THE PERFORMANCE OF THE RESONANT PILE DRIVER

LE RENDEMENT DE LA MACHINE RESONNANTE A BATTRE LES PIEUX

РАБОТА РЕЗОНАНСНОГО ПОГРУЖАТЕЛЯ ДЛЯ ЗАБИВКИ СВАЙ

A. FAWCETT, Chief Civil Engineer, G.K.N. Foundations Limited (England)

SYNOPSIS Data obtained from over forty selected contracts involving a wide variety of soil types and pile sizes is analysed against parameters of shear strength of cohesive soils relative density and grading of granular soils, pile displacement and rate of penetration to indicate the range of conditions to which this method of piling is applicable. The majority of the data refers to sands of relatively uniform grain size where application is well defined. The effectiveness of the method increases with an increase in the range of grain sizes present in the soil and decreases with an increase in density, shear strength and pile displacement. Load test results are given and vibration studies show the potential of the method where driven piles are required in the vicinity of existing structures.

INTRODUCTION

The first prototype Resonant Pile Driver was built in the U.S.A. just over twelve years ago early in 1961. Second generation machines introduced in 1962 underwent continued development in the U.S.A. and the U.K. until the present version was produced in the U.K. during the period 1967-1969.

This high frequency pile driver operates at the resonant frequency of longitudinal vibration of the pile system, typically 70 to 100 Hz, well above the much lower frequency of natural response of the soil, which is generally in the range 10 to 30 Hz. The resonant frequency of the pile system is controlled by the length and weight of the pile together with the speed of sound in the pile material and the effect of clamping the pile to the oscillator unit. The amplitude of longitudinal vibration is controlled by the damping provided by the soil. The pile experiences frictional damping along its buried length and tip or toe damping at the end, both of which must be overcome if the pile is to commence and continue to penetrate the soil.

The machine can be compared with low and medium frequency vibrators of Russian, German French, Polish and Japanese origin of less than 12,000 kg mass and more than 220 kN force using parameters of mass, power, force and frequency as in Table I. Very low frequency vibrators operating at less than 10 Hz can produce a maximum force of about 2000 kN.

TABLE I Machine Characteristics

Parameter 1	Low and medium frequency machines 2	Resonant Pile Driver 3	
Frequency Hz	10 - 39	up to 135	
Max. rated Output kW	155	(a) 740	(b) 370
Mass kg	up to 11,700	10,000	6,610
Power/mass ratio W/kg	12 - 21	74	56
Max. driving force kN	750 @ 39 Hz 1350 @ 18 Hz	*1200 @ 135 Hz * 500 @ 70 Hz	

(a) U.S.A. machine
(b) U.K. machine

* including conservative allowance of 35% increase for magnification at resonance.

CONTRACT DATA

Of the many contracts which have been carried out with the Resonant Pile Driver forty to fifty were chosen to illustrate the capabilities of the machine over a wide variety of pile sizes and soil conditions. Details from approximately half of these are summarised in Table II where the soils are described with the aid of properties which can be established in the course of routine site investigation work.

TABLE II PILES DRIVEN WITH THE RESONANT PILE DRIVER

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SITE AND PILE NUMBER	PILE TYPE AND SIZE	PILE AND SHOE C.S. AREA m^2	DRIVING		DESCRIPTION AND THICKNESS OR PENETRATION OF STRATUM UNDER CONSIDERATION		RATE OF PENETRATION		* w %	* kg/m^3	* w_L %	* w_P %	* c_u u^o kN/m^2	
									† D_{20}	† D_{70}	† $\frac{D_{70}}{D_{20}}$	† C_r	† SPT value N blows/300mm	
			DEPTH m	TIME min		m	MEAN m/min	FINAL m/min	mm	mm			MEAN	AT BASE
No.3	Steel shell	.0994	10.68	0.34	soft clay and silt	10.68	31.40						<6	<6
U.S.A.	pile 356mm dia		12.81	1.04	sand, gravel, boulders	2.13	3.02	1.53					56	56
No.23	Steel pipe pile	.1296	7.62	0.68	silt, peat, loose sand	7.62	11.20						<20	<20
U.S.A.	406mm dia.	.1436	13.97	9.18	fine to coarse sand,	6.35	0.75	not					20	20
	closed ended				some gravel			known						
	Steel shell	.0730	9.75	0.70	fine to medium sand,	9.75	13.93	-					18	21
	pile				trace of silt									
	305mm dia.		12.81	1.20	fine to medium sand,	3.06	6.12	-					32	36
No.24					trace of gravel									
U.S.A.			19.50	4.90	med. to coarse sand and	6.69	1.81	-					51	54
					fine to medium gravel			not						
			23.48	9.70	fine to medium gravel	3.98	0.83	known					74	74
No.62	Steel H pile	.0222	25.60	7.67	sand, silt, clay	25.60	3.34	-					<30	≈40
U.S.A.	356mm,174kg/m		33.10	17.67	medium sand	7.50	0.75	1.53					42	80
No.80	Steel pipe pile	.0824	12.35	1.50	clay with sand lenses	12.35	8.24	-					<11	<11
U.S.A.	324mm dia.		15.40	8.50	fine sand with gravel,	3.05	0.43	not					54	62
	closed ended				clay, silt			known						
No.82	Steel pipe pile	.1296	15.24	2.97	sand, sand and gravel	15.24	5.13	-					11	15
U.S.A.	406mm dia.		16.95	6.97	silty fine sand	1.71	(0.43)	0.153					20-40	40
	closed ended													
6	In-situ	.0994	2.13	0	sand fill, prebored	-								
No.1	concrete	.1256	12.80	3.50	laminated clay	10.67	3.05	-	24	2040	56	23	104/0°	104/0°
U.K.	356mm dia.tube		18.90	8.00	clayey and sandy silt	6.10	1.36	1.22	as T.2. DRAX				30-35∇	30-35∇
			20.40	19.00	fine to medium sand	1.50	(0.14)	<0.15	as T.2. DRAX				37-50∇	37-50∇
	In-situ	.0994	16.46	0.77	very silty organic clay	16.46	21.4	-	55	1650	60	26	≤24/0°	≤24/0°
	concrete	.1256	17.68	1.00	stiff sandy Keuper Marl	1.22	5.3	-	14	2050			87/18°	87/18°
No.2	356mm dia.tube		19.73	5.10	hard sandy Keuper Marl	2.05	(0.50)	0.153	<12	≥2240			150	>150
U.K.	Steel H pile	.0150	16.46	1.26	very silty organic clay	16.46	13.07	-	55	1650	60	26	≤24/0°	≤24/0°
	305mm 117kg/m		17.68	1.43	stiff sandy Keuper Marl	1.22	7.18	-	14	2050			87/18°	87/18°
			19.81	7.65	hard sandy Keuper Marl	2.13	(0.34)	0.23	<12	≥2240			150	>150
T.2.	In-situ	.1296	11.28	3.00	laminated clay	11.28	3.76	1.53	28	1887	56	23	60/0°	60/0°
	concrete	.1595	16.16	9.30	clayey and sandy silt	4.88	0.78	0.5	0.005	0.028	3.7	3.0		
	406mm dia.tube								to	to	to	to	31	34
									0.014	0.052	5.6	4.0		
DRAX			17.68	12.00	fine to medium sand	1.52	(0.06)	0.23	0.065	0.175	2.2	1.8		
TEST									to	to	to	to	48	≥56
SITE									0.080	0.220	2.3	2.2		<110
U.K.	In-situ	.0994	11.28	1.25	laminated clay	11.28	9.02	-	as	above	pile		60/0°	60/0°
T.7	concrete	.1256	16.46	3.75	clayey and sandy silt	5.18	2.07	-	as	above	pile		31	34
	356mm dia.tube		17.37	4.45	fine to medium sand	0.91	1.30	0.91	as	above	pile		40	56
	Steel sheet	.0255	11.58	-	laminated clay	11.58)	4.80	-	as	above	pile			
	piles, pair		16.77	3.50	clayey and sandy silt	5.19)								
	Larssen No.5		19.81	7.00	fine to medium sand	3.04	(0.87)	re-	as	above	pile		50-80	>100
					sandstone at base			fusal						

