Pile capacity in stiff clays – CPT method

La capacité portante des pieux dans les argiles raides – La méthode CPT

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SYNOPSIS: Pile load tests were performed on driven piles bearing in stiff overconsolidated clay at 6 sites on the coastal plains of the Gulf of Mexico. Cone penetration tests were performed using an electrical cone penetrometer "Fugro type". Four published procedures correlating end bearing and skin friction to cone penetration test data were analyzed to determine the best procedure for predicting pile capacity at these sites. In addition, the pile capacity was predicted using four procedures relating laboratory tests to skin friction and end bearing. The CPT method proposed by deRuiter and Beringen (1979) provided the best predictions of pile capacity.

INTRODUCTION

Cone penetration testing "CPT" has been used in Europe for more than 50 years to predict the axial capacity of piles. Its success is primarily due to the fact that the cone is a model pile pushed into the subsoil. However, most of the data base for determining design rules was accumulated using mechanical cone penetrometers.

Nottingham (1975) and others have found variations in the cone bearing and sleeve friction between mechanical and electrical cone penetrometers. One reason for the differences in friction between "Begemann type" mechanical cones and "Fugro type" electrical cones is that soil can enter behind the tip of a mechanical cone causing bearing on the friction sleeve. Internal friction in the cone and between the inner and outer rods while conducting mechanical CPT tests can effect the measured parameters. Relative movement does not occur between the tip and friction sleeve in electrical cones, and thus more accurate measurements are made of friction and end bearing with an electrical cone penetrometer. CPT readings are typically obtained on 20 cm intervals for mechanical cones, while continuous readings are possible for electrical cones. For these reasons, the authors believe that the electrical cone penetrometer is a superior design from the standpoint of quality and quantity of data obtained.

The authors have collected data from 6 sites where pile load and CPT tests using an electrical cone have been performed in stiff clay. The purpose of this paper is to compare the pile capacity predicted using published CPT design procedures with load tests to evaluate the best procedure. Soil borings and laboratory tests were also performed at these sites. Pile capacity was predicted using shear strength data to compare CPT and conventional methods.

GEOLOGY

The sites are located along the Texas and Louisiana Gulf Coast Plain (U.S.A.). Five of the sites were located in the Houston area in Texas and one site was located in Alexandria, Louisiana. The subsoils are Pleistocene in age, and consist of interbedded layers of clay, silt and sand. Soil deposition occured in distributary channels, flat river deltas and inter-delta regions. The sea level was lowered during the glacial stages, which resulted in the soils being overconsolidated due to desiccation.

The subsoils at these sites are predominantly stiff clay. The clays are moderately to heavily overconsolidated (OCR 2 to 10) and the secondary structure typically includes fissures and slickensides.

PILE LOAD TESTS

Ten driven piles and one 9 pile group were load tested to failure, or near failure, at the 6 sites. Other load test data was available but only sites where the subsoils were primarily stiff clay and the load tests had been conducted to plunging failure, or near failure as interpreted by the authors, were selected for this study.

Most of the load tests had been performed using the Quick Load Test for individual piles outlined in ASTM D 1143. Load is applied in increments of 10 to 15 percent of the proposed design load with a constant time interval between increments of 2.5 minutes.

For purposes of this paper, the ultimate load is defined as the maximum load at plunging failure.

TABLE I
PILE LOAD TESTS AND PREDICTED CAPACITY

Site	Pile Size	Pile Length	Ultimate Load*	δ_u	Predicted Pile Capacity - CPT				Predicted Pile Capacity - τ_f			
	m.	m.	$1x10^3$ kg.	cm	de Ruiter	Schmert-mann	L.P.C.	Tumay	Tomlin-son	Wood-ward	Peck	Lambda
A-1	.51	29.9	209	2.0	224	198	224	299	127	146	160	195
A-2	.51	30.5	318	1.5	238	210	233	313	143	164	166	212
A-3	.61	40.5	488	3.0	452	227	404	545	181	224	264	296
A-4	.61	36.6	299	2.2	305	122	226	305	147	179	168	264
B	.76	18.6	263	1.4	248	223	399	312	182	233	286	244
C-1	#3/00	20.7	134	1.0	100	91	143	108	73	94	114	92
C-2	#2/00	17.7	100	0.8	88	78	119	93	61	78	96	76
D-1	.28	13.1	67	0.8	80	51	93	90	45	58	84	85
D-2	.28	13.1	60	0.5	80	51	93	90	45	58	84	85
D-3	.28	13.1	76	0.6	80	51	93	90	45	58	84	85
E-1	.36	9.4	91	1.5	90	80	121	96	55	67	86	82
E-2	.36	13.7	127	1.5	108	107	160	124	73	93	122	122
F-1	.46	9.1	159	1.0	165	133	127	181	109	131	165	175

*to convert to kips (U.S. measurements) multiply values in table by 2.20

The interpreted ultimate capacity was 17 percent greater than the last measured load for the two piles not tested to failure.

