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Title: Designed, Dynamically Load Tested and Installed Pile Foundation in Southwest Florida - A Case History

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DESIGNED, DYNAMICALLY LOAD TESTED AND INSTALLED PILE FOUNDATION IN SOUTHWEST FLORIDA - A CASE HISTORY

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This paper presents a case history of an engineered, monitored, and tested program that provided an effective and satisfactory basis for the completion of pile foundations for Twin Dolphins 1 at La Peninsula Condominiums located in the Isles of Capri in southwest Florida, U.S.A. An 8-story building (with1-story parking underneath) along with recreational facilities (such as a swimming pool and tennis courts) had been planned for final construction. Following an evaluation of various foundation alternatives, a precast prestressed concrete (PPC) pile-supported system was selected.

The building foundations were designed for pile capacities of 445kN (50 tons) and 890kN (100 tons) in compression and 133kN (15 tons) in uplift. A test pile program was performed to provide site-specific pile driving data, verify design assumptions, determine production pile lengths, and evaluate pile driving criteria. A total of 24, 356 mm (14-in.) square, 19.8 m (65 ft) PPC concrete piles were driven and dynamically load tested utilizing a Pile Driving Analyzer (PDA) within the building limits. Dynamic monitoring during probe pile installation and restriking was performed to estimate the ultimate capacity of the piles and to evaluate driving stresses during installation. CAPWAP analyses were preformed on PDA data to better estimate pile capacity, resistance distribution, and predict pile freeze (increase in pile resistance with time) and thus optimized the production pile lengths. Upon completion of probe pile installation, 12 of the probe piles were tested using the Pile Echo Tester (PET) function of the Pile Integrity Sonic Analyzer (PISA). PET testing was performed to evaluate the integrity of piles which had exhibited high driving stresses during PDA testing.

Information gathered during the probe pile driving program was effectively utilized as part of the overall quality control program to install a total of 539 PPC piles (including 24 probe piles) within the building limits at the project site to depths ranging from 9.1 to 19.8 m (30 to 65 ft) below the existing ground elevation as part of the foundation support system. Prior to installation of probe or production piles, a termination criterion was established using 1-dimensional wave equation analyses in addition to the design pile embedment requirement. The predicted pile capacities compared very well with the capacities from the CAPWAP analysis for probe piles.

Use of geotechnical instrumentation and PDA assisted technology enabled each foundation support element to be constructed to its optimum capacity and at optimum cost. Furthermore, by using PDA the consultant was able to quantify a difficult to measure geotechnical phenomenon termed "pile freeze" which eliminated costly overdriving and unnecessary splicing of piles.

INTRODUCTION

Twin Dolphins 1 is located on the Gulf of Mexico in La Peninsula, a secure, gated community on the southwest corner of the Isles of Capri, near Marco island, in southwest Florida, USA. The project consists of an 8-story building over one-story of parking. The tower is of concrete and masonry construction with post-tensioned elevated floor slabs. In August 2000, ASC geosciences, inc. was retained to provide a complete geotechnical exploration, testing, and engineering evaluation as well as proper selection of an economical, effective, and satisfactory foundation support system. Construction commenced in April 2001. A project location, project building layout, and boring location plan is illustrated in Figure 1.

