm) and was measured in accordance with ASTM C 143.

Admixtures were provided by the ready-mix supplier as indicated in Table 1. A commercially available retarder was used in Piles 4 to 7, 12 and 13, 18 and 19, and 22 and 23. A commercially available high-range water reducing admixture was used in Piles 8 and 9.

With the exception of Piles 20 and 21, the minimum concrete compressive strength f_c at strand release was specified to be 3500 psi (24.1 MPa). The measured compressive strength and age of the concrete at strand release are given in Table 1. The strand release sequence (seq. in Table 1) was varied. All

Table 1—Pile specimen details and measured slip results

Pile	Mixture	Slump, in.	Admixture	Spiral	f_c', psi	Strand release		
						Age, h	Sequence (Fig. 2)	f_c, psi
1*	X	4.0	None	Yes	7990	145	2-6-3-7-1-8-5-4	4790
2	X	3.5	None	Yes	7480	46	2-6-3-7-1-8-5-4	4320
4	X	5.0	Retarder	No	6510	51	2-6-3-7-1-8-5-4	3550
5	X	5.0	Retarder	No	6510	51	2-6-3-7-1-8-5-4	3550
6	X	5.0	Retarder	Yes	7220	68	1-2-3-4-5-6-7-8	4080
7	X	5.0	Retarder	Yes	7220	68	1-2-3-4-5-6-7-8	4080
8	X	4.5	HRWR	Yes	6700	27	2-6-3-7-1-8-5-4	5670
9	X	4.5	HRWR	Yes	6700	27	2-6-3-7-1-8-5-4	5670
10	X	3.5	None	Yes	6700	43	2-6-3-7-1-8-5-4	4500
11	X	3.75	None	Yes	6770	43	2-6-3-7-1-8-5-4	4500
12	X	4.0	Retarder	No	7840	48	2-6-3-7-1-8-5-4	3900
13	X	4.0	Retarder	Yes	7840	48	2-6-3-7-1-8-5-4	3900
14	D	4.0	None	Yes	7840	43	2-6-3-7-1-8-5-4	3540
15	D	4.0	None	Yes	7840	43	2-6-3-7-1-8-5-4	3540
16	X	5.5	None	Yes	6310	168	2-6-3-7-1-8-5-4	5770
17	X	5.5	None	Yes	6310	168	2-6-3-7-1-8-5-4	5770
18	D	3.5	Retarder	Yes	6680	49	1-2-3-4-5-6-7-8	3580
19	D	3.5	Retarder	Yes	6680	49	1-2-3-4-5-6-7-8	3580
20	D	4.5	None	Yes	7660	12	2-6-3-7-1-8-5-4	1710
21	D	4.5	None	Yes	7660	12	2-6-3-7-1-8-5-4	1710
22†	X	4.0	Retarder	Yes	9350	48	2-6-3-7-1-8-5-4	4380
23†	X	4.0	Retarder	Yes	9350	48	2-6-3-7-1-8-5-4	4380
24	X	5.5	None	Yes	4490	72	Gang	3420
25	X	5.5	None	Yes	4490	72	Gang	3420
26	X	5.5	None	Yes	6500	66	Gang	3830
27	X	5.5	None	Yes	6500	66	Gang	3830
28	X	4.5	None	Yes	8610	72	2-6-3-7-1-8-5-4	4060
29	X	4.5	None	Yes	8610	72	2-6-3-7-1-8-5-4	4060
30	X	3.5	None	Yes	7130	72	2-6-3-7-1-8-5-4	3730
31	X	3.5	None	No	7130	72	2-6-3-7-1-8-5-4	3730
32	X	4.0	None	Yes	5740	48	Gang	3720
33	X	4.0	None	No	5740	48	Gang	3720

*Pile No. 1 was 40 ft long.
†Piles 22 and 23 had 3/8 in.-diameter strand.

strands except those of Piles 24 to 27 and 32 and 33 were flame-cut from each end of the prestressing bed simultaneously. The traditional top-to-bottom sequence of cutting was used for Piles 6, 7, 18, and 19. Otherwise, a radially symmetric sequence was used, cutting strands in the order: 2-6-3-7-1-8-5-4 (refer to Fig. 2). The symmetric sequence was used to minimize flexural stresses on the section resulting from the unbalanced transfer of prestress force.

