EXPERIMENTALLY DERIVED RELATIONSHIP BETWEEN UNDRAINED SHEAR STRENGTH AND DRIVEN PILE SETS

A Project D report submitted in partial fulfilment of the requirements for the Degree of Master of Engineering

by

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ABSTRACT

This report presents the results of field testing relating to the driving of foundation piles using a variety of standard commercially available plant under normal operating conditions.

Piles were driven into cohesive soils in which shear strength testing was undertaken. The driving energy used and the base area of each pile were normalised on the basis of the energy input per unit area of pile base relative to the standard conditions of NZS:3604 Appendix D.

A relationship between shear strength and normalised pile set has been derived. A practical application of the relationship is presented as an aid to foundation design practitioners.

Ultimate pile capacities were evaluated on a theoretical basis and compared with pile testing undertaken for the preparation of NZS:3604 Appendix D. Recommendations are made regarding the use of static and dynamic pile capacity formulae.

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1. INTRODUCTION

1.1 Background

Since the introduction of NZS:3604 in 1978 many thousands of light timber framed structures have been successfully erected with foundations constructed using driven piles installed in accordance with Appendix D of that standard.

Appendix D specifies pile dimensions, minimum pile driving energy input and for design purposes gives a table of maximum pile sets of 25 mm, 50 mm, or 100 mm for different combinations of floor, wall and roof loadings together with joist spans and pile spacings. (Ref. 7)

Designers of these structures have always faced a difficulty in predicting the depths at which the pile driving set criterion will be achieved especially in deeply weathered soils. If piles are too shallow and the design set is not achieved, additional longer piles must be driven or a closer pile spacing used. If piles are too long material wastage occurs when pile tops are cut off.

In practice the initial piles driven on a site are effectively test piles. Following their driving pile lengths and spacings are modified as required. Most piling contracts however are let on a lump sum basis requiring a reasonable estimate of pile lengths to be made at the time of tendering.

Economies could be achieved in the design of bearers and the selection of pile spacings if information was made available to the designers enabling them to estimate the founding depths at which different pile sets would occurred.

A simple relationship has not been available whereby soil testing data from a typical geotechnical investigation could be related to the design pile set criterion of NZS:3604 giving an anticipated pile founding depth.

1.2 Objectives

The initial objectives of this research were:

(1) To perform a series of pile driving tests using a variety of standard commercially available plant under normal operating conditions.

(2) To drive piles comprising differing materials, diameters and lengths into cohesive soils of widely ranging strength characteristics.

(3) To define a series of acceptance criteria to ensure that only high quality data is used in the analysis.

(4) To derive a relationship between a soil parameter readily measurable by field testing, and pile sets normalised to NZS:3604 Appendix D driving criteria.

During the course of the research information became available leading to a broadening of the objectives :

(5) To compare the ultimate capacity of driven piles using dynamic analysis, static analysis, and relationships derived from pile load testing for NZS:3604.

2. TEST SITES

2.1 Introduction

Pile testing was performed under the author's direction in conjunction with geotechnical investigations and the construction of foundations on residential and commercial projects in the Auckland area. These projects were constructed over several years and were undertaken as a normal part of the consulting engineering work in which the author is engaged. During the period of enrolment for Project D further testing was undertaken to augment the earlier material.

Pile testing data was obtained from the raw test results of about 1000 driven piles installed at over 30 sites. Following the implementation of the pile test acceptance criteria (outlined in Section 4.2) this data base was reduced to 31 piles located at seven sites in the Auckland area.

2.2 Locations

The localities of the seven sites in the Auckland area from which pile driving test data was obtained for use in this study are shown on Fig. 2.1. General information about each site is given in Table 2.1.

2.3 Borehole Drilling

At each locality a geotechnical investigation was undertaken in conjunction with the foundation design for the particular structures to be erected. Boreholes were drilled and subsoil information obtained from which pile design criteria were evaluated.

The borehole drilling methods were chosen according to the anticipated soil conditions and pile founding depths. At all sites except D and F hand augered boreholes of 70 mm diameter were drilled until a target depth of usually 5 m was

reached or the high strength of the soil prevented further augering.

Shear strengths were measured at regular intervals down the boreholes using a Pilcon shear vane. Soil samples were taken for further examination and laboratory testing. Most boreholes were extended using a Scala penetrometer until effective refusal with this device was reached (three consecutive blow counts of ten or more blows per 50 mm increment).

At sites D and F the site geology indicated that the depth to the underlying basement materials was in the 20 m to 30 m range, consequently machine boreholes were drilled. Continuous coring was taken with Pilcon shear vane testing in each core run prior to extrusion. In the higher strength or sandy materials standard penetration tests (SPT) were undertaken. Pocket penetrometer testing was also used.

The logs of boreholes from sites A to F are attached in Appendix A.

2.4 Soil Conditions

At all sites except D and F soil types comprised residual silts and clays formed by weathering of the Waitemata Formation . Undrained shear strengths (s_u) in these materials at the level at which sets were measured varied from 54 kPa to 250 kPa with remoulded shear strengths of 27 kPa to 79 kPa. Sensitivity ratios ranged from 1.6 to 2.7 indicating that the soils were of low sensitivity.

At sites D and F soil types comprised Pleistocene alluvium in the form of silts and clays. Undrained shear strengths (s_u) at the pile tips varied from 30 kPa to 160 kPa with remoulded shear strengths of 12 kPa to 63 kPa. Sensitivity ratios ranged from 1.9 to 2.5 indicating that these soils were also of low sensitivity.

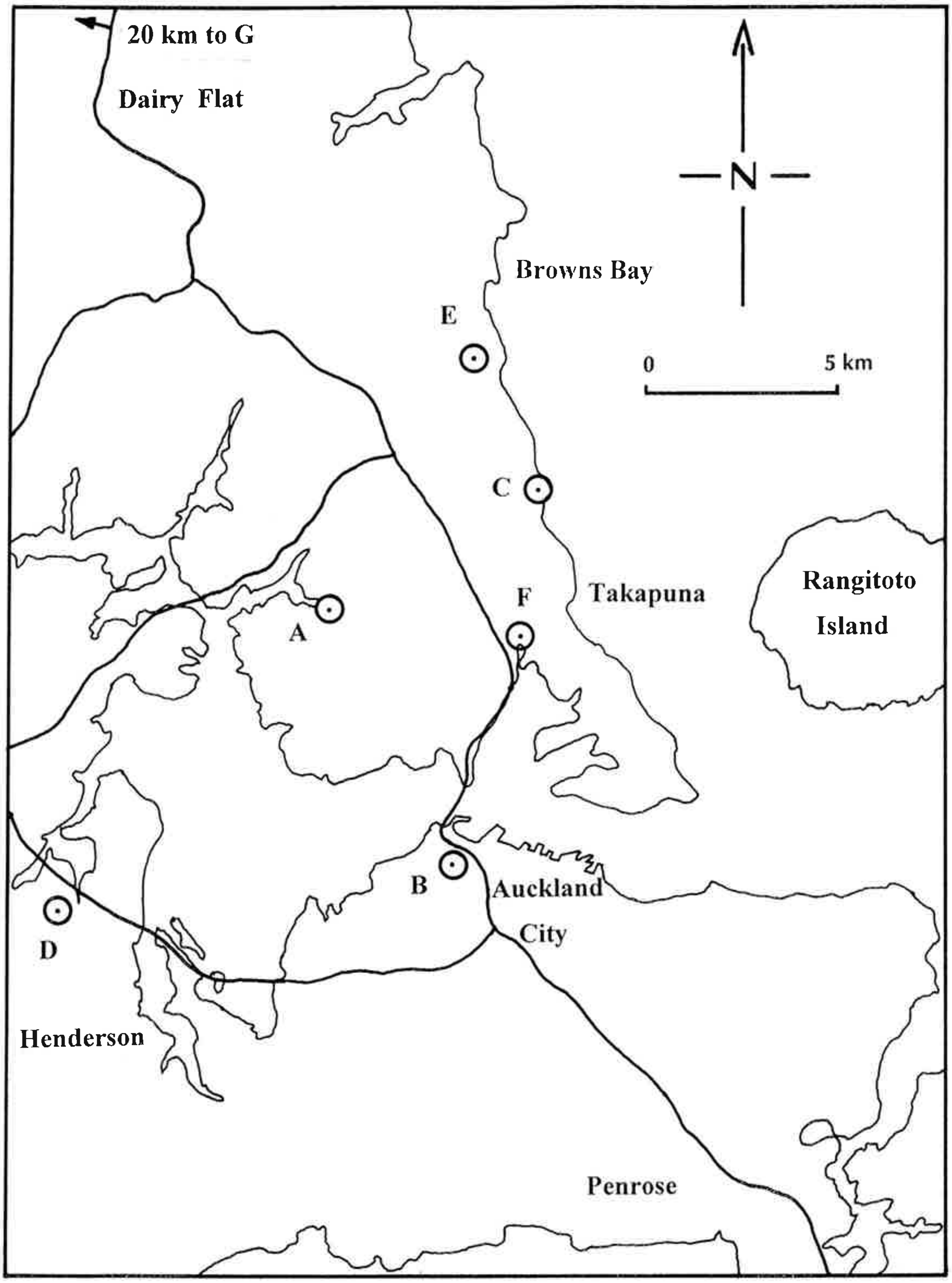

Fig. 2.1 Locations of Pile Test Sites

Test Ref No	Site Location	Soil Type	Soil Description
1	A - Stephanie Cl. Glenfield	Residual Waitemata	Silt some sand, trace clay, sl.-mod. plastic, light grey with orange staining.
2	B - Melford St. St. Marys Bay	Residual Waitemata	Silt, clayey white- grey orange.
3	"	Residual Waitemata	"
4	"	Residual Waitemata	"
5	"	Residual Waitemata	"
6	"	Residual Waitemata	"
7	"	Residual Waitemata	Silt clayey, white grey yellow brown.
8	"	Residual Waitemata	"
9	"	Residual Waitemata	Clay silty, yellow white grey.
10	"	Residual Waitemata	Clay sl. silty, white grey orange.
11	"	Residual Waitemata	"
12	C - The Esplanade Castor Bay	Residual Waitemata	Clay silty, light grey mottled orange.
13	"	Residual Waitemata	"
14	"	Residual Waitemata	"
15	"	Residual Waitemata	"
16	"	Residual Waitemata	"
17	"	Residual Waitemata	"
18	"	Residual Waitemata	"
19	"	Residual Waitemata	"
20	"	Residual Waitemata	Silt sl. clayey, yellow brown limonite staining, occasional grey mottles.
21	"	Residual Waitemata	"
22	D - Lincoln Rd. Lincoln	Pleistocene Alluvium	Clay silty, highly plastic, light grey, orange mottles.
23	"	Pleistocene Alluvium	Silt sandy, low plasticity, light grey, orange mottles.
24	E - Seaton Rd. Murrays Bay	Residual Waitemata	Silt sandy, sl. plastic, light grey, yellow brown.
25	F - Barry's Point Rd. Takapuna	Pleistocene Alluvium	Clay, trace sand, highly plastic, grey with black organic fragments.
26	"	Pleistocene Alluvium	Clay, trace sand, highly plastic, greenish-grey with black organic fragments.
27	"	Pleistocene Alluvium	Clay , highly plastic when remoulded, grey.
28	G - Pinchgut Rd. Kuakapakapa	Residual Waitemata	Silt trace sand, non plastic, lt.grey orange mottles, weathered siltstone gravel.
29	"	Residual Waitemata	Silt trace sand, non plastic, lt.grey orange mottles, rootlets.
30	"	Residual Waitemata	Silt trace sand, non plastic, lt.grey orange mottles, weathered siltstone gravel.
31	"	Residual Waitemata	Silt trace sand, non plastic, lt.grey orange mottles, rootlets.

Table 2.1 General Site Information

3 PILE DRIVING EQUIPMENT

3.1 Introduction

The piles installed at the seven sites in this study were driven by standard commercially available equipment. Five different pile driving companies were involved and each rig was built to suit a particular process and the ease and economy with which piles could be installed by the specialist contractors in competitive tendering situations.

3.2 Pile Driving Rigs

The types of vehicle on which the rigs were mounted included the following:

(1) Four wheel drive trucks and tractors with hammer weights of up to 320 kg. The light weight of these machines and their manouverability allowed access to difficult sites but generally limited their use to domestic situations requiring smaller piles.

(2) Track mounted hydraulic excavators with hammer weights of up to 560 kg. The masts on these larger machines were capable of accommodating longer piles of larger diameter capable of resisting greater loads.

(3) Track mounted crane rigs of up to 35 tonne with hammer weights of up to 3200 kg. These large rigs could instal piles in sections of up to 12 m length which were then connected to the previously driven section using the appropriate method for the type of pile material. The application of these large piles is usually limited to commercial sites.

3.3 Driving Hammers

At all test sites pile driving rigs used drop hammers for driving the piles. Two different types of hammer release mechanism were used, clutch released or hydraulic released.

3.3.1 Clutch Release Mechanisms

On sites A, D, F and G, hammer weights ranged from 180 kg to 3200 kg and were lifted by a wire cable and winch. When a clutch on the winding drum was released the falling hammer dragged the cable reversing the direction of the drum and allowing the hammer to fall onto the pile head .

The use of this type of driving method presented the following difficulties:

(1) To control the drop height the operator read markings on the mast of the rig often at steep angle up from the position where the controls were located. The operator adjusted the hammer lift height by eye estimating the difference between the top and bottom of the pile stroke, (usually within a tolerance of about 5% to 10%).

(2) At the bottom of each stroke the operator applied the brake on the winding drum, preventing the drum from over running and tangling the cable, then disengaged the clutch to lift the hammer for the next stroke. These operations took a fraction of a second to perform. If the brake was applied before the instant of hammer impact the hammer acceleration would be reduced before hitting the pile but sufficient stretch in the cables would take place to still allow the impact to occur.
The timing of the brake application could therefore vary the energy input considerably. When an accurate set measurement was required however, operators usually concentrated closely to give the maximum energy input.

3.3.2 Hydraulic Release Mechanisms

On sites B, C and E, hammer weights ranged from 275 kg to 560 kg and a variation on the above driving method was used. A double acting hydraulic ram pulled the cable raising the hammer. At the end of a one metre stroke the hydraulics returned the ram quickly to its initial position causing minimal resistance to the cable and hammer. The design of the hammer assembly allowed for the set of the pile following the previous hammer blow maintaining a standard one metre hammer drop height.

3.4 Pile Helmets and Driving Caps

With the smaller timber piles the driving hammers fell directly onto the pile head without the use of pile helmets or driving caps. These piles were not subject to hard driving onto bedrock and consequently the pile heads were not usually damaged by this installation method. Where minor damage did occur sufficient excess pile length was usually available to enable the pile top to be sawn off.

In the case of the steel tube piles a short dolly with timber packing over a steel cap was used. The timber packing was replaced after driving every few piles.

Driving of the reinforced concrete piles was achieved using a short helmet with a synthetic lurethane laminated packer. This packer cushions the blow on the concrete and unlike timber will not char when subjected to the heat generated by prolonged driving. (Ref. 10 & 13)

4. PROCEDURE

4.1 Introduction

This section describes a set of criteria applied to the raw pile data base to determine the suitability of data for inclusion in the study. The methods used for pile set measurement are also presented.

4.2 Pile Test Acceptance Criteria

In order to ensure that high quality data was used in the analysis, a set of acceptance criteria was formulated with respect to pile installation and soil testing results. To be included in the data base of the study each of the following nine pile test acceptance criteria conditions had to be met:

(1) Piles needed to be located within 3 metres of a borehole, unless multiple boreholes drilled on the site indicated that minimal lateral variability of soil conditions occurred in the area where the piles were installed.

(2) The soil conditions over the depth where the set was measured were found to be uniform in the adjacent borehole.

(3) Boreholes were tested at regular intervals using a hand held Pilcon Shear Vane calibrated in accordance with BS1377 within the previous 12 months.

(4) Piles driven into cohesive materials only were considered (silts and clay). (Data from non-cohesive soils in which scala penetrometer testing was undertaken was initially included but discounted due to inconsistency of results. Scala testing often has additional friction on the rods during testing and results can vary laterally especially when the depth is approaching an interface with stronger underlying materials.)

(5) During pile installation the pile sets, hammer drop heights, pile diameters (top and bottom) and lengths were all accurately measured.

(6) The formed building platform on which piles were driven was accurately levelled relative to the positions from which boreholes were drilled.

(7) When piles were driven through high strength material lubricants (eg. water), were not used to reduce the driving resistance.

(8) The piles were driven continuously without delays which would otherwise give an apparent set improvement with time as excess pore water pressures dissipated and shaft skin friction took effect.

(9) The pile ends were square and the hammer drops axial.

From the raw data base of 1000 test piles available for potential inclusion in the study, it was found that only 31 piles met all the above acceptance criteria. The project analysis uses test data from these piles.

4.3 Pile Set Measurement

At the seven sites used in this study pile set measurements were recorded using the techniques normally used by each of the piling contractors. On some sites cardboard set cards were attached to piles and a datum beam held close to the pile allowing a pencil mark to be made during driving. On other sites a chalk mark was made directly onto the pile.

All piles were driven to either a pre-defined depth below ground level, refusal or a minimum set in accordance with NZS:3604 Appendix D driving requirements. Consequently temporary compression measurements were not always recorded.

5. TEST RESULTS

5.1 Introduction

Borehole soil testing data together with data recorded from pile testing in accordance with Section 4 is presented and discussed.

