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Dynamic Testing Versus Static Load Tests: Five Case Histories

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SYNOPSIS: Five case histories, where the ultimate bearing capacity of the piles was evaluated by both dynamic measurements and static load tests in Southern Ontario, Canada, are presented. The ultimate bearing capacity of the piles obtained by both methods are compared and found that the ultimate bearing capacities evaluated by dynamic measurements are within 1 to 15 percent of the static load test results analysed by the Offset Limit Load Criterion. In four of the six piles evaluated, the dynamic analysis results are within 10 percent of the static load test results. The correlations have shown that dynamic analysis of pile capacity by dynamic measurements is an excellent alternative to static load test.

INTRODUCTION

Since pile driving causes failure of the soil, it is therefore logical to use dynamic measurements made during pile driving to estimate the ultimate bearing capacity of the pile. The use of dynamic measurements to predict pile capacity was put in use in the early 1970's, and since then the use of dynamic measurements to predict pile capacity has been gaining wide acceptance by practicing civil engineers. In the field, the ultimate static bearing capacity of the piles was evaluated from the strain and acceleration measurements by the case method. The ultimate static bearing capacity was also estimated in the laboratory by the CAPWAP analysis. In the CAPWAP analysis, the hammer-pile-soil, and resistance distribution on a pile was modeled and compared with the strain and acceleration measurements obtained in the field.

Ontario is a province located in the mid-eastern portion of Canada. The southern part of Ontario has close to 80 percent of the population of Ontario. The area was covered by ice sheets a million years ago and the subsoil generally consists of glacial tills. The glacial tills are generally competent to support a building by the conventional type of shallow foundation. However, there are areas with deep deposits of fill, softer clay, loose silt or sand, where deep foundations are required. In these instances, driven piles or augered in-place caissons are used to support the proposed structures.

The estimation of the ultimate static 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 used various kinds of dynamic formulae to estimate the ultimate bearing capacity of piles when the driving system, pile type and size are known. When E.A.L. Smith (1) introduced wave propagation 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 and various instruments for the measurements of strain and acceleration during pile driving, the dynamic monitoring of piles was put into use in the early 70's. This paper presents the results of the dynamic analysis of piles at five sites where static load tests were also undertaken.

THEORETICAL BASIS

The dynamic evaluation of pile capacity using Smith's wave propagation theory has been reported by Rausche, Goble and Likins (1975). In 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 obtained once the pile material and cross sectional area is known. From the acceleration measurement, the velocity of the pile being driven into the ground can be integrated. 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
L	=	Length of Pile
V1	=	Velocity at Impact
V2	=	Velocity at Time $2L/C$
J	=	Damping

The ultimate static bearing capacity of the pile can also be evaluated by another method in the laboratory called CAPWAP analysis. In this analysis, the measured force at the pile top is used as input into the program. Values for the soil parameters, resistance distribution on each pile elements are assumed and a dynamic analysis is performed to obtain the required force at the point of measurement to generate the imposed acceleration. The various parameters are changed in an effort to match the computed top force to the measured top force as close as possible. When the computed top force is matched to the measured top force, the field condition is simulated and the ultimate static bearing capacity of the pile can be obtained.

TEST METHOD

The dynamic measurements were carried out by using two sets of gauges and a portable computer called a Pile Driving Analyser. The gauges consisted of:

The instrumentation for the Pile Driving Analyser was attached near the top of the pile. This consisted of two reusable strain gauges and two accelerometers securely bolted near the top of the pile. For each hammer blow, electrical signals were fed into the preprogrammed 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 forces, the developed energies and the hammer blow rate, etc., are some of the output from the Analyser. The force and velocity wave traces were continually observed in the field and

their analog signals were recorded on magnetic tape by an FM instrumentation tape recorder.

After the dynamic measurements were completed, the piles were subjected to static load test. The static load test was generally carried out in accordance with the ASTM D1143-81 procedures. With the exception of Site A and Site E, all tests were carried out with the standard loading procedures of the ASTM D-1143-81 standard. At Site A and E, the quick load test option outlined in the ASTM procedures 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 in addition to the pressure gauge to monitor the load imposed on the pile. In cases where the pile held twice the design load, the load was maintained for a period of 24 hours prior to unloading.

