Use of CAPWAP for uplift resistance evaluation of wind energy Tower piles

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ABSTRACT: Structures founded on piles derive their support from skin friction and toe bearing. For some structures piles are specified for the primary purpose of providing uplift resistance against forces of wind, flood and seismic loading. The magnitude of support provided by each pile is dependent on its penetration into the competent soil material. Dynamic testing and analyses of 14-inch diameter steel pipe piles installed for five wind-energy generating Towers located near the Atlantic City shore are described in this paper. The Towers are subjected to wind and potential flood loading. The soil conditions at the site consisted of approximately 48-ft (14.6 m) thick layer of fill and organic soils overlying medium dense to dense granular deposits. The fill and organic soils are determined to be unsuitable to provide uplift support for the structures. Only the section of the pile penetrated into the medium dense to dense granular materials would be considered to resist tension. Dynamic testing of several piles were performed and analyzed by CAPWAP® with emphasis on pile shaft resistance evaluation and its distribution along the length of the piles. The friction values contributed from the fill and organic soils were subtracted from the total friction calculated by CAPWAP in the evaluation of uplift pile capacity. In addition, consideration was given to the effect of Poison's ratio in calculating the final uplift resistance from compression loading. Several piles installed for the five wind-energy Towers were tested and evaluated by CAPWAP for both compression and uplift capacities. Based on the test and analysis results, recommendations were made regarding the minimum pile penetration into the soil strata considered to be competent in resisting both the required tension and ultimate compression loads. Results from CAPWAP analysis of the dynamic records established such information and provided confidence to the engineers in evaluating both the uplift and compression capacities of the piles.

1 INTRODUCTION

The project described in this paper consisted of the evaluation of pile foundation installed for five windmill structures constructed to generate 7.5 megawatt (MW) electric power. The windmill structures are located near the coast of Atlantic City in New Jersey, USA. It is the first windmill coastal farm in the United States. The project is predicted to produce approximately 19 million kilowatt-hours of emission-free electricity per year which is enough to power 2500 homes. Each windmill turbine is approximately 381 ft (117 m) tall. Considering loads from wind, wave forces and seismic loading, each windmill turbine is designed to be supported on 24 piles. Most of the piles are driven at a batter of 1:10 and are spaced equally in a circular layout. Based on structural and geotechnical considerations 14 inches (356 mm) outer diameter steel pipe piles with uniform wall thickness of 0.375 inches (9.5 mm) were selected for the project. The toe of each pile was fitted with a conical pile point. The pile driving contractor, Tuleya Pile & Foundation, Inc., used a Pileco D19-42 single acting diesel hammer to install the piles. This hammer has a ram that weighs 17.9 kN and is rated for a maximum energy of 57.6 kN-m.

In addition to providing support for compression loading, the piles are designed for the primary function of providing uplift support generated from lateral forces of wind, flood and seismic loading. Considering the subsurface conditions at the site, installation of the piles to soil strata that provide sufficient uplift is of primary challenge to the geotechnical engineers. The resistance along the pile shaft is dependent on the soil type, strength and pile penetration into competent soil. This resistance force is calculated from dynamic measurements of force and velocity with emphasis on computing the shaft resistance by CAPWAP® (CAse Pile Wave Analysis Program) analysis. Test results of several piles installed at five windmill locations are presented in this paper. In addition, both static compression and tension load testing at windmill Tower 4 location were performed to check the adequacy of the piles to resist the required ultimate compression and tension loads.

2 PROJECT LOCATION AND DESCRIPTION

The Atlantic County Utilities Authority (ACUA) Wind Energy Farm is located in Atlantic City, New Jersey, USA. The owners, Jersey Atlantic Wind LLC in partnership with the original developer Community Energy, Inc. (currently a subsidiary of Ibedrola, S,A.), constructed a total of five windmills providing 1.6 megawatts each. The Tower hubs are 80.6 meters high and 4.3 meters in diameter. The blades are 34.3 meters long for a total height to tip of blade of approximately 117 meters. The tips travel at approximately 75 kilometers per hour.

