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SYNOPSIS: The interaction between soil and various pile types is of interest because it depends not only on the shear strength characteristics of the soil, but also on the pile dimensions, shape, and installation method, and on time after pile installation. This paper presents load test results from three types of displacement piles installed at the same site. The results obtained from the tests are compared with theoretical estimates. The computed values of soil-pile adhesion, back-calculated from the load tests, are discussed and compared with values found in the literature. Estimated pile capacities during driving and retap are also compared and discussed.

INTRODUCTION

A new power plant is being constructed adjacent to an existing power plant that has been in service for several decades. Due to poor subsurface conditions at the site, all of the major existing and new structures are on piled foundations. Three types of piles have been used, including closed-end pipes, mandrel-driven step tapers, and timber piles. Pertinent information about the different types of piles driven and tested is summarized in Table I.

This paper provides a detailed comparison of the load test results, wave equation predictions, and theoretical static capacity estimates for the different types of piles used. Revised soil-pile adhesion design parameters are back-calculated from the load test results and compared with the values used in the initial capacity estimates. The effects of pile freeze and pile taper are analyzed and compared with values typically used in the literature. The importance of well-instrumented pile load tests and associated evaluation techniques is discussed.

TABLE I: PILE INFORMATION

PILE TYPE	PILE NO.	DATE INSTALLED	DIMENSIONS CROSS-SECTION	DIMENSIONS LENGTH (ft)	HAMMER TYPE	RATED ENERGY (ft-lbs)	FINAL BLOWCOUNT (bpi)	RETAP (bpi)	INSTRUMENTATION
PIPE	P1	10/24/72	10 3/4" dia, 1/4" wall	91	n/a	n/a	8	n/a	Butt
	P2	10/24/72	10 3/4" dia, 1/4" wall	80	n/a	n/a	2	n/a	Butt
STEP TAPER	S1	7/19/88	'000' tip, 12' sections	81	VULCAN '0'	24,375	3	5	Butt
	S2	9/13/90	'000' tip, 12' sections	76	VULCAN '80C'	24,450	2	8	Butt, mid, tip
	S3	9/17/90	'000' tip, 12' sections	73	VULCAN '80C'	24,450	3	5	Butt, mid, tip
	S4	8/19/91	'000' tip, 12' sections	66	VULCAN '80C'	24,450	1	3	Butt, mid, tip
	S5	10/12/91	'000' tip, 12' sections	39	VULCAN '0'	24,375	1	2	Butt, mid, tip
TIMBER	T1	4/23/91	8" tip, 13" butt	52	VULCAN '50C'	15,100	3	48	Butt, mid, tip

Compressive pile capacities for the current and existing structures were estimated using conventional theoretical static procedures that take into account pile type and dimensions, soil conditions, and pile installation methods. Wave equation analyses were used to estimate capacities based on the pile driving records. Additionally, several piles were retapped to determine the extent of any soil-pile freeze or relaxation. Extensive pile load testing was performed on the new piles. Load test records dating back to 1970 were also available for the existing structures. The sophistication of the instrumentation used in the tests varied from simple pile head movement monitoring to use of multiple tell-tales.

SOIL CONDITIONS

The site is overlain by approximately 8 feet of fill consisting of sandy clay and clayey sand with some gravel and organics (Stratum I). As is typical of most uncontrolled fill, its strength is variable. The fill is underlain by 10 to 50 feet of very soft to medium stiff clay and silt (Stratum II). Some peat exists in the lower portions of this stratum. The underlying bearing stratum (Stratum III) consists of medium stiff to hard sandy clay and clayey sand. Groundwater was typically at the bottom of the fill, i.e., at a depth of about 8 feet. The values of the engineering properties chosen for the soils are presented in Table II.

ESTIMATED PILE CAPACITY

The soil-pile adhesion values used in estimating pile capacity are included in Table II. Theoretical estimates of the ultimate capacities of the eight piles tested were made using, as a basis, soil parameters derived by conventional testing along with several approaches outlined in the literature (Meyerhof [1976], NAVFAC [1982]). These estimated capacities, presented in Table III, are based on the driven length of the pile. Table III also includes the estimated ultimate capacity of each pile based on the final driving blowcounts (Figures 1 and 2) and retap blowcounts using the wave equation analysis computer program GRLWEAP (1988). The step-taper and timber piles were retapped within 24 hours of installation. All the load tests were conducted about 1 week after the piles were driven. The load versus deflection curve for each pile is shown in Figures 3 and 4.