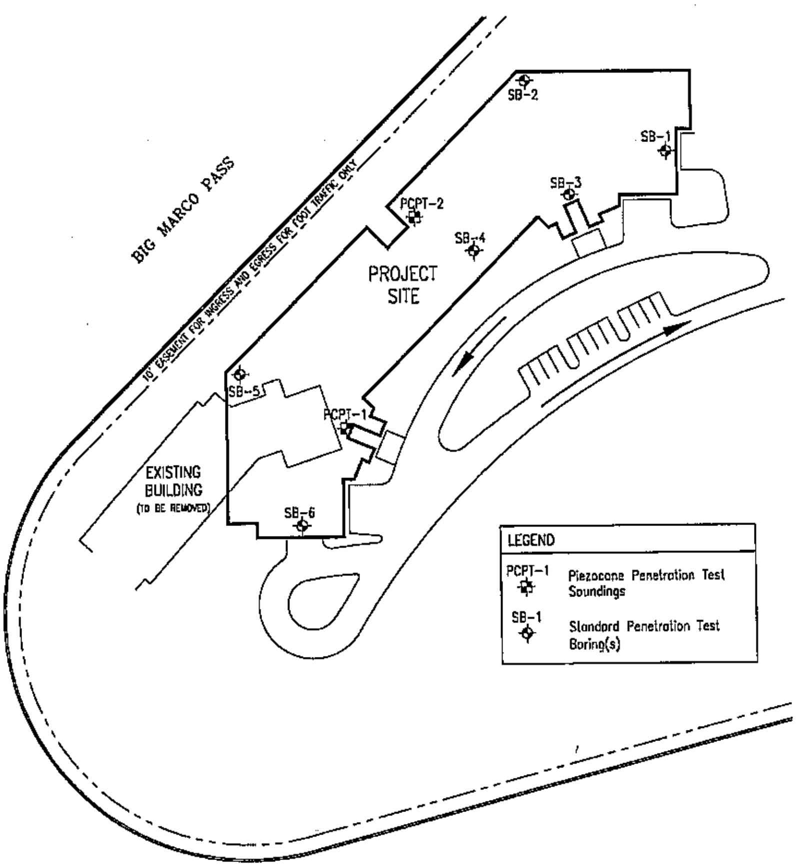
This paper presents a case history of the project detailing the engineering profile of subsoils at the project site, design considerations, test pile installation and monitoring, and quality control and testing methods used.

SUBSURFACE CONDITIONS AND PROJECT DATA

Pre-construction site features included a generally level topography and presence of an existing 4 story, pile-supported, multi-family residential structure. This existing structure was demolished and debris removed from the site prior to commencement of the geotechnical exploration program at the site. Subsequent to the demolition of the existing structure, site features included generally level topography with a seawall and the Gulf of Mexico along the northwest side of the site.

A detailed geotechnical exploration program was undertaken, consisting of six (6) Standard Penetration Test (SPT) borings and two (2) Piezocone Penetration Test (PCPT) soundings. The work was carried out using conventional drilling and sampling techniques.

Figure 1. Project building layout and boring location plan



In general, the project site stratigraphy consisted of very loose to dense poorly-graded sands to silty and clayey sands to depths of approximately 10.1 to 13.1 m (33 to 43 ft) with shallow deposits of compressible organic peat and firm silt. Layers of firm silt, firm to stiff lean clay, and soft to firm fat clay were encountered in some borings at depths of approximately 10.1 to 13.1 m (33 to 43 ft). Beneath these sand and/or silt and/or clay layers, medium dense to very dense weathered and/or fractured limestone was encountered to the boring termination depths of 19.8 m (65 ft). A detailed subsoil profile completed from 6 SPT borings and 2 PCPT soundings to depths ranging from 16 to 20 m (55 to 65 ft) was used. A project building layout and field test location program is indicated in Figure 1.

FOUNDATION DESIGN AND ALTERNATIVES

The first step of the design process was to evaluate various foundation systems and associated costs. Several foundation alternatives were considered for the proposed tower structure including: (i) driven precast prestressed concrete (PPC) displacement piling; (ii) cast-in-place auger piles; and (iii) ground modification using vibro-replacement. In view of the owner's accelerated construction schedule, cost, and availability, a driven prestressed concrete piling system was finally selected for the tower structure. Piles were designed to penetrate into the weathered limestone layer as composite action piles.

The allowable capacity of the piles was estimated using SPT97 software. This program, which was developed and used by the Florida Department of Transportation, FDOT estimates the axial capacity of a pile based on SPT "N" values and soil types. The design method used in SPT97 has been found to be very accurate for driven piles in cohesionless soils (McVay et al., 1989). SPT97 results indicated that prestressed concrete piles driven into the weathered limestone layer to depths of 18.3 to 19.8 m (60 to 65 ft) below the original ground surface would provide a satisfactory and economical foundation alternative.