5.2 Soil Testing Data

The results of field shear strength testing using a Pilcon shear vane are given in Table 5.1. Peak and remoulded shear strengths are recorded for the level at which sets were measured. Soil sensitivity ratios of peak to remoulded shear strength are also given.

Peak and remoulded shear strengths were measured over the driven depth of each pile shaft and the mean shear strength calculated applying a weighting for the thicknesses of the various layers identified on the borehole logs. Any other tests which were undertaken on the soil at the pile base level are also included.

5.3 Pile Driving Data

Table 5.2 records the data obtained from each pile driving test. Pile materials comprised predominantly Tanilised timber (26 piles) with 2 piles being spiral welded steel tube and 3 piles using steam cured reinforced concrete.

The diameters of pile tops and bases were measured together with pile lengths allowing pile masses to be calculated. Pile densities were assumed to be 600 kg/m^3 for timber (following discussions with pile installers (Ref. 4 & 6)), 7850 kg/m^3 for steel and 2400 kg/m^3 for reinforced concrete. Hammer masses recorded were as given by each contractor. Driven pile depths, hammer drop height and driving sets per were recorded by the author or staff working under his direction.

Test Ref No	Site Pile Ref No	Dist. from Pile to BH	Fnd.Level on Borelog	Fnd.Level Su (Peak) Corr. (kPa)	Fnd.Level Su (Rem) Corr. (kPa)	Fnd.Level Su (Pk+Rem)/2 Corr. (kPa)	Fnd.Level Sensitivity Ratio	Fnd.Level Other Tests	Mean Shaft Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)
1	#1	0.5m to BH1	1.2	140	69	105	2.0		145	80
2	#1	1.5m to BH2	2.6	100	43	72	2.3		94	43
3	#2	3.9m to BH2	1.6	95	54	75	1.8		87	43
4	#8	2.0m to BH2	2.3	108	46	77	2.3		98	45
5	#14	2.9m to BH2	3.2	54	27	41	2.0		85	41
6	#17	2.6m to BH1	2.3	92	48	70	1.9		89	47
7	#24	1.6m to BH1	2.8	111	54	83	2.1		70	37
8	#25	2.8m to BH1	2.4	111	54	83	2.1		64	34
9	#29	1.6m to BH1	3.0	73	41	57	1.8		72	38
10	#30	0.8m to BH1	3.1	73	41	57	1.8		73	39
11	#31	2.6m to BH1	2.9	73	41	57	1.8		72	38
12	#5	2.9m to BH5	2.7	132	79	106	1.7		128	70
13	#13	2.4m to BH5	2.1	132	71	102	1.9		128	74
14	#14	1.0m to BH5	2.0	132	71	102	1.9		127	74
15	#15	1.6m to BH5	2.0	132	71	102	1.9		127	74
16	#16	0.4m to BH5	2.6	132	79	106	1.7		126	74
17	#19	2.2m to BH5	2.0	132	71	102	1.9		127	74
18	#20	2.0m to BH5	2.0	132	71	102	1.9		127	74
19	#21	2.6m to BH5	2.2	132	71	102	1.9		128	74
20	#25	2.9m to BH2	2.7	154	-	-	-	WC 42	145	-
21	#27	3.7m to BH2	2.9	200 *	-	-	-		148	-
22	#B 21	1.8m to BH3	3.4	30	12	21	2.5		95	47
23	#B 21	1.8m to BH3	8.4	52	-	-	-	WC 41 LL 63, PI 38	58	26
24	#33	2.9m to BH 1	4.3	250 *	-	-	-		140	64
25	#P 7	4.8m to BH3	15.2	83	35	59	2.4	WC 56	92	30
26	#P 7	4.8m to BH3	19.7	107	55	81	1.9		95	36
27	#P 7	4.8m to BH3	23.7	160	63	112	2.5	WC 47	100	39
28	#1	0.6m to BH1	2.0	73	46	60	1.6		158	59
29	#1	0.6m to BH1	3.0	103	38	71	2.7		141	51
30	#2	2.6m to BH1	2.0	73	46	60	1.6		158	59
31	#2	2.6m to BH1	3.0	103	38	71	2.7		141	51

* Estimated

Table 5.1 Soil Testing Data

Test Ref No	Pile Type	Pile base Dia. (mm)	Pile top Dia. (mm)	Pile Length (Total, m)	Pile Mass (kg)	Driven Depth (m)	Hammer Mass (kg)	Drop Height (m)	Set/Blow Rec. (mm)
1	Timber	140	155	2.0	21	1.2	180	1.0	8.5
2	Timber	145	165	3.0	34	2.6	320	1.5	30
3	Timber	145	165	3.0	34	1.6	320	1.5	35
4	Timber	160	180	3.6	49	2.0	320	1.5	27
5	Timber	150	175	3.6	45	2.0	320	1.5	45
6	Timber	145	170	3.6	42	1.8	320	1.5	40
7	Timber	175	200	4.2	70	2.0	320	1.5	30
8	Timber	170	195	4.2	66	2.0	320	1.5	25
9	Timber	170	195	4.2	66	2.2	320	1.5	30
10	Timber	170	195	4.2	66	2.1	320	1.5	35
11	Timber	170	195	4.2	66	2.0	320	1.5	35
12	Timber	175	195	3.0	49	2.0	275	1.8	20
13	Timber	150	165	2.4	28	1.9	275	1.8	18
14	Timber	150	165	2.4	28	1.8	275	1.8	21
15	Timber	150	165	2.4	28	1.8	275	1.8	20
16	Timber	175	195	3.0	49	2.4	275	1.8	11
17	Timber	150	165	2.4	28	1.8	275	1.8	24
18	Timber	150	165	2.4	28	1.8	275	1.8	25
19	Timber	175	195	3.0	49	2.0	275	1.8	25
20	Timber	175	200	4.2	70	3.4	275	1.8	5.5
21	Timber	175	200	4.2	70	3.6	275	1.8	7
22	Steel Tube	250	250	11.0	780	3.0	3100	1.2	200
23	Steel Tube	250	250	11.0	780	8.0	3100	1.2	144
24	Timber	150	175	4.2	53	3.9	560	0.9	10
25	Concrete	275 x 275	275 x 275	18.0	3267	14.0	3200	1.0	75
26	Concrete	275 x 275	275 x 275	27.0	4901	18.5	3200	1.0	47
27	Concrete	275 x 275	275 x 275	27.0	4901	22.5	3200	1.0	28
28	Timber	200	225	4.2	90	2.0	545	0.9	22
29	Timber	200	225	4.2	90	3.0	545	0.9	16
30	Timber	200	225	4.2	90	2.0	545	0.9	26
31	Timber	200	225	4.2	90	3.0	545	0.9	15

Table 5.2 Pile driving Data

6 ANALYSIS OF RESULTS

6.1 Introduction

In order to evaluate the results from Section 5 using data from piles of different diameter driven with varying energy levels, the measured sets have been normalised using three alternative methods:

6.2 Gross Energy Input

In this method recorded pile sets are normalised by applying a factor to give an energy input per unit area of pile base equivalent to the minimum which would be achieved under NZS:3604 Appendix D.

Piles installed in accordance with NZS:3604 1990 Appendix D Section 5.1 are required to be driven:

> *"..by a hammer having a mass M of not less than 200 kg falling freely through a distance h of not less than 480/M metres (where M is in kilograms)... The free fall of the hammer has been defined so as to ensure that the hammer will deliver to the top of the pile not less than 4800 J of energy per blow.* (Ref. 7)

This is a gross energy input and was based on the original 1974 research data for Appendix D in which the hammer mass was 450 lb (204 kg) and the drop height 94.5 in (2.40 m). (Ref. 2)

$$W.g.h = 204 \times 9.81 \times 2.40 = 4803 \text{ J}$$

A tractor mounted fence post driving rig was used with the hammer being lifted by a wire cable attached to a pulley system activated by a hydraulic ram. This was a similar system to the hydraulic release mechanism outlined in section 3.3.2 above. The net energy delivered to the pile head was assessed applying an 80% efficiency factor to the hammer drop height. (Ref. 2)

In normalising the sets on a gross energy input basis the gross energy delivered to the head of each pile tested in the current study was divided by 4800 to give the Gross Energy Ratio in Table 6.1.

Allowance has been made for the variation in pile base area by dividing the base area of each pile by the minimum pile area allowed in NZS:3604 (a 140 mm dia. pile driven small end first), to give the Area Ratio in Table 6.1.

The above two ratios are combined by dividing the Area Ratio by the Gross Energy Ratio to give the Normalising Factor (Gross) which is applied to the recorded sets giving the Set/Blow Norm (Gross). The resulting variation in shear strength with normalised set is plotted in Fig. 6.1 giving a relationship with a comparatively small scatter.

Regression analysis was undertaken as detailed in Appendix B with the resulting best fit curve:

$$s_{U\,(PEAK)} = 240\, e^{-0.02322\,SET}$$

or in terms of set:

$$set = 236 - 43.1 \log_e s_{U\,(PEAK)}$$

This relationship is plotted on Fig. 6.1 and gives 86.21% explained variation with comparatively low residuals.

The above formulae are limited to a reliable range of about 30 kPa and 200 kPa peak corrected shear strength. The set is normalised as explained previously.

Other relationships which are presented in Sections 6.3 and 6.4 do not achieve as good a correlation. Appendix C details the practical application of the upper formula with typical examples working through the Normalising Factor (Gross).

Test Ref No	Hammer Mass (kg)	Drop Height (m)	Gross Energy Input (J)	Gross Energy Ratio	Area Ratio	Normalising Factor (Gross)	Set/Blow Rec. (mm)	Set/Blow Norm. (mm) (Gross)
1	180	1.0	1766	0.37	1.00	2.72	8.5	23
2	320	1.5	4709	0.98	1.07	1.09	30	33
3	320	1.5	4709	0.98	1.07	1.09	35	38
4	320	1.5	4709	0.98	1.31	1.33	27	36
5	320	1.5	4709	0.98	1.15	1.17	45	53
6	320	1.5	4709	0.98	1.07	1.09	40	44
7	320	1.5	4709	0.98	1.56	1.59	30	48
8	320	1.5	4709	0.98	1.47	1.50	25	38
9	320	1.5	4709	0.98	1.47	1.50	30	45
10	320	1.5	4709	0.98	1.47	1.50	35	53
11	320	1.5	4709	0.98	1.47	1.50	35	53
12	275	1.8	4856	1.01	1.56	1.54	20	31
13	275	1.8	4856	1.01	1.15	1.13	18	20
14	275	1.8	4856	1.01	1.15	1.13	21	24
15	275	1.8	4856	1.01	1.15	1.13	20	23
16	275	1.8	4856	1.01	1.56	1.54	11	17
17	275	1.8	4856	1.01	1.15	1.13	24	27
18	275	1.8	4856	1.01	1.15	1.13	25	28
19	275	1.8	4856	1.01	1.56	1.54	25	39
20	275	1.8	4856	1.01	1.56	1.54	5.5	8
21	275	1.8	4856	1.01	1.56	1.54	7	11
22	3100	1.2	36493	7.60	3.19	0.42	200	84
23	3100	1.2	36493	7.60	3.19	0.42	144	60
24	560	0.9	4944	1.03	1.15	1.11	10	11
25	3200	1.0	31392	6.54	4.91	0.75	75	56
26	3200	1.0	31392	6.54	4.91	0.75	47	35
27	3200	1.0	31392	6.54	4.91	0.75	28	21
28	545	0.9	4812	1.00	2.04	2.04	22	45
29	545	0.9	4812	1.00	2.04	2.04	16	33
30	545	0.9	4812	1.00	2.04	2.04	26	53
31	545	0.9	4812	1.00	2.04	2.04	15	31

Table 6.1 Normalised Sets (Gross Energy Basis)

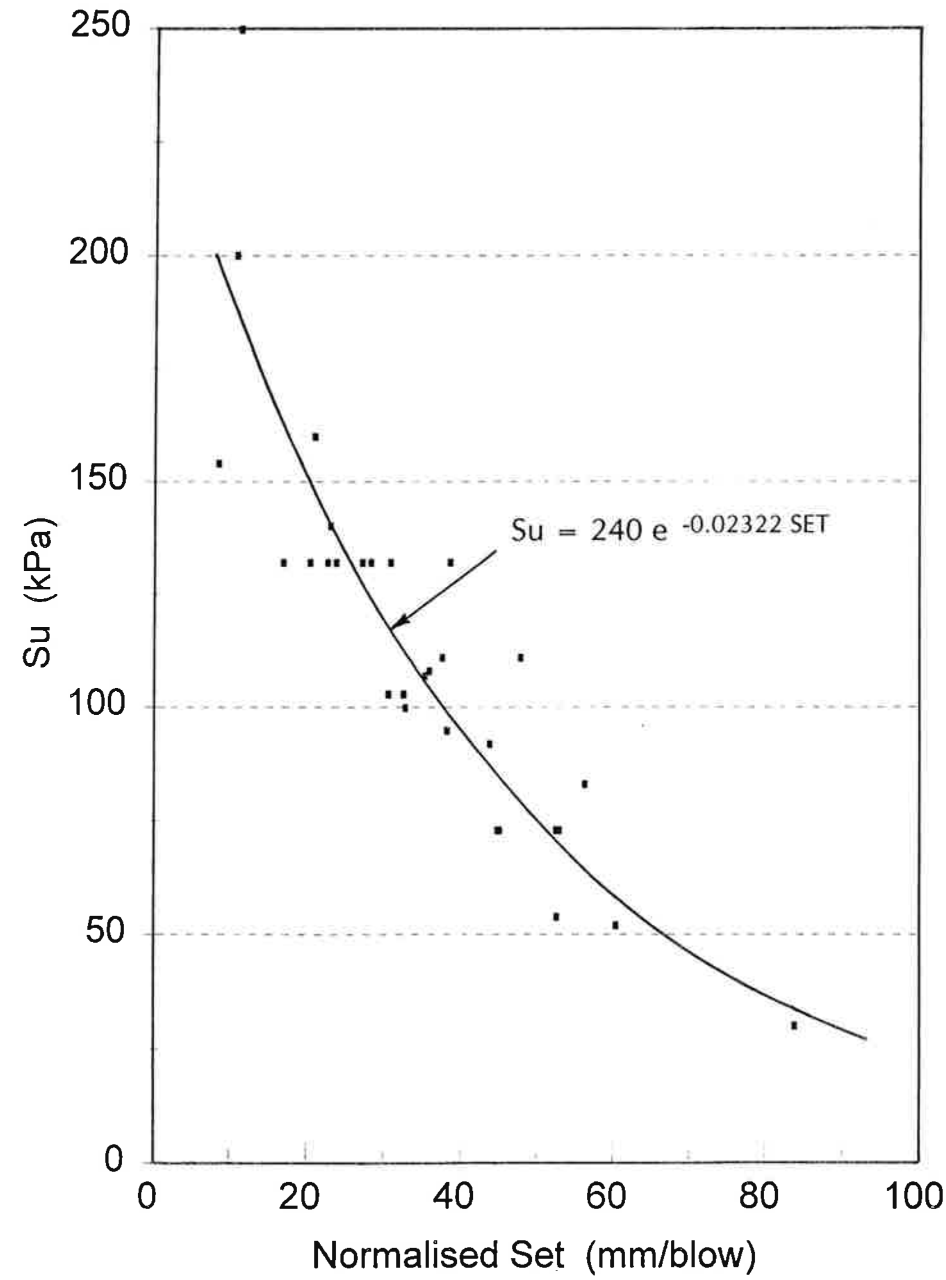

Fig. 6.1 Shear Strength vs. Normalised Set(Gross Energy Basis)

6.3 Net Energy Input

The normalised set in Fig. 6.1 does not take account of the large difference in net energy transmitted to each pile and available to cause the driving action. In this method the previous approach is extended by making an allowance for the variation in efficiency factors for hammer drop heights, coefficients of restitution and hammer blow efficiencies. These factors together determine the net energy input at the pile top which can then be compared with the standard energy available under NZS:3604 driving conditions to produce a set which has been normalised on a net energy basis.

In Table 6.2 an 80% efficiency factor has been applied to all hammer drop heights. There is some debate from pile driving companies that this is too conservative especially with the hydraulically operated release mechanisms. In the absence of any specific test data on individual rigs the general value given in literature was adopted. (Ref. 1)

The coefficient of restitution (e) varies with the type of pile driving hammer, pile material and pile head condition (helmet, packing, dolly, driving cap, etc.). Three different values of (e) were applied to the piles used in the study as follows:

(1) Drop hammers striking the tops of timber piles, e = 0.25.

(2) Drop hammers driving steel tube piles with a short dolly and timber packing over a steel cap, e = 0.32.

(3) Drop hammers driving reinforced concrete piles with a short helmet and synthetic lurethane synthetic packer, e = 0.40. (Ref. 13)

Blow efficiency (n) calculations then follow using the relationship:

$$n = \frac{W + Pe^2}{W + P}$$

where: W = hammer weight

P = pile weight

e = coefficient of restitution

(Ref. 1)

The Net Energy Input is calculated from:

$$E_{NET} = \text{hammer mass} \times g \times \text{drop height} \times \text{hammer efficiency} \times \text{blow efficiency}$$

The Net Energy Ratio is the ratio of the Net Energy Input for each pile to the Net Energy Input for a standard 140 mm dia. pile driven to NZS:3604 conditions as given in Section 6.2 above. It is assumed that this standard pile is of 2.7 m length (the mean pile length covered by the standard), and that the taper complies with NZS:3605 1977, *Specification For Load Bearing Round Timber Piles and Poles.* (Ref. 8). At a density of 600 kg/m^3 the pile mass is 28.15 kg giving the following net energy calculation using the above equation:

$$E_{NET\ 3604} = 200 \times 9.81 \times 2.4 \times 0.8 \times \frac{200 + 28.15 \times 0.25^2}{200 + 28.15}$$

$$= 3331 \text{ J}$$

The Net Energy Ratio and the Area Ratio are combined to give the Normalising Factor (Net) which is applied to the recorded sets giving the Set/Blow Norm (Net).

The resulting variation in shear strength with normalised set is presented graphically in Fig. 6.2. Attention is drawn to the locations of the numbered points corresponding to the four piles with greatest driven depth, (more than 4 m). Three of these points have moved a significant distance from the best fit line when the normalising factor includes the net energy, (compared with Fig. 6.1). Reference to Fig. 6.2 shows that for these piles the Net Energy Ratio has almost halved from the previous gross energy ratio. This is due mainly to the low blow efficiencies used (0.49 to 0.58) compared with the other piles (0.81 to 0.92), and increased coefficient of restitution (0.40) compared with (0.25 to 0.32). These variations occur partly as a result of the large pile masses involved (up to 4901 kg).

Test Ref No	Coeff. of Rest. (e)	Blow Eff (n)	Net Energy Input (J)	Net Energy Ratio	Area Ratio	Normalising Factor (Net)	Set/Blow Rec. (mm)	Set/Blow Norm. (mm) (Net)
1	0.25	0.90	1277	0.38	1.00	2.61	8.5	22
2	0.25	0.91	3427	1.03	1.07	1.04	30	31
3	0.25	0.91	3427	1.03	1.07	1.04	35	36
4	0.25	0.88	3296	0.99	1.31	1.32	27	36
5	0.25	0.88	3331	1.00	1.15	1.15	45	52
6	0.25	0.89	3354	1.01	1.07	1.07	40	43
7	0.25	0.83	3134	0.94	1.56	1.66	30	50
8	0.25	0.84	3161	0.95	1.47	1.55	25	39
9	0.25	0.84	3161	0.95	1.47	1.55	30	47
10	0.25	0.84	3161	0.95	1.47	1.55	35	54
11	0.25	0.84	3161	0.95	1.47	1.55	35	54
12	0.25	0.86	3338	1.00	1.56	1.56	20	31
13	0.25	0.91	3547	1.06	1.15	1.08	18	19
14	0.25	0.91	3547	1.06	1.15	1.08	21	23
15	0.25	0.91	3547	1.06	1.15	1.08	20	22
16	0.25	0.86	3338	1.00	1.56	1.56	11	17
17	0.25	0.91	3547	1.06	1.15	1.08	24	26
18	0.25	0.91	3547	1.06	1.15	1.08	25	27
19	0.25	0.86	3338	1.00	1.56	1.56	25	39
20	0.25	0.81	3147	0.94	1.56	1.65	5.5	9
21	0.25	0.81	3147	0.94	1.56	1.65	7	12
22	0.32	0.82	23927	7.18	3.19	0.44	200	89
23	0.32	0.82	23927	7.18	3.19	0.44	144	64
24	0.25	0.92	3637	1.09	1.15	1.05	10	11
25	0.40	0.58	14457	4.34	4.91	1.13	75	85
26	0.40	0.49	12352	3.71	4.91	1.32	47	62
27	0.40	0.49	12352	3.71	4.91	1.32	28	37
28	0.25	0.87	3340	1.00	2.04	2.04	22	45
29	0.25	0.87	3340	1.00	2.04	2.04	16	33
30	0.25	0.87	3340	1.00	2.04	2.04	26	53
31	0.25	0.87	3340	1.00	2.04	2.04	15	31

Table 6.2 Normalised sets (Net Energy Basis)

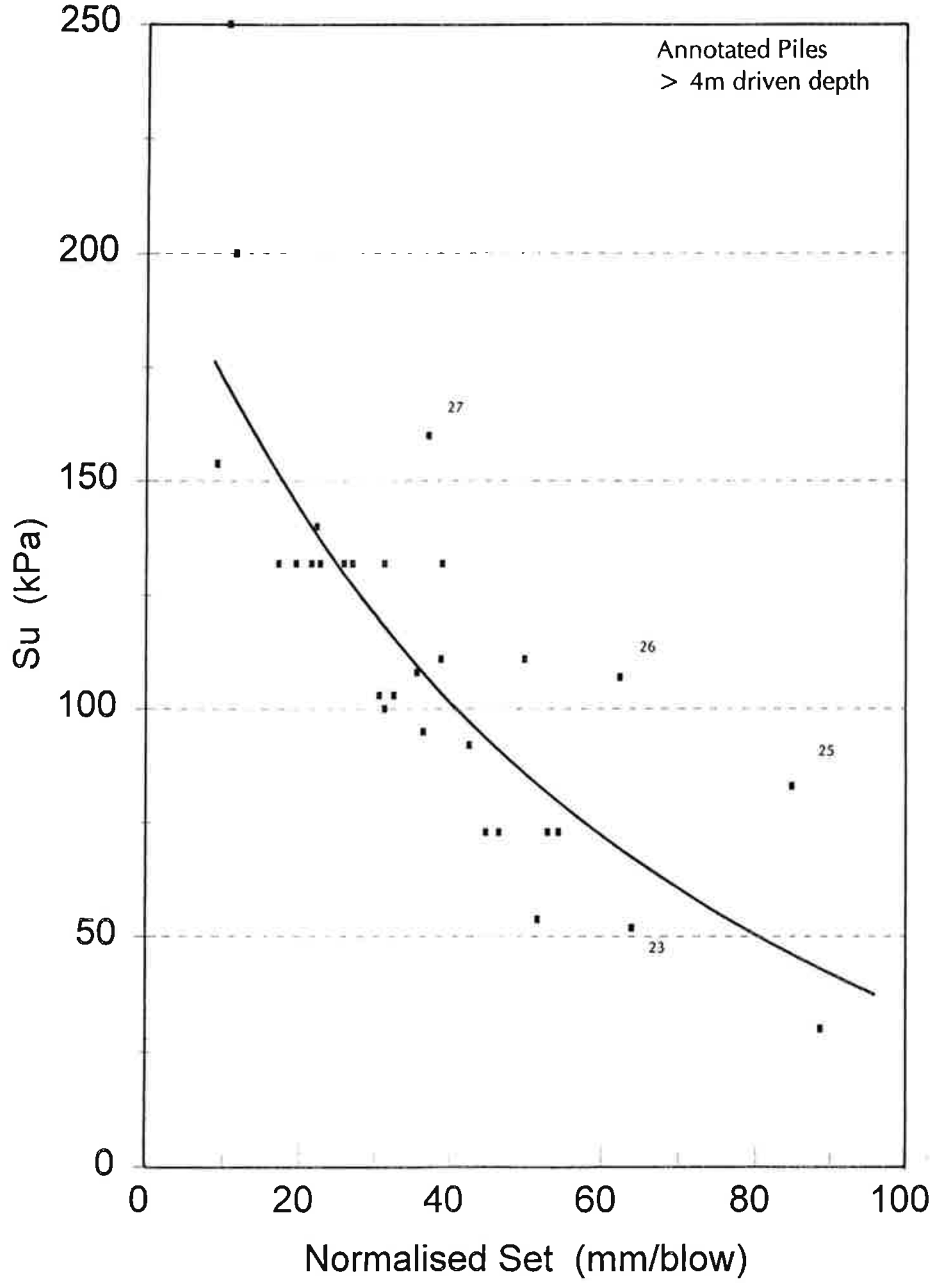

Fig. 6.2 Shear Strength vs. Normalised Set (Net energy Basis)

6.4 Shaft Resistance

In this method an allowance is made for the energy absorbed during driving due to skin friction on the pile shaft.

During the driving of the longer piles (8 m to 22.5 m, Test Ref No 23, 25, 26, 27) it was noted that as the pile bases passed through layers of comparatively low strength the sets did not increase as much as expected, indicating that shaft skin friction was absorbing energy.

In the analysis of ultimate pile bearing capacity the skin friction component is taken as the mean shaft peak shear strength weighted by an adhesion factor alpha, which Flaate has evaluated as a function of s_u (peak) and plasticity index PI, (as reported in Ref. 9). The alpha factor allows for the amount by which the soil adjacent to a pile shaft regains strength after the completion of driving and adheres to the shaft providing skin friction.

The author suggests however that during the driving process the soil adjacent to the pile shaft will be in a highly disturbed state and the driving resistance provided by shaft adhesion will be a function of s_u (remolded) rather than s_u (Peak).

In tables B1, B2, B3 and B4, in Appendix B, a series of alpha factors, 5%, 10%, 20% and 50% have been applied to the mean shaft s_u (remolded) acting on the pile giving a pseudo-static shaft skin friction during driving. This has been added to the assumed pile base resistance during driving (9 $s_{u(peak)}$ Ap) to give the total driving capacity. The previous Normalising Factor (Gross), derived in section 6.2, is then reduced by the proportion of the total driving capacity attributable to shaft skin friction, to give the Final Normalising Factor (Gross). This in turn is applied to the recorded pile set per blow to give the Set/Blow (SF Norm) which is plotted as the four graphs shown on Fig. 6.3.

The above procedure is repeated in tables B5, B6, B7 and B8 with the same alpha factors but using the Normalising Factor (Net) which incorporates the net energy

delivered to the pile top. These results are plotted as the four graphs on Fig. 6.4.

A comparison within each family of these graphs shows that with increasing alpha factors the data points move closer to the y-axis, as would be expected. The effect is greater on deeper piles given their larger shaft areas. The degree of scatter in the data however increases with the alpha factor.

A comparison between these two families of graphs shows that normalising on a net energy basis displaces the curves further along the x-axis and introduces more scatter due mainly to the deeper piles as discussed at the end of Section 6.2 above.

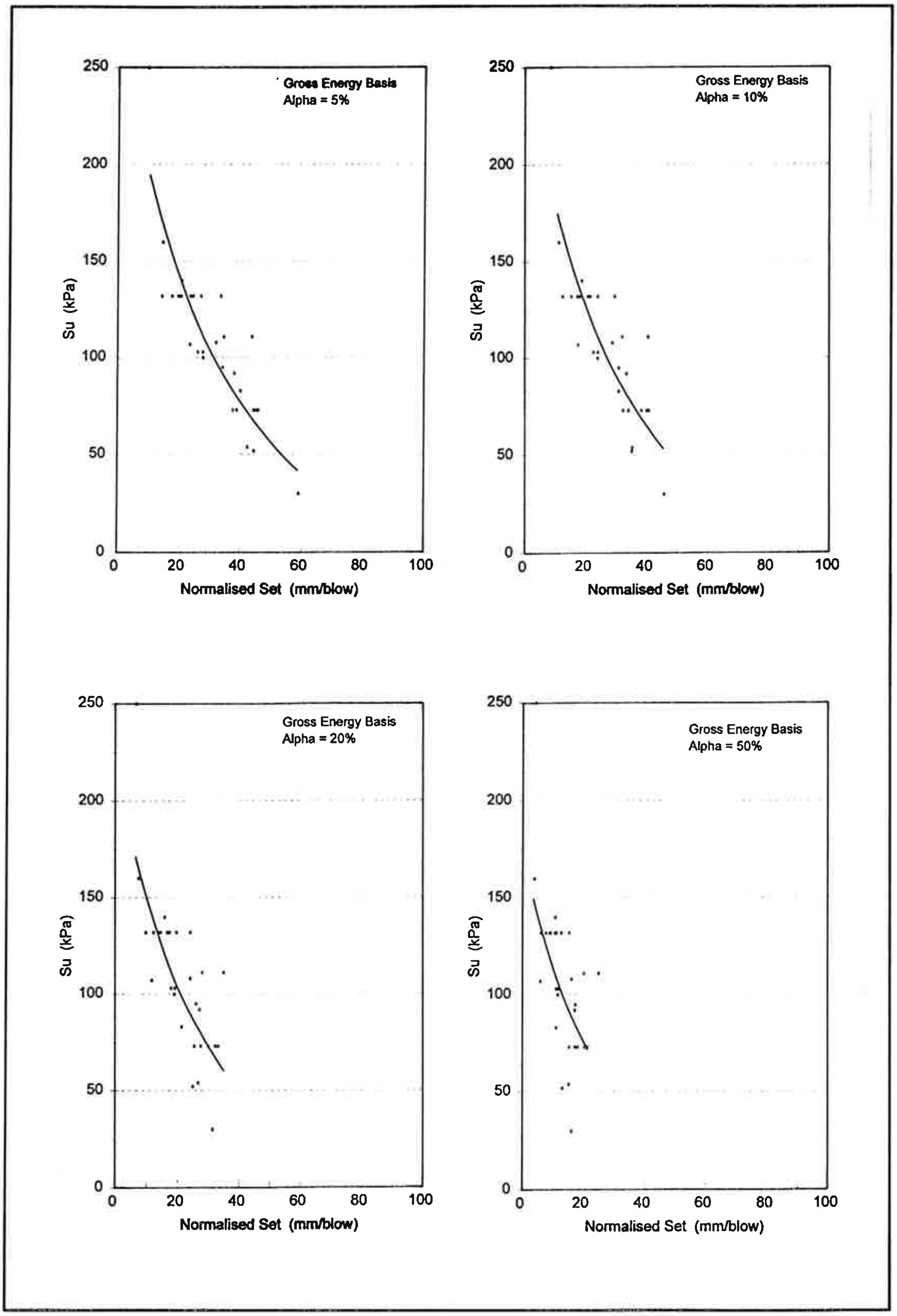

Fig 6.3 Shear Strength vs. Normalised Set (Gross Energy Basis, Shaft Friction Allowance)

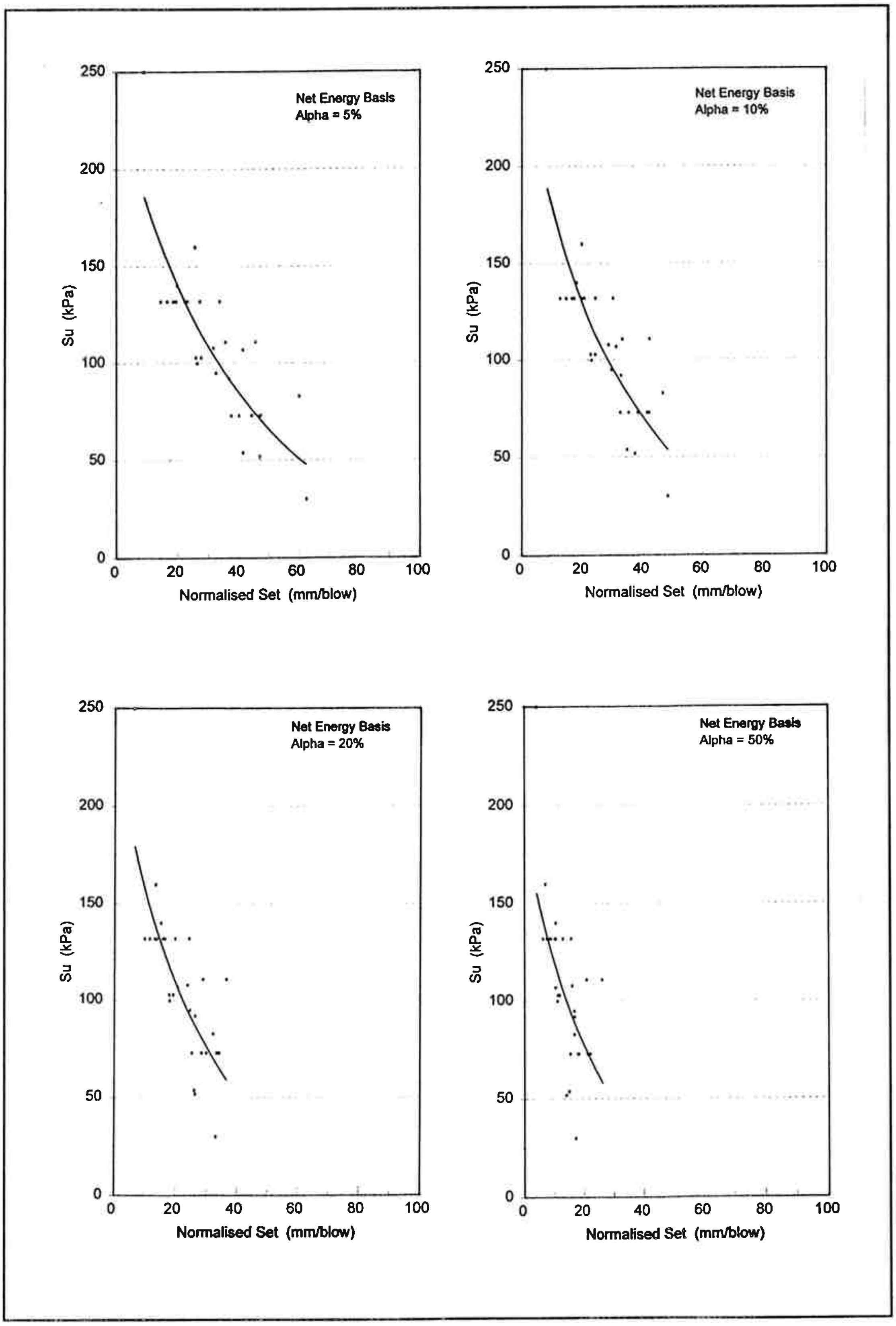

Fig 6.4 Shear Strength vs. Normalised Set
(Net Energy Basis, Shaft Friction Allowance)

7 ULTIMATE PILE CAPACITY

7.1 Introduction

The results of pile testing undertaken previously for NZS:3604 are reviewed and compared with the results of the current research for ultimate pile capacities using both static and dynamic analyses.

