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Comparison of Pile Capacity Evaluated by Dynamic Measurements and Static Load Tests - 3 Case Studes in Ontario, Canada

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SYNOPSIS: Three case studies of projects in Ontario, Canada, are reported where pile capacity was evaluated by static load tests as well as by dynamic methods. The results of both methods are compared, which indicated that dynamic analysis results were within 1 to 14 percent of the static load test results. The correlations have shown that dynamic analysis is an excellent alternative to static load tests for the evaluation of the ultimate bearing capacity of piles.

INTRODUCTION

Since pile driving causes failure of the soil to advance the pile, it is logical to use dynamic measurements made during pile driving to evaluate the ultimate bearing capacity of a driven pile. The use of dynamic measurements to predict pile capacity was put into use in the early 1970's and since then, the use of dynamic measurements to predict pile capacity has gained wide acceptance by practicing civil engineers and contractors. For dynamic monitoring of the piles, the total dynamic resistance was evaluated from the strain and acceleration measurements. By modelling the hammer-pilesoil, and resistance distribution along a pile, the static ultimate bearing capacity of a pile can also be evaluated. The case histories of three sites in Southern Ontario, Canada, present the dynamic measurements obtained at the sites where static load tests were also performed. The ultimate bearing capacity evaluated from dynamic measurements at the three sites was compared with the static load test.

Ontario is a province located in the mid-eastern portion of Canada. The area was glaciated and the subsoil is generally a glacial deposit of variable texture. While the majority of the glacial till deposits are generally competent enough to support a building on conventional shallow spread foundations, there are areas containing deep deposits of soft alluvial clay, loose silt or sand and man-deposited fill where deep foundations are required. In these instances, driven piles or augered cast-in-place caissons are used to support the proposed structures.

The calculation of the ultimate bearing capacity of a driven pile is highly theoretical. Some engineers use basic soil mechanic analysis to estimate the frictional and end bearing resistances of a driven pile. Others use various kinds of dynamic formulae to predict the ultimate bearing capacity of piles when the driving system, pile type and size are known. When Smith (1960) introduced wave propogation theory in the 1930's to be applied to a pile during driving, a new chapter had opened in the analysis of the ultimate bearing capacity evaluation. With the evolution of the digital computers in the early 1970's and the various instruments for the measurements of strain and acceleration during the pile driving, the dynamic monitoring of piles was put into use. This paper presents the results of the dynamic analysis of piles at three sites where static load tests were undertaken.

THEORETICAL BASIS

The dynamic determination of pile capacity, using Smith's wave propogation theory, has been reported by Rausche, Goble and Likins (1985). Basically, during the driving of a pile, the strain and acceleration of the pile induced by the pile driver are measured. From the strain measurement, the force at the pile top can be calculated if the pile material and cross sectional area are known. From integrates of the acceleration measurement, the velocity of the pile being driven into the ground can be determined. From the force and velocity obtained at the pile top, the static capacity of the pile can be estimated by the Case Method:

$$RSP = (F1 + F2) /2 + MC/2L (V1 - V2) - J$$

Where: RSP = Ultimate static bearing capacity
F1 = Force at impact
F2 = Force at time 2L/C
M = Mass of pile
C = Wave speed travelled in the pile
L = Length of pile
V1 = Velocity at impact
V2 = Velocity at time 2L/C
J = Damping

The capacity of the pile can also be analysed by another method, called CAPWAP analysis. In this analysis, the measured force and velocity is used as input into the computer. By varying the resistance distribution along the pile, the soil damping, soil quake, etc., a computer force or velocity that is reasonably similar to the measured force and velocity can be obtained. In this case, the field condition is simulated and, therefore, the ultimate static bearing capacity of the pile can be evaluated.