3 GEOLOGY

Atlantic City occupies the northern end of Absecon Island, which is a classic barrier beach type geologic landform. The island was formed by deposition of sands by littoral drift currents and the development of tidal marshes in sheltered areas on the inner shore during the geologically recent period of rising sea level since the last glacial age. The ACUA/ Community Energy, Inc. Wind Energy Farm project area appears to be in a zone of alternating active beach and back bay marsh type deposition. Thick strata of marsh deposits were encountered between strata to loose to medium dense sands to depths of 13 to 15.5 meters. The barrier beach and tidal marsh was deposited over more ancient coastal plan sediments. The uppermost of the geologic strata is the Cohansey Formation consisting of medium to dense sands with frequent lenses of stiff inorganic clays and silts. These appear to have been encountered at depths of approximately 15.0 to 19.5 meters in the borings. The underlying formations extend to great depth and consisted of interbedded sands, gravels, marls, clays and silts.

4 SUBSURFACE DESCRIPTION

Several boring logs were taken at the project site. The upper layers consisted of peat, and organic silt to a depth of 14.6 m (48 ft) and the depth below the organic silt was described as gray sand with silt and gravel to the boring termination depth of 24.4 m (80 ft). The Standard Penetration Test (SPT) in the bottom strata ranged between 29 to 91 blows per 30 cm (29 to 91 blows/ft). The upper 14.6 m of the soil is considered unsuitable of supporting uplift resistance. Only pile penetration depth in the gray sand with silt and gravel is considered suitable to support uplift resistance generated from the wind, storm and seismic loading. A subsurface section depicting the general soil stratigraphy at the site is shown in Fig. 1.

5 DYNAMIC PILE TESTING OF WINDMILL TURBINE FOUNDATION

Methods to measure force and velocity near the pile top have become a routine practice. Several piles at the five windmill turbine locations were tested dynamically and the measured force and velocity records were analyzed to check both the uplift resistance and compression capacity of the piles. Testing consisted of attached two strain transducers and two accelerometers at approximately 1 m from the top of the piles. During impact driving, the force and velocity records were processed to yield pile driving stresses, hammer energy transferred to the piles, hammer stroke, and other quantities. At the time of testing, the capacity of a pile is computed from one dimensional wave theory referred as the Case Method technique. This method produces the total driving resistance, i.e., the sum of static and dynamic resistance forces. However, the dynamic resistance should be separated from the total computed resistance forces to arrive at the static soil resistance. Using CAPWAP analysis, the total static capacity for each test pile was computed and the result was split between shaft resistance and its distribution along the embedded length of the pile and pile toe bearing value. Records collected during initial driving and during restrike testing after the dissipation of pore water pressure, were analyzed. For long term capacity evaluation, analysis is based on restrike records of the force and velocity obtained several days after the completion of initial driving.

6 CAPWAP METHODOLOGY

Measuring both force and velocity records near the pile top are well established. However, the static and dynamic soil resistance forces plus all forces and motions below the pile top are unknown. In the CAPWAP method of analysis, it is possible to analyze a pile under the action of either the force record or velocity record or their average (which is the force in the downward wave) and an assumed soil model and compare the computed record to the unused upward wave. The difference between the measured and computed curves leads an engineer to conclusions regarding the differences between the actual soil behavior and assumed set of soil parameters. Modifications of these parameters leads to a better match and a subsequent iteration.