Site A

This site is located in Baytown, Texas on the banks of the Houston Ship Channel. Six load tests were conducted at 2 sites to evaluate the type of pile best suited for the new bridge. A test series consisted of a precast concrete pile, a drilled shaft, and a steel pipe pile. Results of the load tests on the drilled shafts are not included in this study.

The subsoil stratigraphy was 21 meters of loose to dense sand underlain by stiff to very stiff clay. The pile capacity shown in Table I for the precast concrete pile is the portion of load carried by stiff clay as indicated by the instrumented pile. Since the pipe pile had not been instrumented, the skin friction on the pile in sand was assumed to be equal to the skin friction on the instrumented pile. The capacity of the pile in stiff clay was then computed by subtracting the load carried in friction in the upper sand from the ultimate pile load.

Site B

This site is located about 60 meters off the Texas City coast in Galveston Bay. One pile load test was conducted on a pipe pile for the design of a new dock. To simulate conditions that would exist after dredging for the dock, the pile was driven inside a 1.07 meter diameter steel casing that had been driven to 10 meters below the mud line and cleaned out. The pile was instrumented with 6 tell tales prior to driving. The subsoil stratigraphy was stiff silty clay and clay.

Site C

The site is located in Amoco Oil Company's refinery in Texas City. Two step tapered pipes were load tested for design of three large pile groups. The piles were instrumented with tell tales at the pile tips. The subsoil stratigraphy is stiff to very stiff clay to silty clay.

Site D

This site is located on the University of Houston campus near downtown Houston. Two reference pipe piles were tested individually, and a 9 pile group was tested to failure. The piles were instrumented with strain gauges and tell tales. The pile capacities shown in Table I are for the 2 reference piles, and average of the 9 pile group. The subsoil stratigraphy is stiff to very stiff clay.

Site E

This site is located in Alexandria, Louisiana. Load tests were performed on two precast concrete piles for design of a highway overpass crossing a railroad right-of-way. The subsoil stratigraphy is stiff to very stiff clay to sandy clay.

Site F

This site is located about 32 kilometers east of downtown Houston, Texas. Five precast concrete piles were load tested for design of a highway interchange. Only 2 of the test piles were load tested sufficiently close to their ultimate capacity that the slope of the load settlement curve indicated ensuign failure. The CPT tests indicate a dense layer of sandy silt and sand interbedded with hard clay lenses below 9.1 meters. Use of cone friction to predict pile capacity without limiting pile friction greatly overpredicted capacity of the 12.2 meter deep piles. Only the 9.1 meter long pile was used for this study because it was bearing primarily in very stiff sandy clay to clay.

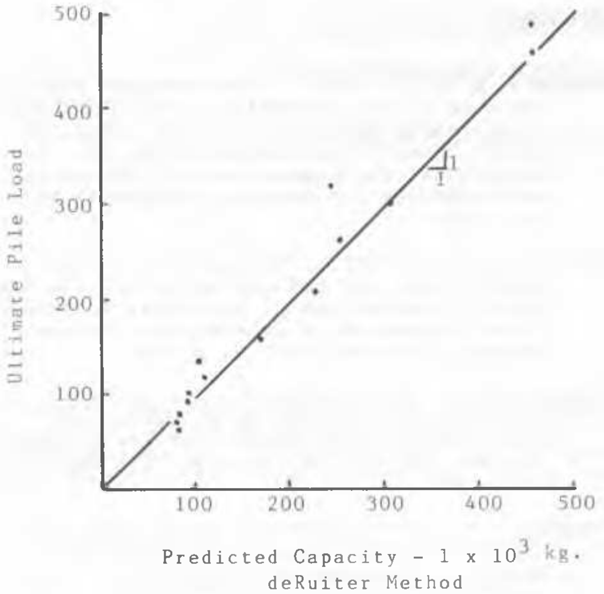

Figure 1

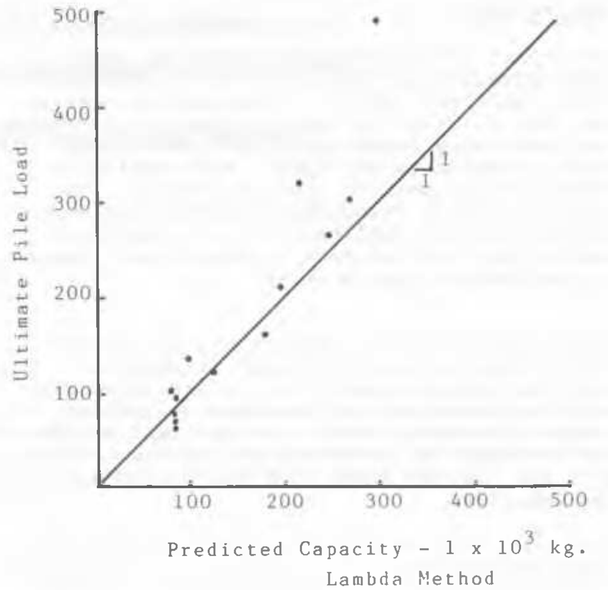

Figure 2

PREDICTED PILE CAPACITY - CPT

Four published procedures were used to predict pile capacity to evaluate the best method. Three of the methods use cone friction to estimate pile friction, and one method uses cone bearing to estimate pile friction. The results are tabulated on Table I and are discussed below.

