A VIBRATORY PILE TEST

by F. Rausche and G. Likins

The results from dynamic tests performed during the installation of two pipe piles using both vibratory and impact driving equipment are reported and compared.

SITE DETAILS

The open end pipe piles had an outside diameter of 60 inches and a basic wall thickness of 1 inch. Pile 111 had a total length of 145 ft with a 40 ft long 1.5 inch wall section starting 55 ft below its top. Pile 114 had a total length of 130 ft with 50 ft of 1.5 inch wall starting 50 ft below its top. Both piles had five internal baffles located near the transducer location.

The vibratory hammer, ICE Model 1412, can be operated between 6.7 and 20 Hz. Its displacement amplitude and power are rated at 1.5 inches and 550 HP, respectively. The eccentric moment and total weight are 10 in-kips and 20.4 kips, respectively. After vibratory "refusal", a Vulcan 060 steam powered impact hammer further installed the pile to the final design penetration. This hammer has a 60 kip ram weight and a 180 kip-ft energy rating.

A report on the soil conditions in the vicinity of Pile 114 indicated loose to medium dense fine sand to a depth of 44 ft (below mudline), firm to very stiff clay to 79 ft and then dense fine sand to 162 ft. The soils at Pile 111 were 9 ft of clayey fine sand, soft to stiff clay to 44 ft, underlain by fine to coarse sand to a depth of 213 ft.

Test Sequence

The ICE 1412 vibrated Pile 111 to a depth of 85 ft below Medium Water Level (43 ft below mudline) in about 4 minutes. The final vibratory rate of penetration was 112 seconds for the last foot. The Vulcan 060 then drove the pile with at first 34 blows per foot (BPF) to a final depth of 122 ft below MWL (80 ft below mudline) at a final blow count of 96 blows per foot.

Pile 114 was also vibrated to a depth of 85 ft below MWL (63 ft below mudline). The vibrating process lasted approximately 9 minutes. The average final rate of penetration over the last 10 feet penetration was 22 seconds per ft, although refusal was encountered for the last foot. The Vulcan impact hammer started at a 75 BPF blow count (at low hammer energies). The blow count decreased (as energy increased) to as little as 32 BPF at 71 ft and reached 114 BPF at 85 ft depth (the design final penetration) below mudline.

Instrumentation

For impact measurements a standard PDA pile monitoring system was used. The sensors were attached to the piles approximately 17 ft below the pile tops. Since the PDA has self balancing (after every "blow") and acquires relatively short records which are digitized at a high sampling rate, a different set of signal conditioning equipment was required under the vibratory hammer. It included two strain manual balancing and amplifying units and two accelerometer power supplies. The data was stored on magnetic tape and viewed on an oscilloscope.

Analysis

Acceleration and strain analog data were replayed from the tape recorder through a 400 Hz Low-Pass filter and digitized at a rate of 2000 samples per second for each channel. The following calculations were then performed:

1. Integration of acceleration to velocity including an integration constant (the average penetration rate). Integration of velocity to displacement.

2. Addition of the hammer weight to the measured force.

3. Integration of the product of force and velocity to yield transferred energy as a time function. Calculate power by dividing transferred energy by the time period.

4. Calculation of "soil resistance" by rigid body assumptions.

5. Calculation of the Fourier coefficients of acceleration and force. Calculation of a dynamic stiffness by dividing the force coefficients by the corresponding displacement values obtained from the acceleration coefficients.

All resulting time and frequency curves were plotted and maxima, minima and amplitudes (spans) were determined and summarized in Table 1. A sample plot result is included.

PDA results were obtained under the impact hammer from beginning to the end of impact pile driving. In the present case, the primary interest was the correlation between bearing capacity predictions from impact and vibratory driving records. Therefore, a very early record of the impact driving of each pile was analyzed by CAPWAPC.

DISCUSSION OF RESULTS

Results from Fourier Analysis

The Fourier coefficients of **both** acceleration and force contained the very dominant peak of the vibratory hammer's base frequency. Higher harmonics are also apparent.

The base natural frequency of the two piles were 58 and 65 Hz for Pile 111 (L = 145 ft) and 114 (L = 130 ft), respectively. The 58 Hz pile frequency was usually indicated in the acceleration records of Pile 111. For Pile 114, the 4th harmonic (60 to 68 Hz) of the hammer frequency is very near the pile's base frequency and the pile frequency was only apparent in the record at 55 ft depth.

An attempt was made to use the Fourier analysis for a calculation of soil response. Probably, the low frequency stiffness values (third spectrum) can be related to the soil response. However, at this time no experience exists and further study is needed.

Hammer Performance

To our knowledge, for the vibratory hammer, no measured performance data exists in terms of power, maximum force, *etc.*, with which we could compare the current results. However, these quantities may be compared with manufacturer's specifications. For example, a 10 kip-inch eccentric moment produces centrifugal forces of 295 kips at a frequency of 17 Hz (the most commonly observed hammer speed). The force amplitude (peak-to-peak) would then be 590 kips. We observed force spans between 360 and 528 kips. The maximum force values reached 308 kips which translates to an average stress of 1.66 ksi. The highest stresses are due to extreme stress concentrations under the clamp, and average axial pile stresses are therefore immaterial as far as the potential of pile damage is concerned.

The maximum power transmitted to the piles was 103 kip-ft/s or 187 HP. There is, of course, appreciable energy (power) remaining in the hammer itself (rotating weights, *etc.*) and it is not known how much power was actually consumed. Furthermore, the power output depends on the hammer's operating frequency which was always less than the rated 20 Hz. All of these reasons help explain why, at most, 34% of the rated (550 HP) power was transferred to the pile.

Soil Resistance and Bearing Capacity

The soil resistance values were calculated under the vibratory hammer based on a rigid body pile model. This is justified since the loading frequency (18 Hz at most) is significantly lower than the pile's natural frequency (about 60 Hz). The elastic behavior of the pile under such relatively slowly varying loads is therefore of lesser importance than under impact hammers.

The difficulty in assessing the bearing capacity of piles under vibratory loadings lies in the degradation of resistance due to the continuous pile motion. The calculated values are therefore only an estimate of the resistance at the time of driving. The positive values are present under the downward and the negative under upward pile motions. No allowance has been made for any dynamic (viscous) resistance effects. Since velocities were generally less than 1.0 ft/s damping forces were probably also small. It is believed that the resistances encountered do contain some dynamic components; however, the static resistance is degraded (liquefaction, no set-up considered). Reducing the total resistance encountered by the dynamic component (maybe as much as 20% in the sand) would therefore not improve the accuracy of the prediction as perhaps the two effects cancel.

The maximum positive resistance values encountered during and at the end of vibratory driving reached 426 and 421 kips for Pile 111 and 810 and 633 kips for Pile 114, respectively. The corresponding CAPWAPC results from the early driving were 474 and 658 kips. The good correlation between the soil resistance results from impact and vibratory data is rather encouraging. Actually, this good correlation may be a coincidence because (a) no dynamic (damping) resistance was deducted from the total vibratory resistance. (The maximum occurred after the time of the highest positive pile velocity but before the velocity zero) and (b) the static resistance occurring during vibratory driving is usually thought to be less than the static resistance occurring during impact driving (liquefaction).

It should be noted that to achieve a match in CAPWAPC, significant impedance increases had to be made in the pile model. For both piles, the impedance was increased in the baffle area. The heavy wall impedance was increased for both piles (but particularly high variations were made for Pile 114). These could be mass effects of the soil or perhaps, more likely, local stress concentrations due to the baffle plates near the transducer locations.