Therefore, CAPWAP is a signal matching procedure which uses the pile top force and velocity measurements generated during hammer impact. In this numerical computation, the pile is divided into a

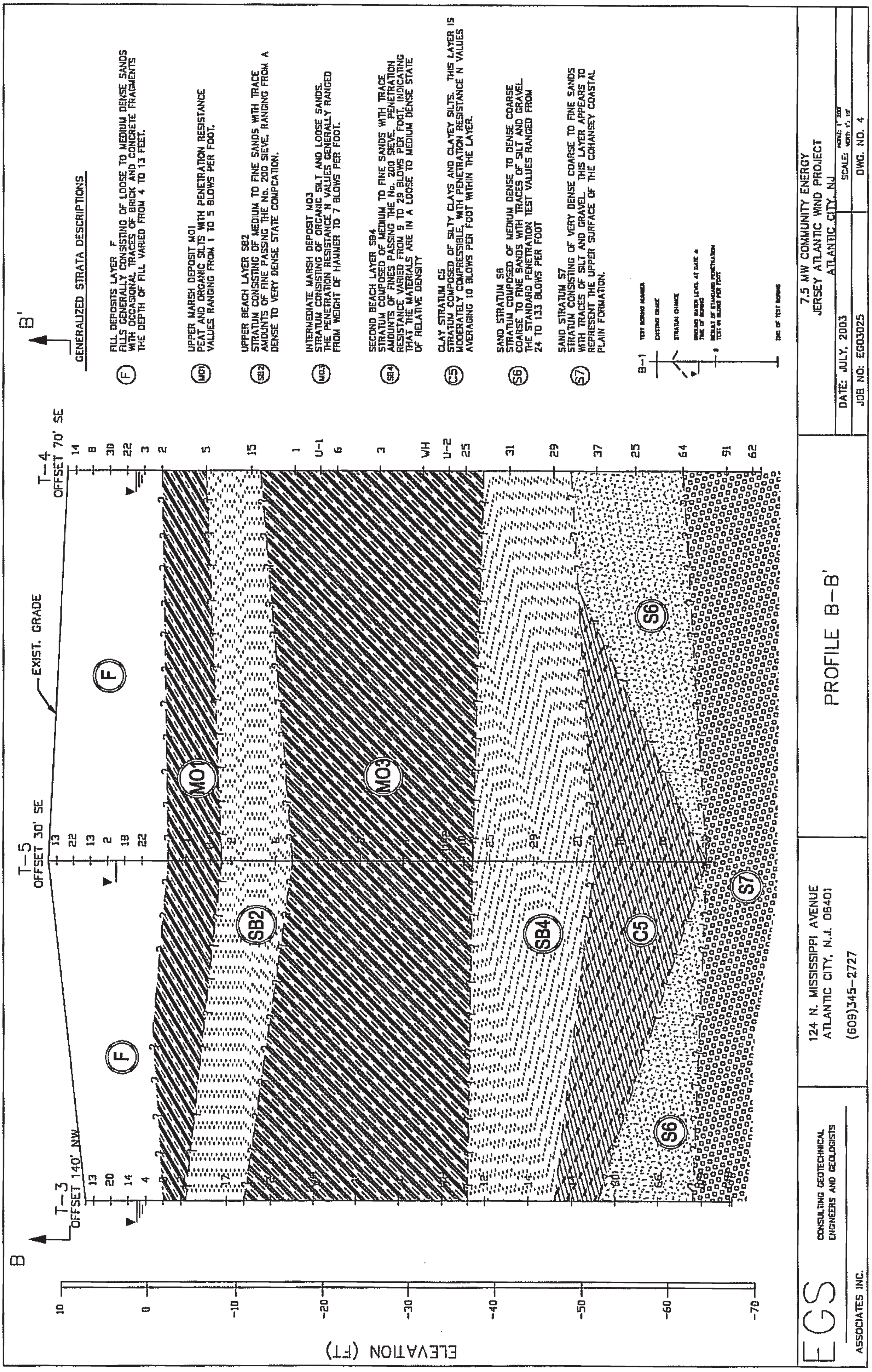

Figure 1. Generalized strata descriptions.

series of segments of uniform properties with soil resistance forces acting at each embedded pile segment. The soil model is considered as an elasto-plastic spring and as a linear dashpot described by three parameters: ultimate resistance, quake and viscous damping factor. In the iteration process, mainly these three parameters are varied in an effort to obtain a good match between the measured and computed forces.