7.2 Research For NZS:3604

During the course of the research access was gained to the results of a program of load tests carried out for TRADA in 1974. A report was prepared by Cooks, Lapish and Compton, consulting engineers (CLC) presenting pile set vs. ultimate pile capacity relationships together with a specification for pile loading and the required driving criteria. This specification formed the basis of NZS:3604 Appendix D, Short Driven Timber Piles (Ref. 5). The piles used in that earlier research comprised timber piles of 140 mm nominal diameter, 1.83 m (6 ft) length and were driven into the ground for a depth of 1.22 m (4 ft). The gross energy input during driving was 4800 J. The data base comprised 32 piles driven at ten sites in the south Auckland area. Pile sets and temporary compressions were measured. The piles were loaded to failure using a trailer mounted hydraulic pile testing rig held down by screw augers. (Ref. 2)

In the analysis of that data CLC derived the following relationship between measured pile sets and the actual ultimate pile capacity (compressive loading):

$$Set = -150.63 \log P_{ULT} + 150.80$$

Rearranging the original relationship in terms of ultimate pile capacity, converting the units to kN and simplifying gives approximately:

$$P_{ULT} = 10^{\left(2 - \left(\frac{Set}{148}\right)\right)} \qquad \text{(set in mm)}$$

CLC also calculated P_{ULT} (dynamic) for the same piles using the Hiley formula and plotted a best fit line through that data. Table 7.1 shows the test data and the above two relationships are both plotted against the recorded sets in Fig. 7.1.

Test Ref No	CLC Set/Blow Rec. (mm)	Ult. Pile Cap.(total) Field Test (kN)	Ult. Uplift Cap. Field Test (kN)	Ult.Pile Cap. Dynamic Analysis Hiley Equ. (kN)	Ratio of UPC Hiley / UPC Test	Ratio of Ult. Uplift Cap./ UPC Total
1/1	50	47.5	14.8	66.7	1.4	0.31
1/2	36	77.8	30.4	92.5	1.2	0.39
1/3	43	70.7	26.5	77.2	1.1	0.37
2/1	110	26.5	16.6	30.8	1.2	0.63
2/2	94	22.0	8.8	36.0	1.6	0.40
2/3	98	26.5	15.0	34.8	1.3	0.57
3/1	82	37.0	21.2	42.0	1.1	0.57
3/2	62	35.2	14.1	54.2	1.5	0.40
3/3	62	53.2	35.7	54.5	1.0	0.67
4/1	149	14.1	5.7	23.2	1.6	0.40
4/2	229	6.0	0.4	15.3	2.6	0.07
4/3	116	10.7	4.3	29.9	2.8	0.40
5/1	98	17.8	7.7	34.3	1.9	0.43
5/2	67	20.5	8.8	50.0	2.4	0.43
5/3	76	22.7	7.1	43.8	1.9	0.31
5/4	91	17.8	12.4	37.4	2.1	0.70
5/5	71	21.2	10.7	47.4	2.2	0.50
6/1	60	36.9	16.7	56.0	1.5	0.45
6/2	80	31.9	22.0	43.1	1.4	0.69
6/3	68	30.4	16.3	50.2	1.7	0.54
7/1	49	51.3	31.1	68.9	1.3	0.61
7/2	50	43.6	24.8	68.0	1.6	0.57
7/3	45	45.2	26.5	72.6	1.6	0.59
8/1	43	47.5	19.4	74.6	1.6	0.41
8/2	46	47.9	21.2	69.7	1.5	0.44
8/3	51	47.8	24.8	64.6	1.4	0.52
9/1	18	51.3	60.2	157.2	3.1	1.17
9/2	21	70.7	50.9	135.0	1.9	0.72
9/3	25	69.0	46.0	116.0	1.7	0.67
10/1	36	60.2	37.2	90.5	1.5	0.62
10/2	65	44.2	18.4	56.2	1.3	0.42
10/3	45	59.4	31.1	73.6	1.2	0.52

Table 7.1 CLC Test Data

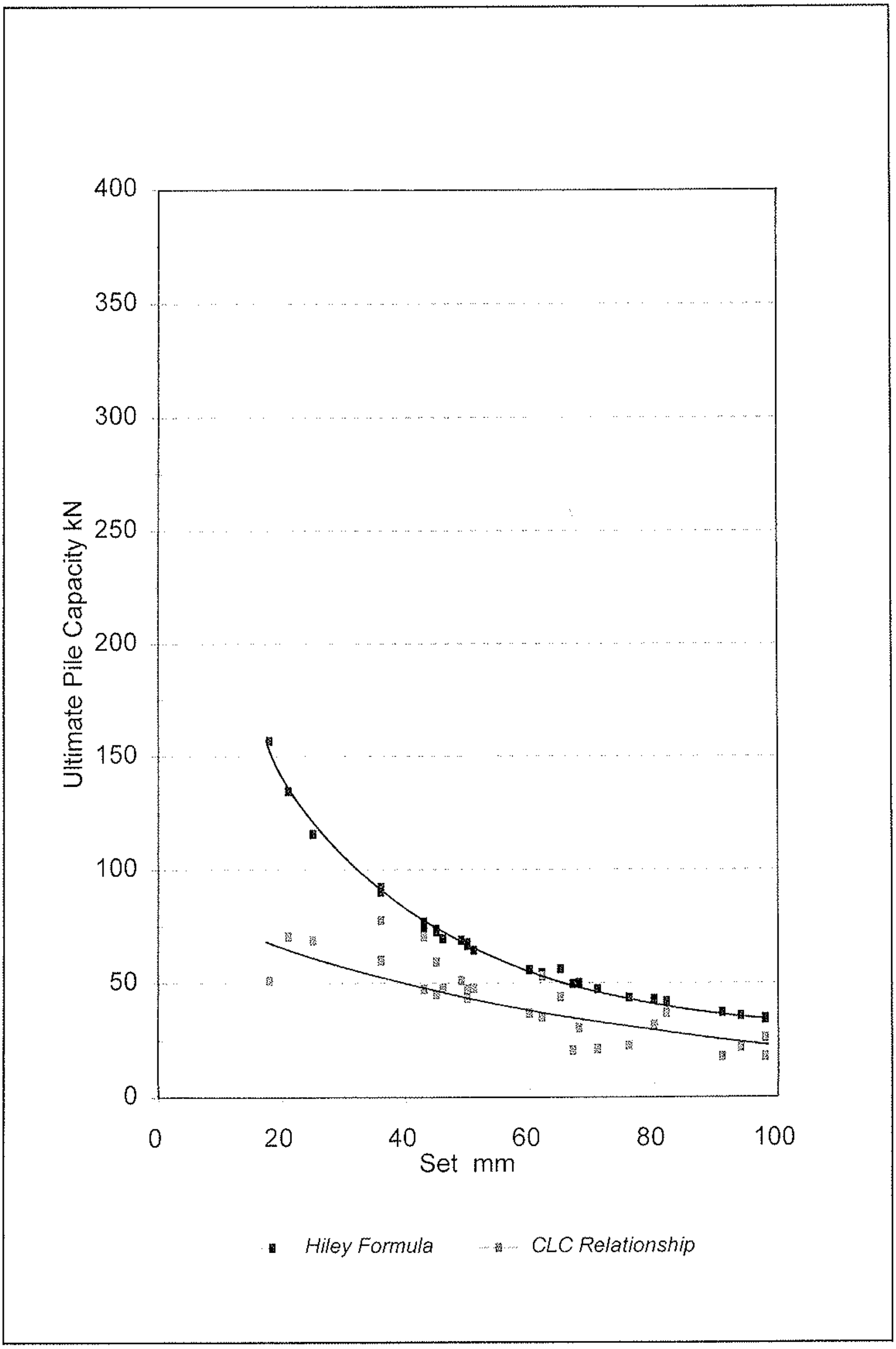

Figure 7.1 CLC Test Results

It can be seen from Fig. 7.1 that the Hiley formula defined the upper edge of the envelope of measured pile capacities. Table 7.1 shows that comparing individual test results Hiley over-predicted the ultimate capacity by factors of 1.1 to 3.1 times. This range of factors was also found by Yonge and Hudson-Smith (Ref. 14). In Fig. 7.1 the ratio of the best fit curves for the Hiley prediction to the actual ultimate pile capacities is about 1.5 to 2.0 over the 20 mm to 100 mm set range.

For design purposes the CLC report recommended using the best fit curve for ultimate pile capacity with factors of safety of 2 or 3 depending on the combination of dead and live loads.

7.3 Current Research

During the research for this present project various relationships were used to predict the ultimate pile capacities on a theoretical basis as shown in tables 7.2. a & b.

Initially a static analysis was used combining base and shaft resistance giving:

$$P_{ULT\ STATIC} = 9\, s_U\, A_P + \alpha\, s_U\, A_S \qquad \text{(Ref. 12)}$$

In the analysis actual pile dimensions and shear strengths at the pile base and along the shaft were used. In Fig 7.2 these results are plotted against measured pile sets normalised for area and gross energy input to NZS:3604 Appendix D requirements as discussed in Section 6.2 above.

The analysis found that with piles of greater than 4 m driven depth the proportion of the pile capacity contributed by skin friction was 85% to 89%, compared with piles of less than 4 m driven depth where this proportion was generally in the 60% to 70% range. In the pile testing undertaken by CLC piles were also tested by withdrawing them vertically out of the ground to assess uplift resistance and hence skin friction. In table 7.1 the proportion of P_{ULT} (compressive) attributed to skin friction from the field test results averages 52%.

The method of normalising the sets to a common basis which the author has used makes no allowance for pile shaft area. Consequently the four longest piles in the study (8.0 m to 22.5 m driven length) gave a significantly higher ultimate capacity for a given normalised set than the remainder of the piles in the data base. Other variations on the normalising technique were used to attempt to overcome this problem however the capacities of the shorter piles in the data base became distorted as a result. In the absence of a significant number of deeper piles, which would have otherwise allowed a more detailed analysis, the author chose to delete the data from those piles of greater than 4 m driven length from this part of the analysis.

The ultimate pile capacity was then modelled dynamically using the Hiley formula. The standard method as outlined in ***Building Industry Authority - Approved Document B1 - Structures Foundations, Appendix A*** was applied:

$$P_{ULT\ HILEY} = \frac{W \times h \times n}{S + C/2} \qquad \text{(Ref. 1)}$$

where:
- W = hammer weight
- h = drop height
- n = efficiency of blow
- S = set
- C = temporary compression

Individual pile and soil properties were used to derive the temporary compression values and other efficiency parameters. In analysing the longer piles the problems outlined above also occurred and consequently these piles were also deleted from the analysis. The results are plotted in Fig 7.2.

The static analysis as plotted on Fig 7.2 correlates within 6% to 33% of the results of actual pile capacity testing as shown by the CLC Relationship on Fig 7.1 The results derived from the Hiley formula give values in the range of 1.3 to 3.0 times as great as the statically derived results, when comparing individual piles. This range of ratios is similar to that found in Section 7.2.

Test Ref No	Pile base Dia. (mm)	Pile Length (Total, m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Peak) Corr. (kPa)	Pile Adhesion Factor Alpha •	Set/Blow Recorded (mm)	Set/Blow Norm. for Area & Energy. (mm)	Assumed Elast. Comp. Pile Hd. Cc (mm) #	Assumed Elast. Comp. Pile Cp (mm) #	Assumed Quake Soil Beneath Pile Cq (mm) #	Assumed Total Temp. Comp. C (mm) #
1	140	2.0	140	145	0.25	8.5	23	2.0	1.4	3.5	6.9
2	145	3.0	100	94	0.30	30	33	1.0	1.1	2.0	4.1
3	145	3.0	95	87	0.30	35	38	1.0	1.1	2.0	4.1
4	160	3.6	108	98	0.30	27	36	2.0	2.5	2.5	7.0
5	150	3.6	54	85	0.30	45	53	1.0	1.3	1.5	3.8
6	145	3.6	92	89	0.30	40	44	1.0	1.3	2.0	4.3
7	175	4.2	111	70	0.35	30	48	2.0	2.9	2.5	7.4
8	170	4.2	111	64	0.35	25	38	2.0	2.9	2.5	7.4
9	170	4.2	73	72	0.35	30	45	1.0	1.5	1.5	4.0
10	170	4.2	73	73	0.35	35	53	1.0	1.5	1.5	4.0
11	170	4.2	73	72	0.35	35	53	1.0	1.5	1.5	4.0
12	175	3.0	132	128	0.30	20	31	2.0	2.1	3.5	7.6
13	150	2.4	132	128	0.30	18	20	2.0	1.7	3.5	7.2
14	150	2.4	132	127	0.30	21	24	2.0	1.7	3.5	7.2
15	150	2.4	132	127	0.30	20	23	2.0	1.7	3.5	7.2
16	175	3.0	132	126	0.30	11	17	2.0	2.1	3.5	7.6
17	150	2.4	132	127	0.30	24	27	2.0	1.7	3.5	7.2
18	150	2.4	132	127	0.30	25	28	2.0	1.7	3.5	7.2
19	175	3.0	132	128	0.30	25	39	2.0	2.1	3.5	7.6
20	175	4.2	154	145	0.25	5.5	8	2.0	2.9	4.0	8.9
21	175	4.2	200	148	0.25	7	11	2.0	4.4	5.0	11.4
22	250	11.0	30	95	0.30	200	84	2.0	2.6	1.0	5.6
23	250	11.0	52	58	0.37	144	60	2.0	2.6	1.5	6.1
24	150	4.2	250	140	0.25	10	11	3.0	4.4	4.5	11.9
25	275 x 275	18.0	83	92	0.30	75	56	0.5	2.2	1.5	4.2
26	275 x 275	27.0	107	95	0.30	47	35	0.5	6.5	2.5	9.5
27	275 x 275	27.0	160	100	0.30	28	21	0.5	6.5	4.0	11.0
28	200	4.2	73	158	0.25	22	45	1.0	1.5	1.5	4.0
29	200	4.2	103	141	0.25	16	33	1.0	2.9	2.5	6.4
30	200	4.2	73	158	0.25	26	53	1.0	1.5	1.5	4.0
31	200	4.2	103	141	0.25	15	31	1.0	2.9	2.5	6.4

• Estimated • Function of Su & PI

Building Industry Authority. B1 Structure - Foundations. Appendix A - Hiley Formula, Table A1 Temporary Compressions.

Table 7.2.a Analysis of Ultimate Pile Capacity

Test Ref No	Ult. End Bng. 9Su Peak (kN)	Ult. End Bng. 9Su Rem. (kN)	Ult. Skin Fr. Su Peak based (kN)	Ult. Pile Cap. Total Static Anal. 9Su+Sk.Fr. (kN)	Ult.Pile Cap. Dynam.Anal. Hiley Equ. (kN)	Ratio of Ult. Skin Fr./ UPC Total
1	19	10	20	40	107	0.51
2	15	6	36	51	107	0.71
3	14	8	20	34	93	0.59
4	20	8	31	51	108	0.62
5	9	4	26	35	71	0.75
6	14	7	24	37	80	0.63
7	24	12	29	53	93	0.55
8	23	11	26	48	110	0.53
9	15	8	32	47	99	0.68
10	15	8	31	46	85	0.67
11	15	8	29	44	85	0.66
12	29	17	45	73	140	0.61
13	21	11	36	57	164	0.63
14	21	11	34	55	144	0.62
15	21	11	34	55	150	0.62
16	29	17	53	81	226	0.65
17	21	11	34	55	129	0.62
18	21	11	34	55	124	0.62
19	29	15	45	73	116	0.61
20	33	-	73	106	316	0.69
21	43	-	78	122	248	0.64
22	13	5	67	80	118	0.84
23	23	-	135	158	163	0.85
24	40	-	70	109	228	0.64
25	56	24	425	482	188	0.88
26	73	37	580	653	239	0.89
27	109	43	743	851	369	0.87
28	21	13	53	73	139	0.72
29	29	11	71	100	174	0.71
30	21	13	53	73	119	0.72
31	29	11	71	100	183	0.71
	= 9 Su x Base area		= circumf. x driven depth x mean shaft Su x alpha		= hammer mass x g x drop ht. x hammer eff. x blow eff. /(set rec.+ Temp. Comp./2)	

Table 7.2.b Analysis of Ultimate Pile Capacity (Cont.)