SITE A

A single storey parking structure was constructed at a site located in North York, Ontario. The contractor elected to use three different pile sizes to suit the various column loads in order to minimize the number of piles 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 m to drive the three types of piles.

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	55
Steel Pipe	244	8.9	1000
Steel Pipe	298	8.5	1140

The subsoil at this site consisted of a fill of variable thickness overlying a compact to very dense sand. The fill consisted of clayey silt, sand, rubble and organics and extended to a depth of 10 to 11 m depth. The wet sand extended to a depth of 22 to 26 m where the boreholes were terminated. All test piles were terminated in the sand. The soil conditions are shown in Figure 1, Borehole Log A.

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 counts were 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 restruck.

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 D-1143-81 procedures. At the maximum load, the pile top settled a distance of 24.71 mm. The offset limit load criterion for this pile was reached at a load of 2170 kN. It appeared, from the load test curve, that the pile would plunge to failure beyond the maximum load of 2240 kN. The results of the load test for the pile at this site are plotted in Figure 2.

SUMMARY OF RESULTS FOR CASE 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 result can be used to establish the soil damping factor to be used in the case method analysis. Provided that the remaining piles are founded in similar soil, the capacity of the remaining piles can be evaluated with reasonable confidence. The ultimate bearing

capacity evaluated by CAPWAP analysis to the Offset Limit Load Criterion (Davisson) was within one percent.