PROBE PILE AND DYNAMIC LOAD TESTING (DLT)

The purpose of the probe pile program was to evaluate the suitability of the contractor's pile driving equipment to provide site-specific pile driving data, determine and verify pile capacities, provide production pile lengths, and establish driving criteria for use during the production pile driving phase of the project.

Probe Pile Driving Operations

A total of twenty four 356 mm (14-in.) square PPC probe piles were dynamically load tested during the probe pile driving and testing program. The probe piles were driven at production pile locations and incorporated into the foundation system of the tower structure. Eighteen 19.8 m (65 ft) long piles were driven at locations designed for 890 kN (100 tons) allowable compression capacity and six 16.8 m (55 ft) long piles were driven at locations designed for 445kN (50 tons) allowable compression capacity.

The pile driving contractor proposed utilizing an MKT DA-55B single-acting diesel hammer to install the piles for this project. This hammer has a maximum rated energy of 57,573 N-m (42,500 ft-lbs), a maximum stroke of 3.2 m (10.5 ft), and a ram weight of 22.2 kN (5,000 lbs). Prior to initiation of the probe pile driving program, driveability analysis using Goble Rausche Likins Wave Equation Analysis Program (GRLWEAP) was performed in an effort to model the actual driving conditions (Rausche et al., 2000). The results of the GRLWEAP analysis indicated that the MKT DA-55B hammer was only marginally acceptable for use on this project due to its relatively light ram weight and long stroke length and that if used, it might cause high driving stresses in the piles. The MKT DA-55B hammer was used for the project despite ASC's recommendation that a hammer with a heavier ram be selected.

The hammer leads used on this project were attached to the crane by a rigid strut. Although the project site was relatively level, the rigid strut caused great difficulty for the pile driving crew to properly align the hammer with the pile since they were unable to transversely adjust the leads with respect to the crane. If the crane was not perfectly level to start with the leads, therefore, could not be properly plumbed.

Dynamic Load Testing

In an effort to optimize penetration and capacity requirements for piles, a DLT program utilizing PDA instrumentation was recommended and performed.

All 24 probe piles were instrumented throughout their entire driving length during installation. Additionally, all 24 piles were instrumented during restrikes. Restrike of the piles was performed after periods of 17 to 93 hours. Efforts were made to allow as much time as was feasible, considering the project schedule, between initial driving and restrike of the piles. The probe piles were initially driven to depths ranging from 11.9 to 18.3 m (39 to 60 ft) . Piles that did not achieve capacity upon initial restike were re-driven to depths ranging from 17.1 to 19.5 m (56 to 64 ft). To prevent the PDA gauges from being driven below the ground surface during testing, it was necessary to excavate around the sides of the pile when driving below 15.2 or 18.3 m (50 or 60 ft) for 16.8 and 19.8 m (55 and 65 ft) long piles, respectively. The PDA was utilized for this site to better evaluate and predict the increase in pile resistance with time (i.e., set-up or freeze). This benefit was incorporated in the determination of production pile lengths.

During probe pile installation operations the driving stresses measured by the PDA were high and at times exceeded the allowable driving stresses. The allowable compressive driving stress of 24,100 kPa (3.5 ksi) was determined using a criteria of 85% of the compressive strength of the concrete minus the prestressing force in the pile. The allowable tensile driving stress of 9,000 kPa (1.3 ksi) was determined using a criteria of 50% of the tensile strength of the concrete plus the prestressing force in the pile. The maximum driving stresses measured by the PDA were on the order of 27,100 and 12,100 kPa (3.93 and 1.75 ksi) compressive and tensile, respectively.

The high driving stresses in the piles can be attributed to two factors: (i), As previously discussed, the light ram weight and long ram stroke resulted in high ram impact velocities and, consequently high pile driving stresses. (ii), Poor hammer to pile alignment caused by the rigid strut connecting the hammer leads to the crane resulted in eccentric loading of the pile and, therefore, increased maximum stresses. Hammer to pile alignment problems could easily be seen in the PDA data as large discrepancies between the data curves produced by the strain transducers mounted on opposite sides of the pile. The pile cushions, 9.84 cm (3.875-in.) thick stacks of rough cut pine boards, were used to drive no more than 2 piles in an effort to minimize driving stresses in the piles.