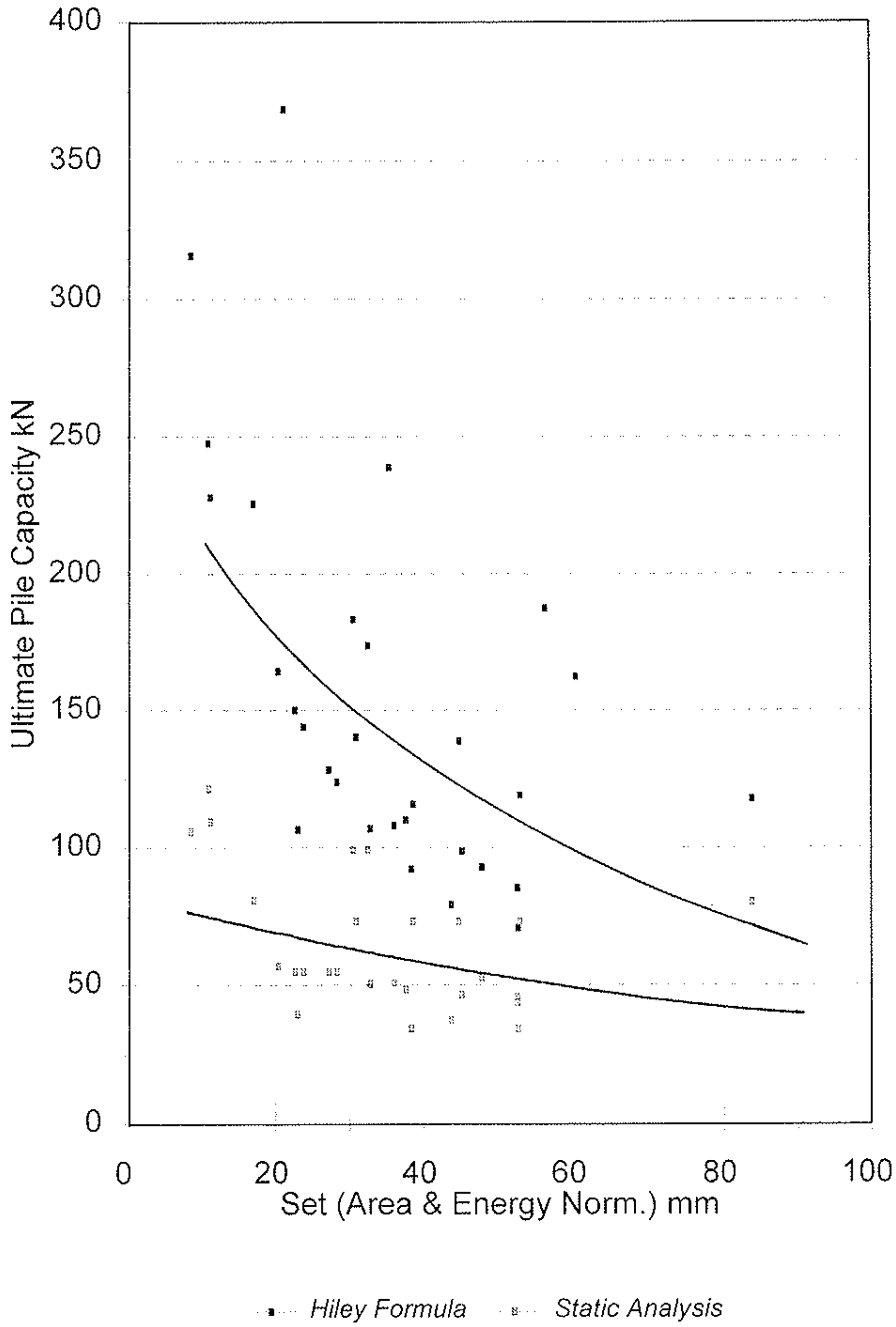

Figure 7.2 Predicted Pile Capacities

8. DISCUSSION

During the course of the study difficulty was experienced in obtaining data for the two extreme ends of the shear strength range under consideration. Most Pilcon shear vanes have a testing range limited to less than 200 kPa shear strength. As a result there are few data points at the upper end of the strength range included in the study. The two which were included at 200 kpa and 250 kpa were both above the range of the shear vanes being used. These values were estimated on the basis of the strain which had occurred up to the maximum reading and the difficulty of augering the soil compared with other sites on which shear vanes with stronger springs had been used.

At the lower end of the range few sites were located with uniform layers of cohesive soil in the 20 kPa to 50 kPa shear strength range. After several months of reviewing projects with driven pile foundations a suitable low strength site was found. The contractor was briefed regarding the driving of three piles adjacent to a borehole however, due to a problem with the timing of access beneath overhead services, these three piles were driven before the author arrived at the site to measure sets above the pile founding depth.

Discussions were undertaken with various people in the piling industry regarding factors which contribute to the variability of pile driving resistance (Ref. 4, 6, 13). Some of the responses are listed below:

(1) Excessive pile taper, causing increased displacement of the soil as pile is driven reducing the sets.

(2) Large knots causing swellings on the pile surface and increasing driving resistance.

(3) Timber saturation in newly treated piles giving a larger pile density and effecting the ratio of pile mass to hammer mass and hence driving efficiency.

(4) High ground water levels, reducing driving resistance through lubricating the pile especially in cohesive materials.

(5) Set improvement with time, through leaving piles during lunch break or overnight before measuring the set.

(6) Pile orientation, driving piles large end first can reduce skin friction during driving.

(7) Formation of an annular gap around piles during driving in stiff clay

The present study has focused on cohesive soils. There is scope for repeating this study in granular soils provided a suitable soil parameter is chosen to which the pile sets can be related. The author attempted a correlation with the Scala penetrometer in non-cohesive soils but could find no strong relationship due to inconsistency of results.

9. CONCLUSIONS

The important findings of the study are concluded below:

(1) A relationship has been derived between the undrained shear strength of cohesive soils and the normalised sets of driven piles. The relationship is shown graphically on Fig. 6.1 and can be expressed mathematically as:

$$s_{U\,(PEAK)} = 240\ e^{-0.02322\ SET}$$

The above formula is limited to a reliable range of about 30 kPa to 200 kPa shear strength soils with driven pile depths of up to 4 m. The sets should be normalised to NZS:3604 Appendix D driving conditions as discussed in Section 6.1.

(2) The practical application of the above formula for design purposes is outlined in Appendix C in which the required shear strength at the pile founding level can be derived for a particular set given the pile base diameter, hammer mass and drop height.

(3) The statically derived ultimate pile capacity (compressive) as discussed in Section 7.2 gives results which are expected to correlate closely with the actual ultimate pile capacity, when sets are normalise for area and gross energy input, provided driven pile depths are less than 4 m. Whilst individual results will vary a best fit curve using least squares curve fitting techniques applied to a statistically significant sample size is expected to give close correlation.

(4) The Hiley formula can be used to estimate ultimate pile capacities for design purposes provided that in the case of piles of less than 4 m driven depth in cohesive soils, a factor of safety of about 5 is applied to the static design loads.

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APPENDIX A

Borehole Logs

Job No:- 84160/14
Project:- Stephania Close
Borehole Location:- Centre of lot
Surface Elevation:- –
Surface Conditions:- Grass

LOG OF BOREHOLE ..1..

(70mm Dia Hand Auger)

Geol Unit	Soil/Rock Description	Graphic Log	Unified Symbol	Depth (m)	Consistency	Moisture Condition	Samples	Shear Strength (kPa)	Water Content %	Groundwater	Comments & other Laboratory & Insitu Testing
	FILL- Sandy SILT, non-plastic, grayish brown with light grey mottles					M/W		V102 R71			Scala Penetro. adjacent.
	SAND, cemented, hard, brown					D		UTP			
	SILT, some sand, minor clay, slightly-mod. plastic, orange brown with light gray mottles light gray with orange staining trace clay		ML	1		M	D	V156 R85 V149 R75 V140 R71 V140 R69 V165 R74			9, 5, 4, 4, 1, 3, 2, 1, 3, 2, 1, 3, 2, 1, 3, 2, 3, 2, 3, 4
	E.O.B. 1.5m										
				2			D				
				3			D				
				4			D				
				5			D				

Date Logged: 29/8/95
Logged By: SMB
Shear Vane No. D.R.2992
Shear Vane Testing Based on BS 1377

Observations:
UTP = unable to penetrate with shear vane

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LOG OF BOREHOLE 1
(70mm Dia Hand Auger)

Job No:- 86200
Project:- Melford St
Borehole Location:- See Drg
Surface Elevation:- "
Surface Conditions:- Lawn

Soil/Rock Description	Unified Symbol	Depth (m)	Samples	Shear Strength (kPa)	Water Content %	Groundwater
FILL (Uncontrolled) Bricks, topsoil, etc.		0–1.45	D (1)			
CLAY Silty, yellow white-grey medium, becoming more silty firmer.	CL	1.45–2.0		V46 R27		
becoming SILT very clayey whitish grey - yellow brown	ML	2.0–2.85	D (2)	V73 R41; V111 R54	Free water during drilling	▽
CLAY sl. silty, whitish-grey orange (unable to retrieve sample)	CL	2.85–3.2	D (3)	V73 R41		
E.O.B.			D (4), D (5)			

Date Logged: 22/8/86
Logged By: GTH
Shear Vane No. D.R. ~~2992~~ 2528
Shear Vane Testing Based on BS 1377

Observations:
UTP – unable to penetrate with shear vane.

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LOG OF BOREHOLE 2
(70mm Dia Hand Auger)

Job No:- 86200
Project:- Melford St
Borehole Location:- See Drg
Surface Elevation:- "
Surface Conditions:- Lawn

Soil/Rock Description	Unified Symbol	Depth (m)	Samples	Shear Strength (kPa)
TOPSOIL, brown				
FILL, CLAY silty, orange brown with topsoil leachings to 0.4m				V68 R35
TOPSOIL				
CLAY silty, orange, whitish grey	CL	1	D	V97 R38
becoming more silty				V95 R54
SILT clayey whitish-grey, orange	ML	2	D	V108 R46; V100 R43
SILT becoming sl. clayey whitish-grey orange	ML	3	D	V54 R27; V54 R27
		4	D	V61 R27
E.O.B.		5	D	

Date Logged: 22/8/96
Logged By: GTH
Shear Vane No. D.R. ~~2992~~ 2528
Shear Vane Testing Based on BS 1377

Observations:
UTP – unable to penetrate with shear vane.

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BORE No 2

SHEET 1 OF 1

SITE THE ESPLANADE CASTOR BAY

REDUCED LEVEL 100.68 m — GROUND WATER LEVEL metres 2.33 m 9/10/86 — JOB No. 86159

SHEAR STRENGTH (Kpa.): UNDR. TRIAXIAL □ UNDIST.; FIELD VANE ○ UNDIST.; S.P.T. RAYMOND "N" VALUE BLOWS/0.3 metres X (scale 20, 40, 60, 80, 100)

WATER CONTENT %; MOISTURE CONTENT ⊡; PLASTIC LIMIT △; LIQUID LIMIT X (scale 30, 40, 50, 60)

Shear strength (vane, kPa)	Depth (metres)	Soil description
		FILL, mainly silts, medium, light grey, some topsoil inclusions
137		SILT, slightly clayey, stiff, light grey, some yellow brown mottles
117	1	some topsoil leached down
143		less clayey band 1.4 - 1.5 m
		clayey, some purple broken mottles
181+	2	some less clayey pockets occasional yellow brown limonite staining
154		occasional grey mottles
181+	3	limonite band 10 mm thick
		SILT, clayey, stiff, dark grey, sand pocket, some limonite staining
181+		less limonite
		difficult to penetrate END OF BORE 3.6 METRES
	4	
	5	

Legend: Gravel, Sand, Silt, Clay, Fill, Topsoil, Peat, Sandstone, Siltstone, Basalt

Vane Results Calibrated In Accordance With BS 1377:1975 Test 5.3.4

DRILLING DATE 7/10/86

LOG OF BOREHOLE..5a

(...70...mm Ø HAND AUGER)

Job No: 86207

Project: TheEsplanade

Borehole Location: see site plan

Surface Elevation: 102.09 (m) Datum: site

Surface Conditions: grassed

Geol. Unit	Soil / Rock Description	Unified Symbol	Depth (m)	Consistency	Moisture Condition	Samples	Shear Strength (kPa)	Water Content %	Groundwater	Comments & other Laboratory & Insitu Testing
FILL	FILL, intermixed clay and gravel			F	M					
	silty clay, highly plastic, intermixed orange and grey,			St		D	V 132 R 93			
	occasional dark grey organic inclusions		1			D	V 68 R 33			
	SILTY CLAY, highly plastic, organic, dark grey	CH		F						
	non-organic, grey mottled orange			St		D	V 175 R 95			
	light grey mottled orange		2			D	V 132 R 71			
						D	V 132 R 79			
	CLAYEY SILT, highly plastic, grey, orange mottling	MH		VSt						
	SILTY CLAY, highly plastic, light grey mottled orange	CH	3			D	V 152 R 93			
	CLAYEY SILT, highly plastic, light grey, orange mottling	MH				D	V 150 R 75			
	trace sand		4			D	V 167 R 75			difficult to auger
	END OF BOREHOLE @ 4.3m									
			5							

Date Logged: 5/6/90
Logged by: AJC/PJ
Shear Vane No.: DR2992
Shear vane testing based on BS 1377

Observations: UTP =unable to penetrate with shear vane

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LOG OF BOREHOLE 3

Sheet 1 of 2

Job No: 87150
Project: LINCOLN ROAD
Borehole Location: SEE SITE PLAN
Surface Elevation: 50.85 Datum: SITE
Surface Conditions: GRASSED

Geol. Unit	Soil / Rock Description	Unified Symbol
FILL	BASECOURSE	
FILL	TOPSOIL	
ALLUVIUM	SILTY CLAY, high plasticity, light grey, orange mottles	CH
ALLUVIUM	with some vertical decayed roots up to 3.0 mm ø	
ALLUVIUM	4.2 m dark brown, organically stained	
ALLUVIUM	CLAYEY SILT, low plasticity, dark grey, with a trace of sand, slightly sandy 5.3 - 5.6 m	ML
ALLUVIUM	SANDY SILT, low plasticity, blue grey, sand medium grained	ML

Consistency: VSt/F; St (from about 1.8 m); F/S (from about 2.0 m); F (from 7 m); F/St (from about 9 m)

Moisture Condition: M; W (from about 2.0 m); M (from 7 m)

Samples	Shear Strength (kPa)
D	V137-60R
D	V132-69R
D	V 99-58R
U100	
D	P25
D	V 32-13R
D	P25
D	V 29-11R
U100	
D	P<25
D	V 24-7R
D	P25
D	V 34-5R
U100	
D	P25
D	P50
D	V47-25R
D	P37
D	V52
U100	
D	P<25
D	P75
D	P50

Drilling Method: AUGER (to about 0.5 m); 75 mm ø OPEN BARREL

Groundwater: 15/6/87

Depth (m): 1 – 10

Date Started 3/6/87
Date Finished 3/6/87
Driller T.Cooksley
Type of Rig Mayhew 750
Shear Vane No. DR2508

Logged by C.Hooper
Observations

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LOG OF BOREHOLE 3

Sheet 2 of 2

Job No: 87150
Project: LINCOLN ROAD
Borehole Location: SEE SITE PLAN
Surface Elevation: SEE SHEET 1 Datum:
Surface Conditions: SEE SHEET 1

Soil / Rock Description	Unified Symbol	Consistency
SANDY SILT, as above, some lenses of sand up to 20 mm thick, trace of decayed wood 10.0 - 10.5 m	ML	F/St
SILTY SAND, dark grey, blue grey	SM	L
CLAYEY SILT, low plasticity, green grey - dark grey, with sandy lenses, trace rounded gravel to 10 mm ø	ML	F
SILTY CLAY, medium-high plasticity, dark grey, blue grey	CL/CH	St
trace of sand 13.0 - 15.25 m, blue grey		
15.25 - 16.0 dark grey, blue grey		F/St
16.0 - 16.5 m brown, organically stained with a trace of decayed wood		
END OF BOREHOLE 16.5 m		

Moisture Condition: M

Samples	Shear Strength (kPa)
D	
D	P 50
N7 2/3/4	
D	P100
D	P100
D	P 62
D	P 75
D	P 75
D	P 75
D	P 50
D	P 62
D	P 50
D	P 62

Drilling Method: 75 mm ø OPEN BARREL; HQ TRIPLE TUBE

Depth (m): 11 – 19

Date Started 3/6/87
Date Finished 3/6/87
Driller T. Cooksley
Type of Rig Mayhew 750
Shear Vane No. DR2508

Logged by C.Hooper
Observations
Interface at 10.5
10°-15° to horizontal

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Job No: 89211
Project: 48 Seaton Road, Murrays Bay
Borehole Location: see site plan
Surface Elevation: 33.65 (m) **Datum:** site
Surface Conditions: grassed fill

LOG OF BOREHOLE..1..
(...70...mm Ø HAND AUGER)

Geological Unit	Soil / Rock Description	Unified Symbol	Depth (m)	Consistency	Moisture Condition	Samples	Shear Strength (kPa)	Water Content %	Groundwater	Comments & other Laboratory & Insitu Testing
FILL	FILL, clayey silt, moderately plastic, yellow brown, some greyish brown topsoil	MH / ML		VSt	M					
	topsoil, silty, greyish brown, trace of decaying topsoil					D	V104 R33			
	clayey silt, yellow brown, topsoil, greyish brown < 60%									
	orange, yellow brown, light grey		1	VSt / St	M / W	D	V79 R23			
RESIDUAL WAITAMATA FORMATION	Topsoil, greyish brown									
	CLAYEY SILT, highly plastic, orange, yellow brown, some light grey	MH		VSt		D	V124 R56			
	moderately plastic, some limonite gravel 2.2 -2.35 m	MH / ML	2			D	V136 R83			
						D	V136 R83			
	light grey, some orange		3			D	V172 R75			
					S					
	SILT, slightly plastic, light grey, yellow brown, orange	ML		VSt / St		D	V106 R52		14/12/89	
	SANDY SILT, slightly plastic, light grey, yellow brown		4	H		D	UTP Est. V≥250			
						D	UTP			
	CLAYEY SILT, moderately plastic, light grey, orange	MH / ML								
	End Of Borehole at 4.8 m		5							