Figure 1

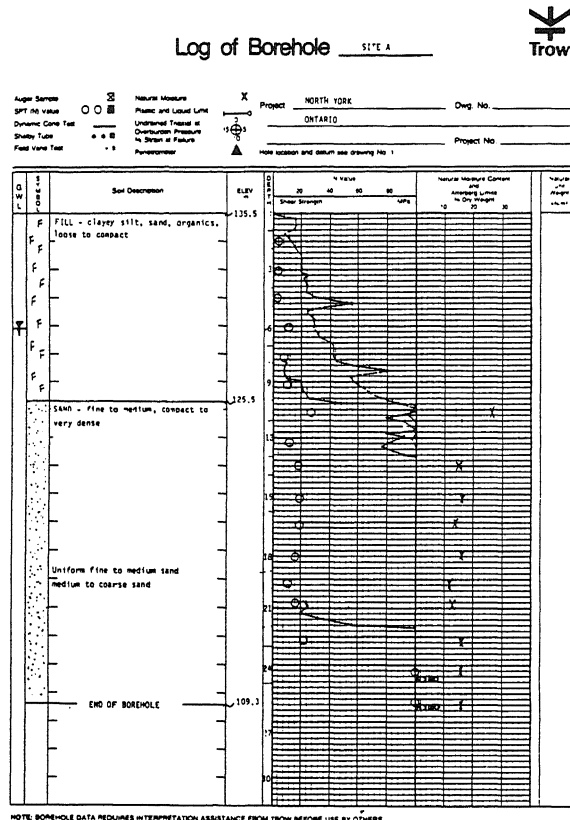


Table 1

TABLE 1 - SUMMARY OF PILE DRIVING ANALYSER TEST RESULTS											
Pile I.D.	Event	Emb. Depth (m)	Hammer	DRIVING RESISTANCE		ENERGY		FORCE		ULTIMATE CAPACITY (kN)	
				Measured blows per 25 mm	Equivalent Blows per 25 mm	Mean (kJ)	Ratio %	Impact (Max.) (kJ)	Max. Stress (MPa)	Case Method	CAPWAP Load* Test
SITE A											
A5	B.O.1.R.	19.25	35 kN at 1.5 m Drop	2/2	25	40	62	1470 (1800)	191 (233)	1840	1825
	B.O.2.R.	20.0	49 kN at 1.5 m Drop	5/11	11	37	49	1360 (2010)	177 (261)	1985	2183 2170
SITE B											
37	B.O.2.R.	9.05	B300	5.0	5.0	8.5	19	1130	165	1260	785
23	B.O.1.R.	9.35	B300	8.0	1.1	11.7	25	1340	190	900	640
13*	B.O.2.R.	9.15	B300	3.0	8.3	9.1	20	1490	165	1175	880 1020
16	B.O.1.R.	9.10	B300	7.0	3.6	11.7	25	1290	180	1045	1015
SITE C											
TP1	B.O.R.	49.96	B400	40/25	40	20.7	33	1910	192	2300	2375 2400
TP2	B.O.R.	33.33	B400	7/13	14	18.1	29	1770	178	1685	1527 1630
SITE D											
24	E.O.1.D	11.75	D12	15/25	15	10.5	34	870 (1130)	235	815	
	B.O.R.	11.75	D12	10/5	50	7.4	24	980 (980)	210	990	921 1080
SITE E											
C-60	B.O.R.	16.45	D30-13	05/12.5	10	42.6	47	1985	211	2840	2710 2935

Notes:
 B.O.I.R. = Beginning of first and second restruck.
 Beginning of restruck results based on the first good blow with substantial penetration.
 E.O.1.D. = End of Initial Driving
 B.O.R. = Beginning of Restruck
 * Load Test failure load defined by Off-set Limit Load Criterion (Davisson) = $(1 + \delta D) \times 10^{-3}$, where δ = elastic deformation of pile, D = pile diameter.

Table 2

TABLE 2 - SUMMARY OF CAPWAP RESULTS

Pile	Event	Embed, Depth (m)	Permanent Toe Displacement		Quake		Damping				Ultimate Static Capacity		
			Calc. (mm)	Meas. (mm)	(mm)		Case		Smith sec/m		(kN)		
					Skin	Toe	Skin	Toe	Skin	Toe	Side	Tip	Total
SITE A													
A3	B.O.I.R.	20.0	0.9	2.2	0.55	0.83	0.234	0.450	0.078	0.115	944	1240	2183
SITE B													
13	B.O.I.R.	9.1	5.1	3	2.5	5.0	0.25	0.40	0.31	0.22	79	701	880
22	B.O.I.R.	9.1	5.3	9.0	2.5	5.5	0.15	0.23	0.32	0.16	103	677	732
28	B.O.I.R.	9.1	5.1	7.0	2.5	6.5	0.14	0.37	0.38	0.26	144	673	817
SITE C													
TP1	E.O.I.D.	46.9	0.69	1.27	3.50	3.50	0.750	0.500	0.271	0.291	1128	701	1819
TP1	B.O.R.	46.9	0.00	0.63	3.2	3.2	1.005	0.400	0.243	0.293	1672	558	2230
TP2	B.O.R.	33.5	2.31	1.81	2.50	2.50	0.669	0.573	0.246	0.317	788	739	1527
SITE D													
24	B.O.R.	11.75	0.15	0.50	3.0	4.5	0.117	0.700	0.2351	0.370	549	372	921
SITE E													
C-60	B.O.R.	16.45	1.12	2.3	7.0	9.0	0.800	0.355	0.163	0.158	1856	852	2710

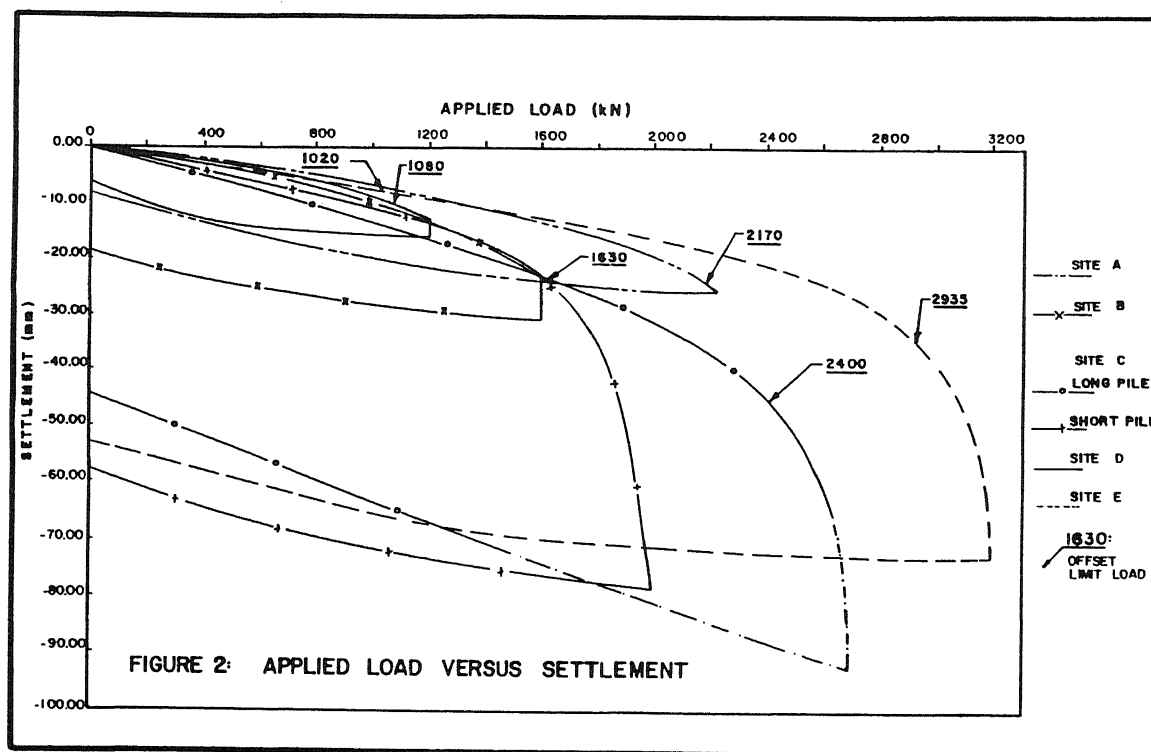
Notes:
E.O.I.D. = End of Initial Driving
B.O.R. = Beginning of Restrike

the fill and the penetration resistance increased abruptly to 10 blows per 8 mm or less on or slightly into the shale bedrock. The maximum design load for the piles was 800 kN with majority of 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 (a decrease in bearing capacity between the end of driving and restrike) of the piles on the shale bedrock occurred. 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 relaxation conditions.

Based on the 10 piles dynamically tested during restriking, the estimated ultimate bearing capacity ranged from 640 to 1015 kN. The penetration resistance of the piles upon restriking 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.

Figure 2



SITE B

A 1 1/2 storey industrial type building was constructed at a site in Mississauga, Ontario. The subsoil at this site consisted of flyash fill overlying a Georgian Bay shale. The building was to be supported by steel pipe driven through the fill and founded on or slightly into the shale bedrock. The fill depth ranged in thickness from 9 to 11 m in thickness. The soil conditions are presented in Figure 3, Borehole Log B.

The piles were 244 mm O.D. with 12 mm wall thickness closed-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 driven easily through

The load test pile achieved an equivalent penetration resistance of 8 blows per 25 mm. Upon restriking, 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 D-1143-81 standard. A maximum load of 1600 kN, equal to twice the maximum design load, was jacked onto 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. The Davisson criterion for this pile was reached at a load of 1020 kN.

