Fellenius, B.H., 1990. Is capacity fully mobilized?
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Static or Dynamic Test - Which To Trust?

On a recent piling project in Ottawa involving the driving of a total of about 250 piles, routine dynamic monitoring was carried out for the purpose of determining hammer performance and pile capacity. The piles consisted of closed-toe, 244 mm (9.625 inch) diameter, steel pipes with 13,8 mm (0.545 inch) wall and minimum 360 MPa (52 ksi) yield to be filled with 35 MPa (5,000 psi) concrete. The design load was 1,100 KN (124 ton). The pile driving hammer was a Delmag D30-32 diesel hammer. This hammer has a ram weight of 29 KN (6,600 lb) and a maximum ram travel of 3.3 m (11 ft), which translates to a maximum nominal energy of 98 KJ (73 ft-kips). The hammer was used at a reduced energy setting, yielding a nominal energy stated to be 70 KJ (52 ft-kips).

The pile driving helmet was originally intended for a larger size pile. To accommodate the smaller pile for the project, a loose helmet insert was used that wobbled and bounced for every blow. The insert, coupled with that the contractor appeared to have difficulty in holding the energy setting on the hammer, caused considerable variation of the transferred energy and impact stress, and, of the penetration of the pile per blow. It therefore became difficult to apply a blow-count termination criterion to the piling work.

The soils at the site consisted of an upper, about 11 m (36 ft) thick clay layer underlain by an about 5 m (16 ft) thick silty sand layer changing into sandy glacial till. Bedrock lies at a depth of about 30 m (100 ft). Of the total of about 250 piles driven within the about 40 m by 60 m (130 ft by 200 ft) site, about 10 percent did not reach the till and terminated with the pile toe in the sand layer at a pile embedment length of 15 m (50 ft). About 60 percent terminated at a penetration smaller than about 5 m (15 ft) into the till and about 5 percent of the piles penetrated deeper than 10 m into the till. Dynamic monitoring at the site was made on three separate occasions and included the testing of one pile at end-of-initial-driving (EOID) and eight piles at restriking (RSTR) conditions. The field data were processed and the results compiled as to transferred energy, impact stress, and Case-Method-Estimate (CMES) of capacity according to routine procedures. Four CAPWAP analyses were performed.

In processing the measurements, values of transferred energy were obtained within the wide range of 25 KJ (18 ft-kip) through 62 KJ (46 ft-kip). The impact stresses varied from 200 MPa (29 ksi) through 275 MPa (40 ksi).

CAPWAP analysis was performed on a test pile denoted Pile 62 that was driven about 4 m (13 ft) into the till and to an embedment depth of 19 m (62 ft) at end-of-initial-driving (EOID). The driving terminated a penetration resistance (PRES) of 6 blows/25 mm. The observed transferred energy at EOID was 37 KJ (27 ft-kip) and the impact stress was 240 MPa (35 ksi). A CAPWAP analysis indicated a capacity of 2,320 KN (260 ton) which "calibrated" the damping factor (J) for CMES (RMAX) EOID-capacity to 0.6. The computed CAPWAP shaft and toe resistances were 870 KN (100 ton) and 1,450 KN (160 ton), respectively.

Pile 62 was monitored also during a restrike (RSTR) fifteen days after the initial driving. The observed transferred energy was 30 KJ (22 ft-kip) and the impact stress was 220 MPa (32 ksi), which values are about similar to those observed at EOID. The corresponding pile penetration, PRES, was 18 blows/25 mm. The CMES capacity (RMAX with a J of 0.2) was indicated to 2,220 KN (250 ton), an obviously "underpredicted" value, and, therefore, no CAPWAP analysis was performed.

Figures 1 and 2 present the wave traced obtained at EOID and BOR, respectively for Pile 62. Notice that the traces indicate that the pile has met with considerable resistance at the pile toe.

