REVIEW OF CPT TESTING AND PILE DESIGN PARAMETERS DERIVED FROM GLACIAL DEPOSITS IN PERTH

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ABSTRACT This paper identifies a glacial meltwater deposit beneath Perth town centre which provides a suitable bearing stratum for piled foundations. Geotechnical testing shows the material to be mainly a laminated silt with a reasonably consistent profile in depth and lateral extent. Site investigation using Cone Penetration Testing (CPT) is shown to provide a better assessment of the in-situ characteristics of the material compared to more conventional techniques. The paper also reviews the results of several pile tests, installed using Continuous Flight Auger (CFA) techniques, and back analysis shows a fairly consistent range of derived parameters. This paper shows the importance of obtaining an accurate assessment of geotechnical characteristics. This is demonstrated with regards to pile design parameters. It is also shown how CPT testing is a valuable technique to assess in-situ geotechnical characteristics in fluvio-glacial deposits.

1. Introduction

Perth is situated on the eastern side of Scotland, within the Midland Valley, and almost due north of Edinburgh. It is located on the River Tay which flows through the city in a north-north-west to south-south-east direction towards the Firth of Tay and the North Sea (see Figure 1).

Figure 1 General location

The geology comprises alluvial and fluvio-glacial deposits overlying a bedrock comprising mainly Sandstone and volcanics of Devonian age. A deep glacial channel is associated with the river and beneath a sequence of Alluvium lies a thickness of fluvio-glacial deposits.

Modern foundations for larger structures require a suitable founding stratum. Although the alluvial gravel could be an option, this has been found to be variable in composition and thickness whereas the potential of the underlying fluvio-glacial deposits seems to be undervalued. This paper provides an assessment from several pile tests carried out on piles taken into the fluvio-glacial deposits.

Older site investigation techniques often do not distinguish the various deposits and for the town centre, fluvio-glacial deposits have often been described as a ‘soft’ Alluvial material. Classification of these glacial deposits and the prediction of their behaviour by using traditional site investigation can be relatively difficult and not very reliable and this is also discussed within the paper. Reference to the use of CPT is included.

2. Town setting and geological model

The town is mainly located on the western bank of the River Tay. To the north of the town the River Almond enters the River Tay, flowing from the north-west, off the Highlands.

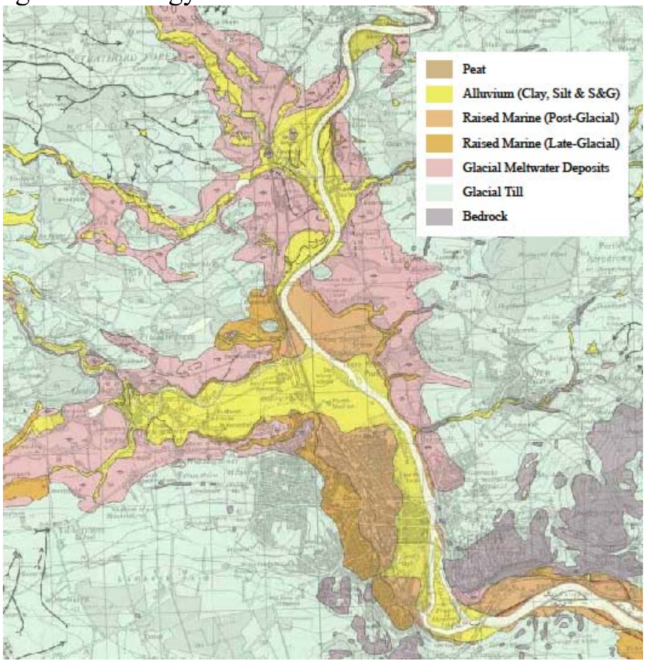
Perth, shown on Figure 2, is located within the Central Lowlands of Scotland, which forms a rift valley bounded to the north by the Highland boundary fault and the south by the southern upland fault. The former fault runs in a south-west to north-east direction from Arran to Stonehaven. The uplift of the Highlands occurred during the Caledonian orogeny. To the north of the fault lie a series of ancient rocks, of mainly Cambrian to Pre-Cambrian age; whilst to the south the Central Lowlands are formed of mainly deposits of Palaeozoic age.