In the present project, the measured downward travelling waves obtained from either initial drive or restrike testing of the piles were input to the CAPWAP program. Several iterations were made until a good match between the downward and upward travelling waves was obtained. The iteration was stopped when the match could not be improved further. The resulting soil element resistance forces were summed to yield the total refined capacity of the piles. The pile toe soil element resistance was then subtracted from the total resistance to yield total skin friction and its distribution along the pile shaft.

7 RESULTS FROM CAPWAP ANALYSES

Several piles located at the five sites were dynamically tested. These piles were driven to penetrations and blow counts indicated in Tables Nos. 1 and 2. The project specification requires that each pile must be driven to an ultimate compression capacity of 1877 kN and an effective uplift capacity of 347 kN. Per geotechnical consideration, the piles should have a minimum embedment of 8.2 m into the lower soil strata, described as a medium dense to dense layer, to resist uplift from lateral force of wind, storm and seismic loading.

The output from CAPWAP includes a refined total pile capacity split between shaft resistance and pile toe bearing. The results from the analysis indicated that the required ultimate compression capacity of the piles could easily be achieved. For uplift resistance evaluation, data from both initial driving and restrike testing of several piles were analyzed to check if the required uplift resistance was satisfied. The total skin friction calculated by CAPWAP was reduced to account for the effect of Poison's ratio in computing tension resistance from compression loading. According to the practice of the first author, a reduction of the computed skin friction by 20% is generally applied to estimate uplift resistance. The upper fill and organic soils are considered unsuitable to provide uplift support. Therefore, the skin friction computed by CAPWAP in the upper layers had to be subtracted from the total skin frictional forces to yield uplift resistance in the lower 8.2 m of pile penetration. As stated above a reduction factor was applied to the calculated uplift resistance to arrive at the usable tension load.

8 EVALUATION OF THE TEST RESULTS

8.1 Towers 1 and 2

The results of the dynamic pile tests performed on five piles at Tower 1, and four piles at Tower 2 are summarized in Table 1. All test piles at Tower 1 were tested during restrike while the piles at Tower 2 were tested during both initial driving and restrike testing. The compression capacity of the piles in Tower 1 ranged between 1825 and 2114 kN, with total skin friction ranges of between 677 and 835 kN. The skin friction at the bottom 8.2 m penetration of the piles ranged between 477 and 716 kN. These values were computed from the force and velocity records obtained during compression loading by hammer impact, and had to be reduced to account for the effect the loading direction had on these results. Therefore, the applicable (effective) resistance values to support uplift ranged between 382 and 573 kN. These values were higher than the required uplift of 347 kN. The above results represent values obtained from restrike testing of the piles.

At the location of Tower 2, the compression capacity of the piles ranged between 1534 and 1860 kN at the end of initial driving. Restrike testing of the piles had to be performed in order to check the long term capacity of these piles. During restrike after 2 to 6 days, the capacities in compression increased and reached values higher than the required ultimate capacity of 1877 kN. Evaluation of tension resistance in the lower 8.2 m of the piles at Tower 2 was based on restrike records, except for pile TP208, which reached the required tension capacity during initial driving. Per CAPWAP analysis results, the three piles tested during restrike indicated tension capacities higher than the required value of 347 kN.

8.2 Towers 3, 4 and 5

Four piles including a Load Test Pile (LTP-1), and three reaction piles were tested at Tower 4 location. Three of the piles, except the load test pile LTP-1, were also tested during restrike a day after their initial driving. According to CAPWAP analyses results, all reaction piles except pile WT417 achieved the required ultimate compression capacity of 1877 kN at the end of initial driving. Pile WT417 reached its required compression capacity during restrike a day later. The uplift resistance, computed by CAPWAP for the lower 8.2 m penetration was lower than the required value of 347 kN for all piles tested within.