TABLE II CONTINUED

LOCK AND DAM NO.4 TEST SITE U.S.A.	Pre-stressed concrete 508mm square	.2580	10.67	30.60	fine to medium sand silty and clayey in places	10.67	(0.35)	re- fusal	0.14 to 0.38	0.23 to 0.80	1.53 to 2.10	1.5 to 2.0	13-28	28
	Steel sheet pile MZ 32	.0106	15.24	2.00 to 9.00	fine to medium sand silty and clayey in places	15.24	7.62 to 1.69	not known	0.14 to 0.38	0.23 to 0.80	1.53 to 2.10	1.5 to 2.0	14-40	40
	(FRUCO 1964)		28.62	+20.0	" " " "	13.38	0.67	"	"	"	"	"	32-68	68
T.4 No.3 U.K.	In-situ concrete 356mm dia.tube	.0994	17.37	2.00	fill, peaty clay, thin sand & gravel layer	17.37	8.68	-	>42	<1800			<42/0°	<42/0°
		.1256	19.20	3.00	stiff grey silty clay	1.83	1.83	-	16	2180	26	19	132/5°	132/5°
			20.42	8.33	hard silty clay and thin sandstone layers	1.22	(0.25)	0.038	14	2210	26	17	191/8°	191/8°
No.4 U.K.	In-situ concrete 324mm dia.tube	.0824	7.31	0.35	very sandy silty clay	7.31	20.9	-	32	1925			39/5°	24/3°
		.1062	19.51	1.10	fine to medium sand	12.20	16.27	10.68	0.079 to 0.097	0.123 to 0.218	1.55 to 2.25	1.2 to 1.6	15∇	27∇ locally 37
			19.81	3.50	weathered sandstone	0.30	(0.17)	0.038					200	200
	In-situ concrete 457mm dia.tube	.1640	7.31	0.58	very sandy silty clay	7.31	12.60	-	32	1925			39/5°	24/3°
		.1973	19.66	3.17	fine to medium sand	12.35	4.75	3.05	as above pile				15∇	27∇
			19.81	5.17	weathered sandstone	0.15	(0.08)	0.038					200	200
4 No.9 HOLLAND	Steel pipe pile 406mm dia. open ended	.0157	6.00	0.55	sand fill	6.00	10.9	-					10-30	
			17.00	-	dense sand, silt layers	11.00)							55	
			21.00	-	layers sand silt & clay	4.00)	3.66	-					25-50	
			24.50	5.60	layers sand silt & clay	3.50)							28	
594 No.10 U.K.	In-situ concrete 406mm dia.tube	.1296 .1595	4.27	0.12	sand with gravel clayey in places 3.4m prebored	0.92	7.66		0.15	0.56	3.73	3.2	28	
			13.57	2.00	fine and fine to medium sand	9.30	4.95	1.53	0.10 to 0.115	0.175 to 0.228	1.75 to 2.10	1.3 to 1.75	20	38
			13.65	3.42	sand & broken sandstone	0.08	(0.05)	0.058					> 60	> 60
11 No.12 U.K.	Steel box pile Larssen 3B	.0158	6.10	1.35	fill & sand with gravel	6.10	4.52	-						
			14.02	4.45	medium sand	7.92	2.56	1.68	0.19 to 0.22	0.30 to 0.42	1.6 to 2.2	0.9 to 1.35	26	32
			17.07	9.35	medium sand	3.05	0.62	0.38	"	"	"	"	45	45
			22.57	17.42	medium sand	5.50	0.78	0.61	"	"	"	"	35	35
			23.17	22.60	very soft sandstone	0.60	-	0.019					90	90
D.2	In-situ concrete 406mm dia.tube	.1296 .1595	6.71	7.33	fill & sand with gravel top 2.74m prebored	3.97	0.54	1.22					26	26
			10.97	8.83	medium sand, trace of gravel	4.26	2.84	1.83	0.19 to 0.22	0.30 to 0.42	1.6 to 2.2	0.9 to 1.35	26	32
			14.62	16.95	medium sand	3.65	(0.45)	0.214	"	"	"	"	45	45
No.14 U.K.	Steel sheet pile Frodingham No.5	.0128	9.75	0.50	6.1m fill, 3.65m sand & gravel	9.75	19.50	-					21-43	21-43
			13.57	6.50	London Clay	3.82	(0.64)	0.153					81/0° at 10.0m	140/0° at 13.5m
No.20 U.K.	In-situ concrete 324mm dia.tube	.0824	9.15	0.97	silty clay/clayey silt	9.15	9.34	-	40-52				< 25/0°	<25/0°
		.1062	11.58	2.90	very silty sandy clay, gravel traces	2.43	1.26	1.40	14	2230	27	17	107/0° to 167/0°	107/0° to 167/0°
			15.85	5.12	" " " "	4.27	1.92	1.31	16	2210	29	17	81/0°	86/0°
			18.90	11.45	" " " "	3.05	0.48	0.354	14	2230			> 96/0°	>120/0°

* applies to cohesive soils, † applies to granular soils and rock, ∇ based on static cone penetrometer results