Figure 2 Perth town map

Within the Pleistocene period the area was subject to several ice ages which significantly affected the landscape. Deep river channels were formed, with the deposition of a thickness of fluvio-glacial deposits, whilst on the higher areas, thicknesses of Glacial Till are recorded. The ice sheets typically moved from the north-west, off the Highlands, and towards the east. The glacial action cut deep valleys in the Perth area with rockhead recorded at below -50mOD in the Perth area. The ground rises away from the rivers to over 100mOD at Scone Airport to the east, Methven to the north-west and higher towards the Highlands.

Deep glacial channels are associated with the rivers Tay and Almond and beneath a sequence of Alluvium clays and gravel, lies a thickness of fluvio-glacial deposits. The local geological information also mentions that away from the rivers various fluvio-glacial deposits are present with some raised marine deposits. The topography of the Perth area suggests the glaciated channel is in the order of two to three kilometres in width, but this decreases northwards up the Tay and Almond valleys. At the confluence of the two rivers, in the district of Muirton, the greatest width of infilling alluvial and fluvial glacial deposits is indicated (see Figure 3).

Figure 3 Geology of the Perth area

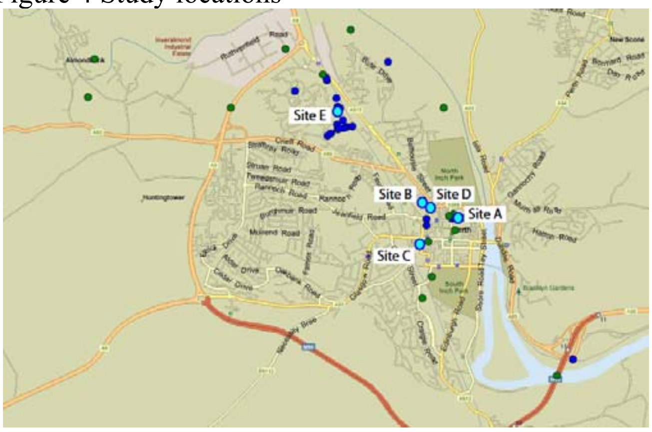


3. Geotechnical data

3.1 General

As part of this paper, we have collated geotechnical data from several investigation sources from around the Perth area (see Figure 4). This has been carried out initially to assess the nature of the underlying deposits within the study area. An interpretation was carried out to: assess the distribution of the various strata; compare to the geological map; assess any variation in geotechnical characteristics.

Figure 4 Study locations



The above shows the locations of the data sources used for this paper. It should be noted that this data only refers to sites where a sequence of fluvio-glacial deposits was identified. The figure divides the sites into the main sites (Sites A-D) where pile test results were available, where CPTs were carried out and also other sites with geotechnical data.

3.2 Geological model

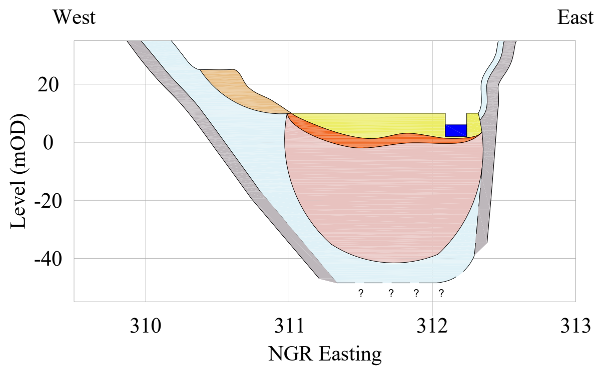
Within the central Perth area, the geotechnical model mainly comprises a thickness of made ground, followed by a cohesive alluvial deposit (Alluvial Clay), which becomes siltier and more granular with depth; passing down into an Alluvial Sand and then Sand & Gravel. This then overlies a glacial meltwater or fluvio-glacial deposit. This stratum is then underlain by a glacial lodgement deposit or bedrock.