Figure 3

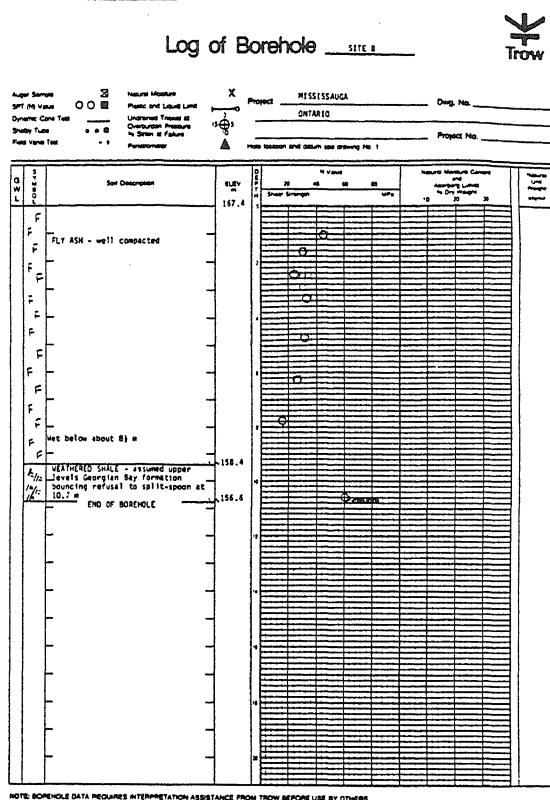
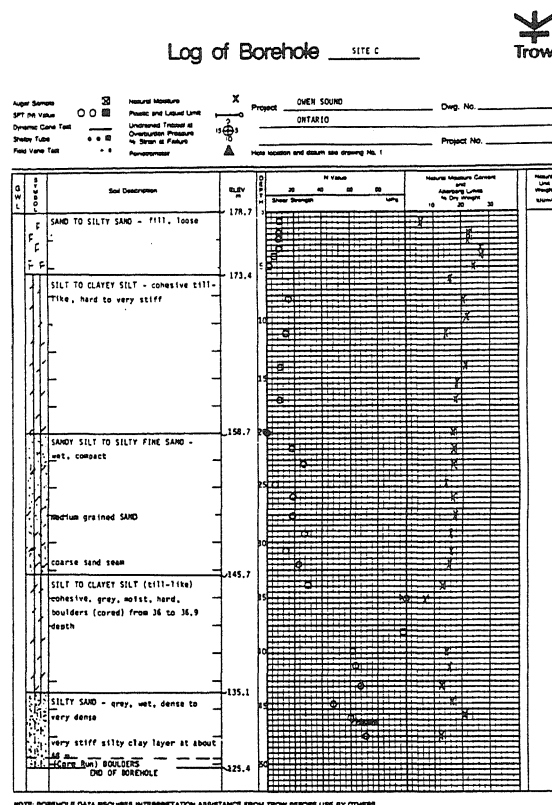


Figure 4



SUMMARY OF RESULTS FOR CASE 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 14 percent. This could be attributed to the fact that in pile relaxation conditions, each restrike may improve the capacity of the pile. Consequently, the capacity of the pile evaluated from the dynamic analysis was low when compared with the load test result.

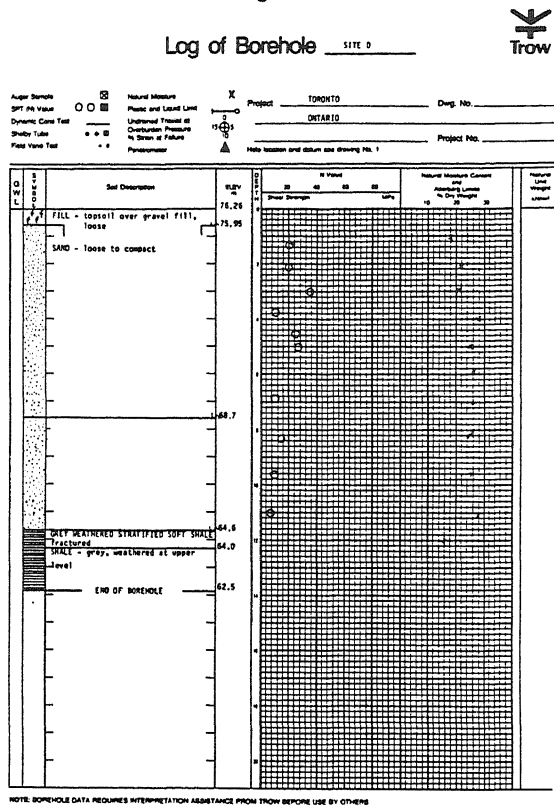
SITE C

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

The two test piles were 2

11 to 12 metres of hydraulic fill overlying shale bedrock. The hydraulic fill consisted of loose to dense fine to medium sand. The subsoil conditions are presented in Figure 5, Borehole Log D.