DYNAMIC MONITORING FIELD WORK

The field work was carried out using two sets of gauges and a portable computer called a Pile Driving Analyser. The attachments consisted of two reusable strain gauges and two accelerometers securely bolted at a minimum distance of 1.5 times the pile diameter from the top of the pile. For each hammer blow, electrical signals were fed into the programmed Pile Driving Analyser and the basic measurements of strain and acceleration were converted into force and velocity parameters as a function of time. From these parameters, the ultimate (mobilized) bearing capacities were automatically

computed. In addition, the maximum compressive and tensile forces, the developed energies and the hammer blow rate, etc., were output from the Analyser. The force and velocity wave traces were continually observed in the field on an oscilloscope and their analog signals were recorded on magnetic tapes by an FM instrumentation tape recorder.

After the dynamic monitoring was completed, one or two piles at each site were static load tested. The static load test was generally carried out in accordance with the ASTM D1143-81 procedures. The tests performed at Site B and Site C were carried out with the standard loading procedures of ASTM D1143-81. At Site A the quick load test option of the standard was used. The load on the pile was placed incrementally with a hydraulic jack to twice the design load or to failure. A load cell was used to monitor the load on the pile. In cases where the pile held twice the design load after standard loading procedures, the load was maintained for a period of 24 hours prior to unloading.

CASE HISTORIES

Site A

A single storey parking structure was constructed at a site located in North York, Ontario. The contractor proposed to use three different pile sizes to suit the various column loads in order to minimize the number of pile to be used. The contractor proposed a driving criteria for the various pile types, using a 35 kN drop hammer falling a distance of 1.2 to 1.5 metres.

The piles used at this site consisted of:

Pile Type	Pile Size O.D. mm	Wall Thickness mm	Design Load kN
Steel pipe	194	8.3	755
Steel pipe	244	8.9	1000
Steel pipe	298	8.5	1140

The soil at this site consisted of a fill of variable thickness overlying compact to very dense sand. The fill consisted of clayey silt, sand rubble and organics and extended to a depth of 10 to 11 metres. The wet sand extended to depths of 22 to 26 metres where the boreholes were terminated. All test piles were terminated in the sand. The soil conditions are shown on Borehole Log No. 1.

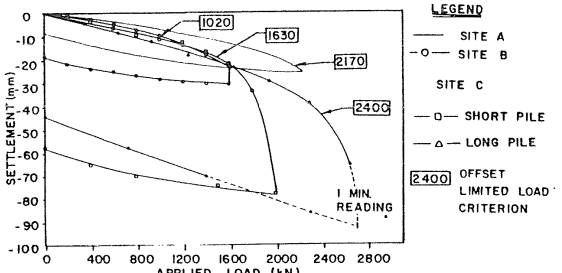
The dynamic results for the load test pile are presented in Table 1. The laboratory CAPWAP analysis results are shown in Table 2. The pile was driven to a final driving resistance of 19 blows per 25 mm under 54 kJ of driving energy. However, the pile top was slightly damaged when the blow count was taken. The following day, after the pile top was trimmed to sound steel, the pile was restruck and the penetration resistance was measured at 11 blows per 25 mm. An input energy of 75 kJ was used during the restrike.

The ultimate bearing capacity of the load test pile evaluated by the dynamic analysis was 2180 kN. The pile was statically load tested to a maximum load of 2240 kN. The load test was carried out in accordance with the quick load test option of the ASTM D1143-81 procedures. At the maximum load, the pile top settled a distance of 24.71 mm. The offset limit load criteria for this pile was reached at a load of 2170 kN. It appeared, from the load test curve, it is evident that the pile would plunge to failure if loaded beyond the maximum load of 2240 kN. The results of the load test for this site as well as Sites B and C are plotted in Figure 2.

Summary

Site A

In situations where different pile sizes are used, dynamic monitoring can be used to correlate the capacities of different pile sections once a correlation with at least one static load test is established. The static load test can be used to establish the soil damping factor for use in the Case Method Analysis. Provided the remaining piles are founded in similar soil, the capacity of the remaining piles can be evaluated with reasonable confidence. The ultimate bearing capacity prediction by CAPWAP analysis for the load test pile was within one percent of the static load test results.



APPLIED LOAD VS. SETTLEMENT

FIG. 2

Site B

A 1½ storey laboratory type building was constructed at a site in Mississauga, Ontario. The subsoil at this site consisted of flyash fill overlying a grey shale. The building was to be supported by steel piles driven through the fill and founded on or slightly into the shale bedrock. The fill depth ranged in thickness from 9 to 11 metres.

The piles were 244 mm O.D. with 12 mm wall thickness, close-ended steel pipes. The piles were driven with a Berminghammer B-300 single acting open-ended diesel hammer. The hammer has a rated energy of 46 kJ. The pile was easily driven through the fill and then the penetrating resistance increased abruptly to 10 blows per 8 mm or less on the shale bedrock. The design load for the piles carried a load of 500 kN or less.

At the early stages of the project, four piles were driven around the site so that a load test pile could be selected. During the restrike, however, it was apparent that relaxation of the shale bedrock had occurred (penetration resistance during restrike was less than that obtained at the end of the initial driving). The magnitude of the relaxation of the piles, however, varied from pile to pile, even after three to four restrikes. Dynamic monitoring was, therefore, suggested to evaluate the capacity of the piles under the relaxing conditions.

Based on the 10 piles tested dynamically upon restrike, the estimated ultimate bearing capacity ranged from 640 to 1015 kN. The penetration resistance of the piles upon restrike ranged from 3 to 8 blows per 25 mm whereas the piles were all driven to a final resistance of greater than an equivalent of 30 blows per 25 mm.

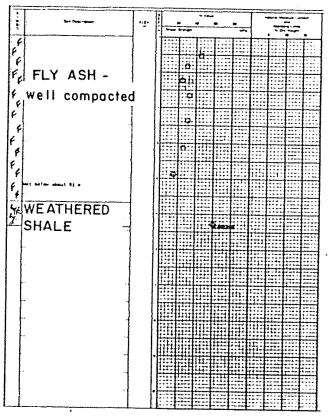


FIG. 1

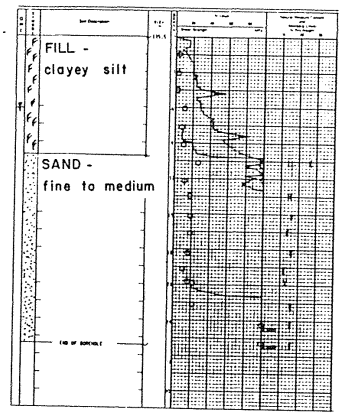


FIG. 3

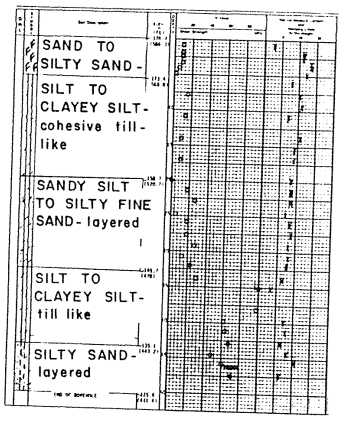


FIG. 4

The load test pile achieved an equivalent penetration resistance of 8 blows per 25 mm. Upon restrike, the ultimate bearing capacity as evaluated by CAPWAP analysis on the first hammer blow was 880 kN.

The static load test was carried out in accordance with the standard loading procedures of the ASTM D1143-81. A maximum load of 1600 kN, equal to twice the maximum design load, was jacked into the pile. The maximum load was held for a period of 24 hours. Under this load, the pile top had settled a distance of 30.65 mm. The net settlement of the pile top was 17.60 mm after the load was removed. During the loading, the pile did not achieve a settlement rate of 0.25 mm per hour or less beyond a load of 800 kN. It was apparent that there was creep taking place on the shale bedrock beyond this load. The Offset Limit Load criterion for this pile was reached at a load of 1020 kN.