TABLE II: SUMMARY OF ENGINEERING PROPERTIES

STRATUM	Classification (USC)	N-value (bpf)	Moisture Content (%)	Dry Unit Weight (pcf)	LL (%)	PI (%)	Undrained Shear Strength (psf)	Pile/Soil Adhesion (psf)
I	CL-SC	13	20	104.1	28	11	---	500
II	CL-OH	3	64	65.2	71	33	400	400
III	CL-SC	31	19	110.5	29	9	4000	1600**

NOTES:
USC – Unified Soil Classification
N-value – Standard Penetration Resistance Value (not ajusted for depth)
LL – Liquid Limit
PI – Plasticity Index
** – adhesion = 2000 psf in stratum III for tapered piles (step-tapered and timber)

LOAD TEST PILE CAPACITY

In a load test, the ultimate capacity of a pile is reached when rapid settlement occurs under sustained load (the pile plunges). In practice, not all the tests were carried to failure, generally due to maximum load restrictions in the loading apparatus. In such cases, other definitions of ultimate capacity may be applied, such as the load that satisfies a settlement criterion (e.g., 1 inch), or twice the load at which the settlement is 0.25 or 0.50 inch. In recent years, the Davisson (1973) method has gained widespread acceptance. Davisson's limit value is defined as the load corresponding to the movement that exceeds the elastic compression of the pile by 0.15 inch, plus a factor equal to the diameter of the pile in inches divided by 120. Davisson's method was selected to estimate ultimate pile capacities for two reasons: 1) it was developed in conjunction with the wave equation analysis, and a good correlation has generally been observed between pile capacities estimated by the two methods, and 2) when load testing a pile to a specified ultimate capacity, the method enables the maximum allowable deflection to be determined in advance. The ultimate capacity of each pile, based on the load test results shown in Figures 3 and 4, was estimated using the Davisson method and is shown in Table III.

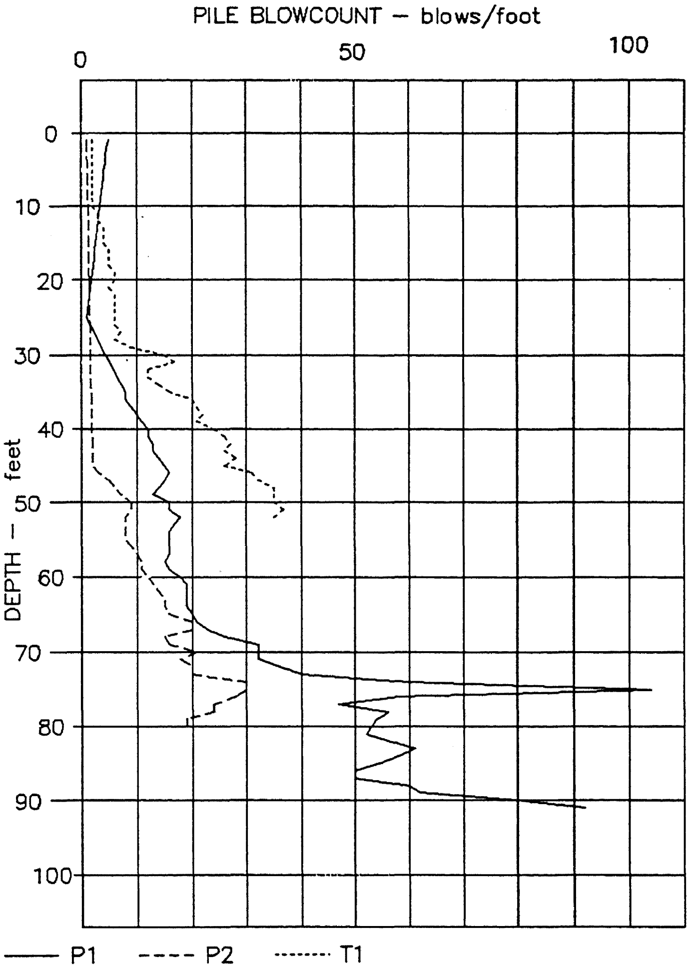
COMPARISONS, CONCLUSIONS, AND RECOMMENDATIONS

Table III shows the ultimate capacity of each pile based on theory, wave equation analysis (final and retap blowcounts), and load test interpretation. These results are compared in Figure 5. The tell-tale information was used in conjunction with the load test results to back-calculate the soil-pile adhesion in Stratum III using methods outlined by Fang (1991). This adhesion in shown in Table IV.

Several conclusions can be drawn from the results presented in Tables II, III, and IV and in Figure 5.

- The back-calculated soil-pile adhesion values from the load test results show good agreement with the estimated values used to compute the theoretical capacity.
- The average soil-pile adhesion developed by the 0.6 percent taper in the step-tapered pile and the 0.8 percent taper in the timber pile is 1.34 times the adhesion for the straight pipe pile. This agrees well with the 1.5 value suggested by Meyerhof (Ref. 1) for tapers exceeding 1 percent. It seems possible, however, that at least part of this increase could be attributed to the corrugated surface of the step-tapered pile and the rougher wood surface in the timber pile.
- Although there is significant variation for individual piles, the average ultimate theoretical capacity compares well with the average interpreted load test capacity.
- The importance of pile retapping to confirm ultimate capacity is evident. In the mainly clay soil conditions, the ultimate capacity based on wave equation analyses increased by a factor of 1.5 to 3 within 24 hours of pile installation.
- Comparison of the retap and load test results indicates that the pile capacities did not increase significantly between 24 hours and 1 week after driving.

Finally, it should be noted that many of the results and conclusions presented here would not have been possible without adequate instru-



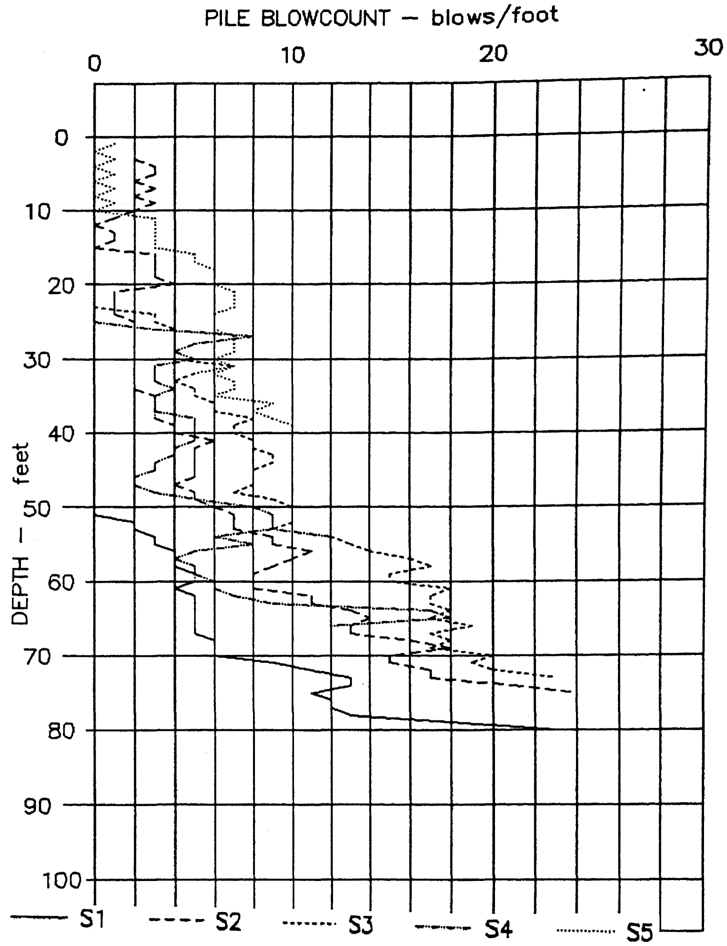


FIGURE 1: PILE BLOWCOUNT versus DEPTH – PIPE and TIMBER PILES

FIGURE 2: PILE BLOWCOUNT versus DEPTH – STEP TAPERED PILES

TABLE III: ULTIMATE PILE CAPACITIES

PILE TYPE	PILE NO.	ULTIMATE PILE CAPACITY (1) THEORETICAL (tons)	WAVE EQUATION ANALYSIS (2) (during driving) (tons)	WAVE EQUATION ANALYSIS (3) (retap) (tons)	(4) LOAD TESTS (tons)	RATIO (1) : (4)	RATIO (3) : (2)	RATIO (3) : (4)
PIPE	P1	179	n/a	n/a	190	1.06	n/a	n/a
	P2	148	n/a	n/a	100	0.68	n/a	n/a
STEP TAPER	S1	117	105	160	115	0.98	1.52	1.39
	S2	152	75	210	215*	1.41	2.80	0.98
	S3	162	105	160	180*	1.11	1.52	0.89
	S4	131	35	105	100	0.76	3.00	1.05
	S5	112	35	75	120	1.07	2.14	0.63
TIMBER	T1	91	55	100	115*	1.26	1.82	0.87
					average =	1.04	2.13	0.97
					median =	1.06	1.98	0.94