deRuiter and Beringen Method

This procedure predicts pile friciton in overconsolidated clay to be 50 percent of cone friction. Pile end bearing is computed as 45 to 65 percent of cone bearing for typical overconsolidated clays. The average ratio of measured/ predicted pile capacity is 1.04 with a coefficient of variation of .17.

Schmertmann

This procedure correlates pile to cone friction using two curves for different pile types. The deRuiter and Beringen method is used to predict end bearing. The average ratio of measured/ predicted pile capacity is 1.43 with a coefficient of variation of .29. Review of the data indicates that this method under predicts capacity of the steel pipe piles.

Tumay and Fayhroo Method

This procedure correlates pile to cone friction using a curve that is a function of cone friction. Pile friction is predicted to be about 50 percent of cone friction for stiff clay. End bearing is computed by the Dutch method modified by Begemann (1963) where end bearing is computed directly from cone bearing. The average ratio of measured/predicted pile capacity is .91 with a coefficient of variation of .18.

The authors believe that this method overpredicts end bearing in stiff clay. Tand and Funegard (1986) predict that end bearing for deep piers in stiff clay is on 45 to 55 percent of cone bearing.

LPC Method (Unofficial)

The Laboratoire des Ponts et Chaussees in France is currently establishing a set of design rules based on the Bustamante-Gianeselli method (1981) but much more detail concerning pile types and installation methods. This procedure uses correlations with cone bearing to estimate pile friction. End bearing on driven piles in clay is predicted to be 60 percent of cone bearing. The average ratio of measured to predicted pile capacity is .94 with a coefficient of variation of .27.

Briaud (1988) has shown the LPC method the most reliable method for predicting pile capacity in mixed soils. The data base for Briaud's paper was obtained using a mechanical cone, while an electrical cone was used for this data base.

PREDICTED PILE CAPACITY - CONVENTIONAL METHOD

Two basic methods (4 different procedures) were used to predict pile capacity using the results of laboratory compressio tests to evaluate pile friction. Three procedures utilize an alpha approach to predict friction from shear strength and the fourth uses an empirical/effective stress method. The results are tabulated on Table I and are discussed below.

Alpha Methods

Pile capacity was predicted using the alpha values proposed by Tomlinson (1957), Woodward (1961), and Peck (1977). These methods correlate pile friction to shear strength as computed from laboratory tests applying a reduction factor referred to as alpha. End bearing is computed using bearing capacity theory. The average ratio of measured/predicted pile capacity is 1.76 for Tomlinson's, 1.42 for Woodward's, and 1.19 for Peck's procedures. There is considerable data scatter.

A reason for the poor predictions using the alpha method is that the shear strength of overconsolidated clays is difficult to predict due to slickensides and fissures typically observed in stiff clays. Interpretations of shear strength by different geotechnical engineers can lead to widely varying predictions of pile capacity.

Lambda Method

Vijayvergiya and Focht (1972) developed an empirical/effective stress method correlating passive pressure around the pile to pile friction by a factor referred to as Lambda. Passive pressure is computed as 2 times the shear strength plus the effective overburden pressure, and Lambda varies with pile length. End bearing is computed using bearing capacity theory. The average ratio of measured/predicted pile capacity is 1.13 with a coefficient of variation of .25.

CONCLUSIONS

The deRuiter and Beringen procedure provided the best prediction of pile capacity for the 8 methods analyzed. A graph of the data is present on Figure 1. The average ratio of measured/predicted pile capacity is 1.04 with a coefficient of variation of .17.

This CPT procedure predicts pile friction in overconsolidated clays to be 50 percent of cone friction, and end bearing to be 45 to 65 percent of cone bearing. The authors prefer use of electrical CPT tests to predict pile capacity because subjective judgment as to interpretation of shear strength from laboratory tests is not required. Also, the data base to predict pile capacity is much greater when using CPT because a continuous log of soil strength is obtained.

The conventional method that provides the best prediction of pile capacity is the "Lambda" procedure. This is an empirical/effective stress procedure. A graph of the data is presented on Figure 2. The average ratio of measured/predicted pile capacity is 1.13 with a coefficient of variation of .25.

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