<u>Indicative geological sequence taken as follows</u>

Made Ground
Peat
Alluvial Clay
Alluvial Silt/Sand
Sand & Gravel (alluvial deposit)
Raised Marine Deposits
Fluvio-Glacial Deposit
Glacial Till / Bedrock

In reviewing this sequence, the thickness of the above layers varied, particularly the alluvial sequence, which in places was absent. Typical geotechnical parameters have been taken for each stratum with an assessment of the profiles across the study area (see Figure 5).

Figure 5 Indicative geological profile across the studied area (see Figure 3 above for key)



The study area is mainly associated with the rivers and not where the glacial till and/or bedrock outcrop on the higher ground. Along the margins, towards the west of central Perth and away from the rivers, raised marine deposits typically occur at higher ordnance levels, and these were difficult to distinguish within the sequence.

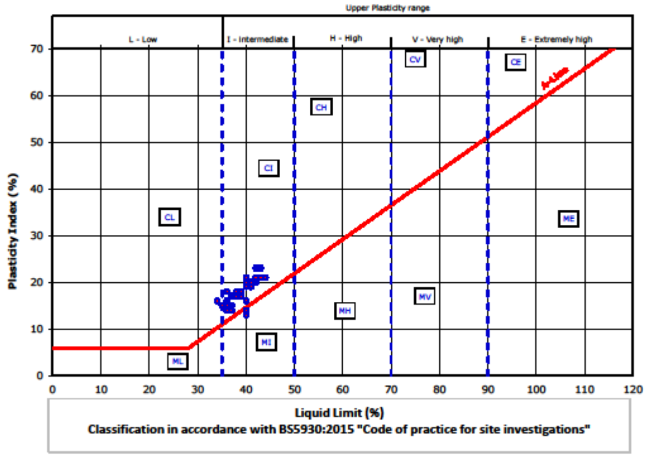
3.3 Discuss geotechnical model

The initial data research for this paper was to consider fluvio-glacial deposits, hereafter referred to as Laminated Silt, associated with the river channels and with regards to the geotechnical properties.

Classification test results for the Laminated Silt has been collected from sites, with geotechnical envelopes for 34 plasticity tests results and 15 grading analysis results shown in Figure 6 and Figure 7 below.

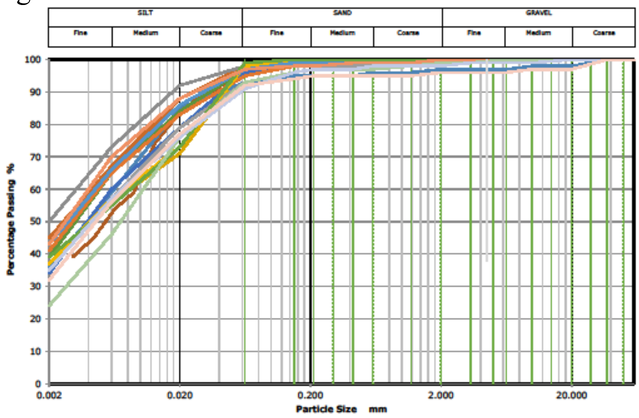
From Figure 6, the results indicate the Laminated Silt could be classified as a cohesive material of intermediate plasticity.

Figure 6 Plasticity index chart



Reviewing the gradings (see Figure 7), the samples show the Laminated Silt comprises nearly 100% fine grained particles and with over 50% of the remaining material of silt size. This could therefore be considered as a low energy glacial meltwater deposit.

Figure 7 Particle size distribution chart



3.4 Review of site investigation data for main sites

Geotechnical data obtained using conventional site investigation techniques for the main sites is presented in Table 1. This data only relates to the Laminated Silt and includes the results of 15 Standard Penetration Tests (SPT) and 11 results from undrained triaxial tests performed on recovered samples.