NOTES: * – extrapolated from load deflection curves

TABLE IV: BACK–CALCULATED ADHESION IN STRATUM III

PILE TYPE	PILE NO.	ULTIMATE SOIL CAPACITY* (tons)	ADHESION IN STRATUM III (psf)	AVERAGE ADHESION (psf)	RATIO TAPER/ PIPE
PIPE	P1	190	2140	1680	1.37
	P2	100	1200		
STEP TAPER	S1	115	1940	2280	
	S2	215	3020		
	S3	180	2260		
	S4	100	1560		
	S5	120	2160		
TIMBER	T1	115	2760		

NOTES: * – from load test results given in Table III

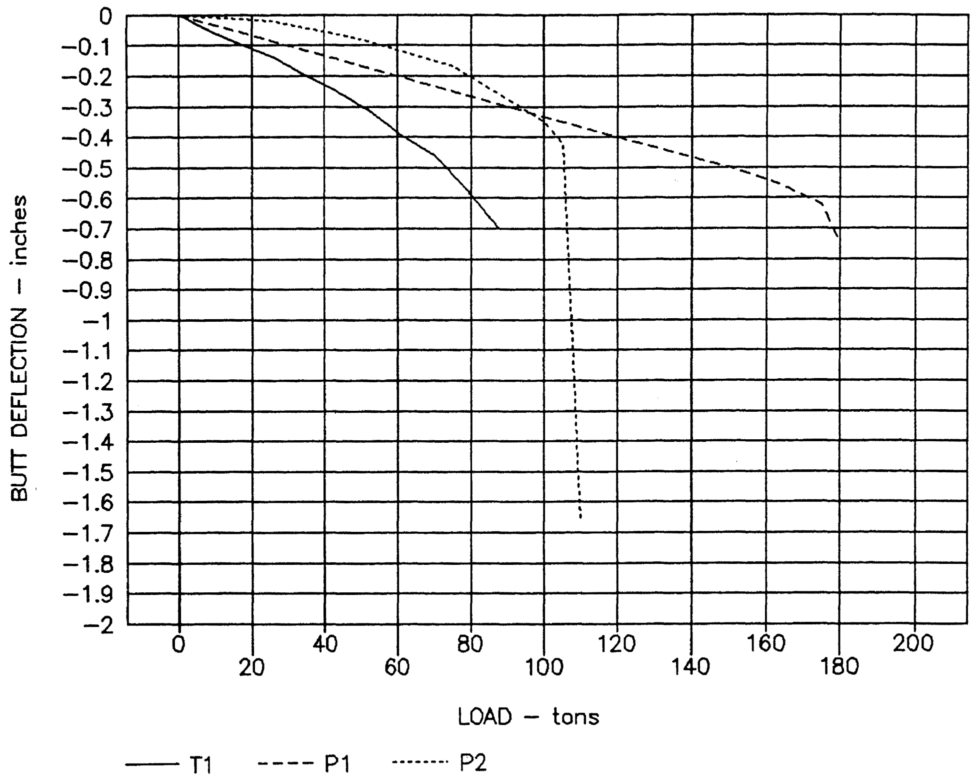


FIGURE 3: PILE LOAD TESTS – PIPE and TIMBER PILES

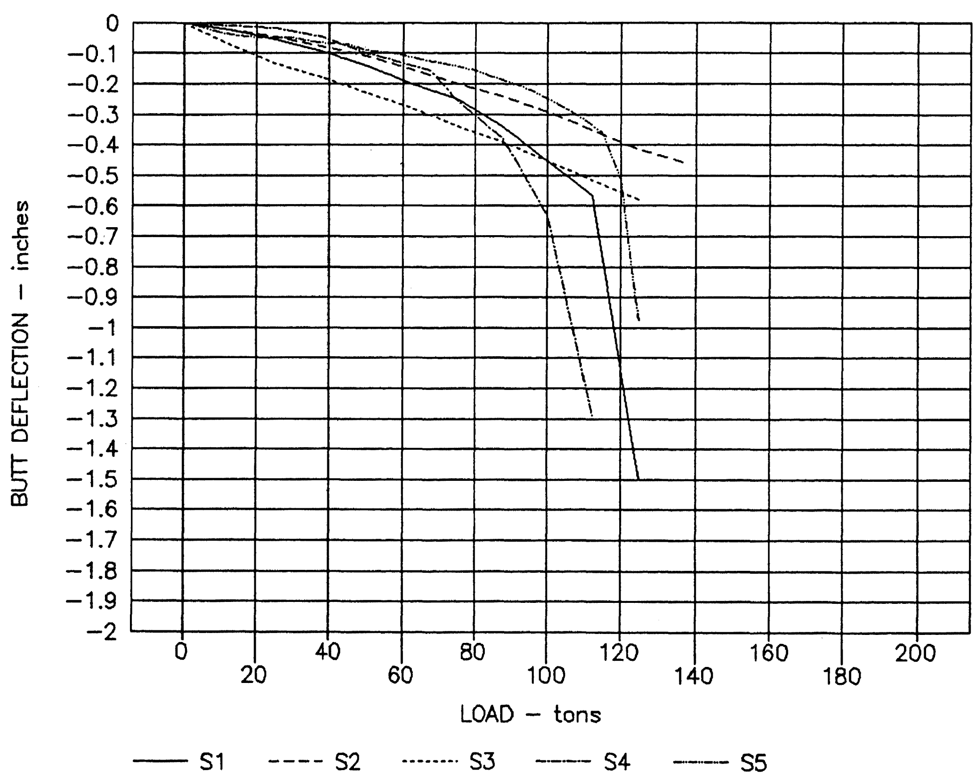


FIGURE 4: PILE LOAD TESTS – STEP TAPERED PILES

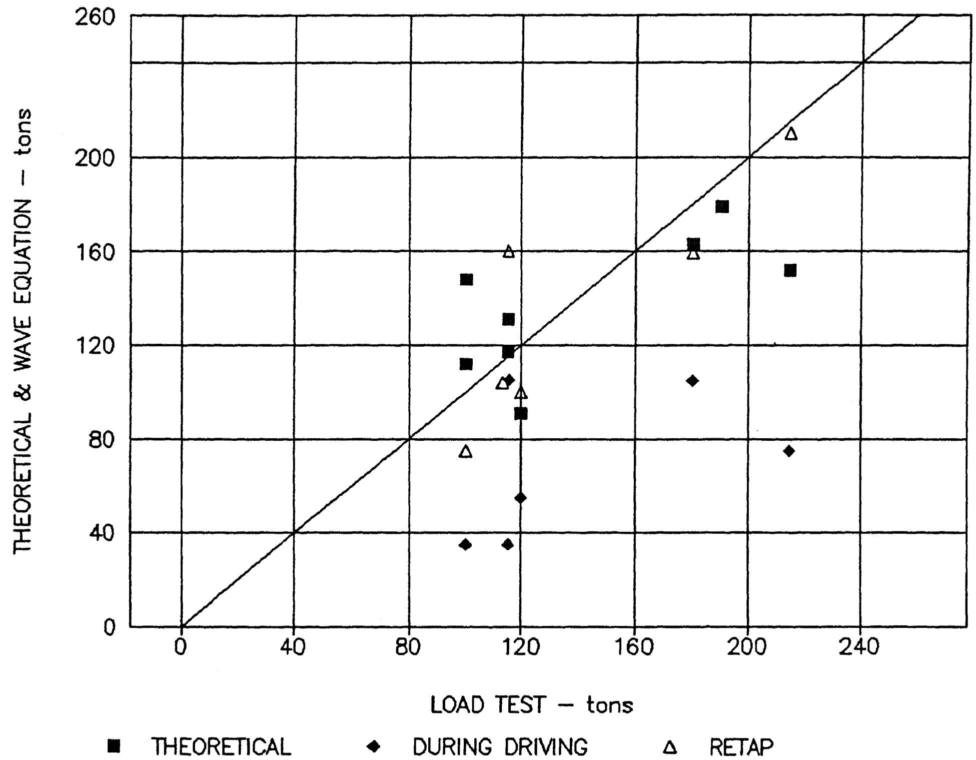


FIGURE 5: ULTIMATE PILE CAPACITIES

mentation of the pile during loading. Ideally, tell-tales (and/or strain gauges) should be installed at major strata interfaces to enable an accurate assessment of soil-pile adhesion/ friction within these strata. At a minimum, these instruments should be placed at the tip of each test pile. In addition, the authors recommend that a probe pile program be performed before load testing, with each probe pile being retapped after about 24 hours (or longer, if warranted). Test piles should be judiciously selected from among the probe piles.

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