Figure 5



The piles consisted of 324 mm O.D. with 4.8 mm wall thickness, closed-ended steel pipe piles. The piles were to be driven to the shale bedrock to carry a design load of 600 kN. The shale bedrock in this area is known to have relaxation problems for small diameter pipe piles and H-piles. (Thompson and Thompson, 1985; Likins and Hussein, 1984). Initially, the contractor used a MKT 9B3 air hammer to drive the piles. However, the hammer proved to be too small for the 324 mm piles and the subsoil condition at this site as the penetration resistance was in excess of 50 blows per 25 mm at shallow depths. Subsequently, a Delmag D-12 single acting diesel hammer was used to drive the piles. A total of seven piles were monitored at this site; a group of four piles, a group of two piles and a single pile.

Based on the dynamic test on CAPWAP Analysis results, presented in Table 1 and 2, the single pile was selected for static load test. This pile was found to have the lowest ultimate bearing capacity, primarily due to the fact that the shaft resistance was lower for the single pile, as the sand did not densify from the pile driving in the same magnitude as the pile groups. The final penetration resistance for this pile at the end of driving was 15 blows per 25 mm. Upon restriking, the penetration resistance increased to an equivalent of 50 blows per 25 mm. The ultimate bearing capacity estimated by the dynamic analysis for this pile was 920 kN. The Offset Limit Load criterion was met at a load of 1080 kN. Comparatively, the result was 15 percent low. The static load test curve is shown in Figure 2.

SUMMARY OF RESULTS FOR CASE D

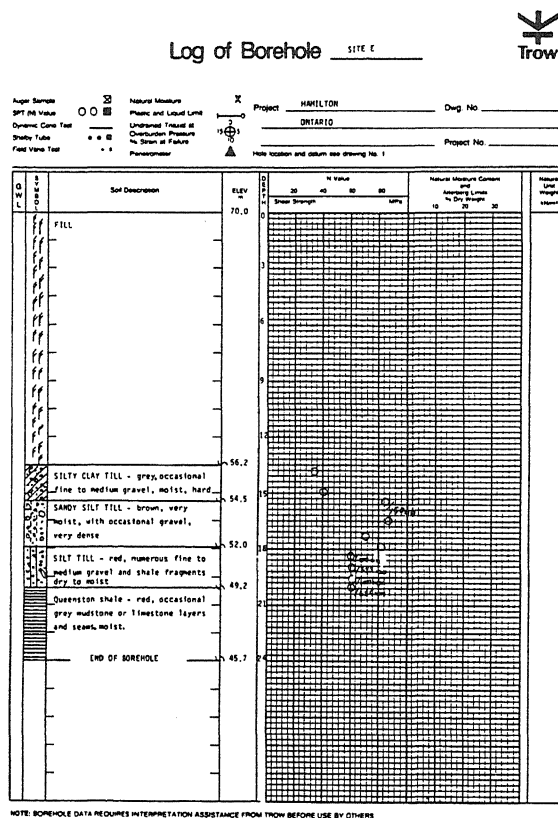
The ultimate bearing capacity of the pile predicted by the dynamic analysis was expected to be low in this situation. The main reason for the low capacity was the fact that the pile did not move under the hammer blows; i.e., very high penetration resistance. Similar to a static load test where the failure loads was not jacked into a pile, the ultimate bearing capacity of a pile could not be assessed in such cases. Another point of interest at this site was that relaxation was not experienced by the 324 mm diameter pipe piles driven to the shale bedrock. This could be an indication that relaxation of piles on shale bedrock is localized and that relaxation problems for layer diameter pipe piles are either non-existent or not as severe as small diameter pipe piles.

SITE E

A major steel plant was expanding the steel making facilities in Hamilton, Ontario. More than 5000 piles were required to support the proposed structure. Up to six pile drivers were used at the site at any one day and some pile drivers were working double shifts in order to increase the piling production. The quality control for the piling included inspection of piles, static load tests and periodic dynamic testing of randomly selected piles.

The subsoil at the site consisted of 13 metres of fill overlying a layer of very stiff to hard silty clay and very dense sandy silt till to a depth of 18 metres. The piles were terminated in a very dense silt till below 18 metres. The subsoil conditions are summarized in Figure 6, Borehole Log E.

Figure 6



The piles installed at this site were 324 mm O.D. with 9.5 mm wall thickness closed-ended pipe piles designed for an allowable load of 1780 kN. The piles were driven to the founding level with three Delmag D30-13 or D30-23 single acting diesel

hammers. The ultimate bearing capacity of the piles was confirmed in a test program consisting of dynamic testing and static load test prior to the production piling. A second static load test was also carried out at the beginning of the production piling to confirm the ultimate bearing capacity of the piles. From the test program, it was established that the piles would have to be driven to refusal (20 blows per 25 mm), in the silt till stratum with a minimum developed stress level during the final driving of 230 MPa.

During a routine dynamic testing on some randomly selected piles, the penetration resistance of some of the piles was found to be less than the specified 20 blows per 25 mm upon restriking. The evaluated capacity of the piles was also less than the average experienced at this site. More dynamic testing was therefore carried out and the results indicated that the Delmag D30 hammers were pre-igniting during installation of the piles and consequently a false penetration resistance was observed. A static load test was requested by the owner on a pile driven with a pre-igniting hammer in order to confirm the findings in the dynamic testing.

The result of the dynamic testing are presented in Table 1. The corresponding CAPWAP analysis of the load test pile is shown in Table 2. The static load test curve is shown in Figure 2. The estimated ultimate bearing capacity of the piles based on the dynamic analysis was 2715 kN. The Offset Limit Load Criterion for the pile was met at 2935 kN. The ultimate bearing capacity of the piles evaluated by dynamic analysis was 7 percent low.

SUMMARY OF RESULTS FOR CASE E

The static load test of the pile at this site confirmed that under pre-igniting conditions of a diesel hammer, the ultimate bearing capacity of the pile was significantly reduced. From a routine visual inspection point of view, there was nothing unusual about the pile since the specified piston rise and the penetration resistance was met for all the pile driven with the pre-igniting hammer. Dynamic measurement, however, revealed the pre-ignition and found that the energy and force delivered to the pile was considerably reduced, primarily due to the cushioning effect on the piston due to the fuel was pre-igniting in the combustion chamber.

The ultimate bearing capacity estimated by the dynamic analysis was found to be 7 percent lower than the Offset Limit Load Criterion. However, in this case, the Offset Limit Load Criterion was not conservative as the pile plunged to failure shortly after this load. The information obtained at this site further reinforced the need for dynamic testing so that the hammer performance could be evaluated.

CONCLUSIONS

The dynamic testing and the static load test at the five sites resulted in the following conclusions:

1. Dynamic testing is an excellent alternative for estimating the ultimate bearing capacity of a driven pile.
2. In order to evaluate the ultimate bearing capacity of a driven pile by dynamic method, the hammer blow analysed must produce a permanent displacement of the pile into the soil in the order of 2 mm per blow. If the permanent displacement due to the hammer blow is

low, dynamic analysis would under-estimate the ultimate bearing capacity of the pile unless further analyses were made.

3. Dynamic analysis can be utilized in situations where different pile sizes were used to carry different design load. 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.
4. In situations where there is relaxation, the ultimate bearing capacity of the piles can best be evaluated by dynamic method of analysis for the various degree of relaxation.
5. Dynamic testing can be used to evaluate hammer performance and to identify problem hammers.
6. Dynamic testing can be used to test many piles in one day, whereas the conventional method of static load test can obtain information for only one pile after a test period of 1 to 2 days.
7. By monitoring the piles for the end of initial driving and restriking, real or apparent relaxation can be differentiated.
8. Relaxation of pipe piles on shale bedrock tends to be localized and may be dependent on the pile diameter.

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