Table 1 Strength properties

Site	Depth (m)	SPT (N values)	Shear Strength (kN/m²)
A	9.6-15.2	7-8	17-36
B	10.5-24.0	1-2	8-41
C	8.0-25.5	9-17	10-13

4. Geotechnical assessment based on CPT

4.1 General

The variation of different materials within a glacial deposit can be a major concern. CIRIA C504, Trenter (1999) comments on possible issues including the mis-identification of boulders as bedrock, the mis-identification of laminated silts and difficulties in obtaining representative samples suitable for testing purposes.

CPT testing can be used as a profiling technique as well as to derive geotechnical characteristics. The test is performed in-situ with a confining pressure around the undisturbed material which increases the reliability. Testing within the Laminated Silt deposits show uniform readings, but also the occasional occurrence of thin layers of sand, typically 10cm in thickness. Such layers are almost impossible to distinguish by cable percussion techniques. Further Laminated Silts are highly sensitive to pore pressure changes and dilatancy, which makes it difficult to sample and undertake reliable laboratory tests.

4.2 Interpretation of CPT results

Within the study area CPT readings for the Laminated Silt deposits, cone resistance (q_c) and friction ratio (R_f), demonstrate a relatively narrow range of values. For the purpose of this paper data from 45 CPT tests to a maximum depth of nearly 46m have been reviewed. R_f results are generally between 2% and 4%. Some of the results indicate more sandy material, by higher R_f values, with these occurring towards the margin of the stratum and to the north.

Interpretation from CPT results is usually based on soil behaviour type (SBT) charts, which use the measured parameters q_c and R_f to interpret the soils. Robertson *et al.* (1986) divides soils into 12 zones and based on measured data from CPT tests. Since both the q_c and f_s increase with depth, due to the increase in effective overburden stress, the CPT data requires normalisation for overburden stress for tests deeper than 20m (Robertson and Cabal, 2015). This resulted in an alternative SBTn chart also used for interpretation, based on normalised CPT data, proposed by Robertson (1990). (see Figures 8(a) and 8(b) below).

Figure 8(a) Robertson *et al.* (1986) SBT chart

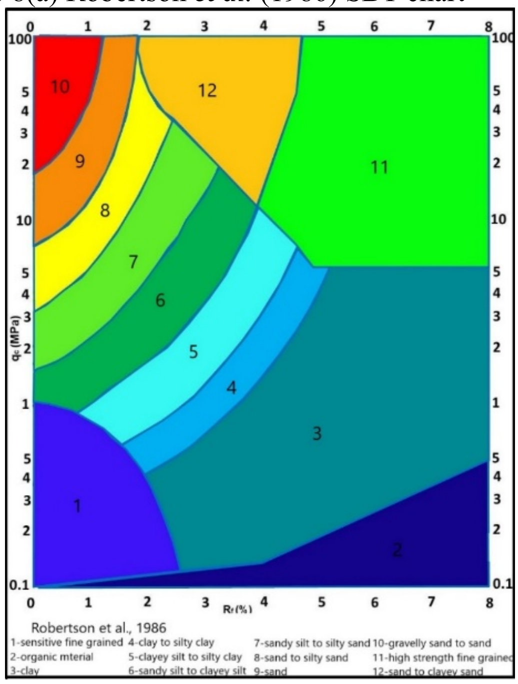
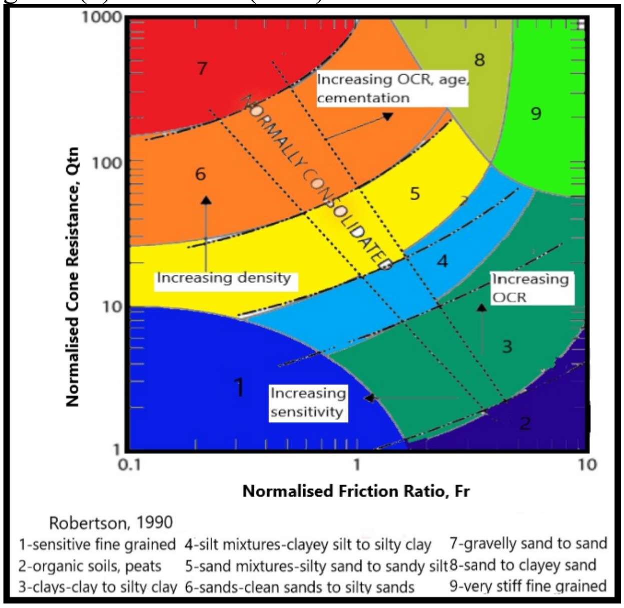


Figure 8(b) Robertson (1990) SBTn chart



The normalised Robertson (1990) SBTn chart interprets soils based on normalised cone resistance, Q_{tn} and includes 9 zones, identifying general trends in ground response (Robertson & Cabal (2015)). A CPT profile from one of the sites taken into consideration in this paper shown in Figures 9(a) and 9(b).

Figure 9(a) Typical CPT profile interpreted based on Robertson *et al.* (1986) SBT

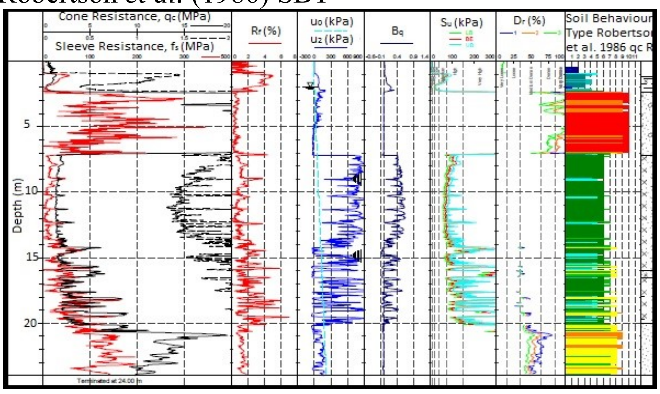
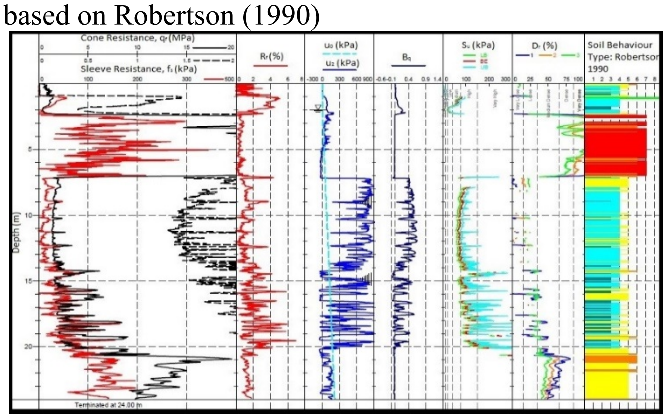


Figure 9(b) Typical normalised CPT profile interpreted based on Robertson (1990)