All strands of Piles 24 to 27 and 32 and 33 were stressed and released simultaneously using a hydraulic gang mechanism described previously by the authors.[11] In addition to providing simultaneous strand release, gang tensioning is also a method of slow release. The strands were released over a period of about 270 s.

Instrumentation

All piles were instrumented to measure the end slip of each strand at each end of each pile as described previously.[11] To investigate transfer length, one pile from each cast was instrumented with electrical resistance strain gages along the center line of the top of the pile, as shown in Fig. 2. These gages were installed after the concrete had hardened and prior to release of the strands.

Internal instrumentation in the form of regular, No. 3 reinforcing bars having multiple strain gages attached was provided in some piles. In Piles 14 and 16, a single, instrumented, No. 3 bar was placed at the centroid of the pile section. In Piles 22, 24, and 30, two instrumented bars were located vertically, 8 in. (200 mm) on center along the centerline of the pile. Such an arrangement permitted capturing concrete strains through the depth of the pile before, during, and after strand release.

A high-speed data acquisition system was used to collect strain gage data at a rate of 400 readings per second during the strand release operation.

OBSERVATIONS FROM EXPERIMENTAL INVESTIGATION

Strand end slip results

The range of strand end slip data is reported in Table 2. This data is described thoroughly in Reference 11. The average strand end slip measured was 0.095 in. (2.41 mm). The average top strand slip was 0.140 in. (3.56 mm) and the average bottom strand slip was 0.058 in. (1.47 mm). Top strand slip regularly

Table 2—Summary of strand end-slip results[11]

Number of piles in study	32
Range of concrete strength f_c', psi	5740 to 9350
Average concrete strength f_c', psi	7070
Range of concrete strength at strand release f_c, psi	3420* to 5770
Average concrete strength at strand release f_c, psi	4000
Range of average strand end slip, in.	0.095
Range of top strand end slip, in.	0.031 to 0.314
Average top strand end slip observed in study, in.	0.140
Range of bottom strand end slip, in.	0.003 to 0.195
Average bottom strand end slip observed in study, in.	0.058
Range of *t*/*b* ratios	1.03 to 45.44
Average *t*/*b* ratio	2.4

*Piles 20 and 21 intentionally released early at strength of 1710 psi.

exceeded the implied permissible strand slip Eq. (3) of 0.1 in. (2.54 mm) while the bottom strand slip typically did not.

t/*b* ratio

The observed top-to-bottom strand slip ratios *t*/*b* vary from 1.03 (Pile 26) to well over 3.0. Based on average top and bottom strand end slip values given previously, the average *t*/*b* ratio is 2.4. These results and those reported previously by the authors[10] and Chew[14] demonstrate very clearly that there is a top bar effect present in prestressed concrete. This top bar effect is analogous to that recognized for reinforced concrete and is influenced by many of the same factors.[11]

Transfer length

Figure 3 and 4 show observed concrete strain versus distance from the free end of the pile for Piles 22 and 24, respectively. Strand transfer length may be estimated from these relationships by estimating the distance from the free end of the pile at which the observed strain becomes essentially constant, that is, the location at which the strand can develop the prestress f_{si}. The discrete nature of the instrumentation permits the transfer length to be estimated to within approximately 3 to 6 in. (75 to 150 mm). Transfer lengths estimated in this manner are reported in Table 3. Also shown in Table 3 are reported end slip measurements for the piles considered. Top and bottom Strands refer to the average values for Strands 1 to 3 and 6 to 8, respectively.

The stress and strain conditions at the top concrete surface are different from those in the strands. It is not reasonable to estimate transfer lengths from strains measured on the free surface of the concrete. However, these estimates are useful qualitative measurements of the top strand transfer length. As such, the relationship between the transfer length from concrete surface strain measurements and the average top strand end slip is shown in Fig. 5. The qualitative measure of transfer length increases with an observed increase in top strand end slip.