A static analysis for Pile 114 using API RP 2A (1989) Method gave 677 kips ultimate shaft resistance (ratioed to actual 60 inch pile from calculated 36 inch pile result) which is in good agreement with both dynamic measurement results. For Pile 111, the similarly predicted shaft resistance was 377 kips, also in good agreement; however, the end bearing was over estimated in the static analysis.

re:usday91

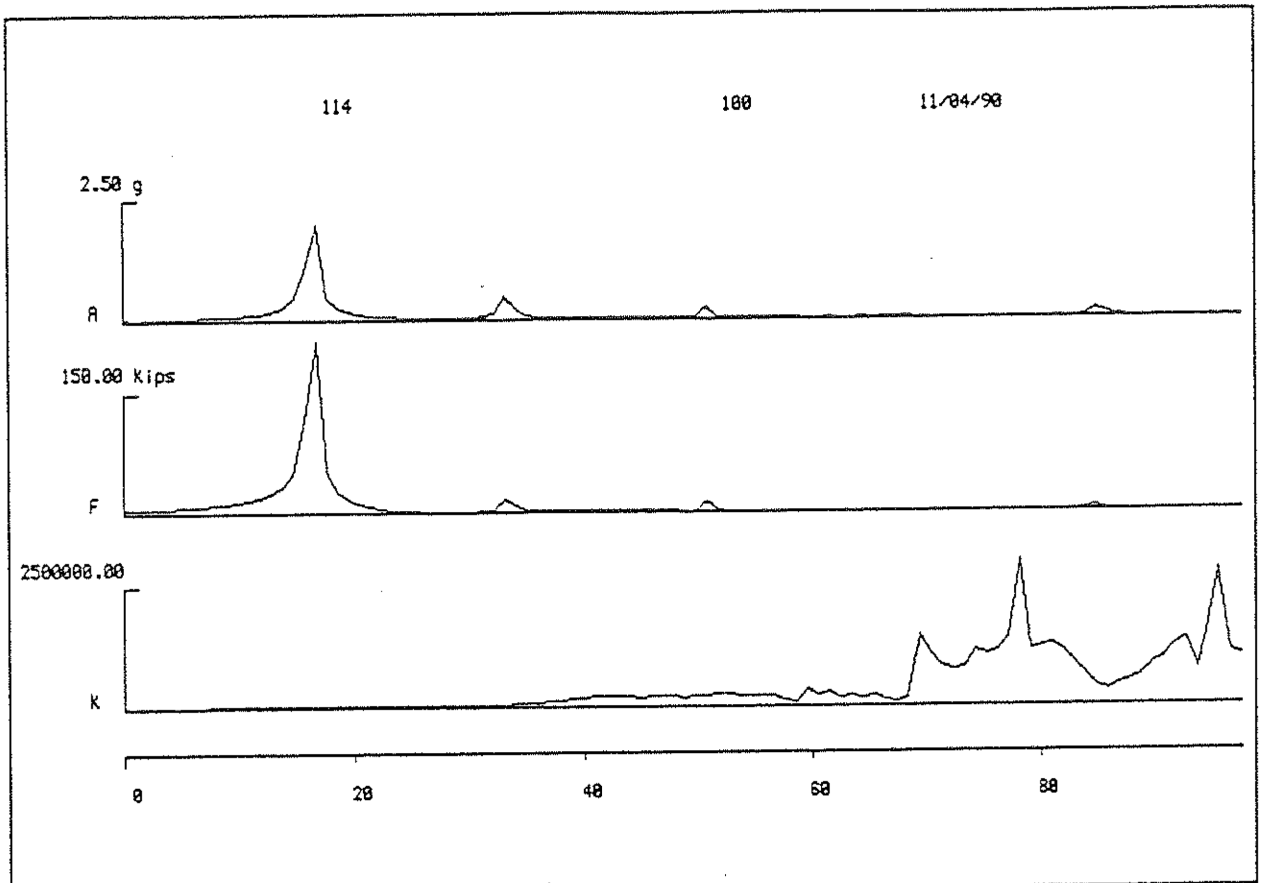
Table 1: Summary of Vibratory Results
(a) Pile 111

Depth Below MWL* ft	Below Mud Line ft	Rate of Penetr-ation ft/s	Frequency Hz	Force Span Max. Min. kips	Acceleration Span Max. Min. g's	Power kip-ft/s (HP)	Resistance Span Max. Min. kips
62	20	.167	17.6	423 272 -150	3.9 2.0 -1.9	36.5 (66.4)	330 -178
68	26	.250	17.6	458 285 -172	3.4 1.7 -1.6	43.9 (79.8)	344 -250
83	41	.125	16.6	499 270 -228	6.0 3.0 -3.0	101 (184)	426 -473
85	43	.009	16.6	510 277 -234	5.8 2.9 -2.9	94 (171)	421 -479

Table 1: Summary of Vibratory Results
(b) Pile 114

Depth Below MWL* ft	Below Mud Line ft	Rate of Penetr-ation ft/s	Frequency Hz	Force Span Max. Min. kips	Acceleration Span Max. Min. g's	Power kip-ft/s (HP)	Resistance Span Max. Min. kips
45	15	.294	15.6	360 205 -155	6.1 2.8 -3.2	40 (73)	291 -231
55	15	.167	16.6	411 223 -189	8.4 4.2 -4.3	80 (145)	420 -415
65	25	.167	16.6	418 227 -191	7.5 3.9 -3.6	78 (142)	406 -336
75	35	.208	16.6	423 218 -205	7.8 3.9 -3.9	79 (138)	404 -311
85	45	.075	15.6	451 242 -209	10.8 4.5 -6.3	103 (187)	810 -473
89	49	.075	16.6	502 277 -223	9.5 4.3 -5.2	92 (167)	733 -528
100	60	.011	17.6	528 308 -220	6.5 3.0 -3.5	59 (107)	633 -470

* Medium Water Level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100
11/04/90
2.50 g
A
150.00 Kips
F
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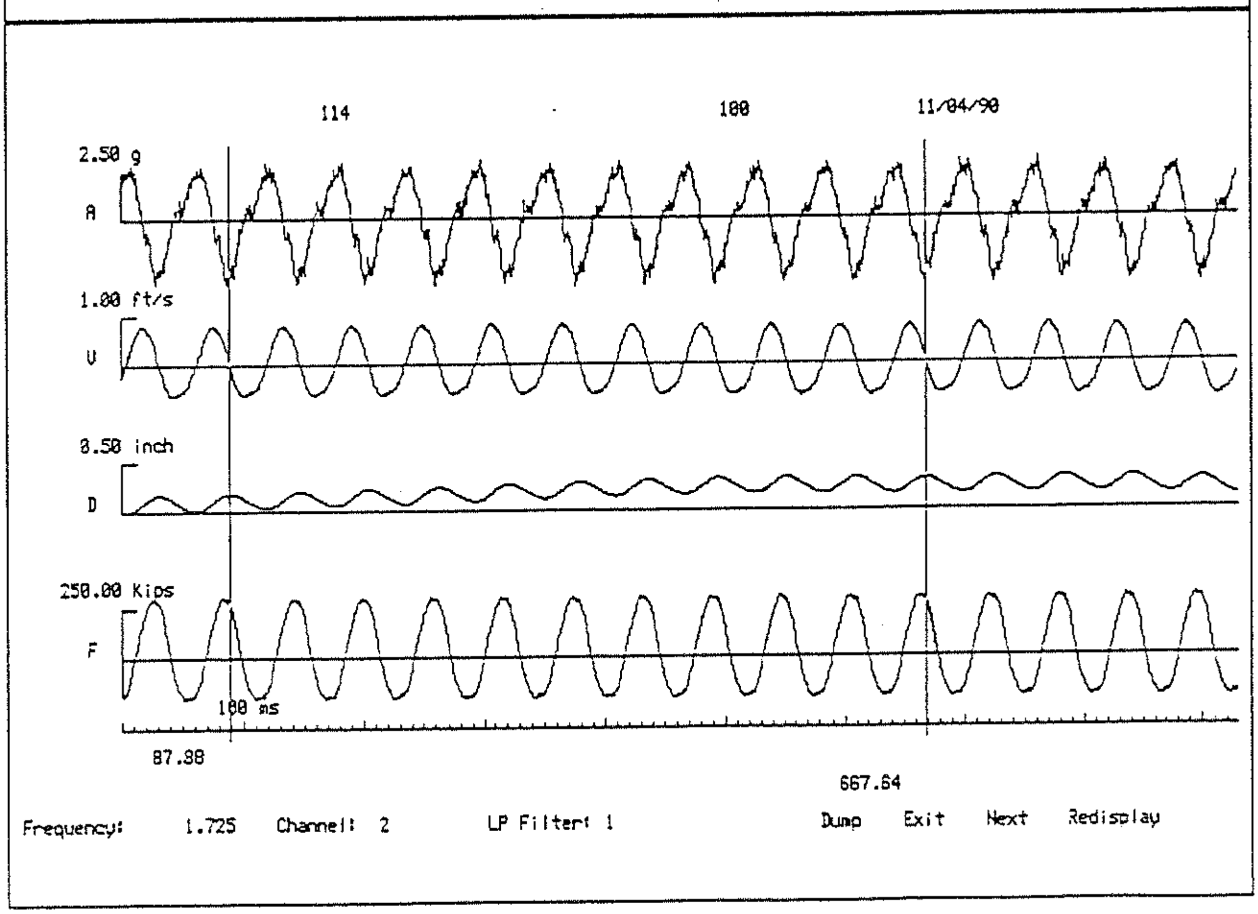
K
0
20
40
60
80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A
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Dump Exit Next Redisplay