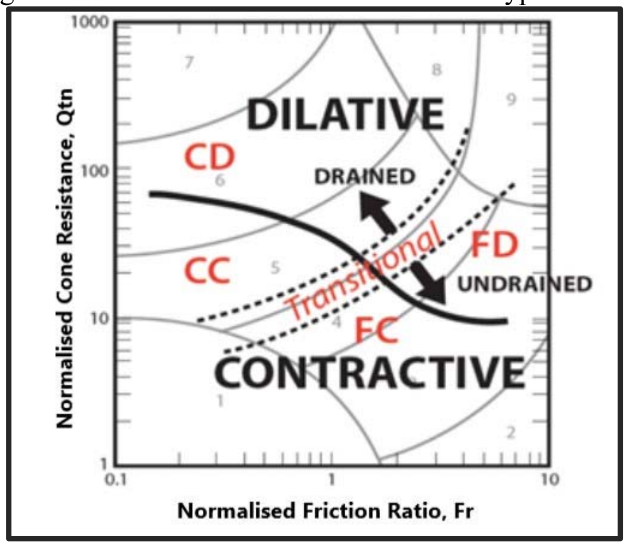


These two figures show how the layer of Laminated Silt, between 7m to 20m depth can be interpreted as sandy silt to clayey silt (Zone 6), based on Robertson *et al.* (1986) SBT (see Figure 9(a)), and clayey silt to silty clay (Zone 4) based on Robertson (1990) SBTn (see Figure 9(b)). In both cases the thin layers of sand below 15m are easily identified.

CPT interpretation for the Laminated Silt based on the Robertson *et al.* (1986) method indicate the material could behave as a sandy Silt to clayey Silt (Zone 6), meanwhile soils interpreted using the Robertson (1990) method indicate behaviour as a clayey Silt to silty Clay (Zone 4).

Looking at a more general normalised CPT SBTn chart from Robertson and Cabal (2014) presented in Figure 10, these soils are falling mainly in the transitional band area of the chart behaving predominantly as undrained and being categorised as fine-grained dilative soils, with higher values of R_f and Q_{tn}, or fine-grained contractive soils when R_f and Q_{tn} are lower.

Figure 10 Normalized CPT Soil Behaviour Type chart



Only a few sites included in this paper were tested using piezocones. From porewater pressure (u_2) measurements within the Laminated Silt, values of 600kN/m² or higher, are obtained. A limited number of dissipation tests undertaken indicate that these deposits exhibit rapid dissipation (recorded times for 50% dissipation mainly between 10 and 20 minutes), although the porewater pressure is generally high.

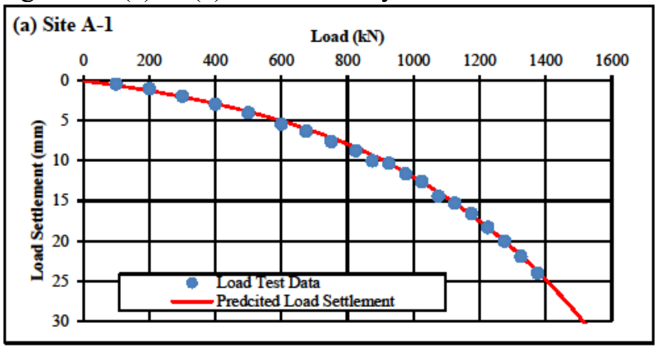
5. Pile assessment

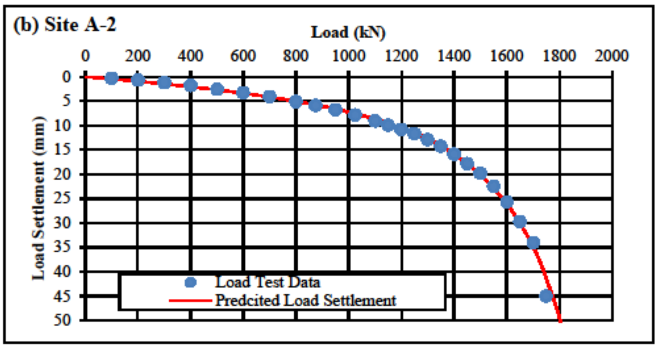
The results of several pile load tests carried out within the Perth area are presented within this paper with most comprising continuous flight auger (CFA) piles taken into the Laminated Silts. The paper mainly concentrates on five preliminary test results, all showing significant displacements, and where the test procedure allowed for a sensible back analysis.