Transfer length estimated from strains at the centroid of the pile (Piles 14 and 16) may reasonably be assumed to capture the average transfer length of all the strands. As can be seen in Table 3, the average strand end slip of Piles 14 and 16 were similar—0.078 and 0.075 in. (1.98 and 1.91 mm), respectively—and below the implied permissible strand end slip of 0.1 in. The estimated transfer length based on strains at the centroid of the

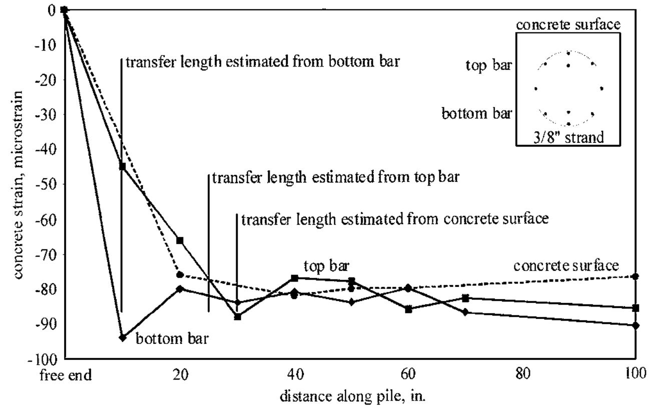

Fig. 3—Concrete strain measurements and estimated transfer lengths for Pile 22.

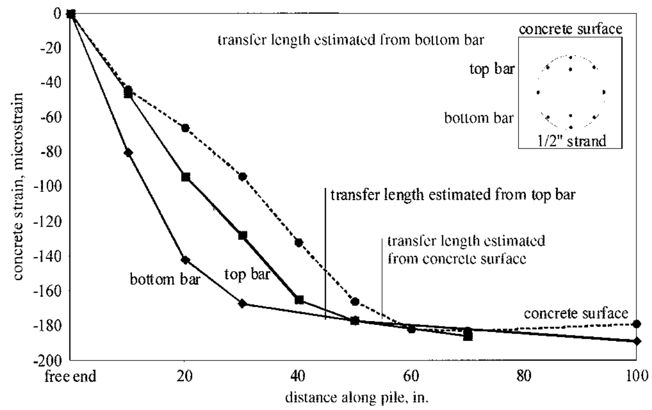

Fig. 4—Concrete strain measurements and estimated transfer lengths for Pile 24.

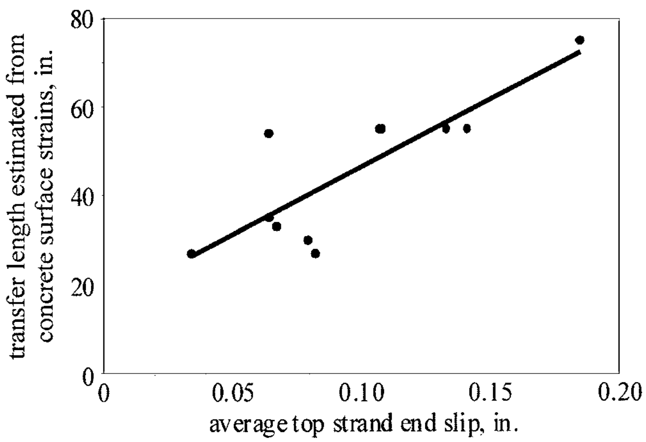

Fig. 5—Estimated transfer length versus strand end slip.

piles was similar near 45 in. (1140 mm), considerably greater than the ACI-prescribed value of 28.5 in. (724 mm).

The transfer length estimated from strains within 2 in. (50 mm) of the top and bottom strands (Piles 22, 24, and 30) provides a good estimate of the actual transfer lengths of these strands. A transfer length estimated in this way illustrates a significant top bar effect, that is, the transfer length of the top strand exceeds that of the bottom strand. The ratios of top to bottom transfer lengths for Piles 22, 24, and 30 are 2.5, 1.8, and 1.7, respectively. The *t*/*b* ratios determined from strand end slip measurements for the same piles[11] are 3.36, 2.03, and 1.17.

Table 3—Transfer length estimated from strain measurements

Pile	Experimentally determined strand end slip values, in.			ACI 318 transfer length, $0.33 f_{se} d_b$, in.	Transfer length ℓ_t estimated from in.			
	Average of all strands	Average of top Strands 1 to 3	Average of bottom Strands 6 to 8		Strains at concrete surface	Strains at centroid of pile	Strains 4 in. above centroid	Strains 4 in. above centroid
1	0.071	0.082	0.066	28.5	27	—	—	—
2	0.021	0.034	0.013	28.5	27	—	—	—
8	0.045	0.064	0.017	28.5	54	—	—	—
10	0.046	0.067	0.013	28.5	33	—	—	—
12	0.061	0.107	0.022	28.5	55	—	—	—
14	0.078	0.108	0.033	28.5	55	40	—	—
16	0.075	0.133	0.049	28.5	55	45	—	—
20	0.084	0.185	0.031	28.5	75	—	—	—
22	0.050	0.079	0.040	21.5	30	—	25	10
24	0.105	0.141	0.066	28.5	55	—	45	25
30	0.029	0.064	0.021	28.5	35	—	25	15

Table 4—Transfer length calculated from strand end slip measurements

Pile	Location	ε_c, με	f_c at release, psi	f_{si}	δ, in.	Transfer length ℓ_t, in.		
						ACI 318 $0.33 f_{se} d_b$	Calculated	Estimated
14	Average	–165	3540	$0.566 f_{pu}$	0.078	28.5	29.6	40
	Top				0.108		41.0	—
	Bottom				0.033		12.5	—
16	Average	–182	5770	$0.791 f_{pu}$	0.075	28.5	20.4	45
	Top				0.133		36.2	—
	Bottom				0.049		13.3	—
22	Average	–84	4380	$0.570 f_{pu}$	0.050	21.5	18.9	—
	Top	–83			0.079		29.8	25
	Bottom	–85			0.040		15.1	10
24	Average	–180	3420	$0.608 f_{pu}$	0.105	28.5	37.1	—
	Top	–182			0.141		49.8	45
	Bottom	–178			0.066		23.3	25
30	Average	–178	3730	$0.628 f_{pu}$	0.029	28.5	9.9	—
	Top	–167			0.064		21.9	25
	Bottom	–190			0.021		7.2	15

It can also been seen from Table 3 that the estimated transfer length of top strands regularly exceeded the ACI-prescribed value of 28.5 in. (724 mm) while the estimated bottom strand transfer length typically did not. This observation is consistent with the strand end slip results.[11]

RELATIONSHIP BETWEEN TRANSFER LENGTH AND STRAND END SLIP

The relationship between transfer length and strand end slip is given in Eq. (2). In this equation, taking E_s = 29,000 ksi (200,000 MPa), δ as the measured strand end slip measurement, and knowing the initial prestress f_{si}, transfer length can be calculated.

The total initial prestress force in the pile P_i can be calculated by

$$P_i = \varepsilon_c E_c A_c \tag{6}$$

where A_c is taken as the transformed sectional area of the pile.

To estimate the initial prestress (including losses), ε_c is taken as the concrete strain in the pile at a location where the strand forces are fully developed. This value strain is determined by averaging all available strain data at a location beyond the transfer length, typically at the furthest instrument from the free end of the pile (Fig. 2). For the calculations presented, the elastic modulus of concrete is based on the concrete strength at strand release f_c and computed by ACI 318-99[9] equation

$$E_c = 57,000\sqrt{f_c} \tag{7}$$

The initial prestress in each strand f_{si} is determined as

$$f_{si} = \frac{P_i}{nA_{ps}} \tag{8}$$

where n = 8, the number of strands in each pile. Because of the top bar effect, the initial prestress in each strand is not exactly the same. The difference, however, is not significant once all strands have been transferred. The strain values shown in Table 4 and those shown in Fig. 3 and 4 clearly show that once all strands have been transferred, the concrete strain in the pile is essentially uniform through the pile section. Finally, by substituting f_{si} into Eq. (2), the transfer length ℓ_t can be calculated. Transfer lengths determined in this manner are shown in Table 4. Top and bottom strands refer to the average values for the strands 1 to 3 and 6 to 8, respectively.

Transfer lengths calculated in this manner are relatively consistent with those estimated graphically (above). Average transfer lengths of all strands in the pile sections are generally consistent with the ACI 318-99[9]-prescribed value of $0.33f_{se}d_b$ ($0.048f_{se}d_b$ in MPa units). However, because transfer length is proportional to end slip, the transfer lengths of top strands exceed that of bottom strands. From a designer's perspective, the use of the ACI transfer length relationship is appropriate provided that a factor, similar to the top bar factor for reinforced concrete, is applied to top-cast strands.

To obtain more accurate estimates of transfer length, the strands themselves must be instrumented. This is an exceptionally difficult prospect due to the size and varying orientation of the strand wires. In a continuing study[15] of the effects of traditional-versus-slow release of prestressing force, the authors are attempting to measure strand strains directly, with limited success. Therefore, it is believed that it is more practical to measure strand end slip and concrete strain at a location well beyond the transfer length to estimate the transfer length using Eq. (2).

TOP BAR EFFECT ON PILE PERFORMANCE

Strands located near the top of a section may be expected to have greater transfer lengths than those near the bottom. At all locations within the greatest transfer length, there will be a strain gradient through the pile section as shown in Fig. 6. This gradient can also be seen as the difference in strains at a particular section in Fig. 3 and 4. Before the top strand transfer length is achieved, the compressive strains below the pile centroid are greater than those above it. In both Piles 22 and 24 (Fig. 3 and 4) at the location of the estimated transfer length of the bottom strands, although no tensile strains are present, the curvature of the pile section is approximately 6×10^{-6} rad/in. In the case of Pile 22, the strain on the top surface of the pile at the estimated bottom strand transfer length is very close to zero.

While the gradient, by itself, should not be expected to result in tensile stress at any location along the pile, it may be significant enough to affect the moment capacity, and particularly the cracking moment, over the longest strand development length (transfer length plus flexural bond length). The gradient, therefore, must be accounted for in determining handling, driving, and service loads. As has been seen in this investigation, the transfer lengths of top strands can become quite long. In particular, this region may be reasonably expected to include the critical section of the pile near the pile-to-pile cap connection (Fig. 1). Cracking and pile capacity must be investigated at this location, accounting for the gradient resulting from variance in strand transfer lengths.

The effect of the gradient on the moment capacity of an individual pile will depend on the orientation of the top and bottom of the pile with respect to the applied moment. Figure 7 shows factored moment-axial load interaction diagrams of Pile 24 at locations 30, 50, and 100 in. (762, 1270, and 2540 mm) from the free end of the pile. These interaction diagrams have been generated using real pile material properties and actual strand end slip values[11] for each strand. The interaction curves are shown as a region bounded by the cases where the moment is implied in the most favorable and least favorable directions. Referring to Fig. 6, the most favorable direction is represented by a clockwise moment applied to the left end of the pile, while the least favorable moment is a counterclockwise moment.

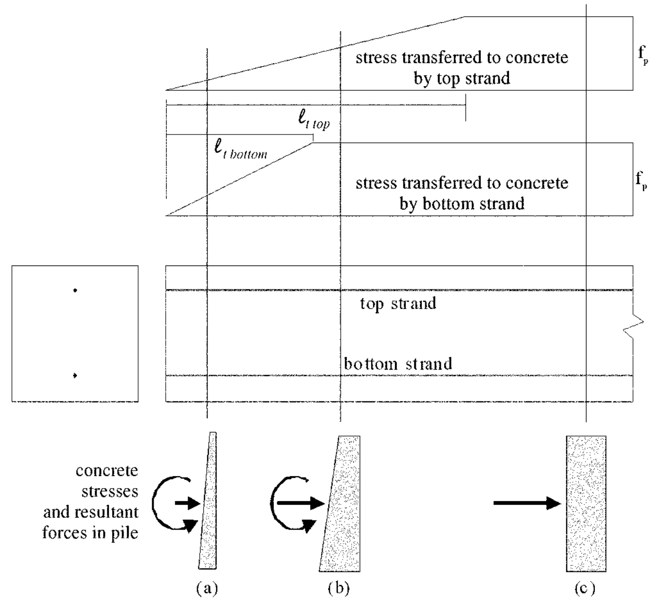

Fig. 6—Concrete stresses resulting from top bar effect in prestressed piles.

Also shown in Fig. 7 is the interaction diagram for Pile 24 if the end slip of all eight strands was equal to the ACI-implied allowable slip of 0.1 in. (2.54 mm). If all strands have equal slip, there is no most or least favorable direction.

Pile 24 was selected for this demonstration because the average end slip of all strands was 0.105 in. (2.67 mm), close to the ACI-implied allowable value of 0.1 in. (2.54 mm). Additionally, the t/b ratio was 2.14—a relatively typical, if not somewhat better than average, result from this investigation. Pile 24 may be considered to be a good quality pile.

At a location 30 in. (762 mm) from the pile end, the factored moment capacity of the pile at reasonable service axial load levels varies from the ACI-assumed response by approximately ± 6%. Further along the pile, at 50 in. (1270 mm), the variation from the ACI response is similar, but only at lower axial load levels. Finally, beyond the transfer region, at 100 in. (2540 mm), the response is only affected by the average end slip and its variance from the ACI-implied value of 0.1 in. (2.54 mm).

The interaction diagram at 100 in. (2540 mm) presented in Fig. 7 clearly shows the effect of the variance of average end slip. In the case of Pile 24, the average end slip exceeds the ACI-implied end slip by 5%. At service axial load levels, the factored moment capacity of the pile varies by a similar amount. At low axial loads, however, the pure factored moment capacity of the pile is as much as 13% less than the expected response. As previously mentioned, Pile 24 is typical of this investigation and may be considered a good quality pile.

TESTING AND ACCEPTANCE CRITERIA FOR STRAND TRANSFER LENGTH

Strand transfer length and end slip are indications of the quality of the bond between prestressing strand and concrete. Based on the observations of this and previous investigations,[10,11] the authors propose the following in-plant test procedure to determine the quality of strand bond.

Measurement of strand end slip has been shown to allow qualification of the strand transfer length. Provided that a top bar effect factor, similar to that used for reinforced concrete, is introduced for top-cast strands, the average strand end slip

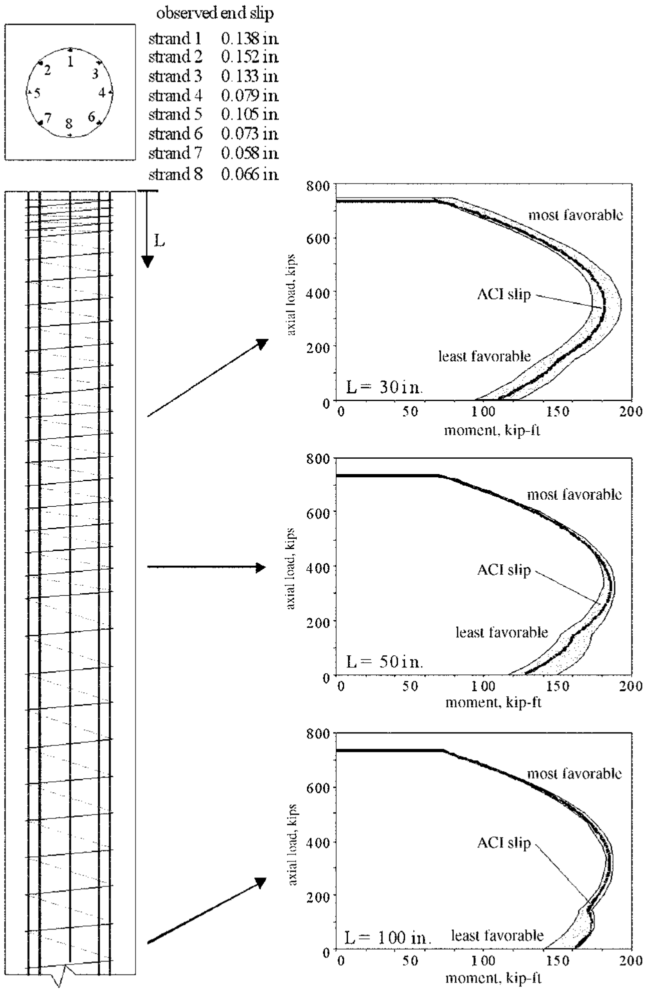

Fig. 7—Axial load—moment interaction diagrams for Pile 24.