CAPWAP analysis was performed also on blow data from a second test pile denoted Pile 167 that was driven to an embedment dept of 21 m (69 ft) and terminated at an EOID PRES of 14 blows/25 mm. No dynamic measurements were taken at the end of the initial driving. However, the pile was monitored during a restrike 4 days after the initial driving. The penetration resistance at restrike was 6 blows/25 mm. The observed transferred energy was 35 KJ (26 ft-kip) and the impact stress was 220 MPa (32 ksi). Wave traces from a restrike blow are presented in Figure 3. Notice that the traces indicate that considerable toe resistance was mobilized in the blow. CAPWAP analysis of the restrike blow indicated a capacity of 2,130 KN (240 ton) which "calibrates" the damping factor (J) for CMES (RMAX) capacity to 0.1. The CAPWAP computed shaft and toe resistances were 540 KN (60 ton) and 1,580 KN (180 ton), respectively.

To verify the dynamic testing results, 12 days after the restrike measurements on Pile 167, the pile was subjected to a static loading test. The test was a quick test with the load increased by a small increment every 10 minutes. Reaction was obtained by two anchors drilled and grouted into the bedrock. The anchors were inserted through casings that were wash drilled through the soil. The applied load was measured by means of a separate strain gage load cell.

Figure 4 presents the results in the form of a load-movement diagram showing that the pile started to fail at the applied load of 1,200 KN (135 ton) and full plunging failure occurred at 1,300 KN (150 ton)!

Needless to say, the low capacity determined in the static test created some consternation for the engineers, and, naturally, the discrepancy between the CAPWAP results and the static test would have provided dynamic hearts of lesser fortitude with some jolts of worry. The correctness of the loads applied in the test were of course questioned, but as a load cell had been used, the load values were considered true. (The importance of using a load cell for determining the load applied to the pile head is illustrated in Figure 5 showing the difference between load measured by the load cell and the load calculated from readings of the jack-pressure gage).

There was a large amount of sand on the ground surface near the test pile. The sand provided footing conditions for the crew performing the static test that were superior to those of the wet clay surface covering the rest of the site. However, the sand had not been brought in to facilitate the testing. It came from below when the anchor casings were installed. It was clear that the loss of sand during the anchor installation had reduced the density of the sand and till in the vicinity of the lower portion of Pile 167 as well as below the toe of the pile.

Pile 167 was restruck with dynamic measurements three days after the static test to a PRES of 2 blows/25 mm. The observed transferred energy was 34 KJ (25 ft-kip) and the impact stress was 220 MPa (32 ksi). The wave traces are presented in Figure 6. Notice that the traces show only little indication of toe resistance.

CAPWAP analysis on the restrike blow indicated a capacity of 1,320 KN (148 ton) which value is in excellent agreement with the capacity determined in the static loading test. The CAPWAP shaft and toe resistances were 610 KN and 710 KN, respectively. The shaft resistance value is close to the one computed for the restrike blow before the anchors were drilled, but the toe resistance value has reduced to less than half of the earlier one.

In re-driving Pile 167, no significant resistance was encountered until the pile reached a depth of 30 m (100 ft), where the driving was terminated at a PRES of 12 blows/25 mm.

To replace the failed static test on Pile 167, Pile 62 was subjected to a static loading test. The test was carried out 13 days after the previous restrike and 28 days after EOID. The toe movement was recorded by means of a telltale to the pile toe.

Figure 7 presents the results in the load-movement diagram showing that just before the maximum load of 2,380 KN (267 ton), the pile head started to move progressively. Full failure was not reached, but appears to be close at hand, probably no larger than

TABLE I RESULTS FROM DYNAMIC TESTING AND CAPWAP ANALYSIS

BLOW No.	DPTH (m)	EMAX (KJ)	FMAX (KN)	FIMP (KN)	SIMP (MPa)	CMES (KN)	J (--)	CPWP (KN)	PRES (Bl/25 mm)
Pile 62 (Test pile)									
EOID	19	37	2370	2370	235	2310	0.6	2320	6
BOR	19	30	2230	2230	220	2220	0.2	--	18
Pile 167 (Test pile)									
BOR1	21	35	2210	2200	220	2080	0.1	2130	6
BOR2	21	34	2220	2210	220	1420	0.6	1320	2
EOR	30	41	2150	2150	215	2240	0.2	--	12
Pile 251									
BOR	22	49	2530	2520	250	2660	0.3	2680	10

DPTH = Embedment depth
EMAX = Maximum value of the energy transferred into the pile
FMAX = Maximum measured compression
FIMP = Impact force
SIMP = Impact stress
CMES = Maximum Case Method Estimate (RMX)
CPWP = Capacity calculated by CAPWAP analysis
PRES = Penetration resistance