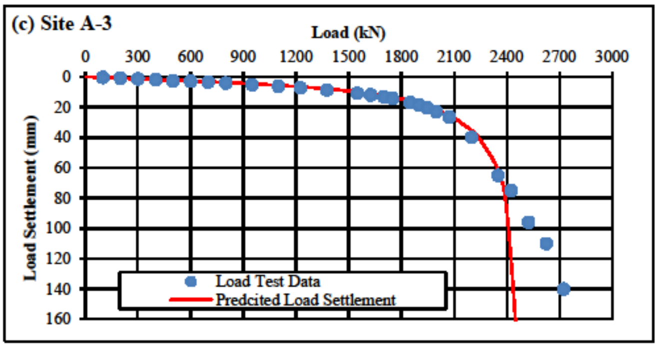
The results of five preliminary pile tests, for three sites, have been reviewed. The load tests were carried out using a procedure in general accordance with the ICE Specification for Piling and Embedded Retaining Walls although amended to include a single load cycle, with the test continued with incremental hold cycles and with automatic monitoring. For this the load was kept constant during a particular load hold period to allow frequent readings to be assessed for an infinite time displacement. The procedure was designed to allow a suitable back analysis of the data and this was carried out using the Cemset/Cemsolve approach; this is outlined and described in a paper by Fleming (1992). The Cemsolve approach tries to model results from a maintained load test using several parameters to allow two hyperbolic functions to represent the characteristic behaviour of the pile. These are then matched to the test data and discussion of these and other relevant comments considered with the interpretation are given below.

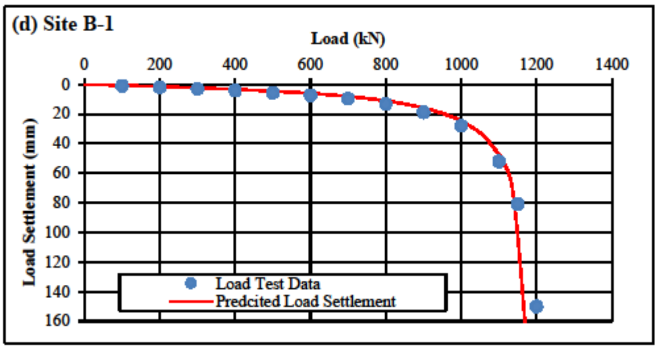
The back analysis of the five sets of test data all produced good graphs (see Figure 11) and typically showed that both shaft and base components were mobilised. The results are from three sites, denoted as sites A, B and C, with three tests for site A. For Site A these were all of the same diameter with varying lengths to allow an assessment of shaft friction within the Laminated Silt. Table 2 below provides details of the results

Figures 11(a) to (e) Pile test analyses – Sites A to C









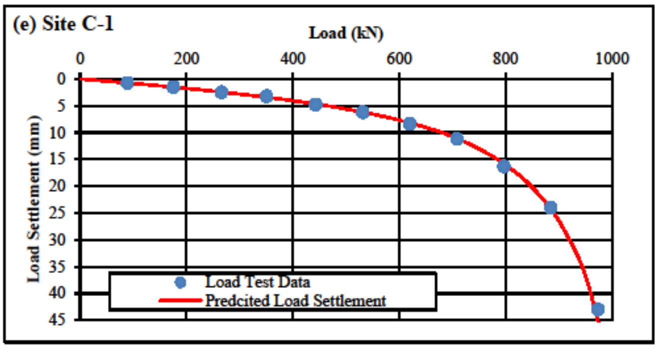


Table 2 Pile Test Results (* denotes enhanced base capacity partly within Sand and Gravel)

Site reference		**A-1**	**A-2**	**A-3**	**B-1**	**C-1**	**D1-4**
Pile diameter	mm	450	450	450	350	350	300
Pile length	m	10.5	16.5	22.5	17.75	16.0	18.3
Depth to Laminated Silt (LS)	m	10.5	10.5	10.5	11.0	8.6	11.0
Friction length	m	8.5	14.5	20.5	8.75	9.4	7.3
Ultimate shaft friction	kN	847	1325	1768	763	698	707
Ultimate base capacity	kN	1957*	772	799	456	393	320
Unit base stress	kN/m²	12303	4853	5023	4739	4084	4526
Base stiffness	kN/m²	65000	57147	75000	65000	60901	50000
Laminated Silt thickness	m	0.0	6.0	12.0	6.75	7.4	7.3
Calculated friction above LS	kN	678	678	678	170	145	363
Calculated friction in LS	kN	28	506	949	395	408	344
Calculated unit LS friction	kN/m²	n/a	60	56	53	50	50