TABLE II CONTINUED

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SITE AND PILE NUMBER	PILE TYPE AND SIZE	PILE AND SHOE C.S. AREA m^2	DRIVING DEPTH m	DRIVING TIME min	DESCRIPTION AND THICKNESS OR PENETRATION OF STRATUM UNDER CONSIDERATION	m	RATE OF PENETRATION MEAN m/min	RATE OF PENETRATION FINAL m/min	* w % / † D_{20} mm	* kg/m^3 / † D_{70} mm	* w_L % / † D_{70}/D_{20}	* w_P % / † C_r	* C_u u^o kN/m^2 / † SPT value N blows/300mm MEAN	AT BASE
T.4	In-situ concrete 356mm dia.tube	.0994	4.75	0.55	fill then loose sand	4.75	8.64	-					11	11
		.1256	15.23	1.45	soft silty clay/clayey silt with sand layers	10.48	11.03	7.62					7	7
No.16 U.K.			19.81	4.00	fine sand	4.58	1.79	2.28	0.08 to 0.16	0.22 to 0.29	1.6 to 3.0	2.0 to 2.4	14	14
			21.02	4.17	soft marl with hard marl fragments (Keuper)	1.21	7.12	10.66	20	2085	25	17	30	30
			23.32	9.33	friable marl with hard marl fragments (Keuper)	2.30	(0.45)	0.114	11	2277	25	17	200/14° N=70	N > 100
3/17	Steel sheet pile Larssen 3/20	.0089	3.66	6.40	mixture clay sand gravel	3.66	0.57	-					38	47
No.17 U.K.			9.15	7.67	fine to medium sand gravel in top 1.5m	5.49	4.32	7.62	0.11 to 0.15	0.24 to 0.32	2.14 to 2.20	2.5 to 3.0	26	26
			11.60	13.47	London Clay	2.45	(0.42)	0.153					124/0° at 9.45m	191/0° at 11.5m
No.18 U.K.	Steel sheet pile Larssen No.3	.0079	5.18	0.33	1.2m fill then sand and gravel, clayey locally	5.18	15.70		4.00 to 8.50	28.0 to 80.0	5.0 to 9.4	4.0	24-56	24-56
			7.32	1.70	sandy friable Keuper Marl	2. .4	1.56	0.762	16 to 18	2213 to 2120			60-90 81/26° to 120/10°	60-90 81/26° to 120/10°
T.2	In-situ concrete 324mm dia.tube	.0824	6.10	1.18	fill & firm sandy clay	6,10	3.39	-						
No.19 U.K.		.1062	9.15	2.25	sandy flint gravel	3.05	2.85	3.66	0.60 to 19.0	16.0 to 45.0	2.25 to 45.7	3.0 to 4.5	50	42
			15.23	2.90	weathered chalk angular fragments in soft matrix	6,08	9.35	10.15					10-20	< 20
			21.33	4.20	hard chalk fragments some putty chalk	6.10	4.69	5.06	30	1940			25-30	25-30
			23.17	5.00	closely fissured chalk	1.84	2.30	1.92					30-40	40-50
T.D.1	In-situ concrete 324mm dia.tube	.0824	5.18	0.25	soft peaty silty clay	5,18	20.72	-	>50					
		.1062	7.17	-	sandy silty clay with gravel)	6.40	3.66	3.66	20	2060	39	21	93/0°	
No.23 U.K.			11.58	2.00	as above but laminated in places)				23	2000	31	16	67/0°	
			15.23	4.42	sandy silty clay laminated in places	3.65	1.51	1.40	24	2000	47	22	81/0°	81/0°
			15.54	4.92	fine to medium sand	0.31	0.62	re-fusal	0.127	0.330	2.6	3.5	47	47
T.P.2	In-situ concrete 324mm dia.tube	.0824	12.98	0.71	loose sand & peaty clay	12.98								
		.1062	16.46	1.83	mixed sand & gravel	3.48							20	> 22
			16.47	4.17	mixed sand & gravel	0.01	-	re-fusal	0.30	10.0	33.3	5.0	62-65	62-65

* applies to cohesive soils, † applies to granular soils and rock, ∇ based on static cone penetrometer results

Fig.1 defines the terms D_{70} and D_{20}, the ratio of which is a uniformity coefficient, and C_r the mean slope of the grading curve between the 5% and 95% points measured in units of soil fraction. The majority of the detailed data presented relates to U.K. experience where it has become common practice to carry out Standard Penetration Tests in 150 mm and 200 mm boreholes. Boreholes of 75 mm to 90 mm are more common