Pile 62, BOR: Blow measured before preparing for static test

Pile 167, BOR1: Blow measured before preparing for static test
Pile 167, BOR2: Blow measured after completion of static test

UNIPILE, VERSION 1.0

PILE CAPACITY ANALYSIS

Project No: 1990 CLEVELAND USERS DAY
Project ID: Pile 62
Pile Type: 9.625 inch pipe

Pile Circumferential Area, A_s: 0.770 m^2/m
Pile Cross Section Area, A_t: 0.047 m^2
Toe Coefficient, N_t: 200

Hydrostatically distributed groundwater table at Depth 1.0 m

Live Load, Q_l:	550 KN	Shaft Resistance, R_s =	810 KN
Dead Load, Q_d:	550 KN	Toe Resistance, R_t =	1,735 KN
Total Load, Q_u:	1,100 KN	Total Resistance, R_u =	2,545 KN

Factor of Safety = 2.31

Neutral Plane located at the Pile Toe

DEPTH (m)	TOTAL STRESS (KPa)	PORE PRES. (KPa)	EFF. STRESS (KPa)	INCR. R_s (KN)	Q_d+R_s (KN)	R_u-R_s (KN)
LAYER 1	Clay: 1800 kg/m^3			β = 0.40	c'$_t$ = 0	c'$_b$ = 0
0.00	0.00	0.00	0.00		550	2545
1.00	18.00	0.00	18.00	3	553	2542
11.00	198.00	100.00	98.00	178	731	2364
LAYER 2	Silty Sand: 2000 kg/m^3		β = 0.60		c'$_t$ = 0	c'$_b$ = 0
11.00	198.00	100.00	98.00		731	2364
16.00	298.00	150.00	148.00	284	1015	2080
LAYER 3	Sandy Till: 2200 kg/m^3		β = 0.90		c'$_t$ = 0	c'$_b$ = 0
16.00	298.00	150.00	148.00		1015	2080
19.00	364.00	180.00	184.00	345	1360	1735
PILE TOE						

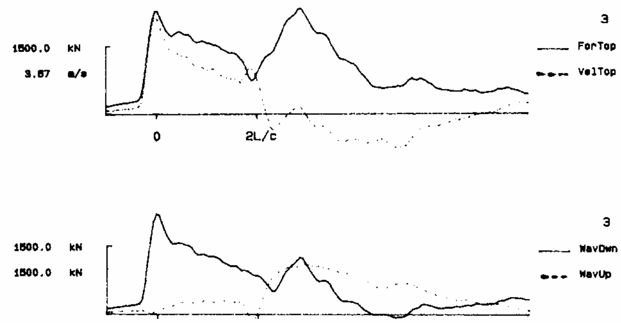

Figure 1 Wave traces from Pile 62 at EOID

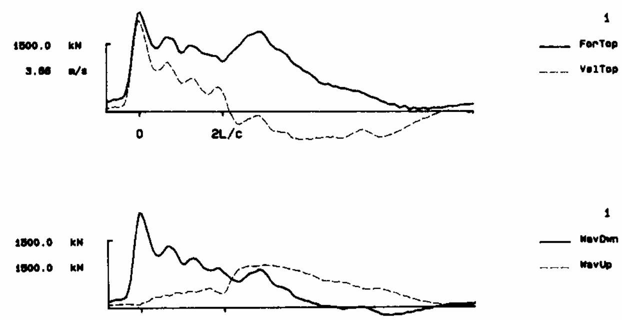

Figure 2 Wave traces from Pile 62 at BOR

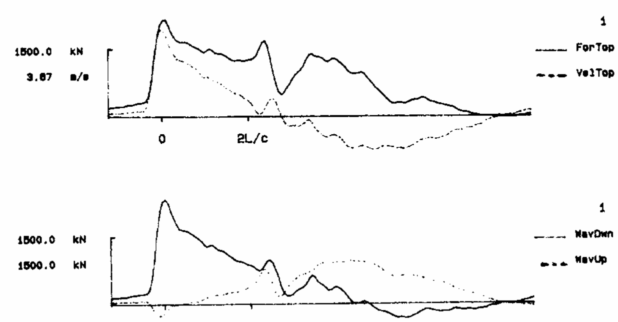

Figure 3 Wave traces from Pile 167 at RSTR

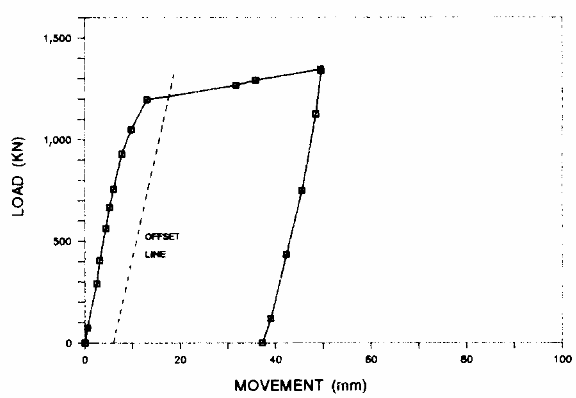

Figure 4 Load-movement diagram from Pile 167 static loading test

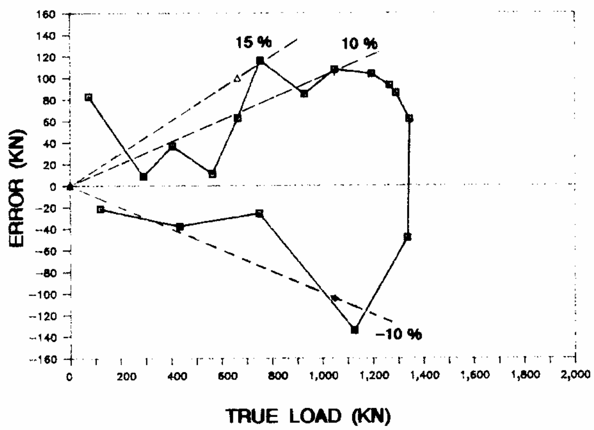

Figure 5 Error in applied load when determined from pressure in jack

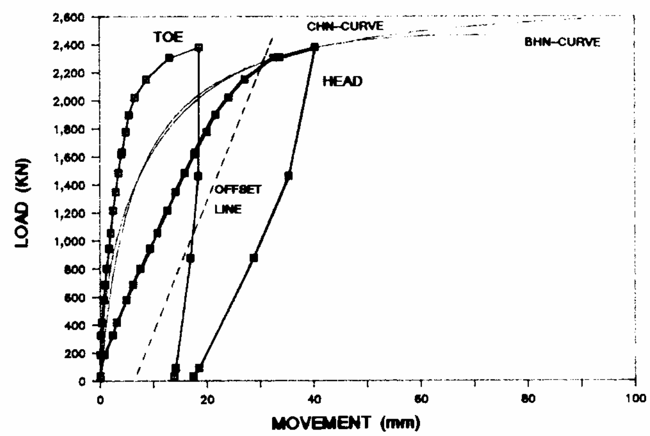

Figure 7 Load-movement diagram from Pile 62 static loading test

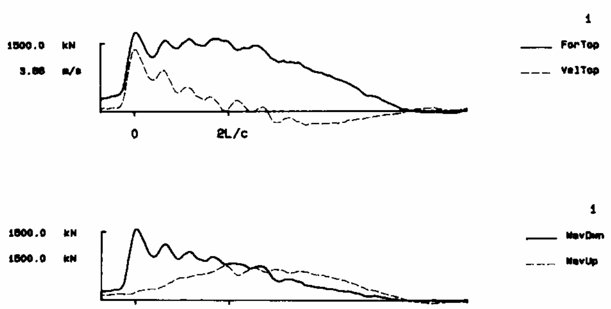

Figure 6 Wave traces from Pile 167 at RSTR

about 2,500 KN (280 ton).

The results have been analyzed by means of the FAILPILE program and showing the Davisson Offset-Limit Load of 2,220 KN, the Brinch-Hansen Failure Load of 2,470 KN (280 ton) (not reached in the test), and the Chin Extrapolation Load of 2,770 KN (310 ton). The Brinch-Hansen and Chin values were computed from the last three load values. The load-movement diagram in Figure 7 has been supplemented with the Chin and Brinch-Hansen curves, that is, curves that demonstrate how closely the data match the theoretical curves used for determining the Brinch-Hansen and Chin values.