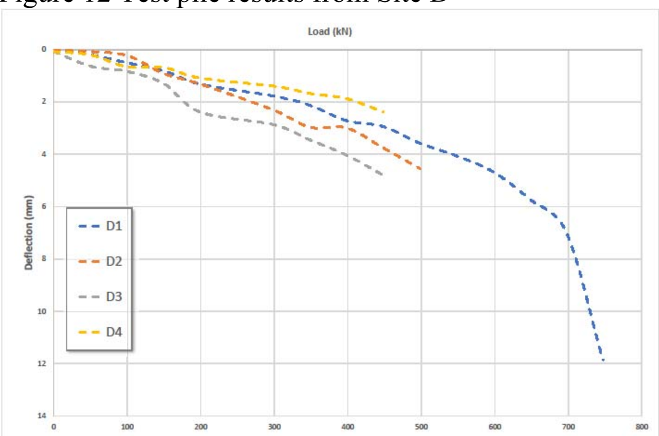
The Table presents the data including the pile details. An allowance for a shaft adhesion of 20kN/m² is included for a thickness of made ground and alluvial clay. Also included is an assessment of adhesion within both the Laminated Silt and overlying soils. The results indicate that the back calculated shaft adhesion within the Laminated Silt varies between 50 and 60kN/m² with no apparent variation with depth. The values seem reasonably consistent within the maximum thickness of the stratum tested which was 12m.

The results suggest slightly more variation within base resistance, although this is partly related to the pile size. Comparison with the calculated base stress is more consistent with typical values between 4084 and 5023kN/m². Values for base stiffness also varied with values between 57147 and 75000kN/m² assessed. Although these shows slightly greater variation it should be noted that this may also be dependent on the relative pile displacements during the test.

The result from the shortest of these tests, denoted as A-1, was for a pile base close to the boundary of the Alluvial Sand and Gravel and underlying Laminated Silt. Although the result gave a good match for shaft resistance from the overlying soils, a higher base resistance was indicated which is thought to be attributable to the more granular nature of the overlying strata.

Load test data was also obtained for a further site located close to site B and denoted as Site D. This included the results of four load tests, all of CFA construction and on piles of 300mm diameter, and including significant embedment into the Laminated Silt. Although all four tests were taken beyond the assessed working load, only one showed any significant movement to consider for back analysis. Further a sensible interpretation was made difficult with the test procedure including several load cycles and an insufficient number of readings to allow assessment of infinite time deflections. A graphical plot of this data is included below (see Figure 12) with the results suggesting comparable back-assessed pile parameters to those in Table 2 above.

Figure 12 Test pile results from Site D



6. Conclusions

This paper shows that the Glacial Laminated Silt, within the Perth area, could provide a suitable bearing stratum for piles. It indicates that this stratum is reasonably consistent, extending to considerable depths of over 40m near the River Tay, and geotechnically could be classified as a silt.

Normal cable percussive techniques produce too much disturbance meaning they do not show the appropriate geotechnical parameters for the Laminated Silt. The paper shows this relates both to stratum identification and also with standard in-situ and laboratory testing not reflecting comparable strength values to CPT testing.

The Laminated Silt stratum mainly seems to behave as a cohesive material. The pile test results do not show any significant increase in derived pile parameters with depth, which indicates that it is not behaving in an effective stress manner.

The pile test results show comparable data for the Laminated Silt although with perhaps higher adhesion and end bearing.

Comparing the derived pile parameters to a typically CPT assessed shear strength of 75kN/m² indicates an adhesion factor in the order of 0.75 and bearing capacity factor of 50.

7. Acknowledgments

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