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Physical characteristics of subglacial tills

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A regional database of the physical properties of glacial tills has been interrogated to produce characteristic design values and baseline construction values. Glacioterrestrial glacial till, one of the most distributed deposits in the world, is typically a heterogeneous mixture of clays, silts, sands, gravels and cobbles, which can contain remnants of earlier till including glaciolacustrine and fluvioglacial deposits that have been gravitationally compacted and sheared. This results in a complex deposit, which is spatially variable both in composition and fabric to the extent that the selection of design profiles is challenging. A study of the intrinsic properties of the tills in the North East of England together with a statistical analysis has led to the identification of two distinctly different, heavily overconsolidated tills that have profiles of strength, water content and density that lead to characteristic values based on the regional database and baseline values based on the local database that provide *a priori* knowledge for future investigations. This *a priori* knowledge has been used to determine the characteristic and baseline values for a new dataset from the region after demonstrating that the data fit with the regional database.

KEYWORDS: geology; glacial soils; site investigation; design

On a interrogé une base de données régionale des propriétés physiques des moraines argileuses pour produire des valeurs de calcul caractéristiques et des valeurs de construction de référence. Les moraines argileuses glacioterrestres , un des dépôts les plus répandus dans le monde entier, se composent généralement d'un mélange hétérogène d'argiles, de limon, de sables, de graviers et de galets, pouvant contenir des restes de moraines précédentes, y compris des dépôts lacustres glaciaires et fluviaux compactés et cisaillés par gravitation. On obtient ainsi des dépôts complexes, à composition et structure spatiale variables, au point de rendre difficile la sélection de profils caractéristiques. Une étude des propriétés intrinsèques des moraines du nord-est de l'Angleterre, ainsi qu'une analyse statistique, ont permis d'identifier deux moraines particulièrement différentes et fortement surconsolidées, présentant des profils de résistance, teneur en eau et densité, permettant d'obtenir des valeurs caractéristiques fondées sur la base de données régionale et des valeurs de référence découlant de la base de données locale, constituant des connaissances à priori pour des examens futurs. On a utilisé ces connaissances à priori pour déterminer les valeurs caractéristiques et de référence pour un nouvel ensemble de données pour la région, après avoir démontré que les données sont conformes à la base de données régionale.

INTRODUCTION

Over 60% of the British Isles was covered by an ice sheet at some time (Hughes *et al.*, 1998), resulting in extensive glacioterrestrial and glaciofluvial deposits (Fig. 1) that are typical of some of the most widely distributed deposits in the world. The most common of these deposits, the glacioterrestrial deposits, were either formed subglacially as lodgement till or deformation till or deposited from within the ice of a retreating glacier in the form of melt-out till or flow till. The lodgement and deformation tills are typically heterogeneous mixtures of clays, silts, sands, gravels and cobbles that have been gravitationally compacted and sheared under several different temperature profiles. Melt-out tills are subglacial, supraglacial or englacial deposits that can be similar in composition to other subglacial tills but can also include extensive lenses of clays, sands and gravels.

Quality sampling is usually restricted to clay-matrix-dominant till that is free of cobbles. Any gravel present, which is usual, may affect the sampling, and lead to a wide range of test results for a given property, making it difficult to select design parameters unless there is a clear set of rules to take into account the natural variability and the impact the fabric and composition have upon the derived parameters. For example, Fig. 2 shows a profile of undrained

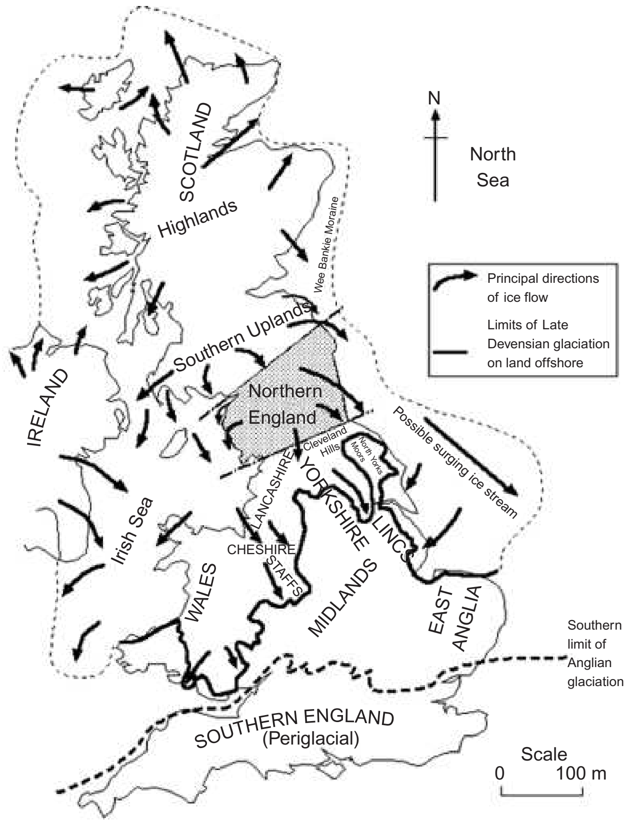

Fig. 1. Limits of the Anglian and Late Devensian glaciation in the United Kingdom (after Hughes *et al.*, 1998). Ice sheet model for British Isles either confluent with Scandinavian ice or separate as shown (Hart & Boulton 1991)

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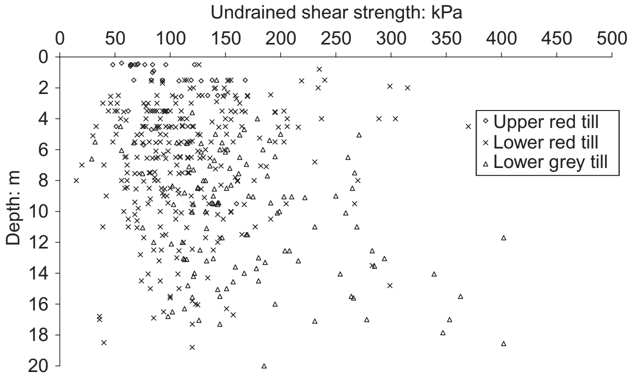


Fig. 2. A profile of undrained shear strength of lodgement tills from one site

shear strength of clay-matrix-dominant tills from a site in the North East of England. This paper uses an extensive database of physical characteristics of tills from the North East of England to demonstrate the difficulty, and develops a framework to identify the design values of subglacial tills. The data are taken from routine ground investigations that were carried out according to the British Standard current at the time of the investigation. The framework is based on a statistical method suggested by Eurocode 7 (2004) to provide characteristic values for design, and applies the same method to assess baseline values for construction.

FORMATION OF TILL

Tills are formed either by gravitational compaction and shearing (lodgement and deformation tills), which takes place as the ice advances, or by gravitational compaction (melt-out and flow tills), which takes place as the ice either advances or retreats. