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Uplift Load Tests on Driven Piles

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SYNOPSIS: Details and results of uplift load tests on 25 piles at 15 sites are presented. The allowable uplift load on each pile determined from the BOCA code criterion is compared with an allowable capacity based on small movements at design load. In the majority of cases, the BOCA capacities are significantly lower.

INTRODUCTION

Uplift load design and testing of piles has become more prevalent in recent years, in response to an increased use of piles to anchor structure foundations under tension. This paper presents data from 25 uplift pile load tests at 15 sites. The sites were for either industrial or power projects, some being existing facilities and some grass-roots sites. The piles were driven, but varied in type, length, size, soil conditions, and loading. The majority of the tests were on production piles, although several tests were performed as part of special pre-production test programs.

The paper has two main purposes:

1. Present details and results of previously unpublished uplift load tests to add to the fairly small existing database.
2. Examine the results of the tests and compare allowable uplift loads interpreted from the tests using a conservative movement criterion, with the allowable values based on the BOCA (1990) code criterion for uplift pile load tests.

SUBSURFACE CONDITIONS AND PILE DETAILS

The pile load test site locations and site subsurface conditions are shown in Table I, with pile types, sizes, and lengths given in Table II. In all cases, the piles were designed for compression as well as uplift loading, with the compression loading generally governing the pile length. As would be expected for pile sites, the near-surface soils were typically relatively loose sands, soft clays, or uncontrolled fills. Several sites had crustal conditions, with stiffer overconsolidated materials forming the top 10 or 20 feet, underlain by softer soils. At about one-third of the sites, the piles were driven to bedrock. Where bedrock was relatively shallow, uplift capacities were generally low.

The type of pile selected was based most often on economic considerations. However, other factors frequently applied, such as availability; ease of handling, driving, and splicing; long-term corrosion resistance; and suitability for driving through obstructions. In more than one case, owner preference dictated the type of pile used.

PILE INSTALLATION AND TESTING

The piles were driven with air, steam, or diesel hammers, as shown in Table II. The driving equipment and criteria were generally chosen to achieve the design compressive, rather than uplift, capacity.

The uplift pile load tests were performed in general accordance with ASTM D 3689. In most cases, the uplift tests on the pile were made after compression testing had been performed, using the compression test setup modified for pulling up rather than pushing down. In the cases where the pile was tested only in uplift, the test setup was much simpler, using fairly small footings/mats on the ground for reaction.

Most of the uplift test piles were loaded to the ultimate uplift capacity, computed using conventional static analysis, unless outright failure (i.e., continuous upward pile movement under constant load) occurred before that load was reached. The design uplift capacity before load testing was assumed to be half of this computed ultimate load capacity. In a few cases where the final design uplift load had been established with certainty and was less than half of the computed ultimate load, the pile was loaded to only twice that design load. Some of the tests used multiple load cycles, although most were single cycle. The majority of the tests had tell-tales installed to the tip. A few of the tests used multiple tell-tales and strain gauges.

LOAD TEST RESULTS

The 25 uplift pile load test results are presented in Table III, with plots of the applied load versus butt movement shown in Figure 1. The "initial design load" in Table III refers to the uplift design value assumed before load testing and is equal to one-half of the ulti-