over an entire section should not be permitted to exceed the ACI-implied allowable end slip given by Eq. (3). In determining this average, both top and bottom strands must be considered. Alternatively, a single measurement of a top strand may be made. If the end slip is less than 1.5 times that determined by Eq. (3), the pile is acceptable; otherwise, further measurements are required. Measurement of strand end slip in a precast plant requires some forethought, and accommodations must be made prior to release of the strands.

Figure 8 shows the method for measuring strand end slip used in this study and recommended for determining strand end slip in a prestressing plant. This method was originally developed by Bruce Russell at the University of Oklahoma. Measuring strand end slip requires that a gap be left between the end of the finished pile and the prestressing bulkhead (Fig. 8(a)). This gap must be long enough to remove the end form, install the strand collars, and take depth gage readings while the strands are still stressed. Variations of this procedure can be made to accommodate variations in prestressing procedures. The procedure is as follows:

1. Once the concrete is cured sufficiently, the end form is removed (or slid back along the strands);

2. A collar is securely fastened around each strand to be measured at a location approximately 1 in. (25.4 mm) from the face of the concrete. The collar has two holes, parallel and to either side of the strand, through which a depth gage may be inserted;

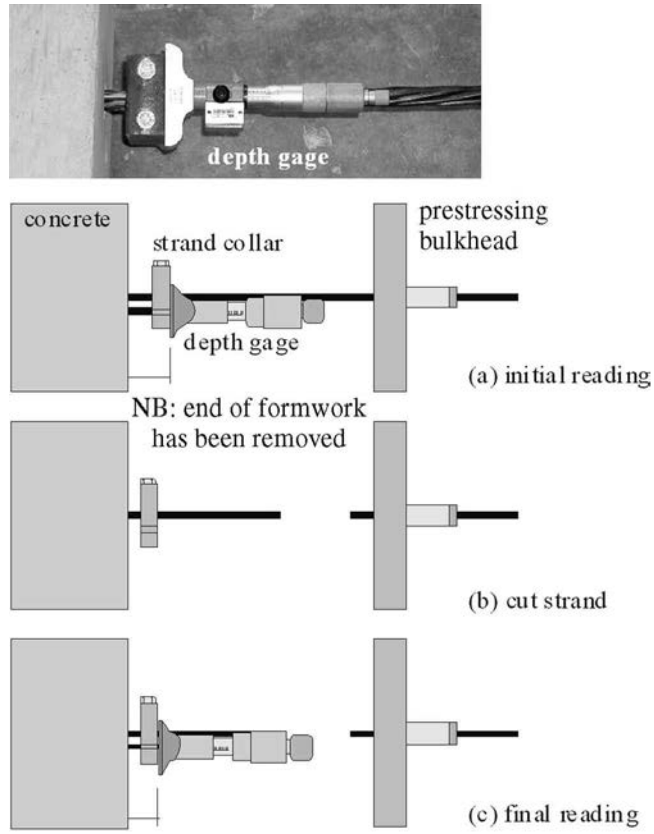

Fig. 8—Method for measuring strand end slip.

3. An initial measurement of the location of the collar, relative to the concrete surface, is made using the depth gage (Fig 8(a)). A measurement is taken on either side of the strand and averaged to account for any misalignment of the collar;

4. The strands are released, resulting in the strands slipping into the concrete (Fig. 8(b));

5. A final pair of measurements is made using the depth gage (Fig. 8(c)). The final measurement subtracted from the initial measurement is the amount of strand end slip plus elastic shortening of the strand over the gage length; and

6. The actual strand end slip is found by subtracting the expected elastic shortening of the strand, over the gage length, upon release of the strand. It is noted that the strand end slips reported throughout this study include the elastic shortening component. In some cases, this component may represent close to 0.01 in. (0.25 mm).