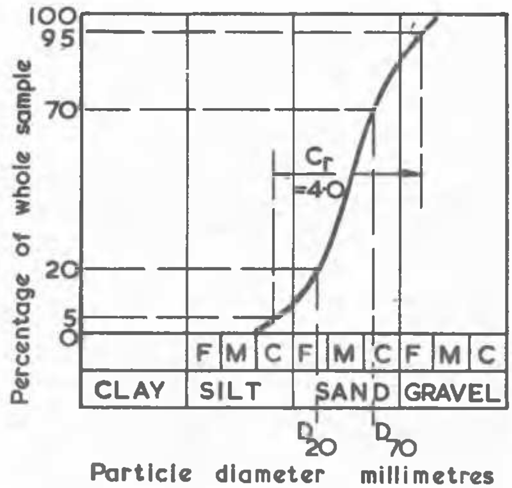

Fig.1 THE SLOPE OF THE GRADING CURVE

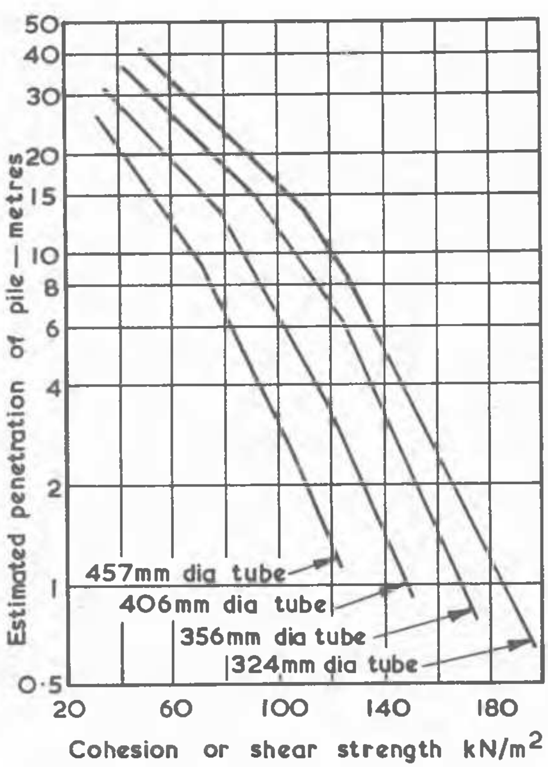

Fig.2 DISPLACEMENT PILES IN CLAY

in the U.S.A. and in an attempt to correct for this variation all S.P.T. results for U.S.A. sites have been reduced by 20%.

Where piles were driven to refusal, defined for the purpose of this paper as less than 300 mm/min. the mean rate of penetration is shown in brackets in Table II to indicate that it is affected by slow driving at near refusal conditions. The maximum power used in the drives varied from 150 kW for the low displacement steel piles of less than $0.025 m^2$ cross sectional area to 260-330 kW for the larger displacement piles.

ANALYSIS OF RESULTS

The potential of this method of driving can be appreciated from Table II where rates of penetration of 7.5 - 20 m/min. are recorded and total drive times of only a few minutes are seen to be achieved with suitable combinations of soil and pile type. The information obtained can be compared graphically for each of three main soil types to obtain approximate performance criteria for drive times of up to ten minutes.

CLAY SOILS

Displacement piles

The pattern of driving in clay soils shown in Fig.2 is based largely on the results obtained from Drax U.K. with laminated silty lake clay of high plasticity, C_u = 57 to 105 kN/m^2. The suggested criteria have been extended on the basis of the experience gained with weaker alluvial clays and other stiffer glacial clays of lower plasticity. Limited trials in London Clay indicated considerable damping with possible penetrations varying from 2m. to 3m. as the pile diameter is reduced from 450 mm to 300 mm, subject to C_u at the final toe level not exceeding 100 and 170 kN/m^2 respectively.

Low displacement Piles

Sheet piles can be driven 2.5 to 4.5 m into London Clay in under ten minutes. The clay increases in strength with depth and penetration appears to be limited to the depth at which C_u reaches 140 to 170 kN/m^2. Results from Drax indicate possible penetrations of laminated clays and glacial clays of 12 to 14m. and 5 to 8m. where C_u = 55 to 60 kN/m^2 and 95 to 100 kN/m^2 respectively.

GRANULAR SOILS

The success with which piles can be driven into granular soils is dependent upon their grading and relative density and the pile displacement. The majority of data relates to fine grained granular soils within the following grading limits.

D_{20} = 0.08 to 0.16mm, D_{70} = 0.175 to 0.42mm
D_{70}/D_{20} = 1.6 to 2.6, C_r = 1.1 to 2.4

Uniformly graded sands at near maximum relative density are virtually impossible to penetrate with displacement piles, even as thin layers, but the degree of penetration increases with a reduction in pile displacement and relative density as shown in Fig.3.

The four zones in Fig.3 relate to ease of driving as follows

Zone A total penetration of 10m - 15m
Zone B total penetration of 7.5m - 10m
Zone C penetration limited to about 3m
Zone D refusal at less than 1m penetration