All piles in Tower 4 did not achieve ther required uplift capacity during restrike, except for reaction pile WT418 which achieved an uplift capacity of 367 kN. With longer waiting time, it is likely that the uplift resistance could be achieved. The empirical formula developed by Svinkin and Scov (2000); $\mathbf{R_U(t)/R_{EOD} - 1 = B(log_{10}(t) + 1}$ was utilized to estimate pile set-up. The computed compressive capacities, after one month and six months, indicated that pile

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Table 1. Summary of Dynamic Pile Test Results

Test Piles at Windmill Towers 1 and 2

Project: Jersey Atlantic Windmill Towers
Location: Atlantic City, New Jersey

Hammers: Pileco D19-42 single acting diesel
Pile: 14"ODx0.375" (356 mm OD x 9.5 mm) with conical point

				Results from CAPWAP Analysis			
Pile Number	Final Depth Below Ground m	Reported Blow Counts blows/25 cm	Test Type	Total Capacity kN	Total Shaft kN	(a) Friction at Lower 8.2 m of Pile kN	(b) Uplift Resistance 80% of (a) kN
TOWER 1							
TP123	21.2	80	RS	1895	783	679	543
TP113	16.8	100	RS	2114	678	488	390
TP104	16.8	90	RS	1886	677	519	415
TP108	17.1	120	RS	1873	835	716	573
TP119	17.1	70	RS	1825	743	477	382
TOWER 2							
TP216	22.1	40	ED	1534	447	317	254
	22.1	80	RS	1740	641	425	340
	22.8	120	RD	1890	653	451	360
TP201	21.7	80	ED	1775	535	470	376
	22.8	110	RD	1893	650	472	378
TP220	22.1	60	ED	1712	486	318	255
	22.1	80	RS	1912	695	537	429
TP208	22.0	80	ED	1860	531	462	370

Notation:ED —— End of Initial Driving; RS —— Restrike; RD —— Redrive(a) —— Friction at bottom 8.2 m of pile is considered effective from geotechnical consideration(b) —— 20% reduction for the effect of compression loading in estimating uplift

set-up increases capacity by factors of approximately 1.35 and 1.51, respectively. These factors could be applied to the uplift capacity obtained from the CAPWAP analyses in the pile segments within the granular strata beneath the organic deposits.

The LTP-1, tested during initial driving, indicated a compression capacity of 1882 kN which is higher than the required ultimate value of 1877 kN. The effective uplift resistance based on CAPWAP analysis of the end of initial drive record obtained on the LTP-1 was 291 kN which is lower than the required value of 347 kN. This pile was not dynamically tested during restrike.

Pile 309 at Tower 3 achieved the required compression capacity of 1877 kN at the end of initial driving while pile TP500 at Tower 5 achieved this capacity during restrike a day later. The uplift capacity considered effective, i.e., in the lower 8.2 m of pile penetration, was 420 kN for pile TP309 which is higher than the required value of 347 kN while pile TP500 achieved the same uplift capacity of 420 kN, during the restrike the test after the dissipation of the pore water pressure.

9 STATIC COMPRESSION AND TENSION TESTS

''Proof'' static load tests of both compression and tension were however performed on the LTP-1 several days after the pile was initially driven. The compression load test was performed based on ASTM D1143 Standard Method of Piles Under Axial Compressive Load and the tension test based on ASTM D-3689 Method 7.5 Constant Time Interval Loading. The test pile sustained the required ultimate compression load of 1877 kN for 12 hours with gross settlement of 13.7 mm. The net settlement after removing the load was 3.9 mm. Applying the Davisson's Failure Limit, pile LTP-1 could fail at axial compression load of 2446 kN. The compression test curve is indicated in Fig. 2.