Dynamic load tests on probe piles confirmed that the subsoil conditions at the project site were highly variable, thus making the site ideally suited for dynamic load testing utilizing a PDA. It was determined to be the most appropriate testing method to account for such variability. Because PDA testing is relatively inexpensive and quick, many tests were performed to provide an interpretation of a large portion of the site. Additionally, PDA testing provided a profile of soil resistance verses embedded pile depth for the test piles. Alternately, 24 static-load tests utilizing expensive telltale instrumentation would have been required to obtain the quality and quantity of useful information as obtained during dynamic load testing utilizing the PDA.

The ultimate pile capacity predicted using the PDA ranged from 489 to 2580 kN (55 to 290 tons) at the end of initial driving (EOID) and from 1068 to 2758 kN (120 to 310 tons) at the beginning of restrike (BOR). The time elapsed between EOID and BOR ranged from 17 to 93 hours. Piles at this site exhibited set-up ranging from 44 to 756 kN (10 to 170 kips), or 2 to 127 percent. The pile set-up is expressed as a ratio of pile capacity increase over initial pile capacity in percent. Piles with poor quality PDA data were not used in set-up calculations. A summary of PDA results is tabulated in Table 1.

Results of CAPWAP Analyses

Dynamic load test data obtained in the field using the PDA was further analyzed utilizing the Case Pile Wave

Table 1. Summary of Pile Freeze or Set-up

PROBE PILE No. (7)	PDA CAPACITY AT EOID "a" (1) (kN)	PDA CAPACITY AT BOR "b" (2) (kN)	EMBEDMENT DEPTH (m)	TIME ELAPSED BETWEEN EOID AND BOR (hours)	INCREASE [(b-a)/a] x 100 (%)
TP1	890	1160	12.2	40.0	30.0
TP2	2580	2760	15.8	40.0	6.9
TP3	620	1070	16.5	23.0	71.4
TP4	840	1110	18.3	29.5	31.6
TP4 A(7)	800	1160	19.5	17.5	44.4
TP5	1070	1160	18.3	31.5	8.3
TP5 A(7)	1160	1070 (5)	19.5	17.0	—
TP6	930	1070	18.3	27.0	14.3
TP6 A(7)	980	1070	19.2	18.0	9.1
TP7	980	1240	14.9	48.0	27.3
TP8	1820	1910 (3)	16.1	31.5	4.9
TP9(4)	490	1110	16.8	76.5	127.3
TP9 A(7)	1240	1420	18.9	18.0	14.3
TP10(4)	1160	(5)	13.7	72.5	—
TP11(4)	1240	1560	13.7	93.0	25.0
TP12(4)	1290	2000	13.7	72.0	55.2
TP13	1690	2000	13.7	46.5	18.4
TP14	1730	1820 (3)	13.7	70.0	5.1
TP15	1110	1870	13.4	43.0	68.0
TP16	2040	2220	13.7	44.0	8.7
TP17	840	1330	11.2	43.0	57.9
TP18	(5)	890	12.2	28.0	—
TP18 A(7)	2040	2090	17.1	38.5	2.2
TP19	930	1110	18.3	34.0	19.0
TP19 A(7)	1470	1780	14.5	39.0	21.2
TP20	1870	2090	13.7	43.0	11.9
TP21	2220	2670	14.0	66.5	20.0
TP22	2000	2180	14.0	47.0	8.9
TP23	1160	1510	14.3	48.0	30.8
TP24	(6)	1470	14.0	42.0	—