Summary

Site B

In situations where there is relaxation, dynamic monitoring can be used to compare the ultimate bearing capacity of piles under different relaxation conditions. The capacity evaluated by the dynamic monitoring in this case was low by approximately 16 percent. This could be attributed to the fact that in pile relaxation conditions, each restrike may improve the capacity of the pile. Consequently, after the restrike, the ultimate bearing capacity of the load test pile, was higher when compared with the capacity evaluated from the dynamic testing.

Site C

A test program was undertaken at a site in Owen Sound, Ontario, to evaluate the allowable bearing capacity of piles founded at two slightly different soil strata. The soil at this site consisted of 4 to 5 metres of sandy fill overlying a thick stratum of clayey to sandy silt extending to a depth of 44 metres. The silt is generally compact with a very dense zone near 32 to 34 metres depth. Beneath this silt stratum is a very dense bouldery till.

The two test piles were 244 mm O.D. with 13.8 mm wall thickness, close-ended steel pipe piles. The piles were driven with a Berminghammer B-400 single acting diesel hammer, with a rated energy of 62 kJ. The two test piles were dynamically monitored to the end of the driving as well as during the restrike on the following day.

The long pile was driven to a depth of 46.96 metres where it achieved a penetration resistance of 20 blows per 25 mm. The short test pile was driven to a depth of 33.5 metres where a penetration resistance of 8 blows per 25 mm was achieved. During the restrike, the penetration resistance of the two test piles was measured to be at 40 and 14 blows per 25 mm for the long and short piles.

The ultimate bearing capacities of the two test piles as evaluated by CAPWAP analyses were 2375 and 1525 kN for the long and short piles respectively.

The static load test was carried out in accordance with the standard loading procedures of ASTM D1143-81. Both piles were load tested to a plunging failure. For the long pile, a maximum load of 2950 kN was jacked onto the pile. A maximum load of 2000 kN was jacked onto the short pile. The Offset Limit Load criterion was reached at 2400 kN for the long pile and 1630 kN for the short pile.

Summary
Site C

The ultimate bearing capacities of the two test piles were successfully evaluated by the dynamic testing method at this site. During the dynamic monitoring of the first pile, it was evident that the estimated ultimate bearing capacity of the pile at the higher level would be substantially less than the 2600 kN that the designer had hoped for. As a result, the pile was driven to the lower depth.

The results obtained from the dynamic analysis of the two test piles when compared with the static load test results were within 1 percent for the long pile and 7 percent for the short pile. The test program proved to be an advantageous exercise since the capacity of the short pile expected by the designer did not materialize. Had the production piling been carried out with the high design load significant redesigning and extra cost for the piling would have occurred. This would be not only costly to the owner but cause delay to the construction.

CONCLUSIONS

1. The ultimate bearing capacity of a driven pile can be evaluated accurately by dynamic method of analysis.

2. The results of Site C have shown that even when the penetration of the pile is less than 2 mm per blow, the ultimate bearing capacity of a pile can still be evaluated by dynamic analysis.

3. Dynamic analysis can be used in situations where different pile sizes carry different design loads. By performing a static load test on one pile size, the ultimate bearing capacity of the other pile sizes can be evaluated dynamically with a similar degree of confidence, (Site A).

4. In situations where there is relaxation, the ultimate bearing capacity of the piles can best be evaluated by the dynamic method of analysis for the various degrees of relaxation, (Site D).

5. Dynamic monitoring can be used to test many piles in one day, whereas the conventional method of load testing can obtain information for only one pile after a test period of 1 to 2 days.

6. The hammer performance and the driving stresses can be evaluated from dynamic testing. By comparing the developed energy and force in the pile, real or apparent relaxation can be differentiated.