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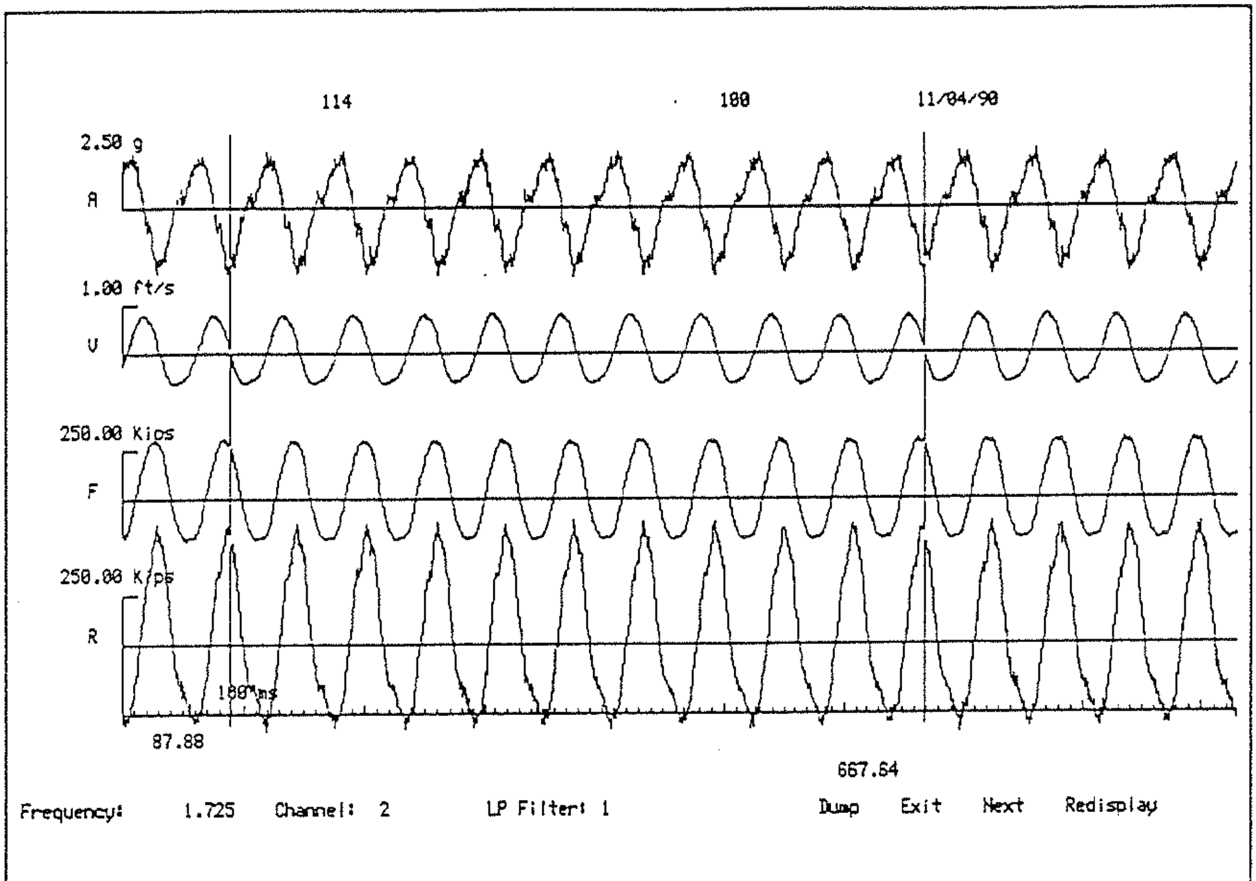
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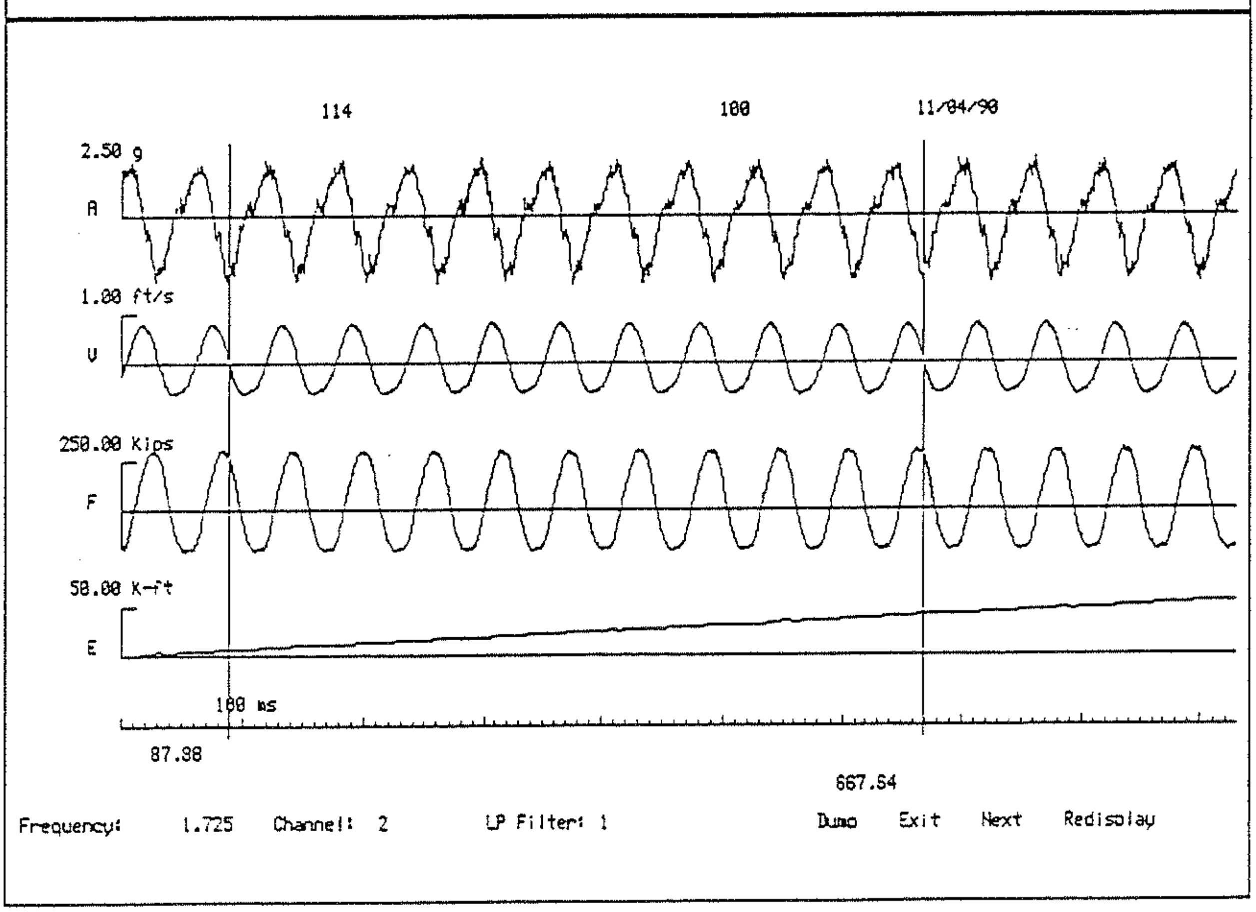
667.64
Frequency: 1.725 Channel: 2 LP Filter: 1