Notes: (1) EOID = End of Initial Driving.
(2) BOR = Beginning of Restrike.
(3) The PDA lost power during the first restrike attempt and data was not collected. Capacities presented in table reflect 2nd restrike attempt.
(4) Pile driven in a cluster of 4 test piles.
(5) PDA data quality was poor due to poor hammer-pile alignment.
(6) PDA data quality was poor due to damage at the top of the pile.
(7) Piles TP-4 thru 6,9,18, and 19 achieve required capacity at either EOID or at the first restrike. These piles were then driven to deeper depths, allowed time to develop.
(8) 1 ft = 0.3028 m; 1 ton = 8.897 kN

Analysis Program (CAPWAP) for a more comprehensive determination of the soil and pile behavior during pile driving (ref 2). CAPWAP analyses were performed on a total of 17 blows collected during initial drive and restrike of probe piles. These analyses provide a better evaluation of total ultimate pile capacity, as well as estimates of skin friction and end bearing capacities. Several variables must be entered in the PDA prior to testing, such as pile and soil damping values. Usually the exact values of these variables are not known and they are always subject to refinement. The CAPWAP analysis is a wave-matching process where these variables are adjusted to achieve the best match between the CAPWAP models force and velocity waves and the actual force and velocity waves measured by the PDA. This analysis provides refinement of the raw PDA data and the pile capacity estimated in the field during driving. Results from the CAPWAP analyses are presented in Table 2. The CAPWAP adjusted capacities varied from the measured PDA capacities by 2 to 26%. Adjustments of this magnitude are common on sites with generally variable subsurface soil conditions and are due to the soils at the pile location having slightly different properties than those were assumed for PDA testing.

Pile Integrity Testing

Upon completion of probe pile driving operations pile integrity testing using the Pile Echo Tester (PET) function of the Pile Integrity Sonic Analyzer (PISA) was performed on a total of 12 probe piles that had experienced excessive driving stresses to evaluate their structural integrity. PET is a low-strain testing method in which a hand held hammer is used to generate a compressive stress wave in the pile. An accelerometer attached to the pile measures reflections of the stress wave as it travels along the pile. The results of the PET testing showed that there was no major structural damage to the piles above the weathered limestone strata. Because the stress wave loses energy as it travels along the pile, reflections from below the top of the weathered limestone layer were too weak to provide useful data.

Table 2. Summary of CAPWAP Results

PROBE PILE No.	EMBEDMENT DEPTH (m)	BLOW COUNT (bpf)$^{(2)}$	ULTIMATE PDA CAPACITY (kN)	MAX. TRANSFERRED ENERGY (N-m)	ULTIMATE CAPWAP CAPACITY (kN)		
					SIDE FRICTION	END BEARING	TOTAL $^{(1)}$
TP1	12.2	17	836	22100	713	92	804
TP2	15.8	72	2613	24000	1060	1449	2510
TP2	16.5	96	2800	28300	1012	1551	2564
TP3	16.2	26	658	15200	610	75	685
TP3	16.2	77	1120	6800	986	426	1412
TP7	14.6	23	1000	19600	520	456	976
TP7	14.9	55	1293	7200	860	324	1184
TP9	16.5	11	524	19400	415	35	450
TP9	16.8	42	1142	11200	1012	244	1256
TP12	13.4	32	1276	17800	818	408	1227
TP12	13.7	108	2040	18300	1167	452	1619
TP13	13.4	48	1898	20600	269	1764	2033
TP13	13.7	72	1969	22500	1209	643	1852
TP16	13.7	52	2044	23000	511	1320	1830
TP16	13.7	108	2258	21500	877	1431	2308
TP17	11.6	18	813	18400	566	262	828
TP17	11.9	54	1338	10800	674	389	1063

Notes: (1) A safety factor of 2.0 was used in determining allowable pile capacities discussed in this report.
(2) 1 ft = 0.3028 m; 1 ton = 8.897 kN

Production Pile Lengths

Following completion of the probe pile and DLT program specific pile lengths and driving criteria to achieve the required capacities were finalized, taking into consideration the excavated and prepared surface elevations of various foundation element areas within the building limits. The PDA assisted DLT program resulted in a fully optimized pile layout plan utilizing 2 different pile lengths to achieve allowable compression capacities of 445 kN (50 tons) and 4 different pile lengths to achieve allowable compression capacities of 890 kN (100 tons). Production pile driving criteria were determined to be 40 blows per foot (bpf) at the end of EOID and 6 blows per inch (bpi) at the BOR for 100 ton piles, and 20 bpf at the EOID and 3 bpi at BOR for 50 ton piles.

Pile Installation and Quality Control

Following the geotechnical consultant's review of the pile layout plan, details of pile driving specifications were finalized for the production pile program to proceed. Production pile driving commenced, and a full-time monitoring and logging of the program was provided. Records of pile number, location, date of installation, length of pile, blows per foot, and unusual occurrences for each pile were kept. The approval for the pile driving termination was given by an ASC engineering representative upon the required driving criteria being achieved.

A total of 539 PPC piles were installed during the probe and production pile installation phases. A pile foundation layout, load test location, and pile length delineation plan is illustrated in Figure 2.

During the logging and monitoring of the production pile driving operation, 515 PPC piles were installed and rated for 445 and 890 kN (50 and 100 tons) allowable compression capacities, based on either the EOID or BOR results. Piles that did not meet the EOID driving criteria were later retapped using BOR criteria to verify pile capacity after set-up.

Based on the geotechnical consultant's continuous and satisfactory monitoring of the pile installation program (e.g., logging the blowcount and pile embedment depths) the PPC pile foundation system, as installed, was approved and accepted for the building. The Twin Dolphins 1 at La Peninsula project is scheduled for completion in 2002.

OBSERVATIONS, REMARKS, AND CONCLUSIONS

The authors believe that the use of properly installed and effectively monitored and tested precast prestressed concrete piles was economical as compared to the other foundation alternates and that

PDA and PET testing proved to be key elements of the overall approval and acceptance process.

Optimization of the pile penetration depths based on a dynamic load testing program utilizing PDA was achieved for this project.

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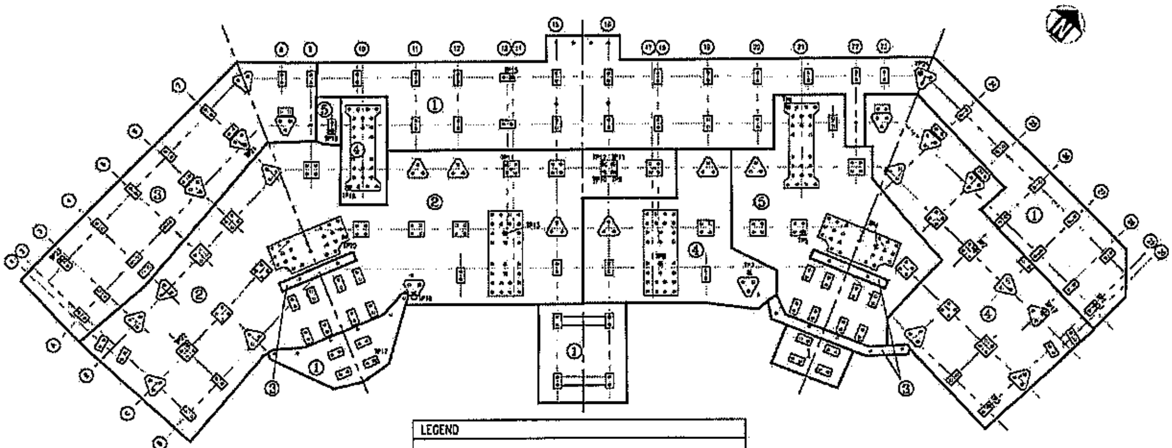
Figure 2. Foundation Layout and Pile Delineation Plan



LEGEND

TP1 Dynamic Load Test Pile

Areas	Depth	Number of Piles (ea)	Capacity (tons)
1	30	94	50
2	46	154	100
3	50	50	50/100
4	55	122	50/100
5	65	84	100
Total		504 [1]	

Note 1 – Excludes 24 Probe Piles

Note 2 – 1mm=0.04in; 1m=3.28ft; 1kN=0.11tons

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