Date Logged: 13 / 12 / 89
Logged by: GJH
Shear Vane No.: DR2992
Shear vane testing based on BS 1377

Observations:
UTP =unable to penetrate with shear vane

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RILEY CONSULTANTS LTD — LOG OF BOREHOLE 3 — Sheet 1 of 4

PROJECT NO: 93139

PROJECT: Anzac St

BOREHOLE LOCATION: see site plan

SURFACE ELEVATION: 11.61 DATUM: L+S

SURFACE CONDITIONS: Gravel

GEOL UNIT	SOIL / ROCK DESCRIPTION	UNIFIED SYMBOL	DEPTH (m)	SAMPLE TYPE	SPT	SHEAR STRENGTH (kPa)	DRILLING METHOD	GROUND WATER	w%
FILL	FILL, scoria + silt								
TUFF	GRAVELLY SILT, light orange/brown with black, grey + brown gravels, 5-15mm dia	–	1	B			AS	7/5/93 ▼	
			2	B	3,4,4 N=11		SPT		51
			3	B			OB		
	Fgiving sand layer, brown; bands of limonite gravels			B	4,4,6 N=10		SPT		
	Clay, fine sand gravels, well bedded, highly plastic, dark, brown		4	B					74
PLEISTOCENE DEPOSITS	CLAY, highly plastic, dark grey, some roots, moist, organic smell	CH				V53 K19	OB		
	CLAYEY SILT, moderately plastic, brownish grey with grey mottles	MH	5	B		V203			
	CLAY, highly plastic, grey	CH					OB		
	SILT, some clay, non-slightly plastic, grey with orange/brown mottles	ML	6	B	1,2,5 N=8	UTP	SPT		
	SANDY SILT, non plastic grey	SM							
PEAT	PEAT, black, fibrous	Pt	7	B			OB		152
	non decomposed wood fragments		8				OB		
	silty sand layer, 5-7mm, grey, with black organic fragments						OB		
	Tree		9	B			OB		303
	silty sand layer as above								

DATE STARTED: 26/4/93
DATE FINISHED: 26/4/93
DRILLER: [illegible]
TYPE OF RIG: MAYHEW 1000
LOGGED BY: SAN
SHEAR VANE No.: DR 626
OBSERVATIONS:

RILEY CONSULTANTS LTD — LOG OF BOREHOLE 3 — Sheet 2 of 4

PROJECT NO: 93139

PROJECT: Anzac St

BOREHOLE LOCATION:

SURFACE ELEVATION: 11.61 DATUM: L+S

SURFACE CONDITIONS: Gravel

GEOL UNIT	SOIL / ROCK DESCRIPTION	UNIFIED SYMBOL	DEPTH (m)	SAMPLE TYPE	SPT	SHEAR STRENGTH (kPa)	DRILLING METHOD	w%	OTHER
PEAT	SAND, fg, dark brown with organic fragments	SP SM					OB		
	PEAT, black, fibrous, wood fragments	Pt	11	B			OB	512	Organic Content ≈ 60%
	× Sett 97mm		12	B			OB		
	some highly plastic grey clay						OB		
PLEISTOCENE DEPOSITS	SILT non plastic, grey with fine black organic fragments, with silt ...	ML	13	B	N=7	V160 K67	SPT		
	CLAY, highly plastic, grey with black organic fragments	CH		B	N=13				
	silt layer, non plastic, light brownish grey, 100mm		14				OB		
	trace sand			B		V48 K21			
	× Sett = 75mm		15	B		V83 K35	OB	56	
	lighter grey		16	B		V97 K83	OB		
	minor silt		17	B		V111 K57	OB		
	no silt, greyish green		18	B		V112 K54	OB		
	× Sett = 47		19	B		V103 K55	OB		

DATE STARTED: 26/4/93
DATE FINISHED: 26/4/93
DRILLER: [illegible]
TYPE OF RIG: MAYHEW 1000
LOGGED BY: SAN
SHEAR VANE No.: DR 626
OBSERVATIONS:

Key (printed on each sheet)

SAMPLE TYPES
- AS - Auger Sample
- SPT - Standard Penetration Test
- WS - Wash Sample
- SH - Undisturbed 100mm Shelby Tube Sample
- RC - Rock Core
- OB - Open Barrel Push Sample
- B - Bag Sample

SAMPLE CONDITION
- Undisturbed
- Disturbed
- Sample Lost
- SPT (N=number of blows to drive sampler 300mm)

FIELD SHEAR STRENGTHS
- V - Shear Vane (corrected to BS:1377)
- P - Pocket Penetrometer

LABORATORY TESTS
- w - Water Content (%)
- ρd - Dry Density (kg/m3)
- LL - Liquid Limit (%)
- PI - Plasticity Index (%)
- UCS - Unconfined Compressive Strength (MPa)
- LS - Linear Shrinkage (%)
- %F - Percentage Fines (-75 um)
- CONS - Consolidation Test
- TRAX - Triaxial Compression Test
- ORG - Organic Content Test (%)
- PSD - Particle Size Distribution

RILEY CONSULTANTS LTD — LOG OF BOREHOLE 3 (Sheet 3 of 4)

PROJECT NO: 93139
PROJECT: Anzac St
BOREHOLE LOCATION: -
SURFACE ELEVATION: 11.61 DATUM: LTS
SURFACE CONDITIONS: Gravel

GEOL UNIT	SOIL / ROCK DESCRIPTION	UNIFIED SYMBOL
PLEISTOCENE DEPOSITS	some organic fragments — darker greyish green mudstone, non plastic, light greyish green	
	SILT, non plastic, greyish green with some dark green gravels — darker green	ML
	CLAY (mudstone), non plastic, highly plastic when remoulded, green with dark green mottles — grey, no green grey highly plastic, brown with black mottles	CH
	SILT, non plastic, grey	ML
	SAND, some silt, grey, f-m, dense	SM
	CLAY, highly plastic, grey with some black mottles	CH
	SANDSTONE / SILTSTONE, weakly cemented, dark grey (WAITEMATA SERIES)	

DEPTH (m)	TYPE	SPT	SHEAR STRENGTH (kPa)	DRILLING METHOD	SAMPLE RECOVERY %	w%
~20.5	B		V109 R55	OB		
~21.5	B		V111 R60	OB		
~22.5	B	3/5/10	V151 R47	OB / SPT		
~22.9	B	N=21		SPT		
~24	B		V160 R63	OB		47
~24.8	B	3/4/12	V184 R66	OB / SPT		
~25.2	B	N=28		SPT		
25.3–28				WASH DRILLED		
~28.3	B	3/4/7, N=12		SPT		
28.5–29.9				WASH DRILLED		

× SPT = 28 blows

DATE STARTED: 26/4/93
DATE FINISHED: 26/4/93
DRILLER: DRILLWELL
TYPE OF RIG: MAYHEW 1000
LOGGED BY: SAV
SHEAR VANE No.: DR626
OBSERVATIONS:

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PROJECT NO: 93139
PROJECT: Anzac St
BOREHOLE LOCATION: See site plan
SURFACE ELEVATION: 11.61 DATUM: LTS
SURFACE CONDITIONS: Gravel

GEOL UNIT	SOIL / ROCK DESCRIPTION
WAITEMATA SERIES SANDSTONE/SILTSTONE	SANDSTONE / SILTSTONE, weakly cemented, dark grey
	E.O.B @ 31.45m

DEPTH (m)	TYPE	SPT	DRILLING METHOD
30–31			WB
~31.2	B	50/...	SPT

DATE STARTED: 26/4/93
DATE FINISHED: 26/4/93
DRILLER: DRILLWELL
TYPE OF RIG: MAYHEW 1000
LOGGED BY: SAV
SHEAR VANE No.: DR626
OBSERVATIONS:

SAMPLE TYPES
- AS - Auger Sample
- SPT - Standard Penetration Test
- WS - Wash Sample
- SH - Undisturbed 100mm Shelby Tube Sample
- RC - Rock Core
- OB - Open Barrel Push Sample
- B - Bag Sample

SAMPLE CONDITION
- Undisturbed
- Disturbed
- Sample Lost
- SPT (N=number of blows to drive sampler 300mm)

FIELD SHEAR STRENGTHS
- V - Shear Vane (corrected to BS:1377)
- P - Pocket Penetrometer

LABORATORY TESTS
- ω - Water Content (%)
- ρd - Dry Density (kg/m3)
- LL - Liquid Limit (%)
- PI - Plasticity Index (%)
- UCS - Unconfined Compressive Strength (MPa)
- LS - Linear Shrinkage (%)
- %F - Percentage Fines (-75 μm)
- CONS - Consolidation Test
- TRIAX - Triaxial Compression Test
- ORG - Organic Content Test (%)
- PSD - Particle Size Distribution

LOG OF BOREHOLE ..1..

(70mm Dia Hand Auger)

Job No:- 95129
Project:- PINCHGOT RD
Borhole Location:-
Surface Elevation:-
Surface Conditions:- GRASSED

Depth (m)	Soil/Rock Description	Unified Symbol	Moisture Condition	Samples	Shear Strength (kPa)
	TOPSOIL silty dark brown		M		
	SILT some clay, slightly plastic, orangey brown, topsoil staining	ML			V200 R76
	inclusions: silt minor sand non plastic brownish grey, no topsoil staining				
1	SILT trace sand, non plastic, light grey, orange mottles limonite staining			D	V110 R32
					V211+
	weathered siltstone lumps				
2				D	V73 R46
	rootlets				V112 R32
3				D	V103 R38
	slightly plastic		M/W		V103 R52
4	pockets of grey silt		W	D	V115 R53
	SILT some sand, non plastic, greyish brown, light brown mottles				V118 R55
5				D	
	EOB 5.2m				

Date Logged: 23/2/95
Logged By: SMB/PR
Shear Vane No.: DR2992
Shear Vane Testing Based on BS 1377

Observations:
UTP – unable to penetrate with shear vane.

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APPENDIX B

Analysis

ANALYSIS

Regression analysis was undertaken on each graph presented in the study. The computer program R was used to perform the analysis. This program was developed by Robert Gentleman and Ross Ihaka of University of Auckland.

The least squared method was used to study relationships between the variables in order to select the most appropriate mathematical models to fit the data. Various models were used using power transformations including logarithmic and quadratic.

The following is an example of the analysis which was undertaken for Section 6.2 Gross Energy Input and Section 6.3 Net Energy Input:

The variables referred to are as follows:

set	=	set/blow (Normalised)
supk	=	shear strength (Peak)
surm	=	shear strength (Remolded)

(Note): log refers to natural logarithims (base e)

For fig. 6.1 the best fit curve (the model with the highest percent of variation explained, 86.21%) was as follows:

$$\log(\text{supk}) = 5.4806 - 0.02322\ \text{set}$$

which can be simplified to give:

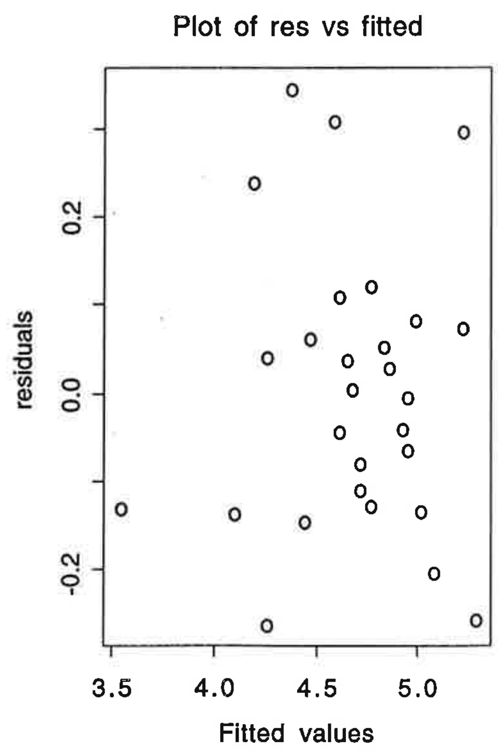
$$s_{U\,(PEAK)} = 240\ e^{-0.02322\ SET}$$

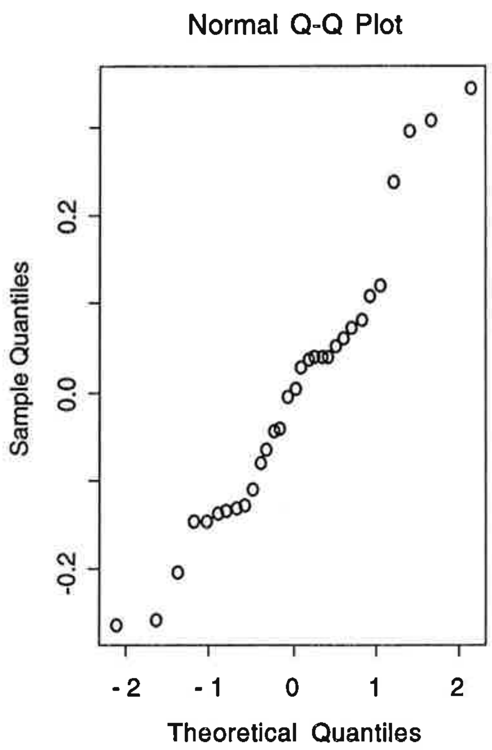
The details of the analysis are as follows:

```
> regress(set,log(supk))
                 Coef      Std Err      t-value      p-value    C.I.lower
Intercept  5.48056805  0.068492603     80.01693 0.000000e+00   5.34048495
set       -0.02321567  0.001723981    -13.46632 5.240253e-14  -0.02674161
            C.I.upper
Intercept  5.62065116
set       -0.01968974

Percent of variation explained:  86.21
Estimate of error Std dev:  0.1579508
Error df:  29

           Deg freedom  Sum squares  Mean square  F-statistic  p-value
Regression 1            4.524198     4.524198     181.3417     0
Residual   29           0.7235056    0.02494847
Total      30           5.247703
```





The alternative logarithmic variation gives:

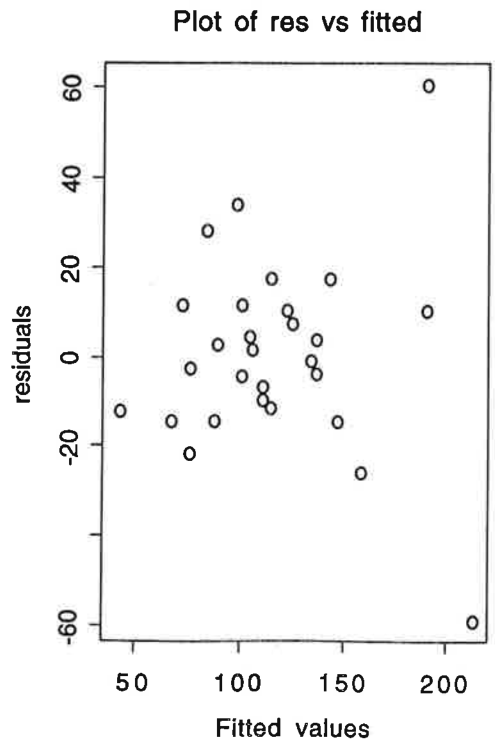
$$\text{supk} = 363.28 - 72.168 \log(\text{set})$$

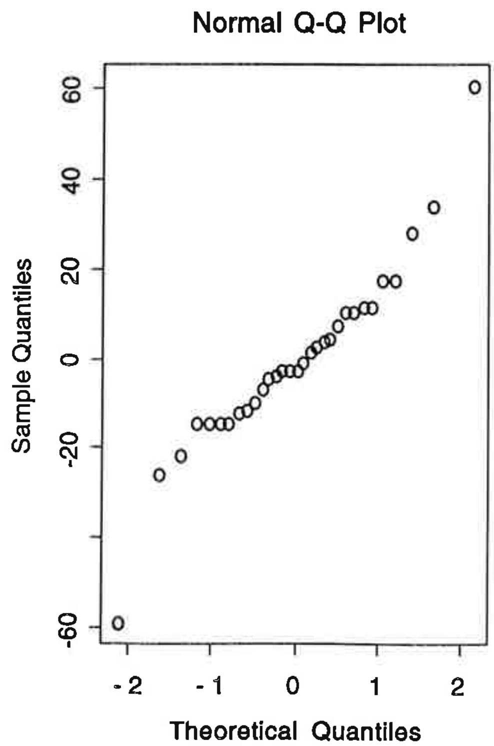
with 78.11% explained variation.

```
> regress(log(set),supk)
                 Coef       Std Err      t-value      p-value     C.I.lower
Intercept    363.28174    24.978840     14.54358 7.327472e-15     312.19427
log(set)     -72.46778     7.123537    -10.17301 4.465894e-11     -87.03705
             C.I.upper
Intercept    414.36920
log(set)     -57.89851

Percent of variation explained:  78.11
Estimate of error Std dev:   20.92507
Error df:   29

           Deg freedom  Sum squares  Mean square  F-statistic  p-value
Regression 1            45313.98     45313.98     103.4900     0
Residual   29           12697.89     437.8583
Total      30           58011.87
```





Analysing a model with both variables logarithmic gives:

$$\log(\text{supk}) = 6.9641 - 0.76012 \log(\text{set})$$

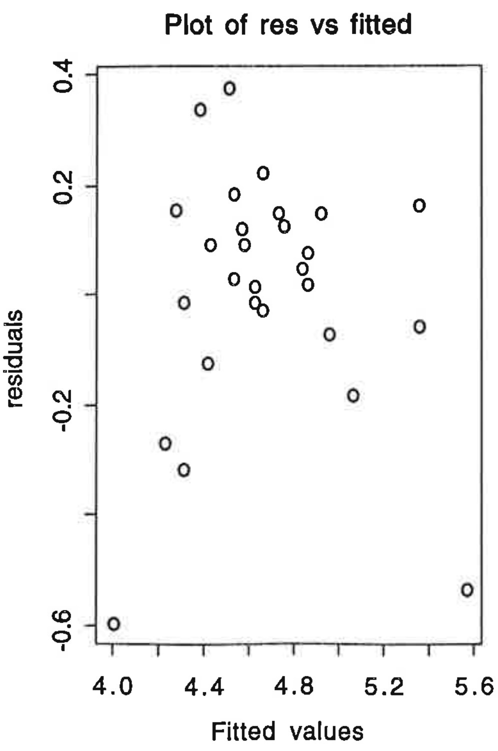
with 73.84% explained variation.