Table 2. Summary of Dynamic Pile Test Results

Test Piles at Windmill Towers 3, 4 and 5

Project: Jersey Atlantic Windmill Towers
Location: Atlantic City, New Jersey

Hammers: Pileco D19-42 single acting diesel
Pile: 14"ODx0.375" (356 mm OD x 9.5 mm) with conical point

				Results from CAPWAP Analysis			
Pile Number	Final Depth Below Ground m	Blow Counts Reported bls/25 cm	Test Type	Total Capacity kN	Total Shaft kN	(a) Friction at Bottom 8.2 m of Pile kN	(b) Uplift Resistance 80% of (a) kN
TOWER 3							
P309 Batter	19.5	400	RS	2250	715	525	420
TOWER 4							
RP2 Plumb	17.8	70	ED	1884	478	272	218
	17.8	200	RS	1988	534	372	298
WT418 Batter	19.2	100	ED	1888	429	302	242
	19.2	120	RS	1957	534	459	367
WT417 Batter	18.0	80	ED	1734	355	248	200
	18.0	120	RS	1895	507	374	300
LTP-1 Plumb	18.9	80	ED	1882	463	363	291
TOWER 5							
TP500 Plumb	23.4	50	ED	1736	568	425	340
	23.4	100	RS	1885	705	526	420

Notation:ED —— End of Initial Driving RS —— Restrike(a) —— Friction at bottom 8.2 m of pile is considered effective from geotechnical consideration(b) —— 20% reduction for effect of compression loading in estimating uplift

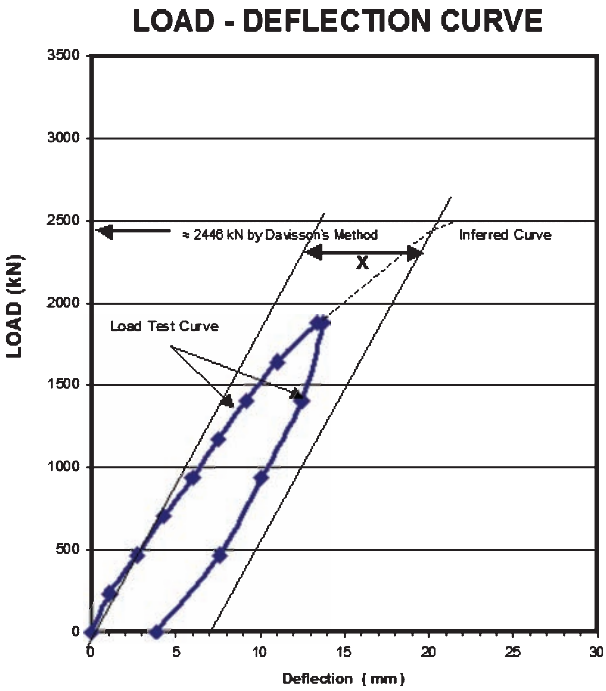

Figure 2. Static load test results in compression.

The same pile sustained a tension load of 347 kN for 12 hours with gross deflection of 2.9 mm. The net deflection after the load was removed was 1.45 mm.

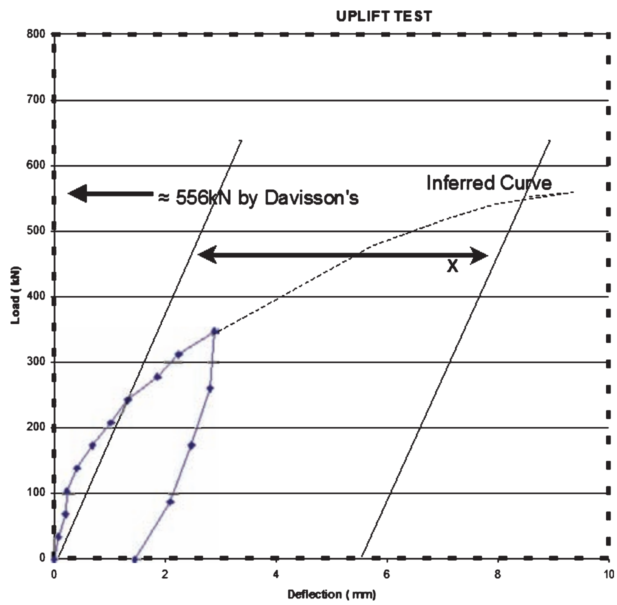

Figure 3. Static load test results in tension.