Gravelly soils with a greater range of particle size show higher S.P.T. results

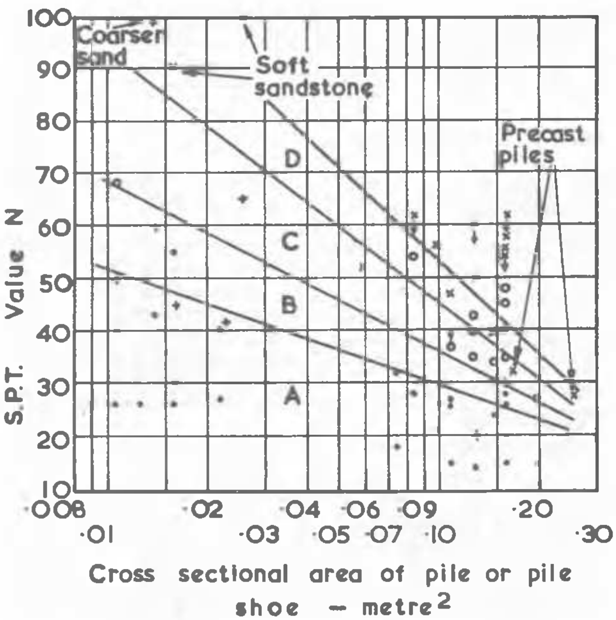

Fig.3 DRIVING IN UNIFORM FINE-MEDIUM SAND

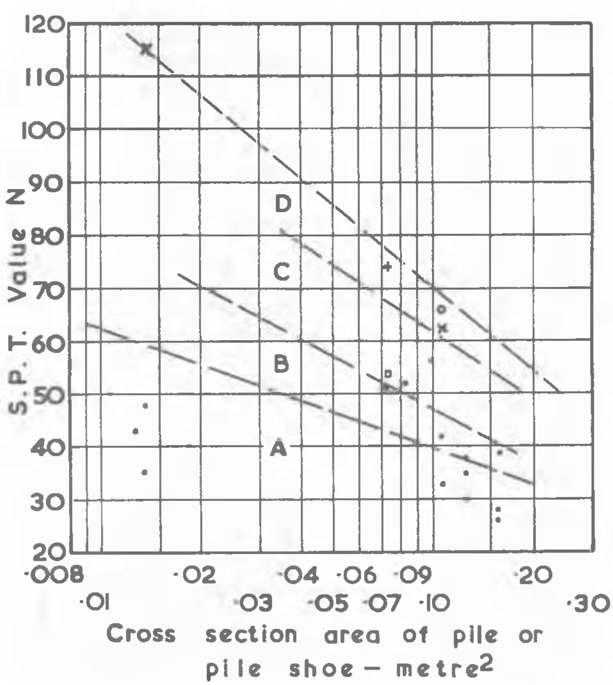

Fig.4 DRIVING IN SAND AND GRAVEL

than sandy soils for the same relative density. In agreement with this, experience with the Resonant Pile Driver shows piles can be driven into sand and gravel with relative ease where S.P.T. values indicate near refusal conditions for uniformly graded sands, Fig.4. The grading limits of the coarser soils are very approximately

D_{20} = 0.3 to 0.5mm, D_{70} = 4 to 28mm.
D_{70}/D_{20} = 3 to 60, C_r = 3 to 6

Whilst the number of case histories for uniformly graded sand produce reasonably accurate limits the limits shown on Fig.4. are obviously less definite and require verification by further observations.

Since tip resistance determines whether the pile will begin to penetrate the soil the area of any oversized pile shoe should be used where applicable when referring to Figs.3 and 4.

Group effect

Although driving by high frequency vibrations produces less general site compaction than the repeated quake caused by percussive driving, the pile displacement increases the density of the soil in the vicinity of the pile. If pile spacings are such that the zones of increased density overlap and particularly overlap the pile positions, driving will become more difficult.

This group effect, or the interference of one pile with another, can be approached theoretically using approximate relationships between the S.P.T. value, relative density and the angle of internal friction. This has been done for a group of four piles in fine sand, See Fig.5, using $_{max}$ = 43° where N =40 or more at maximum relative density, taking a zone of influence of diameter 7D centred on the pile position.

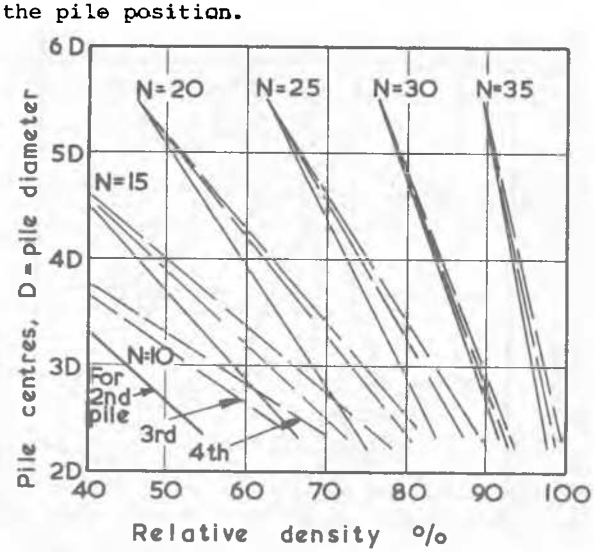

Fig.5 MAXIMUM RELATIVE DENSITY PRODUCED BY PRIOR DRIVES IN A ZONE OF DIAMETER = 4D CENTRED ON THE REMAINING PILE POSITION

It is assumed that the majority of flow paths or failure planes produced as the tip resistance is overcome are located within a zone of diameter 4D also centred on the pile position and that if the density in this zone reaches the critical value indicated on Fig.3 the resistance to driving will increase and may prevent penetration. For example a single pile with a shoe area of $0.10m^2$ can be driven through thick deposits of sand with N values of up to 30. If on a given site N=20 Fig.5 indicates that serious group effect is not likely to occur if the pile spacing exceeds about 3D.