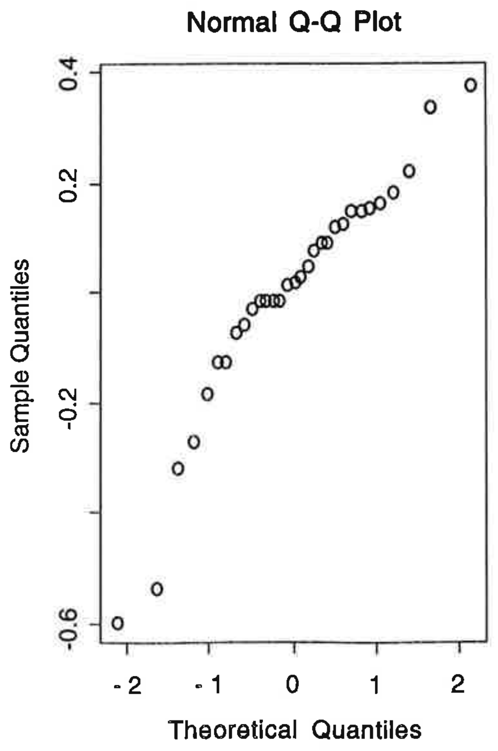
The details of the analysis are as follows:

```
> regress(log(set),log(supk))
                 Coef      Std Err       t-value      p-value    C.I.lower
Intercept   6.9640860  0.25973891    26.811871 0.00000e+00    6.4328603
log(set)   -0.6701157  0.07407309    -9.046682 6.08912e-10   -0.8216121
            C.I.upper
Intercept   7.4953117
log(set)   -0.5186192

Percent of variation explained:  73.84
Estimate of error Std dev:  0.2175863
Error df:  29

           Deg freedom  Sum squares  Mean square  F-statistic  p-value
Regression 1            3.874733     3.874733     81.84246     0
Residual   29           1.372970     0.0473438
Total      30           5.247703
>
```





Remolded shear strength vs set was also analysed

The best fit curve gave:

$$\log(\text{surm}) = 4.7937 - 0.023175 \text{ set}$$

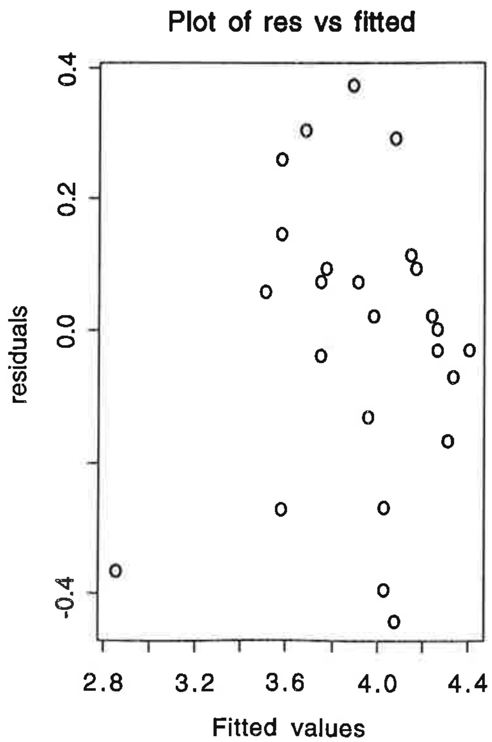
with 72.37% explained variation.

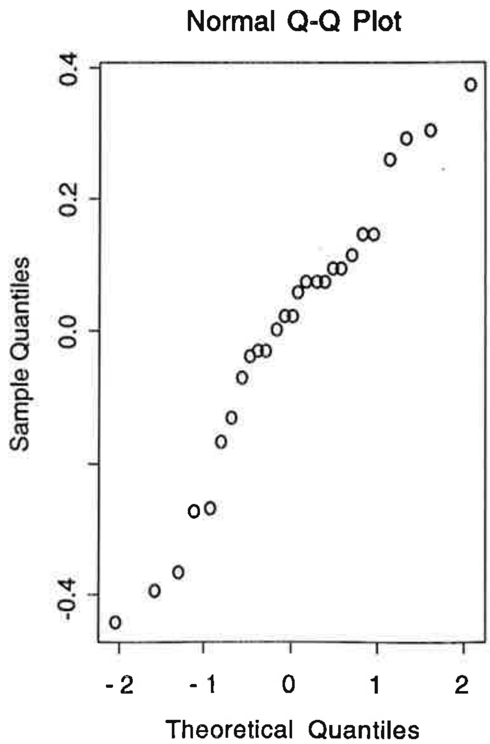
The details of the analysis are as follows:

```
> regress(set,log(surm))
                Coef         Std Err          t-value        p-value      C.I.lower
Intercept   4.79371759   0.116950568        40.98926 0.000000e+00     4.55285339
set        -0.02317514   0.002863897        -8.09217 1.905656e-08    -0.02907344
             C.I.upper
Intercept   5.03458180
set        -0.01727683

Percent of variation explained:  72.37
Estimate of error Std dev:  0.2153847
Error df:  25

           Deg freedom  Sum squares  Mean square  F-statistic  p-value
Regression 1            3.037804     3.037804     65.48321     0
Residual   25           1.159764     0.04639058
Total      26           4.197569
```





Multiple regression was also trialed varying both shear strength (peak) and shear strength (remolded) with set concurrently giving:

$$set = 209.786 - 36.0254 \log(supk) - 1.5526 \log(surm)$$

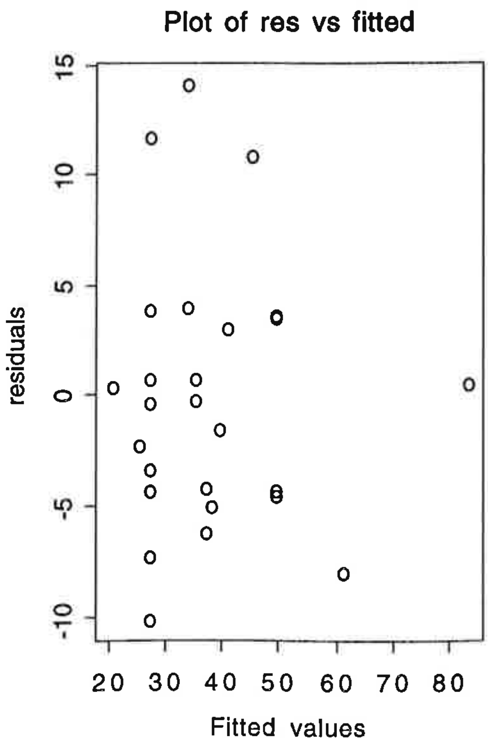
with 83.90% explained variation.

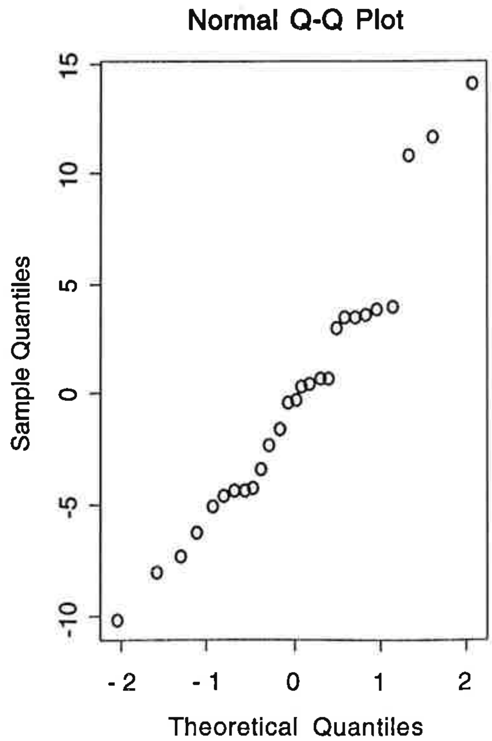
The details of the analysis are as follows:

```
> regress(log(supk),log(surm),set)
                 Coef       Std Err        t-value      p-value       C.I.lower
Intercept   209.786084    16.803101    12.4849625 5.480061e-12    175.10619
log(supk)   -36.024470     8.690517    -4.1452618 3.647942e-04    -53.96082
log(surm)    -1.552570     7.764563    -0.1999559 8.431997e-01    -17.57784
             C.I.upper
Intercept    244.46598
log(supk)    -18.08812
log(surm)     14.47270

Percent of variation explained:  83.9
Estimate of error Std dev:  6.16004
Error df:  24

            Deg freedom  Sum squares  Mean square  F-statistic  p-value
Regression  2            4745.368     2372.684     62.52776     0
Residual    24           910.7062     37.94609
Total       26           5656.074
```





The following tables are referred to in Section 6.4 and comprise the analysis which took place in the preparation of Figs. 6.3 and 6.4.

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr. 5.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Gross)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	2	19	22	0.90	2.72	2.44	8.5	21
2	145	165	2.6	100	43	3	15	18	0.85	1.09	0.92	30	28
3	145	165	1.6	95	43	2	14	16	0.89	1.09	0.98	35	34
4	160	180	2.0	108	45	2	20	22	0.89	1.33	1.19	27	32
5	150	175	2.0	54	41	2	9	11	0.80	1.17	0.94	45	42
6	145	170	1.8	92	47	2	14	16	0.87	1.09	0.95	40	38
7	175	200	2.0	111	37	2	24	26	0.92	1.59	1.46	30	44
8	170	195	2.0	111	34	2	23	25	0.92	1.50	1.38	25	35
9	170	195	2.2	73	38	2	15	17	0.86	1.50	1.29	30	39
10	170	195	2.1	73	39	2	15	17	0.86	1.50	1.30	35	45
11	170	195	2.0	73	38	2	15	17	0.87	1.50	1.31	35	46
12	175	195	2.0	132	70	4	29	33	0.88	1.54	1.35	20	27
13	150	165	1.9	132	74	3	21	24	0.86	1.13	0.97	18	18
14	150	165	1.8	132	74	3	21	24	0.86	1.13	0.98	21	21
15	150	165	1.8	132	74	3	21	24	0.86	1.13	0.98	20	20
16	175	195	2.4	132	74	5	29	34	0.85	1.54	1.31	11	14
17	150	165	1.8	132	74	3	21	24	0.86	1.13	0.98	24	24
18	150	165	1.8	132	74	3	21	24	0.86	1.13	0.98	25	25
19	175	195	2.0	132	74	4	29	33	0.87	1.54	1.34	25	34
20	175	200	3.4	154	-	0	-	-	-	1.54	0.00	5.5	-
21	175	200	3.6	200	-	0	-	-	-	1.54	0.00	7	-
22	250	250	3.0	30	47	6	13	19	0.71	0.42	0.30	200	59
23	250	250	8.0	52	26	8	23	31	0.74	0.42	0.31	144	45
24	150	175	3.9	250	64	6	40	46	0.86	1.11	0.96	10	10
25	275 x 275	275 x 275	14.0	83	30	23	56	80	0.71	0.75	0.53	75	40
26	275 x 275	275 x 275	18.5	107	36	37	73	109	0.67	0.75	0.50	47	23
27	275 x 275	275 x 275	22.5	160	39	48	109	157	0.69	0.75	0.52	28	15
28	200	225	2.0	73	59	4	21	25	0.84	2.04	1.71	22	38
29	200	225	3.0	103	51	5	29	34	0.85	2.04	1.73	16	28
30	200	225	2.0	73	59	4	21	25	0.84	2.04	1.71	26	44
31	200	225	3.0	103	51	5	29	34	0.85	2.04	1.73	15	26

Table B1 Normalised Sets (Gross Energy Input, α = 5%)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr. 10.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Gross)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	4	19	24	0.81	2.72	2.21	8.5	19
2	145	165	2.6	100	43	5	15	20	0.73	1.09	0.80	30	24
3	145	165	1.6	95	43	3	14	17	0.81	1.09	0.88	35	31
4	160	180	2.0	108	45	5	20	24	0.80	1.33	1.07	27	29
5	150	175	2.0	54	41	4	9	13	0.67	1.17	0.79	45	35
6	145	170	1.8	92	47	4	14	18	0.77	1.09	0.84	40	33
7	175	200	2.0	111	37	4	24	28	0.85	1.59	1.35	30	40
8	170	195	2.0	111	34	4	23	27	0.85	1.50	1.28	25	32
9	170	195	2.2	73	38	5	15	20	0.76	1.50	1.14	30	34
10	170	195	2.1	73	39	5	15	20	0.76	1.50	1.14	35	40
11	170	195	2.0	73	38	4	15	19	0.77	1.50	1.16	35	41
12	175	195	2.0	132	70	8	29	37	0.78	1.54	1.20	20	24
13	150	165	1.9	132	74	7	21	28	0.75	1.13	0.85	18	15
14	150	165	1.8	132	74	7	21	28	0.76	1.13	0.86	21	18
15	150	165	1.8	132	74	7	21	28	0.76	1.13	0.86	20	17
16	175	195	2.4	132	74	10	29	39	0.73	1.54	1.13	11	12
17	150	165	1.8	132	74	7	21	28	0.76	1.13	0.86	24	21
18	150	165	1.8	132	74	7	21	28	0.76	1.13	0.86	25	22
19	175	195	2.0	132	74	9	29	37	0.77	1.54	1.19	25	30
20	175	200	3.4	154	-	0	-	-	-	1.54	0.00	5.5	-
21	175	200	3.6	200	-	0	-	-	-	1.54	0.00	7	-
22	250	250	3.0	30	47	11	13	24	0.54	0.42	0.23	200	46
23	250	250	8.0	52	26	16	23	39	0.58	0.42	0.25	144	35
24	150	175	3.9	250	64	13	40	53	0.76	1.11	0.84	10	8
25	275 x 275	275 x 275	14.0	83	30	46	56	103	0.55	0.75	0.41	75	31
26	275 x 275	275 x 275	18.5	107	36	73	73	146	0.50	0.75	0.37	47	18
27	275 x 275	275 x 275	22.5	160	39	97	109	205	0.53	0.75	0.40	28	11
28	200	225	2.0	73	59	8	21	29	0.72	2.04	1.47	22	32
29	200	225	3.0	103	51	10	29	39	0.74	2.04	1.51	16	24
30	200	225	2.0	73	59	8	21	29	0.72	2.04	1.47	26	38
31	200	225	3.0	103	51	10	29	39	0.74	2.04	1.51	15	23

Table B2 Normalised Sets (Gross Energy Input, $\alpha = 10\%$)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr. 20.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Gross)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	9	19	28	0.69	2.72	1.86	8.5	16
2	145	165	2.6	100	43	11	15	26	0.58	1.09	0.63	30	19
3	145	165	1.6	95	43	7	14	21	0.68	1.09	0.74	35	26
4	160	180	2.0	108	45	10	20	29	0.67	1.33	0.89	27	24
5	150	175	2.0	54	41	8	9	17	0.51	1.17	0.59	45	27
6	145	170	1.8	92	47	8	14	22	0.62	1.09	0.68	40	27
7	175	200	2.0	111	37	9	24	33	0.73	1.59	1.17	30	35
8	170	195	2.0	111	34	8	23	30	0.74	1.50	1.12	25	28
9	170	195	2.2	73	38	10	15	24	0.61	1.50	0.91	30	27
10	170	195	2.1	73	39	9	15	24	0.61	1.50	0.92	35	32
11	170	195	2.0	73	38	9	15	24	0.63	1.50	0.95	35	33
12	175	195	2.0	132	70	16	29	45	0.64	1.54	0.98	20	20
13	150	165	1.9	132	74	14	21	35	0.60	1.13	0.68	18	12
14	150	165	1.8	132	74	13	21	34	0.61	1.13	0.70	21	15
15	150	165	1.8	132	74	13	21	34	0.61	1.13	0.70	20	14
16	175	195	2.4	132	74	21	29	49	0.58	1.54	0.90	11	10
17	150	165	1.8	132	74	13	21	34	0.61	1.13	0.70	24	17
18	150	165	1.8	132	74	13	21	34	0.61	1.13	0.70	25	17
19	175	195	2.0	132	74	17	29	46	0.62	1.54	0.96	25	24
20	175	200	3.4	154	-	0	-	-	-	1.54	0.00	5.5	-
21	175	200	3.6	200	-	0	-	-	-	1.54	0.00	7	-
22	250	250	3.0	30	47	22	13	35	0.37	0.42	0.16	200	31
23	250	250	8.0	52	26	33	23	56	0.41	0.42	0.17	144	25
24	150	175	3.9	250	64	25	40	65	0.61	1.11	0.68	10	7
25	275 x 275	275 x 275	14.0	83	30	92	56	149	0.38	0.75	0.29	75	21
26	275 x 275	275 x 275	18.5	107	36	147	73	219	0.33	0.75	0.25	47	12
27	275 x 275	275 x 275	22.5	160	39	193	109	302	0.36	0.75	0.27	28	8
28	200	225	2.0	73	59	16	21	36	0.57	2.04	1.15	22	25
29	200	225	3.0	103	51	20	29	50	0.59	2.04	1.20	16	19
30	200	225	2.0	73	59	16	21	36	0.57	2.04	1.15	26	30
31	200	225	3.0	103	51	20	29	50	0.59	2.04	1.20	15	18