Dump Exit Next Redisplay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V
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Frequency: 1.725 Channel: 2 LP Filter: 1
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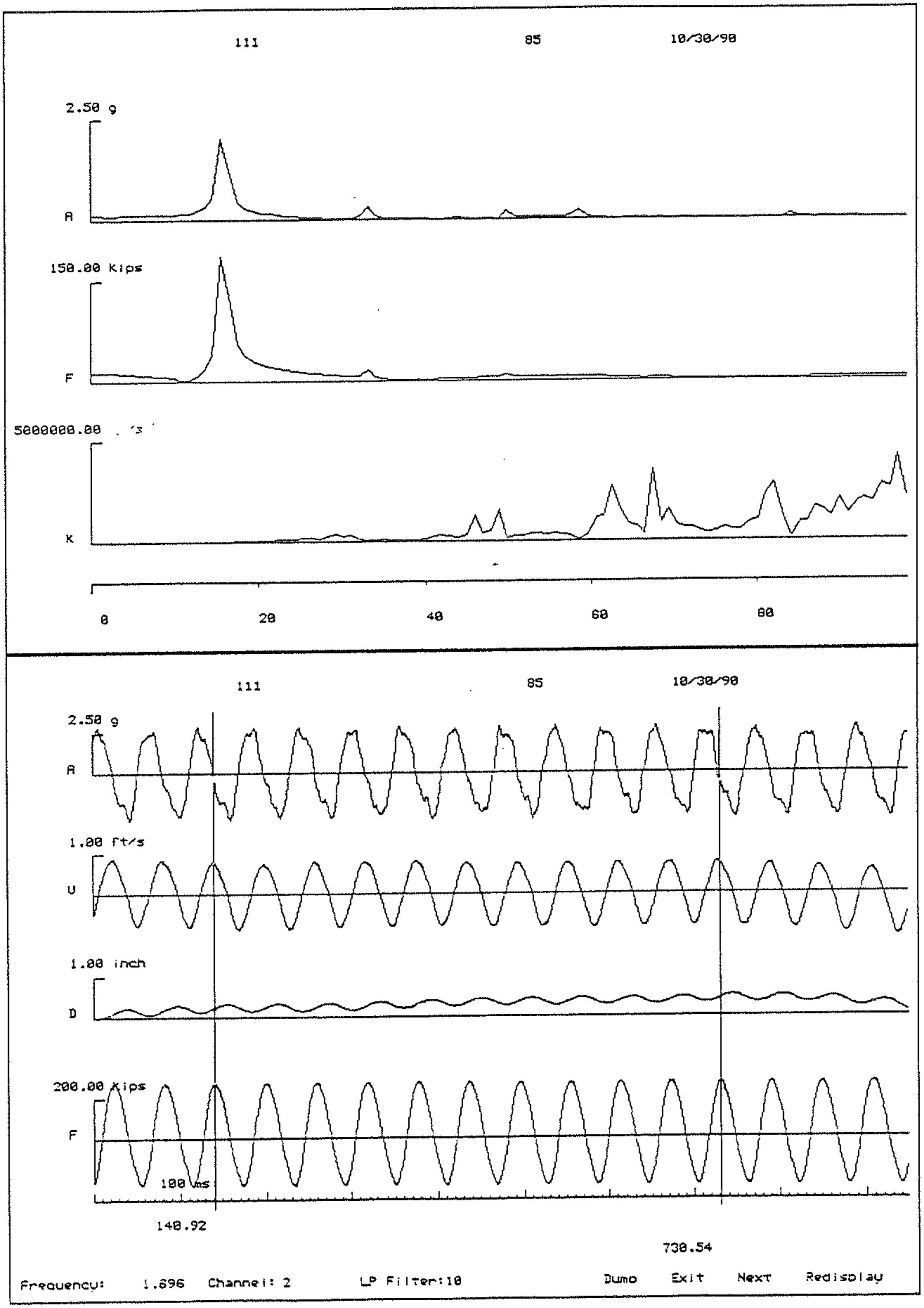
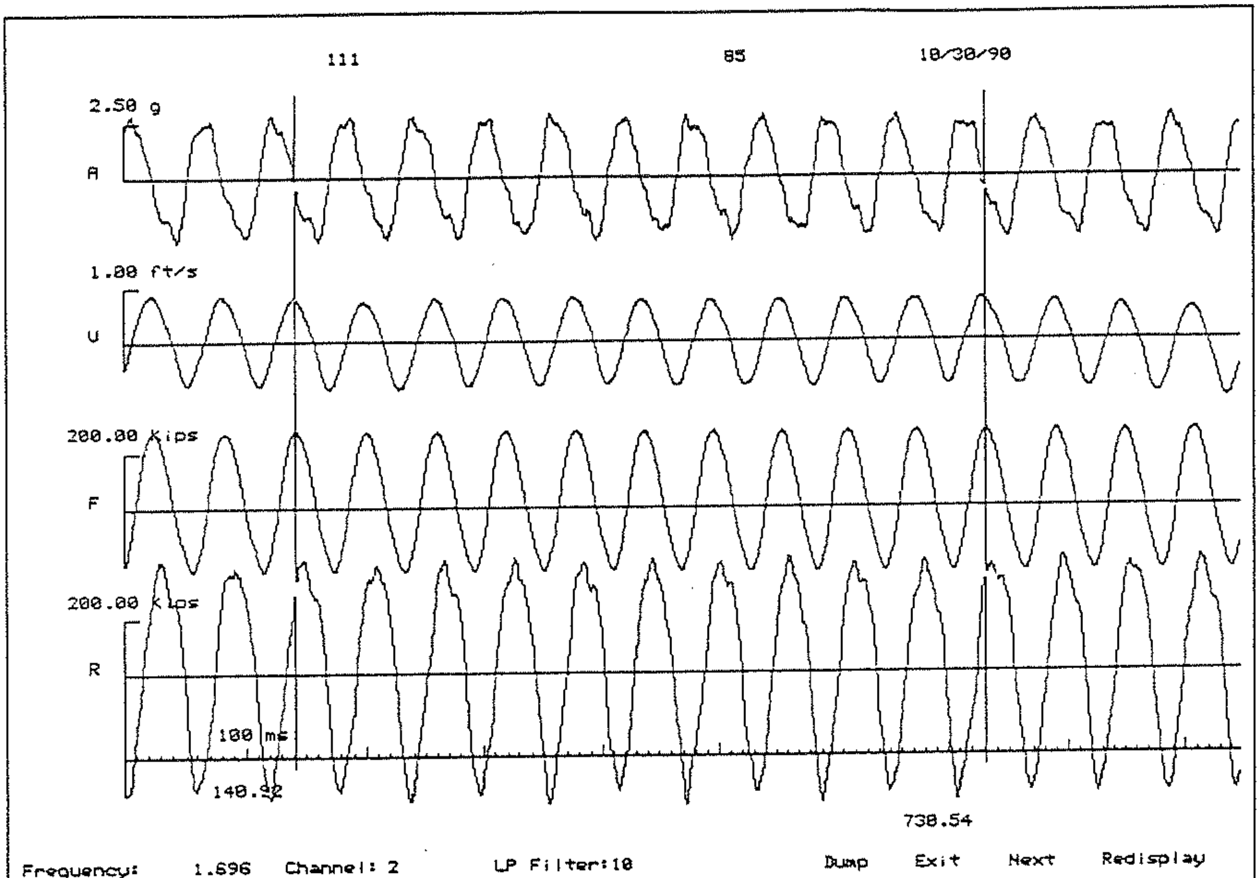