As mentioned, dynamic testing of the Pile 62 at EOID had indicated a capacity of 2,320 KN (260 ton). Dynamic testing at RSTR had indicated a capacity larger than 2,220 KN (250 ton) as an underpredicted value (the hammer could not move the pile; PRES equal to 18 blows/25 mm).

Table I summarizes the dynamic measurements of Piles 62 and 167 and includes also records and CAPWAP capacity computed on a blow from a third test pile, Pile 251, monitored at a PRES of 10 blows/25 mm. (The data from the other five piles monitored at the site are not included). The Pile 251 CAPWAP computed capacity is 2,680 KN (300 tons) and the CMES (RMAX) capacity for a J-factor of 0.3 is 2,660 KN (300 ton). These values are similar to the static capacity determined for Pile 62, which again verifies the relevance of the dynamic testing method.

To calculate an upper bound value of the shaft resistance acting on Pile 62, an effective stress analysis was performed using the UNIPILE program and beta-factors in the clay, sand, and till of 0.4, 0.6, and 0.9, respectively. The calculation indicated a shaft resistance equal to 800 KN (90 ton). To obtain a total capacity of about 2,500 KN requires a toe resistance of about 1,700 KN (190 ton), that is, a toe bearing coefficient, N_t, equal to 200. These calculations confirm that in order to achieve a pile capacity of 2,500 KN (280 ton), the piles must be driven so that toe resistance dominates.

Summary

Dynamic monitoring of nine-inch pipe piles driven closed-toe into a deposit of clay underlain by silty sand changing into sandy glacial till. Bedrock lies at a depth of about 30 m (100 ft).

Values of transferred energy were obtained within the wide range of 25 KJ (18 ft-kip) through 62 KJ (46 ft-kip). The impact stresses varied from 200 MPa (29 ksi) through 275 MPa (40 ksi).

Dynamic monitoring at end-of-initial-driving (EOID) was carried out on a test pile terminated at a penetration resistance (PRES) of 6 blows/25 mm. CAPWAP analysis indicated a capacity of 2,320 KN (260 ton) which "calibrates" the damping factor (J) of the CMES (RMAX) EOID-capacity to 0.6. The pile was monitored also during a restrike fifteen days after the initial driving. The pile penetration corresponded to PRES of 18 blows/25 mm. No CAPWAP was performed. The CMES capacity (RMAX with a J of 0.2) was indicated to 2,220 KN (250 ton), which is an obviously "underpredicted" value.

A second test pile was monitored at restrike 4 days after initial driving. The penetration resistance at restrike was 6 blows/25 mm. CAPWAP analysis of the restrike blow indicated a capacity of 2,130 KN (240 ton) "calibrating" the damping factor (I) for CMES (RMAX) EOID-capacity to 0.6. The pile was monitored also during a restrike fifteen days after the initial driving. The pile penetration corresponded to PRES of 18 blows/25 mm. No CAPWAP was performed. The CMES capacity (RMAX with a J of 0.2) was indicated to 2,220 KN (250 ton), which is an obviously "underpredicted" value.

A second test pile was monitored at a restrike 4 days after initial driving. The penetration resistance at restrike was 6 blows/25 mm. CAPWAP analysis of the restrike blow indicated a capacity of 2,130 KN (240 ton) "calibrating" the damping factor (J) for CMES (RMAX) capacity to 0.1.

A static loading test was carried out on the second pile twelve days after the restrike measurements. Reaction was obtained by two anchors drilled and grouted into the bedrock. The anchors were inserted through casings that were wash drilled through the soil and their installation severely disturbed the soil at and below the pile toe. As a consequence, the pile reached soil failure already at the load range of 1,200 KN to 1,300 KN (135 ton to 150 ton).

The test pile was restruck with dynamic measurements three days after the static test to a PRES of 2 blows/25 mm. CAPWAP analysis on the restrike blow indicated a capacity of 1,320 KN (148 ton) which value is in excellent agreement with the capacity determined in the static loading test.

The first test pile was also subjected to a static loading test. The test was carried out 13 days after the previous restrike and 28 days after EOID. The static test indicated that just before the maximum load of 2,380 KN (267 ton), the pile head started to move progressively. Full failure was not reached, but appears to be no larger than about 2,500 KN (280 ton). Also the results of this static test agree well with the results of the dynamic test and CAPWAP analysis.