Table B3 Normalised Sets (Gross Energy Input, $\alpha = 20\%$)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr. 50.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Gross)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	22	19	42	0.47	2.72	1.27	8.5	11
2	145	165	2.6	100	43	27	15	42	0.35	1.09	0.39	30	12
3	145	165	1.6	95	43	17	14	31	0.46	1.09	0.50	35	18
4	160	180	2.0	108	45	24	20	44	0.45	1.33	0.60	27	16
5	150	175	2.0	54	41	21	9	30	0.29	1.17	0.34	45	15
6	145	170	1.8	92	47	21	14	35	0.40	1.09	0.43	40	17
7	175	200	2.0	111	37	22	24	46	0.52	1.59	0.84	30	25
8	170	195	2.0	111	34	19	23	42	0.54	1.50	0.81	25	20
9	170	195	2.2	73	38	24	15	39	0.38	1.50	0.58	30	17
10	170	195	2.1	73	39	23	15	38	0.39	1.50	0.58	35	20
11	170	195	2.0	73	38	22	15	37	0.41	1.50	0.61	35	21
12	175	195	2.0	132	70	41	29	69	0.41	1.54	0.64	20	13
13	150	165	1.9	132	74	35	21	56	0.38	1.13	0.43	18	8
14	150	165	1.8	132	74	33	21	54	0.39	1.13	0.44	21	9
15	150	165	1.8	132	74	33	21	54	0.39	1.13	0.44	20	9
16	175	195	2.4	132	74	52	29	80	0.36	1.54	0.55	11	6
17	150	165	1.8	132	74	33	21	54	0.39	1.13	0.44	24	11
18	150	165	1.8	132	74	33	21	54	0.39	1.13	0.44	25	11
19	175	195	2.0	132	74	43	29	72	0.40	1.54	0.62	25	15
20	175	200	3.4	154	-	0	-	-	-	1.54	0.00	5.5	-
21	175	200	3.6	200	-	0	-	-	-	1.54	0.00	7	-
22	250	250	3.0	30	47	55	13	69	0.19	0.42	0.08	200	16
23	250	250	8.0	52	26	82	23	105	0.22	0.42	0.09	144	13
24	150	175	3.9	250	64	64	40	103	0.38	1.11	0.43	10	4
25	275 x 275	275 x 275	14.0	83	30	231	56	287	0.20	0.75	0.15	75	11
26	275 x 275	275 x 275	18.5	107	36	366	73	439	0.17	0.75	0.12	47	6
27	275 x 275	275 x 275	22.5	160	39	483	109	592	0.18	0.75	0.14	28	4
28	200	225	2.0	73	59	39	21	60	0.34	2.04	0.70	22	15
29	200	225	3.0	103	51	51	29	80	0.36	2.04	0.74	16	12
30	200	225	2.0	73	59	39	21	60	0.34	2.04	0.70	26	18
31	200	225	3.0	103	51	51	29	80	0.36	2.04	0.74	15	11

Table B4 Normalised Sets (Gross Energy Input, α =50%)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr 5.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Net)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	2	19	22	0.90	2.61	2.34	8.5	20
2	145	165	2.6	100	43	3	15	18	0.85	1.04	0.88	30	26
3	145	165	1.6	95	43	2	14	16	0.89	1.04	0.93	35	33
4	160	180	2.0	108	45	2	20	22	0.89	1.32	1.18	27	32
5	150	175	2.0	54	41	2	9	11	0.80	1.15	0.92	45	42
6	145	170	1.8	92	47	2	14	16	0.87	1.07	0.92	40	37
7	175	200	2.0	111	37	2	24	26	0.92	1.66	1.52	30	46
8	170	195	2.0	111	34	2	23	25	0.92	1.55	1.43	25	36
9	170	195	2.2	73	38	2	15	17	0.86	1.55	1.34	30	40
10	170	195	2.1	73	39	2	15	17	0.86	1.55	1.34	35	47
11	170	195	2.0	73	38	2	15	17	0.87	1.55	1.36	35	47
12	175	195	2.0	132	70	4	29	33	0.88	1.56	1.36	20	27
13	150	165	1.9	132	74	3	21	24	0.86	1.08	0.92	18	17
14	150	165	1.8	132	74	3	21	24	0.86	1.08	0.93	21	20
15	150	165	1.8	132	74	3	21	24	0.86	1.08	0.93	20	19
16	175	195	2.4	132	74	5	29	34	0.85	1.56	1.32	11	15
17	150	165	1.8	132	74	3	21	24	0.86	1.08	0.93	24	22
18	150	165	1.8	132	74	3	21	24	0.86	1.08	0.93	25	23
19	175	195	2.0	132	74	4	29	33	0.87	1.56	1.36	25	34
20	175	200	3.4	154	-	0	-	0	ERR	1.65	ERR	5.5	-
21	175	200	3.6	200	-	0	-	0	ERR	1.65	ERR	7	-
22	250	250	3.0	30	47	6	13	19	0.71	0.44	0.31	200	63
23	250	250	8.0	52	26	8	23	31	0.74	0.44	0.33	144	47
24	150	175	3.9	250	64	6	40	46	0.86	1.05	0.91	10	9
25	275 x 275	275 x 275	14.0	83	30	23	56	80	0.71	1.13	0.80	75	60
26	275 x 275	275 x 275	18.5	107	36	37	73	109	0.67	1.32	0.88	47	41
27	275 x 275	275 x 275	22.5	160	39	48	109	157	0.69	1.32	0.92	28	26
28	200	225	2.0	73	59	4	21	25	0.84	2.04	1.71	22	38
29	200	225	3.0	103	51	5	29	34	0.85	2.04	1.73	16	28
30	200	225	2.0	73	59	4	21	25	0.84	2.04	1.71	26	44
31	200	225	3.0	103	51	5	29	34	0.85	2.04	1.73	15	26

Table B5 Normalised Sets (Net Energy Input, $\alpha = 5\%$)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr 10.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Net)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	4	19	24	0.81	2.61	2.12	8.5	18
2	145	165	2.6	100	43	5	15	20	0.73	1.04	0.76	30	23
3	145	165	1.6	95	43	3	14	17	0.81	1.04	0.84	35	29
4	160	180	2.0	108	45	5	20	24	0.80	1.32	1.06	27	29
5	150	175	2.0	54	41	4	9	13	0.67	1.15	0.77	45	35
6	145	170	1.8	92	47	4	14	18	0.77	1.07	0.82	40	33
7	175	200	2.0	111	37	4	24	28	0.85	1.66	1.41	30	42
8	170	195	2.0	111	34	4	23	27	0.85	1.55	1.33	25	33
9	170	195	2.2	73	38	5	15	20	0.76	1.55	1.18	30	35
10	170	195	2.1	73	39	5	15	20	0.76	1.55	1.18	35	41
11	170	195	2.0	73	38	4	15	19	0.77	1.55	1.20	35	42
12	175	195	2.0	132	70	8	29	37	0.78	1.56	1.21	20	24
13	150	165	1.9	132	74	7	21	28	0.75	1.08	0.81	18	15
14	150	165	1.8	132	74	7	21	28	0.76	1.08	0.82	21	17
15	150	165	1.8	132	74	7	21	28	0.76	1.08	0.82	20	16
16	175	195	2.4	132	74	10	29	39	0.73	1.56	1.15	11	13
17	150	165	1.8	132	74	7	21	28	0.76	1.08	0.82	24	20
18	150	165	1.8	132	74	7	21	28	0.76	1.08	0.82	25	21
19	175	195	2.0	132	74	9	29	37	0.77	1.56	1.20	25	30
20	175	200	3.4	154	-	0	-	0	ERR	1.65	ERR	5.5	-
21	175	200	3.6	200	-	0	-	0	ERR	1.65	ERR	7	-
22	250	250	3.0	30	47	11	13	24	0.54	0.44	0.24	200	48
23	250	250	8.0	52	26	16	23	39	0.58	0.44	0.26	144	37
24	150	175	3.9	250	64	13	40	53	0.76	1.05	0.80	10	8
25	275 x 275	275 x 275	14.0	83	30	46	56	103	0.55	1.13	0.62	75	47
26	275 x 275	275 x 275	18.5	107	36	73	73	146	0.50	1.32	0.66	47	31
27	275 x 275	275 x 275	22.5	160	39	97	109	205	0.53	1.32	0.70	28	20
28	200	225	2.0	73	59	8	21	29	0.72	2.04	1.47	22	32
29	200	225	3.0	103	51	10	29	39	0.74	2.04	1.51	16	24
30	200	225	2.0	73	59	8	21	29	0.72	2.04	1.47	26	38
31	200	225	3.0	103	51	10	29	39	0.74	2.04	1.51	15	23

Table B6 Normalised Sets (Net Energy Input, α = 10%)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr 20.% (kN)	End Brg. Driving (kN)	Total Cap. Driving (kN)	End Brg. Normalising Factor	Normalising Factor (Net)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	9	19	28	0.69	2.61	1.79	8.5	15
2	145	165	2.6	100	43	11	15	26	0.58	1.04	0.60	30	18
3	145	165	1.6	95	43	7	14	21	0.68	1.04	0.71	35	25
4	160	180	2.0	108	45	10	20	29	0.67	1.32	0.88	27	24
5	150	175	2.0	54	41	8	9	17	0.51	1.15	0.58	45	26
6	145	170	1.8	92	47	8	14	22	0.62	1.07	0.66	40	26
7	175	200	2.0	111	37	9	24	33	0.73	1.66	1.22	30	37
8	170	195	2.0	111	34	8	23	30	0.74	1.55	1.16	25	29
9	170	195	2.2	73	38	10	15	24	0.61	1.55	0.95	30	28
10	170	195	2.1	73	39	9	15	24	0.61	1.55	0.95	35	33
11	170	195	2.0	73	38	9	15	24	0.63	1.55	0.98	35	34
12	175	195	2.0	132	70	16	29	45	0.64	1.56	0.99	20	20
13	150	165	1.9	132	74	14	21	35	0.60	1.08	0.65	18	12
14	150	165	1.8	132	74	13	21	34	0.61	1.08	0.66	21	14
15	150	165	1.8	132	74	13	21	34	0.61	1.08	0.66	20	13
16	175	195	2.4	132	74	21	29	49	0.58	1.56	0.91	11	10
17	150	165	1.8	132	74	13	21	34	0.61	1.08	0.66	24	16
18	150	165	1.8	132	74	13	21	34	0.61	1.08	0.66	25	17
19	175	195	2.0	132	74	17	29	46	0.62	1.56	0.97	25	24
20	175	200	3.4	154	-	0	-	0	ERR	1.65	ERR	5.5	-
21	175	200	3.6	200	-	0	-	0	ERR	1.65	ERR	7	-
22	250	250	3.0	30	47	22	13	35	0.37	0.44	0.17	200	33
23	250	250	8.0	52	26	33	23	56	0.41	0.44	0.18	144	26
24	150	175	3.9	250	64	25	40	65	0.61	1.05	0.64	10	6
25	275 x 275	275 x 275	14.0	83	30	92	56	149	0.38	1.13	0.43	75	32
26	275 x 275	275 x 275	18.5	107	36	147	73	219	0.33	1.32	0.44	47	21
27	275 x 275	275 x 275	22.5	160	39	193	109	302	0.36	1.32	0.48	28	13
28	200	225	2.0	73	59	16	21	36	0.57	2.04	1.15	22	25
29	200	225	3.0	103	51	20	29	50	0.59	2.04	1.20	16	19
30	200	225	2.0	73	59	16	21	36	0.57	2.04	1.15	26	30
31	200	225	3.0	103	51	20	29	50	0.59	2.04	1.20	15	18

Table B7 Normalised Sets (Net Energy Input, $\alpha = 20\%$)

Test Ref No	Pile base Dia. (mm)	Pile top Dia. (mm)	Driven Depth (m)	Fnd.Level Su (Peak) Corr. (kPa)	Mean Shaft Su (Rem) Corr. (kPa)	Shaft SkFr. Su (Rem) Ftr 50.% (kN)	End Bng. Driving (kN)	Total Cap. Driving (kN)	End Bng. Normalising Factor	Normalising Factor (Net)	Final Normalising Factor	Set/Blow Rec. (mm)	Set/Blow Norm. (mm)
1	140	155	1.2	140	80	22	19	42	0.47	2.61	1.22	8.5	10
2	145	165	2.6	100	43	27	15	42	0.35	1.04	0.37	30	11
3	145	165	1.6	95	43	17	14	31	0.46	1.04	0.48	35	17
4	160	180	2.0	108	45	24	20	44	0.45	1.32	0.59	27	16
5	150	175	2.0	54	41	21	9	30	0.29	1.15	0.33	45	15
6	145	170	1.8	92	47	21	14	35	0.40	1.07	0.42	40	17
7	175	200	2.0	111	37	22	24	46	0.52	1.66	0.87	30	26
8	170	195	2.0	111	34	19	23	42	0.54	1.55	0.84	25	21
9	170	195	2.2	73	38	24	15	39	0.38	1.55	0.60	30	18
10	170	195	2.1	73	39	23	15	38	0.39	1.55	0.60	35	21
11	170	195	2.0	73	38	22	15	37	0.41	1.55	0.63	35	22
12	175	195	2.0	132	70	41	29	69	0.41	1.56	0.64	20	13
13	150	165	1.9	132	74	35	21	56	0.38	1.08	0.41	18	7
14	150	165	1.8	132	74	33	21	54	0.39	1.08	0.42	21	9
15	150	165	1.8	132	74	33	21	54	0.39	1.08	0.42	20	8
16	175	195	2.4	132	74	52	29	80	0.36	1.56	0.56	11	6
17	150	165	1.8	132	74	33	21	54	0.39	1.08	0.42	24	10
18	150	165	1.8	132	74	33	21	54	0.39	1.08	0.42	25	10
19	175	195	2.0	132	74	43	29	72	0.40	1.56	0.62	25	16
20	175	200	3.4	154	-	0	-	0	ERR	1.65	ERR	5.5	-
21	175	200	3.6	200	-	0	-	0	ERR	1.65	ERR	7	-
22	250	250	3.0	30	47	55	13	69	0.19	0.44	0.09	200	17
23	250	250	8.0	52	26	82	23	105	0.22	0.44	0.10	144	14
24	150	175	3.9	250	64	64	40	103	0.38	1.05	0.40	10	4
25	275 x 275	275 x 275	14.0	83	30	231	56	287	0.20	1.13	0.22	75	17
26	275 x 275	275 x 275	18.5	107	36	366	73	439	0.17	1.32	0.22	47	10
27	275 x 275	275 x 275	22.5	160	39	483	109	592	0.18	1.32	0.24	28	7
28	200	225	2.0	73	59	39	21	60	0.34	2.04	0.70	22	15
29	200	225	3.0	103	51	51	29	80	0.36	2.04	0.74	16	12
30	200	225	2.0	73	59	39	21	60	0.34	2.04	0.70	26	18
31	200	225	3.0	103	51	51	29	80	0.36	2.04	0.74	15	11

Table B8 Normalised Sets (Net Energy Input, α = 50%)

APPENDIX C

Practical Application

Practical Application

A foundation designer is often in the situation of having to estimate the depth to which piles must be driven in order to resist design loadings. If foundations have been designed to NZS:3604 Appendix D the formula derived in Section 6.2 can be applied to provide an estimate of the required shear strength in cohesive soils to achieve the set requirements of that appendix. Any variation on the Appendix D installation specification can be allowed for through normalising the set.

<u>Example:</u>

A Contractor has a pile driving rig with a 400 kg hammer and hydraulic release mechanism designed to give a 1m drop height. Piles are of 165mm diameter base and are driven small end first. What shear strength material would be expected to give a set of 25mm per blow under NZS3604 Appendix D?

<u>Solution:</u>

The following formula from Section 6.2 is based on the gross energy relationship:

$$s_{U\,(PEAK)} = 240\ e^{-0.02322\ SET}$$

The above set per blow has been normalised to the standard NZS:3604 Appendix D driving conditions on the basis of gross energy input per unit area of pile base. Normalising the set in the example as detailed in Section 6.2 gives:

$$\text{Gross Energy Ratio} = \frac{400 \times 9.81 \times 1.0}{4800}$$

$$= 0.8175$$

$$\text{Area Ratio} = \frac{\pi \times 0.165^2/4}{\pi \times 0.140^2/4}$$

$$= 1.3890$$

$$\text{Normalising Factor} = \frac{1.3890}{0.8175} = 1.699$$

$$\text{Set / Blow}_{(NORM)} = \text{Set / blow}_{(APPENDIX\ D)} \times 1.699$$

$$s_{U\,(PEAK)} = 240\,e^{-0.02322 \times (25 \times 1.699)} = 90 \text{ kPa}$$

Engineering judgement is now required in interpreting the available borehole logs to determine the expected driven pile depth. It should be accepted that errors will be introduced if the nine criteria of Section 4.2 are not followed. In the study it was found that lateral variations in shear strength away from a bore hole had a major effect. It should also be remembered that the material below the base of a pile influences the driving resistance and ultimate pile capacity to a depth of about three pile diameters. (Ref. 10)