111
85
10/30/90
2.50 g
A
150.00 Kips
F
5000000.00
K
0
20
40
60
80
111
85
10/30/90
2.50 g
A
1.00 ft/s
V
1.00 inch
D
200.00 Kips
F
100 ms
140.92
730.54
Frequency: 1.696
Channel: 2
LP Filter:10
Dump
Exit
Next
Redisplay

X


111
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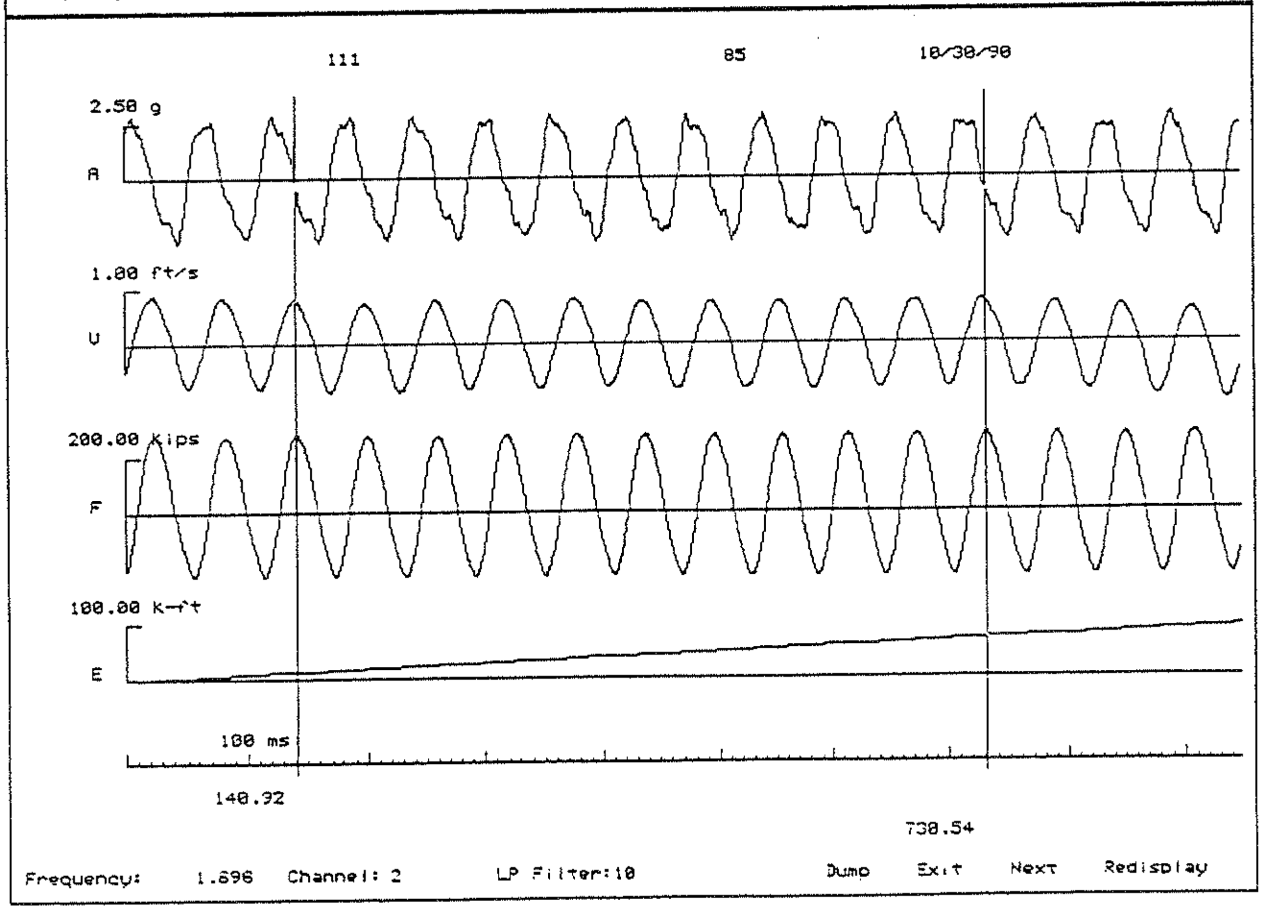
111
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A
1.00 ft/s
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GRL & ASSOC INC 11-4-90