SOFT ROCKS

Very soft, weakly cemented, friable rock whose surface structure is often affected by relatively deep weathering can be penetrated for a limited distance (2.5 to 4.5m) by displacement piles of up to $0.125m^2$ in area. Noticeable examples of such rocks are Keuper Marl, the very silty clays of the Hastings Beds, possibly the Weald clays and chalk, see U.K. sites Nos. 2, 3, 16, 18 and 19. On site No.19 U.K. a steel H pile was driven into the chalk to a total depth of 23.17m in 2.58 min. Triassic sandstone and weathered Coal Measure shales and sandstone can be penetrated 0.5 to 1.5m with low displacement steel piles but displacement piles reach refusal after approximately 0.2 to 0.5m.

TRANSMITTED VIBRATIONS

An operating frequency at least twice that of most soil types, i.e. greater than 60 Hz, is desirable if soil response or resonance is to be avoided. It is also well above the natural frequency of normal ceilings and floors which tend to be the first building members to respond to transmitted vibrations. In this respect the Resonant Pile Driver has a very real advantage over other vibratory drivers. It has been used and often specified on sites in the U.S.A. and the U.K. where piles were required 3m and often 1.5m to 1.85m away from adjoining property,

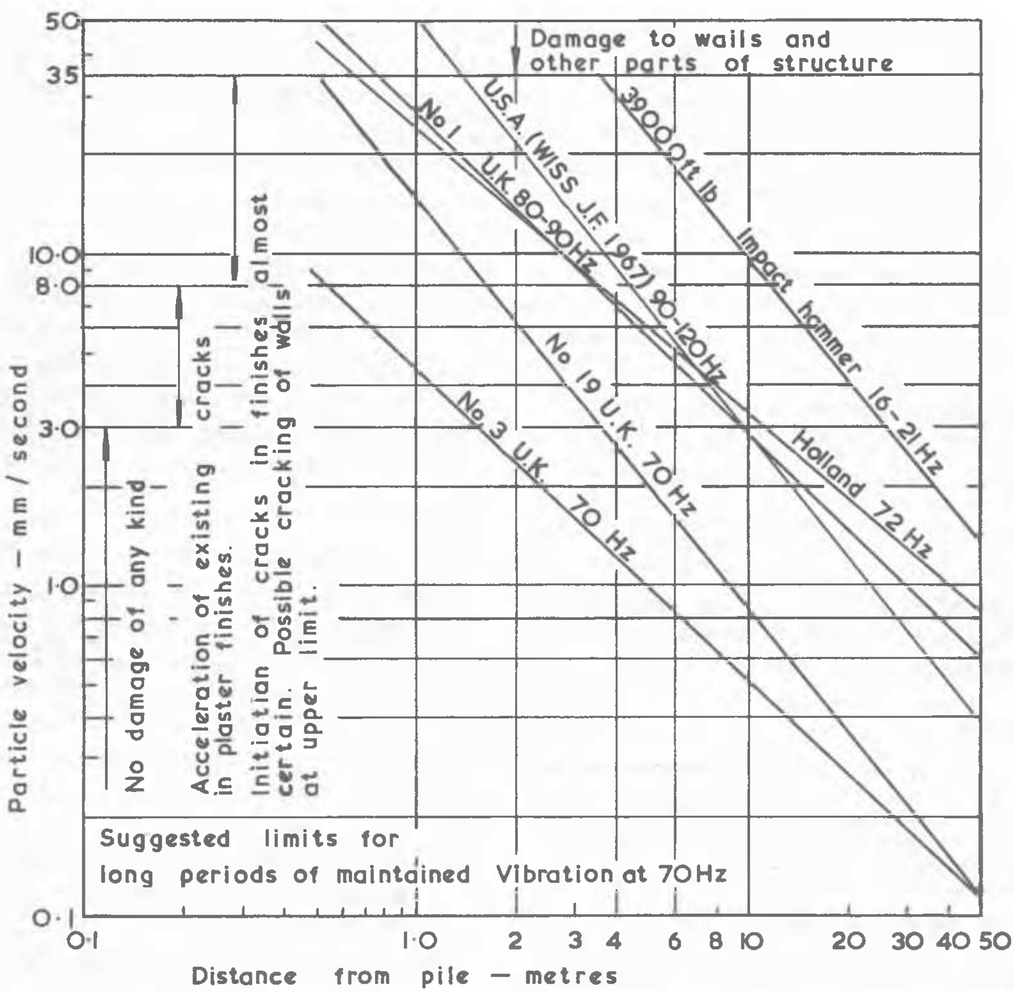

Fig.6 VARIATION OF MAXIMUM SOIL PARTICLE VELOCITY WITH DISTANCE FROM PILE

TABLE III TYPICAL PILE TEST RESULTS

	2	3	4	5	6	7	8	9	10
						Pile Settlement			
Site	Pile Length m	Nominal Pile Diameter mm	Driving Time min	Contract Working Load W_1 kN	Max. Test Load W_2 kN	at W_1 mm	at zero load mm	at W_2 mm	at zero load mm
No. 3 USA Cambridge, Mass.	12.52	356 ∇	1.04	700	2100	3.30	-	18.30	8.50
No.82 USA St.Gabriel, Louisiana	17.08	406 †	6.97	450	900	0.89	0.25	14.98	12.95
Drax Test Site	17.68	400*	12.00	1000	1900	3.38	0.51	12.25	5.38
England UK	17.37	350*	4.45	600	2000	1.46	0.25	11.16	5.06
No. 1 UK Drax, England	18.20	400*	8.0	1000	2400	2.67	0.18	16.30	7.63
No. 2 UK Avonmouth, England	19.73	350*	5.10	600	900	2.87	0.25	5.40	2.11
No. 3 UK Hastings, England	20.78	350*	10.47	500	1050	4.75	-	18.20	6.45
No. 4 UK Selby, England	19.52	330*	4.63	600	900	2.46	-	4.29	0.53
No. 7 UK Southampton, England	15.40	350*	2.65	300	1000	1.90	-	6.00	1.35
No.10 UK Glasgow, Scotland	11.60+	400*	≃4.0	700×	1900	2.70	-	18.46	13.40
No.12 UK Blackley, England	13.72	400*	10.83	800	2600	4.50	-	18.48	8.94
No.12 UK Blackley, England	25.60	box pile	15.15	1300	2600	11.63	1.98	32.90	12.13
No.13 UK Swansea, Wales	17.38	400*	8.50	600	900	1.93	1.02	3.81	1.52
No.16 UK Weston-S-Mare, England	21.96	350*	3.58	620	930	1.83	0.51	3.22	0.84
No.19 UK Canterbury, England	19.82	330*	5.02	520	800	1.17	0.25	2.03	0.25
No.19 UK Canterbury, England	21.35	330*	1.33	520	1300	1.78	0.00	11.4	7.11
No.21 UK Weston-S-Mare, England	24.10	350*	6.28	580	920	2.21	-	5.08	2.49
No.23 UK Croston England	16.47	330*	4.17	300	450	1.50	-	2.90	0.50
No.23 UK Croston, England	15.25	330*	≃5.0	300	450	2.40	-	7.0	2.00

Notes: Pile loads given on the basis of 1 ton f ≈10 kN
∇ Shell Pile † Pipe Pile *Cast in-situ Pile
+Special test pile constructed with compressible base, designed to measure friction only
× Working load for normal pile

services or equipment which were sensitive to vibration.

Fig.6 presents the results of five vibration surveys made where conditions vary from soft soils and rapid driving at Site No.3 U.K. to very dense sand prohibiting penetration of displacement piles beyond 6m at the Holland test site. The levels of vibration vary accordingly. The lines refer to maximum recorded values of particle soil velocity which occur for short periods of 5 to 10 seconds during a drive, the remainder of the drive being completed with velocities of about 50% of the maximum values. At a given distance the maximum transmitted vibrations are typically 30% to 15% of those associated with alternative forms of pile drivers.

TEST RESULTS

The reduction of soil resistance produced by the high frequency vibrations is only temporary and as shown in Table III piles under test exhibit normal load/settlement characteristics.

ADVANTAGES AND DISADVANTAGES

In common with other vibratory drivers the equipment demands a larger base machine than required for simple drop hammers. Hence larger contracts or potentially difficult soil or environmental conditions are required to offset the cost of establishing the equipment on site. In the correct soil conditions the method of piling offers advantages of speed, lack of ground quake and reduced danger from transmitted vibrations, vibrated concrete throughout the length of in-situ piles, ease of extraction of steel piles or pile tubes together with lack of damage during driving steel piles.

CONCLUSION

Contract experience demonstrates the successful application of high frequency vibrations to the problem of pile driving. The penetrating power in both cohesive and granular soils improves noticeably as the pile displacement is reduced but is seriously limited by stiff clays and uniformly graded sands of high relative density.

REFERENCES

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(2) WISS, J.F. (1967) Damage effects of pile driving vibration, Highway Research Record No. 155 p. 14-20.