Table 1
SUMMARY OF CAPWAP RESULTS

Pile	Event	Embed. Depth (m)	Permanent Toe Displacement Calc. (mm)	Permanent Toe Displacement Meas. (mm)	Quake (cm) Skin	Quake (cm) Toe	Damping Case Skin	Damping Case Toe	Damping Smith sec/m Skin	Damping Smith sec/m Toe	Ultimate Static Capacity (kN) Skin	Ultimate Static Capacity (kN) Toe	Ultimate Static Capacity (kN) Total	Remarks
SITE A	CAPWAP Analyses based on Pile Driven to Contractor's Criteria.													
A5	B.O.I.R.	19.20	3.3	1.0	.25	.92	0.370	0.178	.29	.08	402	1424	1826	
	CAPWAP Analysis After Redriving Piles													
A5	B.O.2.R.	20.0	0.9	2.2	0.53	0.83	0.234	0.450	0.078	0.115	948	1240	2183	
SITE B														
13	B.O.2.R.	9.13	5.1	3	.25	.50	.25	.40	.51	.22	79	701	880	
22	B.O.3.R.	9.1	3.3	9.0	.25	.55	.15	.25	.52	.16	105	627	732	
28	B.O.I.R.	9.1	5.1	7.0	.25	.65	.40	.57	.88	.26	144	673	817	
SITE C														
TP1	E.O.I.D.	46.9	0.69	1.27	3.50	3.50	0.730	0.500	0.271	0.291	1128	701	1819	Long pile
TP1	B.O.R.	46.9	0.00	0.63	3.2	3.2	1.005	0.400	0.245	0.293	1672	558	2230	Ultimate bearing capacity = 1672 + 701 = 2373 kN short pile
TP2	B.O.R.	33.5	2.31	1.81	2.50	2.50	0.669	0.575	0.246	0.317	788	739	1527	

Notes:
E.O.I.D. = End of Initial Driving
B.O.R. = Beginning of Restrike

TABLE 2
SUMMARY OF PILE DRIVING ANALYSER TEST RESULTS

Pile I.D.	Event	Emb. Depth (m)	Hammer Type	DRIVING RESISTANCE Measured blows per mm	DRIVING RESISTANCE Equivalent Blows per 25 mm	ENERGY Mean (kJ)	ENERGY Ratio %	FORCE Mean (kN)	FORCE Stress (MPa)	ULTIMATE CAPACITY Estimated (kN)	ULTIMATE CAPACITY CAPWAP	ULTIMATE CAPACITY Load Test	Remarks
SITE A													
A5	19.25	B.O.I.R.	35 kN x 1.5 m Drop	2/2	25	40	62	1470 (1800)	191 (233)	1840	1825		
	20.0	B.O.2.R.	49 kN x 1.5 m Drop	5/11	11	37	49	1360 (2010)	117 (261)	1985	2183	2170	
SITE B													
37	9.05	B.O.2.R.	B300	5.0	5.0	8.5	19	1130	165	1255	785		
23	9.35	B.O.I.R.	B300	8.0	3.1	11.7	25	1340	190	1020	640		
13*	9.15	B.O.2.R.	B300	3.0	8.3	9.1	20	1490	165	1430	880	1020	
16	9.10	B.O.I.R.	B300	7.0	3.6	11.7	25	1290	180	1360	1015		
SITE C													
TP1	49.96 (154)	B.O.R.	B400	40/25	40	20.7	33	1910	192	2565	2373	2400	Long pile.
TP2	33.53 (110)	B.O.R.	B400	7/13	14	18.1	29	1770	178	2445	1527	1630	Short shallow pile.

Notes:
E.O.I.D. = End of Initial Driving
B.O.R. = Beginning of Restrike
* Load Test failure load defined by Off-set Limit Load Criterion (Davisson) = $\frac{4}{120}$(4+8D) x 10^{-3}, where = elastic deformation of pile, D = pile diameter.

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