As noted previously, an acceptance-testing protocol may include all strands in a pile, a few strands distributed through the depth of the pile, or simply a top-cast strand. Clearly, however, all strands that may be required for determining acceptance must have had initial measurements made on them for this method to be useful.

CONCLUSIONS AND RECOMMENDATIONS

Strand transfer length and end slip measurements were made on 32 18 in. (457 mm) square prestressed concrete piles. Transfer length estimates were made based on concrete compressive strains resulting from the transfer of prestress to the concrete. The average strand end slip measured was 0.095 in. (2.41 mm). The average top strand slip was 0.140 in. (3.56 mm) and the average bottom strand slip was 0.058 in. (1.47 mm). Top strand slip regularly exceeded the ACI-implied permissible strand slip (Eq. 3) of 0.1 in. (2.54 mm) while the bottom strand slip typically did not. The average top strand slip to bottom strand slip ratio (t/b) was 2.4, clearly demonstrating a top bar effect present in prestressed concrete. This top bar effect is analogous to that recognized for reinforced concrete and is influenced by many of the same factors.

Estimated strand transfer lengths were consistent with end slip values. The estimated transfer length of top strands regularly exceeded the ACI-prescribed value of 28.5 in. (724 mm) for 1/2 in. strands, while the estimated bottom strand transfer length typically did not.

Estimated transfer length is proportional to strand end slip. These values vary considerably from pile to pile and within an individual pile. Generally, however, the ACI transfer length relationship provides an appropriate estimate of the average transfer length of all strands in a section. Use of this transfer length relationship should include a top-cast strand factor, similar to the top bar factor for reinforced concrete that is applied to top-cast strands.

Application of a top-cast strand factor should be included in the determination of pile capacity and the investigation of critical sections during handling, driving, and in service. It has been shown that neglecting the increased transfer length of top-cast bars can result in a significant underestimation of pile flexural capacity, even for piles that must be considered to be of good quality. There were many laboratory-cast piles in this investigation and many commercially cast piles in a previous study that would have even greater capacity reductions due to excessive strand end slip. Finally, from a practical point of view, it is felt that, conservatively, all piles should be considered to be oriented in their least favorable direction when handled and in place. It is likely that similar effect will occur in other prestressed concrete products having both straight and draped strands. This effect should be accounted for when considering development length issues.

Based on the observations of this investigation, it is felt that direct measurement of strand end slip is an appropriate method of quality control, assuming that a top-cast strand factor is considered in design. Average strand end slip over an entire section should not be permitted to exceed the ACI-implied allowable end slip given by Eq. (3). In determining such an average, both top and bottom strands must be considered. Alternatively, a single measurement of a top strand may be made. If the end slip is less than 1.5 times that determined by Eq. (3), the pile is acceptable; otherwise, further measurements are required. Measurement of strand end slip in a precast plant requires some forethought, and accommodations must be made prior to release of the strands.

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NOTATION

A_c = transformed sectional area of pile
A_{ps} = cross-sectional area of prestressing strand
d_b = diameter of prestressing strand
E_c = Young's modulus of concrete
E_s = Young's modulus of steel
F_i = force in single prestressing strand
f_c = concrete compressive strength at release of prestressing
f_c' = 28-day concrete compressive strength
f_{dev} = force that is developed in prestressing strand at location x
f_{ps} = initial prestressing force
f_{pu} = ultimate tensile strength of prestressing strand
f_{se} = long-term effective stress in prestressing strand
f_{si} = effective stress in prestressing strand after release
ℓ_b = flexural bond length of prestressing strand
ℓ_t = transfer length of prestressing strand
N = number of prestressing strands in cross section
P_i = force in concrete section
t/b = ratio of top strand end slip to bottom strand end slip
x = distance along pile
δ = strand end slip
δ_{all} = implied allowable end slip
ε_c = concrete strain

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