TABLE I. Test Locations and Soil Conditions

Site	Location	Typical Soil Conditions
1	New York	15' stiff clay, 80' soft to m-stiff clay, then shale
2	New York	13' sand fill, 9' dense to v-dense sand, then limestone
3	New Jersey	15' loose sand, 45' soft clay, 10' m-dense sand, then v-dense sand
4	New Jersey	25' m-dense sand, then m- to v-dense sand and gravel
5	Pennsylvania	20' soft clay, 20' m-dense sand and gravel, then decomposed mica schist
6	Delaware	15' sand fill, 20' soft to m-stiff clay, then m-dense to dense sand
7	South Carolina	13' m-stiff clay, 5' soft clay and loose sand, then dense sand
8	Mississippi	40' stiff silt (loess), 65' m-stiff to stiff clay and silt, then dense gravel
9	Louisiana	20' m-stiff clay w/some sand, 50' m-stiff to stiff clay, then v-stiff clay
10	Florida	30' m-dense sand, 8' soft clay, 10' m-dense sand, 25' stiff clay, then dense sand
11	Florida	10' sand fill, 10' soft silt, 10' stiff clay, 10' gravel and marl, then marl
12	Florida	50' loose to m-dense sand, then m- to v-dense sand w/limestone lenses
13	St. Croix, USVI	5' sand fill, 7' soft to m-stiff organic clay, 12' v-stiff clay, then marl
14	Egypt	60' soft silt and clay, 15' m-dense sand, 35' stiff clay, then dense sand
15	Egypt	20' stiff clay, then m-dense to dense sand

mate load computed from static analysis. The maximum applied load is thus equal to the computed ultimate capacity. (For piles 11P and 2H, the design load was based on required capacity and the maximum applied load was less than the computed ultimate capacity). Test 7P failed outright before reaching planned maximum applied load. In four other tests (4P1, 5S, 8S1, and 13H), the movement at maximum applied load was excessive. For the remaining 20 tests, it is apparent from the Figure 1 curves that the piles were still some way from outright failure after the maximum uplift load was applied. Considering that the maximum applied load on the piles was in most cases equal to the computed ultimate load, it appears that the values of soil-pile adhesion and skin friction used in the computations were quite conservative.

INTERPRETED PILE CAPACITIES FROM LOAD TESTS

As noted above, most uplift pile load tests are not continued to outright failure. Thus, to obtain the "ultimate" (and hence allowable) uplift pile load, the load test results must be interpreted. The BOCA code provides one such interpretation. It states: "The maximum allowable uplift load shall be one-half that load which produces an upward movement of the pile butt equal to the gross elastic extension of the pile plus 0.1 inch." Thus, according to BOCA, "ultimate load" occurs when the tip of the pile moves up by 0.1 inch. Many local and regional codes have adopted the BOCA code criterion. The majority of the piles reported in this paper are at facilities designed to the BOCA code or to codes using the BOCA criterion. Thus, the implications of such a criterion are important.

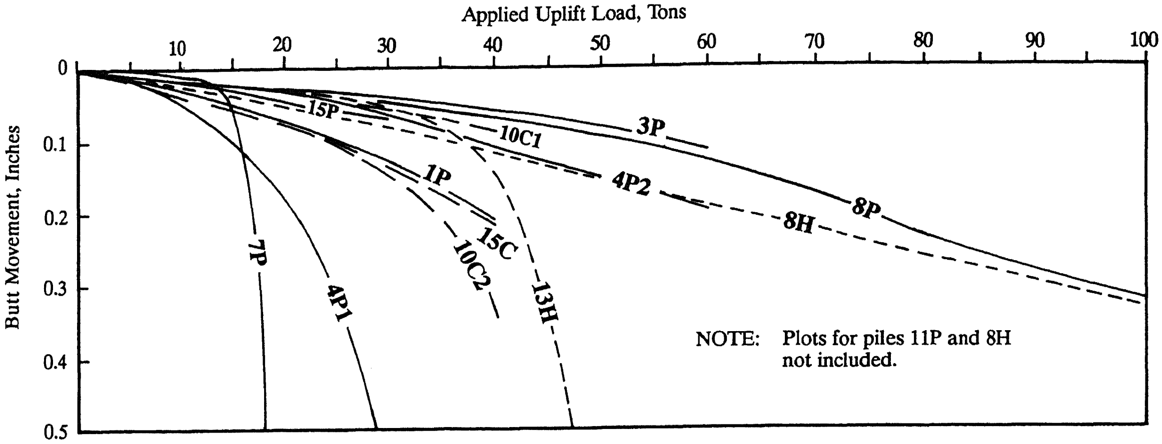
The BOCA code criterion requires knowledge of the gross elastic extension of the pile. If the test pile is fitted with a bottom (tip) tell-tale, then the gross elastic extension can be measured at any load by subtracting the bottom tell-tale reading from the butt reading. Unfortunately, most tension tests, including those reported here, do not have bottom tell-tales. In such cases, gross elastic extension must be estimated. One method is to subtract the residual movement of the pile, i.e., the butt movement remaining when the uplift load is reduced to zero, from the total butt movement at the maximum applied load. This method gives an approximate estimate only, since it assumes that the pile has complete elastic rebound. This will generally not be the case, since total elastic recovery will be prevented by resistance to axial pile contraction by the soil, resulting in residual tensile stresses in the pile. Thus, while the value of elastic extension obtained by subtracting residual from maximum load movements should provide a reasonable prediction in most cases, it will be an underestimate of the actual elastic extension. These values of estimated elastic extension are listed in Table IV.

The second method of calculating elastic extension is by computation. The elastic movement of a pile of length L, cross-sectional area A, and elastic modulus E under an applied uplift load P is pl/aE, where p is the effective load acting on the effective area a over the effective length l of the pile. There are obvious

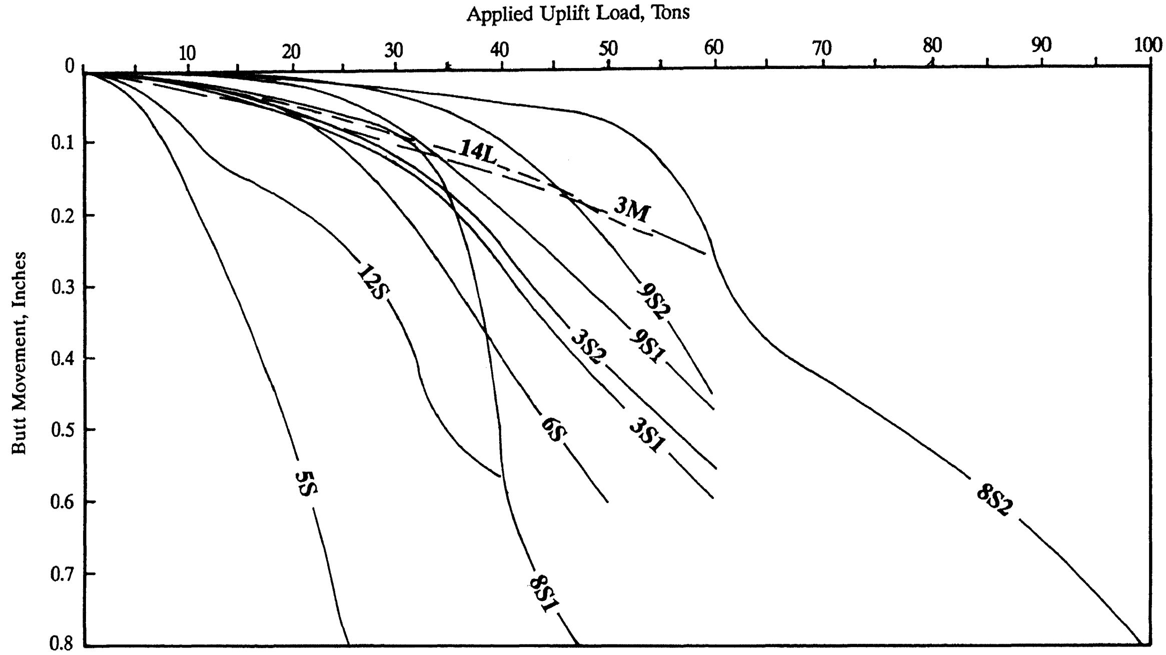
TABLE II. Details of Test Piles and Hammers

					Hammer			
Pile Type	Pile(1)	Size	Penetration (Predrill), feet	Year Driven	Type	Make	Rated Energy, ft-lb	Final Blow-count, bpi
Concrete-Filled Pipe	1P	12.75" OD, .25" wall	98	1990	Air	Vulcan 06	19,500	6.5
	3P	14" OD, .375" wall	79	1991	Air	Raymond 2/0	32,500	10
	4P1	14" OD, .375" wall	58	1991	Diesel	ICE 640	40,000 (max.)	3
	4P2	14" OD, .375" wall	85	1991	Diesel	ICE 640	40,000 (max.)	3
	7P	12.75" OD, .23" wall	18	1980	Air	Vulcan 06	19,500	1
	8P	14" OD, .375" wall	108 (52)	1975	Steam	Raymond 4/0	48,750	30
	11P	10" OD, .25" wall	42	1983	Air	Vulcan 06	19,500	5
	15P	14" OD, .375" wall	38 (18)	1986	Diesel	Kobe K-25	52,600 (max.)	3
Mandrel-Driven Step-Taper, Concrete Filled	3S1	#000 tip, #4 butt	79	1991	Diff Air	Raymond 80c	24,450	6
	3S2	#0 tip, #6 butt	77	1991	Diff Air	Raymond 80c	24,450	6
	5S	#000 tip, #2 butt	40	1984	Diff Air	Raymond 80c	24,450	5
	6S	#000 tip, #4 butt	81	1988	Air	Vulcan 0	24,375	5
	8S1	#0 tip, #7 butt(2)	90 (48)	1975	Steam	Raymond 2/0	32,500	6
	8S2	#0 tip, #8 butt(2)	110 (56)	1975	Steam	Raymond 2/0	32,500	9
	9S1	#1 tip, #5 butt	51 (35)	1990	Diff Air	Raymond 80c	24,450	5.5
	9S2	#1 tip, #7 butt	82 (55)	1990	Diff Air	Raymond 80c	24,450	1.5
	12S	#000 tip, #6 butt	84	1987	Diff Air	Raymond 80c	24,450	2
Lacor	14L	14" OD Lacor shell(3)	118	1988	Diesel	Delmag D-36	83,100 (max.)	2.5
Monotube	3M	8" tip, 12" butt, .21" wall	74	1991	Diff Air	Raymond 80c	24,450	8
Precast Concrete	10C1	14" x 14" Prestressed	77	1989	Diesel	ICE 640	40,000 (max.)	2
	10C2	18" x 18" Prestressed	53	1989	Diesel	ICE 640	40,000 (max.)	7
	15C	12.6" x 12.6"	38	1981	Diesel	Delmag D-30	54,250 (max.)	2.5
H-Pile	2H	HP 10 x 42	22	1987	Air	Vulcan 06	19,500	6
	8H	HP 14 x 73	111 (58)	1975	Steam	Raymond 4/0	48,750	30
	13H	HP 14 x 73	29	1982	Diesel	MKT DA35B	25,200 (max.)	23

Notes: (1) First numeral denotes site; letter denotes pile type.
(2) 12-foot long, 10.75-inch OD, .25-inch wall pipe welded on bottom of shell.
(3) 36-foot long, 11.8-inch OD, .32-inch wall pipe welded on bottom of Lacor shell.



(a) Pipe, H, and Precast Concrete Piles



(b) Step-Taper, Lacor, and Monotube Piles

Fig. 1. Applied Load versus Movement

difficulties in computing this movement. The first involves estimating p and l, since these values depend on how the load is distributed from the pile into the soil. For example, where relatively stiff clay is near the surface, the entire P can be transferred into the soil through the clay, leaving no tension load in the pile length below. In such a case, the tension load in the pile would be P at the butt reducing to zero over some fairly short length. In contrast, for piles driven through very soft or loose soils a short distance into very stiff or dense materials, the majority of the pile length will experience the entire load P. (Unless outright failure occurs, there will be no uplift load at the tip of the pile, regardless of the load distribution pattern.) The few piles tested with tell-tales and/or strain gauges at positions other than the tip showed the majority of the load being transferred into the soil well above the mid-point, although the load transfer pattern was a function of the soil and the amount of load applied. The computed values of pl/aE shown in Table IV were based on an assessment of soil conditions, pile length, and maximum applied load for each pile. Generally, pl was taken as PL/2 for the shorter piles and PL/3 for the longer piles.

The second difficulty with computing elastic extension is in estimating the effective area carrying the uplift load when the pile is mostly or partly concrete. The tensile strength of concrete is commonly taken as about 10 percent of its compressive strength. Although little data exist on the elastic modulus of concrete in tension, it can be assumed to be similar to that in compression. The resulting strain to concrete failure in tension is on the order of 0.01 percent. The combination of low concrete tensile strength and low strain to failure will tend to cause progressive cracking down through the loaded length of the concrete pile. For this reason, the concrete area in the pipe, shell, and non-prestressed precast concrete piles was neglected in computing elastic extension. Where the prestress was higher than the applied stress in prestressed piles, the elastic modulus of concrete was used. The area of steel used in the elastic extension computation always included the rebar, although even this required some judgement when most of the rebar was only in the top part of the pile. The area of the steel shell was included in the elastic extension estimate for pipe piles, but was neglected in the step-taper shells; neglecting the steel in the shell gave better agreement with the elastic extension obtained by the first method.

The computed values of pl/aE are listed in Table IV. They compare relatively well with elastic extension measured by subtraction in most cases. The largest variation is in test 8S1, where the difference between movement at the maximum applied load and residual load is almost 2 inches, compared with a computed extension of less than 1/2 inch. The 2-inch extension strongly suggests that the rebar(s) to which the load was applied had a significant free length above (or within) the pile.

Given the difficulty of estimating elastic extension using the pl/aE approach, the measured difference between movement at maximum applied load and residual movement was used to estimate gross elastic extension for the BOCA allowable load. Only in cases where maximum movement or residual movement values were not available were the computed extensions used.

The allowable uplift loads based on the BOCA code criterion are listed in Table IV. In many cases, these loads are less than the assumed design loads before load testing given in Table III. This stems from the BOCA definition of ultimate load being at 0.1-inch upward movement of the pile tip. It can be seen that the per-

TABLE III. Pile Load Test Results

Pile	Initial Design Load, tons	Maximum Applied Load, tons	Maximum Movement in inches at:		
			Initial Design Load	Maximum Applied Load	Residual (Zero) Load
1P	20	40	0.070	0.21	0.10
3P	30	60	0.038	0.11	0.03
4P1	30	60	0.60	2.00	1.95
4P2	30	60	0.066	0.20	0.05
7P	10	19	0.005	>1.0	--
8P	50	100	0.088	0.33	0.13
11P	7.5	15	0.009	0.034	NA
15P	15	30	0.028	0.067	NA
3S1	30	60	0.15	0.59	0.21
3S2	30	60	0.091	0.56	0.22
5S	20	40	0.51	1.20	0.72
6S	25	50	0.09	0.60	NA
8S1	50	100	0.85	2.40	0.43
8S2	50	100	0.064	0.81	0.27
9S1	30	60	0.075	0.48	0.17
9S2	30	60	0.032	0.45	0.13
12S	20	40	0.19	0.56	0.19
14L	27.5	55	0.07	0.22	0.04
3M	30	60	0.10	0.26	0.10
10C1	20	40	0.04	0.086	0.07
10C2	20	40	0.078	0.33	0.30
15C	20	40	0.067	0.22	0.15
2H	7.5	15	0.023	0.089	0.06
8H	50	100	0.15	0.34	0.08
13H	27.5	55	0.045	1.50	--

NA - not available

manent upward movements of the pile tips at maximum applied load measured in the 25 load tests (movement at residual load shown in Table III) are, in most cases, greater than 0.1 inch. As noted earlier, most of these tests are still some way from outright failure. This appears to indicate that the BOCA 0.1-inch criterion may be too stringent. (It may be noted that the BOCA criterion for compression load tests allows 0.75-inch downward movement at "ultimate" load.) The authors suggest that an alternative interpretation of allowable uplift load capacity be considered that is based on criteria that take into account both the maximum applied load and the movement of the pile at the allowable (design) capacity. Discussion with several engineers involved with the design of sensitive structures subjected to tension loading (such as chimneys and silos) indicates that pile movements up to 1/4 inch would be acceptable at design uplift load. Based on this, the uplift load test results on the 25 piles were re-examined using the following criteria:

- The allowable uplift load should be one half the maximum applied load, provided movements at the allowable load are 1/8 inch or less (i.e., applying a factor of 2 to the 1/4-inch value).
- If movements at half the maximum applied load are more than 1/8 inch, the allowable uplift load should be the load that causes 1/8-inch movement.

The allowable uplift capacities computed using the above criteria are listed under "non-BOCA" in Table IV. Out of the 25 piles tested, one showed a lower capacity (23 percent) using the non-BOCA approach. This was pile 8S1, where almost 2 inches of elastic movement was measured. Fifteen piles showed a lower capacity using the BOCA criterion. Eight of these were step-taper shell piles. The capacity differences in the 15 piles ranged from 3 to 33 percent, with an average difference of 19 percent.

TABLE IV. Interpreted Allowable Uplift Pile Capacities

	Estimated Elastic Extension, inches		Allowable Capacities, tons		Difference(3), percent
Pile	Residual Method (1)	pl/aE	BOCA	non-BOCA(2)	
1P	0.11	0.148	≥20	≥20	--
3P	0.08	0.061	≥30	≥30	--
4P1	0.05	0.079	16	18	+11
4P2	0.15	0.116	≥30	≥30	--
7P	--	0.014	8	9.5	+16
8P	0.167	0.163	39	≥50	+22
11P	--	0.030	≥7.5	≥7.5	--
15P	--	0.027	≥15	≥15	--
3S1	0.38	0.38	23.5	≥30	+28
3S2	0.34	0.37	23.5	≥30	+28
5S	0.48	0.19	6.5	8.5	+24
6S	--	0.32	19	≥25	+24
8S1	1.97	0.47	38	31	-23
8S2	0.54	0.57	40.5	≥50	+19
9S1	0.31	0.24	27	≥30	+10
9S2	0.32	0.39	29	≥30	+ 3
12S	0.37	0.23	16	16.5	+ 3
14L	0.18	0.27	≥27.5	≥27.5	--
3M	0.16	0.107	≥30	≥30	--
10C1	0.016	0.038	≥20	≥20	--
10C2	0.03	0.017	13.5	≥20	+33
15C	0.07	0.097	16.5	≥20	+18
2H	0.029	0.011	≥7.5	≥7.5	--
8H	0.202	0.138	40	50	+20
13H	--	0.03	20	≥27.5	+27

Notes: (1) Movement at maximum applied load minus movement when load is zeroed.
(2) Non-BOCA capacity is half of maximum applied load if movement at non-BOCA capacity is less than 1/8 inch. Otherwise, non-BOCA capacity is load at 1/8 inch.
(3) Difference = (non-BOCA - BOCA)/non-BOCA, percent.

SUMMARY AND CONCLUSIONS

Details and results of uplift load tests on 25 piles at 15 sites have been presented in tables and figures. The allowable uplift capacity using the BOCA code criterion was computed for each pile and compared with an allowable capacity based on a pile butt movement of no more than 1/8 inch at design load. For nine of the piles, there was no difference in computed capacity. For one pile, the BOCA capacity was more. For 15 of the piles, the BOCA capacity was less, by an average of 19 percent. The differences were most frequent in the step-taper piles.

Given the typically short-term and transient nature of most uplift loads, the authors believe that the BOCA code criterion may be too stringent in many cases and may unnecessarily penalize pile uplift capacity. They recommend that an alternative approach based on maximum applied load and limited movement at design load be considered.

REFERENCE

BOCA National Building Code, Building Officials and Code Administrators International, Inc., Eleventh Edition, 1990.