114 PILE

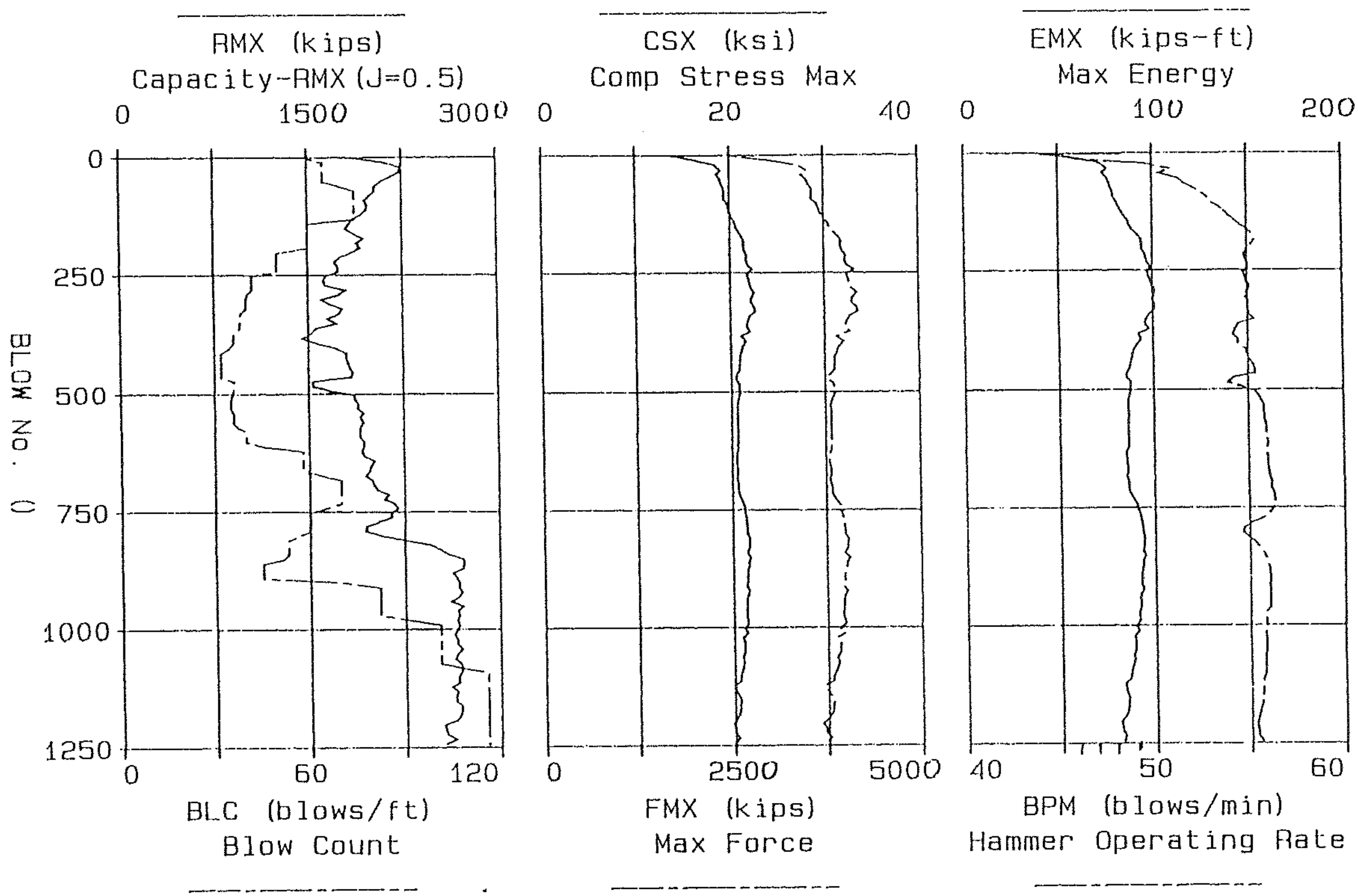


Figure 3

CAPWAPC - GRL & Associates, Inc.
PN 111 EARLY 12/13/90
Blow No. 11

Final CAPWAPC Capacity: Ru 474.0, Skin 423.2, Toe 50.8 Kips

Soil Sgmnt No.	Depth Below Gages ft	Depth Below Grade ft	Ru Kips	Sum of Ru Up Kips	Sum of Ru Down Kips	Unit Resist. w. Respect to Depth Kips/ft	Unit Resist. w. Respect to Area Kips/f2	Smith Damping s/ft	Quake inch
				474.0					
1	73.5	5.5	13.1	460.8	13.1	1.97	.13	.234	.080
2	80.2	12.2	20.8	440.0	33.9	3.11	.20	.234	.080
3	86.9	18.9	28.5	411.6	62.4	4.26	.27	.234	.080
4	93.6	25.6	36.1	375.5	98.5	5.40	.34	.234	.080
5	100.3	32.3	43.8	331.7	142.3	6.55	.42	.234	.080
6	106.9	38.9	60.9	270.8	203.2	9.11	.58	.234	.080
7	113.6	45.6	73.3	197.4	276.5	10.97	.70	.234	.080
8	120.3	52.3	73.3	124.1	349.9	10.97	.70	.234	.080
9	127.0	59.0	73.3	50.8	423.2	10.97	.70	.234	.080
Average Skin Values			47.0			7.17	.45	.234	.080
Toe			50.8				2.59	.195	.080

ALL CLAY (segments 1–9)

Soil Model Parameters/Extensions		Skin	Toe
Case Damping		.300	.030
Unloading Level	(% of Ru)	0	
Soil Plug Weight	(Kips)		.50

EXTREMA TABLE

Pile Sgmnt No.	Depth below Gages ft	max. Force Kips	min. Force Kips	max. Comp. Stress Kips/in2	max. Tension Stress Kips/in2	max. trnsfd. Energy Kips-ft	max. Veloc. ft/s	max. Displ. in
1	3.3	3333.6	-1602.5	17.99	-8.65	97.34	8.7	.912
3	10.0	3334.9	-1523.4	18.00	-8.22	96.93	8.8	.900
6	20.1	3228.9	-1370.5	17.43	-7.40	96.73	9.0	.910
10	33.4	3692.3	-1187.4	19.93	-6.41	96.50	7.6	.900
14	46.8	3845.5	-1544.1	13.95	-5.60	96.04	7.3	.890
18	60.2	3922.1	-1272.6	14.23	-4.62	95.84	7.6	.890
22	73.5	3058.2	-1095.8	11.09	-3.97	95.69	8.6	.890
25	83.6	2971.8	-950.4	16.03	-5.13	89.56	8.4	.880
29	96.9	2910.7	-768.5	15.70	-4.15	77.82	8.3	.880
33	110.3	2586.8	-566.2	13.96	-3.05	58.67	11.0	.890
37	123.7	959.2	-183.3	5.17	-.99	27.34	12.8	.890
38	127.0	533.8	-68.2	2.88	-.37	10.27	12.9	.899
Absolute	36.8			19.97		(T=	23.7 ms)	
	3.3				-8.65	(T=	36.4 ms)	

X

CAPWAPC - GRL & Associates, Inc.
PN 111 EARLY 12/13/90
Blow No. 11

PILE PROFILE AND PILE MODEL

	Depth ft	Area in2	E-Modulus Kips/in2	Spec. Weight Kips/ft3	Circumf. ft
1	.00	185.30	30000.0	.492	15.710
2	37.00	185.30	30000.0	.492	15.710
3	37.00	275.68	30000.0	.492	15.710
4	77.00	275.68	30000.0	.492	15.710
5	77.00	185.35	30000.0	.492	15.710
6	127.00	185.35	30000.0	.492	15.710

Toe Area (ft2) 19.635

Segmnt No.	Depth B.G. feet	Impedance Kips/ft/s	Imp. Change %	T. Slack inch	C. Slack inch	Circumf. feet
1	3.34	330.68	.00	.000	.000	15.710
3	10.03	405.68	22.68	.000	.000	15.710
8	26.74	330.68	.00	.000	.000	15.710
11	36.76	330.68	.00	.000	.000	15.710
12	40.11	480.54	.00	.000	.000	15.710
13	43.45	491.97	.00	.000	.000	15.710
19	63.50	591.97	20.33	.000	.000	15.710
24	80.21	337.12	.00	.000	.000	15.710
25	83.55	330.77	.00	.000	.000	15.710
38	127.00	330.77	.00	.000	.000	15.710

Pile Damping (%) 1.0, Time Incr (ms) .199, Wave Speed (ft/s) 16810.7

PN: 111 EARLY

Case Method Capacity Results

	J=0.0	J=0.1	J=0.2	J=0.3	J=0.4	J=0.5	J=0.6	J=0.7	J=0.8	J=0.9
Rs	1676.	1184.	693.	201.	0.	0.	0.	0.	0.	0.
Rx	1676.	1487.	1393.	1332.	1272.	1211.	1157.	1121.	1085.	1049.
Ru	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
Ra Ra2	803.	1120.								

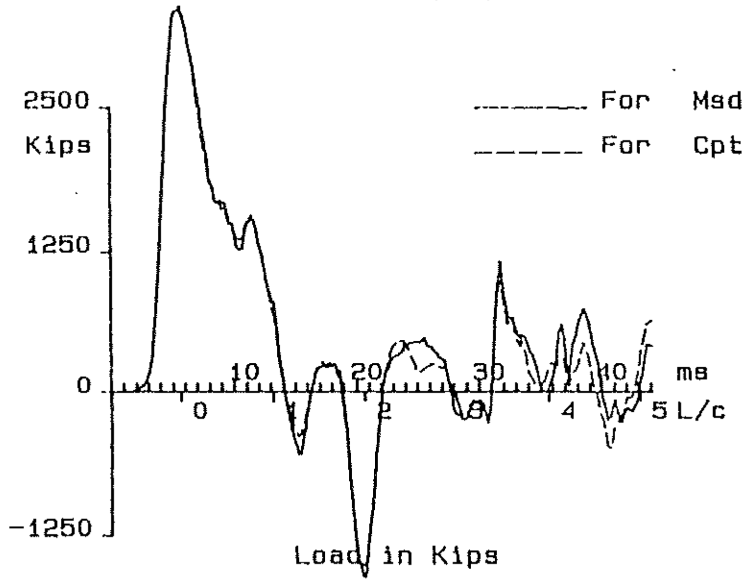
Current CAPWAPC Ru = 474.0; Corresponding J(Rs) = .24; J(Rx) = 1.00

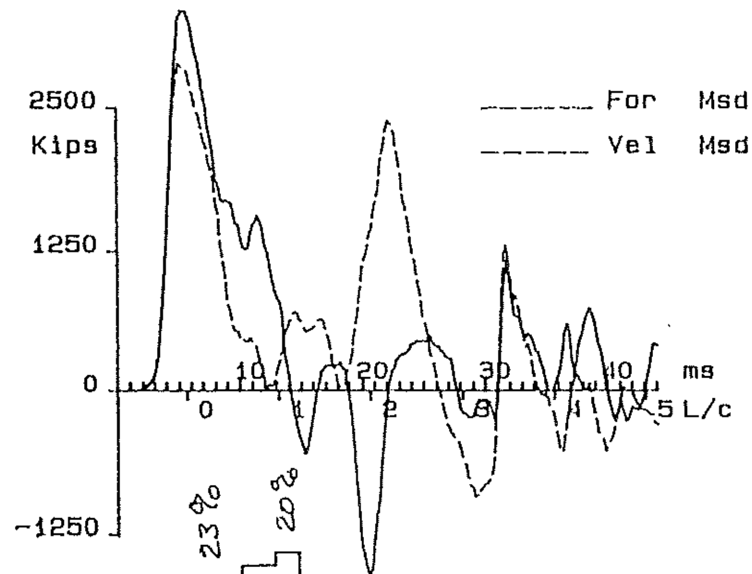
VMAX	VFIN	V1*Z	F1	FMAX	DMAX	DFIN	EMAX	EFIN	R EX	R EF
8.73	-.94	2830.3	3326.9	3333.6	.912	.830	97.3	94.2	1861.8	3297.6