Applying the Davisson's Failure Limit, the test pile would fail at a tension load of 556 kN. Results of the static test include the contribution of the resistance of the upper soil layer considered undesirable to support uplift. The static tension test curve is indicated in Fig. 3.

10 CONCLUSIONS

Several piles were dynamically tested during the installation of the foundation piles for the windmill structures at the coastal line of Atlantic City, New Jersey. Requirements for compression loading can be checked easily with routine dynamic pile testing. However, checking the uplift resistance of the piles against the forces of wind, flood and seismic loading was a major challenge. With the use of dynamic pile testing and subsequent analysis of the records by the CAPWAP analysis program, the total skin friction along the length of the piles was computed. It was necessary to reduce the computed shaft resistance in order to account for the effect of compression loading (Poisson's ratio effect) in establishing valid tension pile capacity. In addition, the soil resistance in the lower 8.2 m of pile penetration was considered effective in providing uplift resisting from forces of wind, storm and seismic loading of the structures. Some piles tested during initial driving indicated uplift resistance less than the required value of 347 kN in the lower 8.2 m of pile penetration, while most of the piles tested during restrike after a waiting period of between one and seven days had uplift resistance higher than the required value as indicated in Tables Nos. 1 and 2. The compression capacity of the piles was easily achieved during either initial driving or restrike after soil setup took place.

Pile LTP-1, located at Tower 4, indicated a CAPWAP computed compression capacity of 1882 kN and an uplift resistance of 291 kN at the end of initial driving. The uplift resistance represents 80% of CAPWAP computed tension capacity in the lower 8.2 m of pile penetration. This pile satisfied the compression requirement of 1877 kN at the end of initial driving. Both compression and tension static proof loads applied to this pile, after a few days of its initial driving, indicated that the pile could support at least 1877 and 347 kN, respectively. Although, the compression and tension static tests were terminated at proof loads of 1877 and 347 kN, respectively, failure loads in compression and tension of approximately 2447 and 556 kN, respectively, were projected from the static load test curves based on the Davison's Failure Limit.

Based on dynamic testing, both compression and uplift resistance of the piles were checked. An advantage was taken of the capability of the CAPWAP program to compute skin resistance forces at any location along the pile penetration. The shaft resistance calculated for selected soil layers within the penetration of the piles was used to check if that resistance could provide sufficient uplift or tension capacity. Based on the tests and analyses results, it was concluded that piles in Towers 1 and 2 should be installed to minimum penetrations of 17 m and 22 m, respectively, at blow counts of 32 blows per 10 cm with the hammer operating at an average stroke of 2.8 m. Similarly, conclusions regarding the installation of the production piles at Towers 3, 4 and 5 were made based on the PDA testing and CAPWAP analyses results. Piles at Towers 3 and 4 were to be driven to a penetration of at least 19 m to blow counts of 32 blows per 10 cm with the hammer operating at an average stroke of 2.8 m. The dynamic testing and CAPWAP analyses indicated that piles at Tower 5 required a deeper penetration of 24 m and that the blow counts at final driving should be approximately 32 blows per 10 cm with the hammer operating at an average stroke of 2.7 m at the end of driving. CAPWAP analyses provided valuable information to cost-effectively establish the above criteria and adequate installation of the piles supporting wind turbine Towers in unfavourable subsurface condition.

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