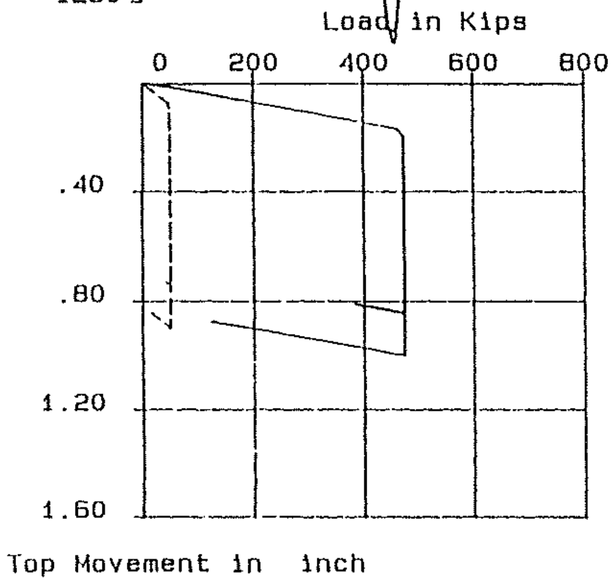
X

CAPWAPC - GRL & Associates, Inc.
PN 111 EARLY

Blow 11 12/13/90







Pile Top

Bottom

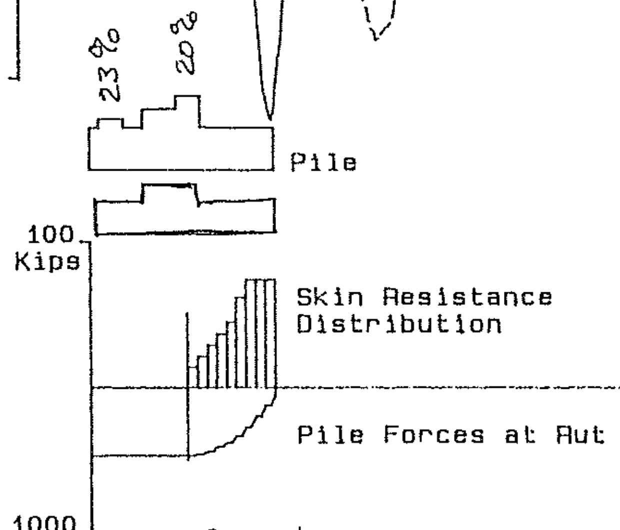
Rut = 474.0 Kips

Rsk = 423.2 Kips

Rto = 50.8 Kips

Dy = .20 inch

Dmx = 1.00 inch



SOFT to STIFF CLAY
.13 to .70 K/ft²

SS .234
ST .195

X

CAPWAPC - GRL & Associates, Inc.
PN 114 EARLY 12/13/90
Blow No. 16

Final CAPWAPC Capacity: Ru 657.6, Skin 629.4, Toe 28.2 Kips

SAND
CLAY

Soil Sgmnt No.	Depth Below Gages ft	Depth Below Grade ft	Ru Kips	Sum of Ru Up Kips	Sum of Ru Down Kips	Unit Resist. w. Respect to Depth Kips/ft	Unit Resist. w. Respect to Area Kips/f2	Smith Damping s/ft	Quake inch
				657.6					
1	60.1	9.6	92.4	565.3	92.4	13.83	.88	.827	.080
2	66.8	16.3	92.4	472.9	184.7	13.83	.88	.827	.080
3	73.4	22.9	92.4	380.5	277.1	13.83	.88	.827	.080
4	80.1	29.6	92.4	288.2	369.5	13.83	.88	.827	.080
5	86.8	36.3	92.4	195.8	461.8	13.83	.88	.827	.080
6	93.5	43.0	70.3	125.5	532.1	10.53	.67	.827	.080
7	100.1	49.6	32.4	93.1	564.5	4.86	.31	.827	.080
8	106.8	56.3	32.4	60.6	597.0	4.86	.31	1.241	.080
9	113.5	63.0	32.4	28.2	629.4	4.86	.31	1.241	.080
Average Skin Values			69.9			9.99	.67	.870	.080
Toe			28.2				1.44	3.520	.080

Soil Model Parameters/Extensions	Skin	Toe
Case Damping	1.656	.300

EXTREMA TABLE

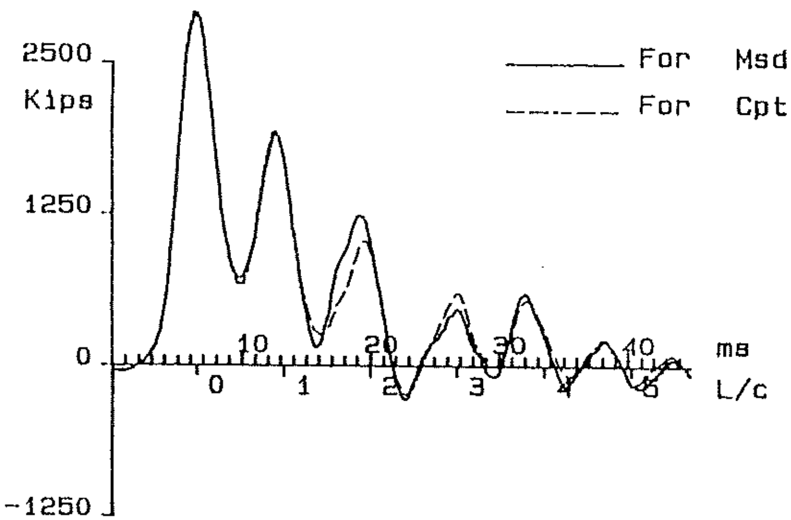
Pile Sgmnt No.	Depth below Gages ft	max. Force Kips	min. Force Kips	max. Comp. Stress Kips/in2	max. Tension Stress Kips/in2	max. trnsfd. Energy Kips-ft	max. Veloc. ft/s	max. Displ. in
1	3.3	2887.1	-288.7	15.58	-1.56	57.47	6.5	.370
3	10.0	2666.7	-171.4	14.39	-.92	55.35	7.1	.340
6	20.0	2492.3	-98.2	13.45	-.53	54.99	7.3	.330
9	30.0	2743.9	-91.4	14.80	-.49	54.42	6.9	.310
13	43.4	3330.7	-157.2	12.08	-.57	53.87	5.2	.280
16	53.4	3487.9	-178.0	12.65	-.65	53.61	4.4	.280
20	66.8	2912.4	-159.5	10.56	-.58	46.59	4.6	.270
23	76.8	2204.1	-150.6	8.00	-.55	32.96	4.4	.270
26	86.8	1917.1	-159.3	10.34	-.86	26.71	3.9	.260
30	100.1	1187.5	-154.3	6.41	-.83	15.92	4.3	.260
33	110.2	676.2	-110.7	3.65	-.60	10.27	4.6	.260
34	113.5	659.7	-112.0	3.56	-.60	7.61	4.6	.264
Absolute	3.3			15.57		(T=	21.6 ms)	
	3.3				-1.55	(T=	37.9 ms)	

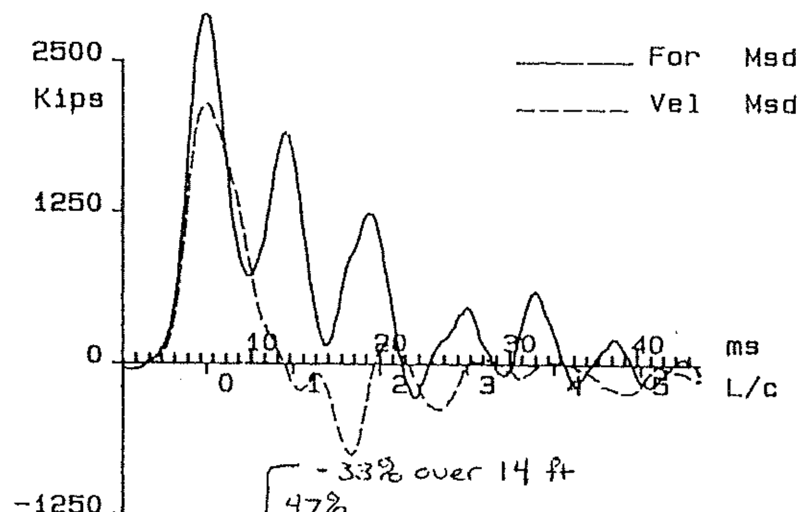
X

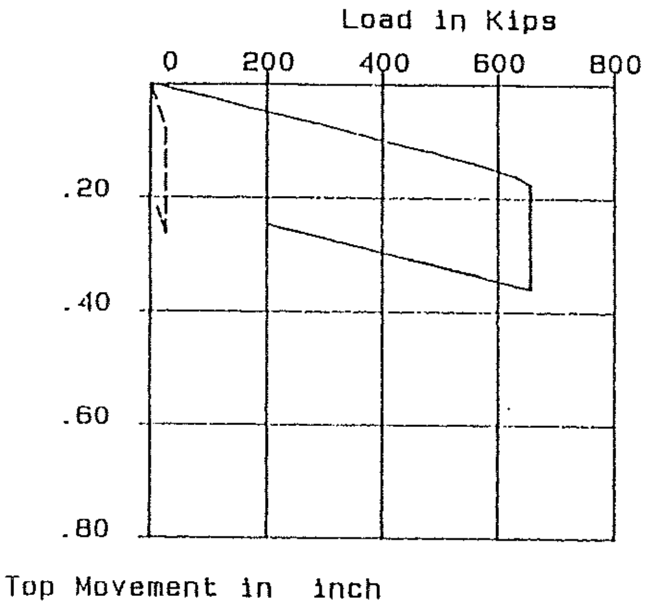
CAPWAPC - GRL & Associates, Inc.

PN 114 EARLY

Blow 16 12/13/90







Pile Top

Bottom

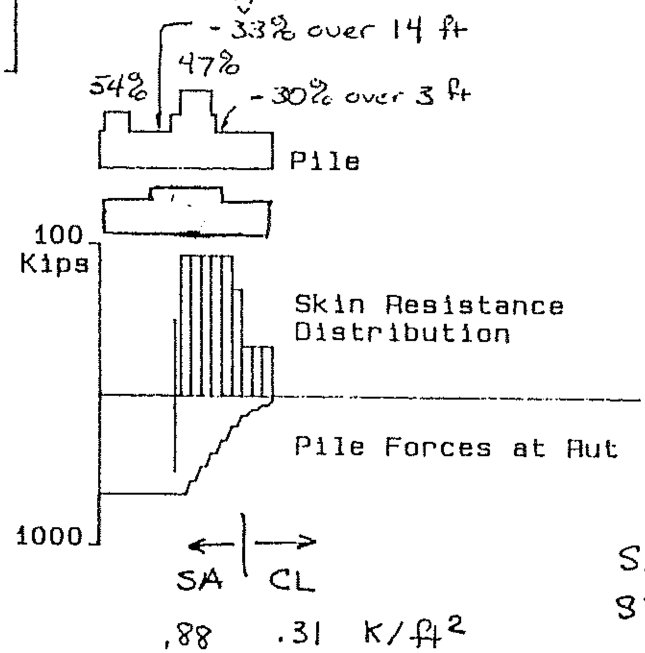
Rut = 657.6 Kips

Rsk = 629.4 Kips

Rto = 28.2 Kips

Dy = .18 inch

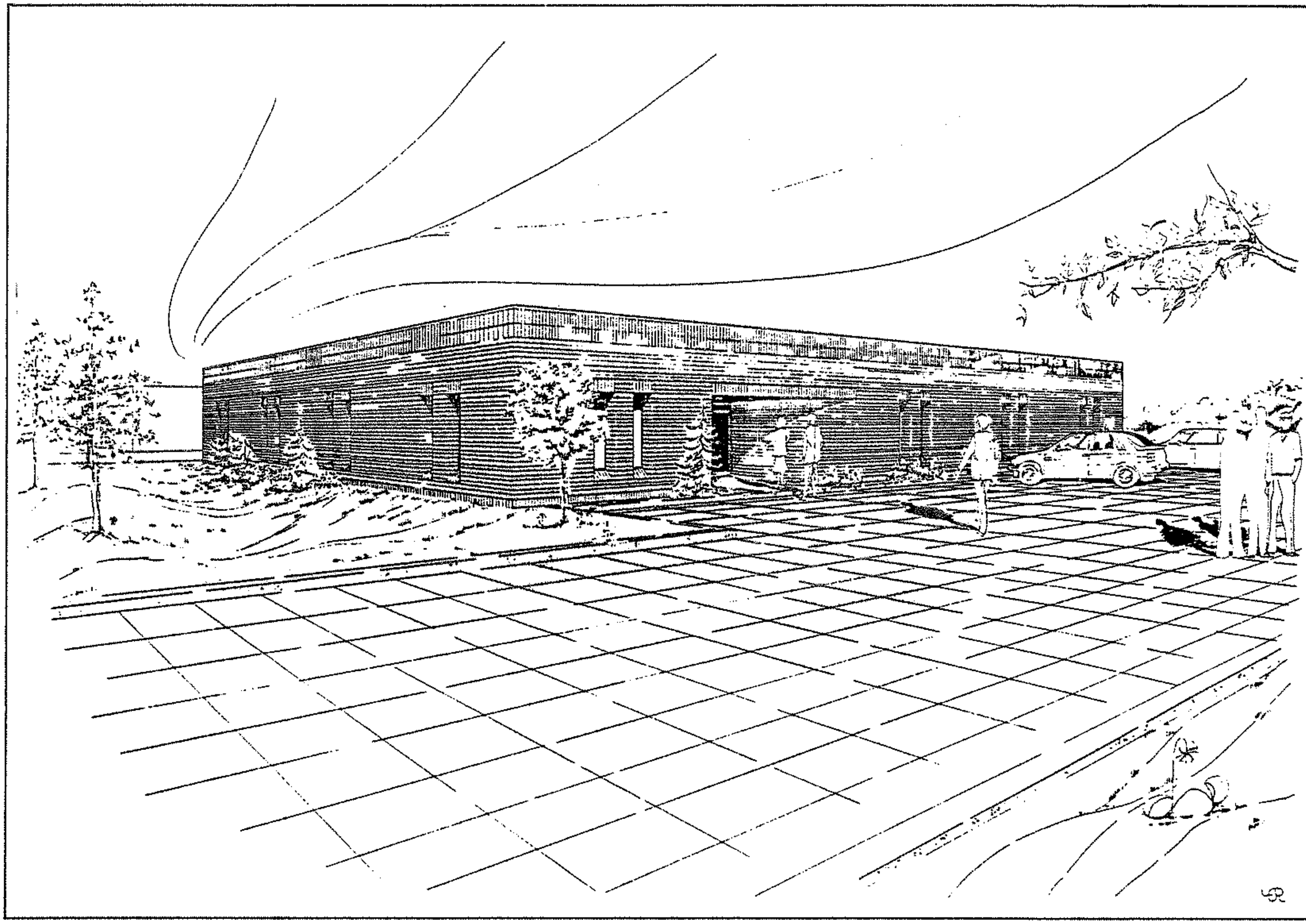
Dmx = .36 inch



SS .87

ST 3.52

Cleveland 1991



PDA USERS DAY • CLEVELANI

August 23 and 24, 1991

ILE DYNAMICS, INC.

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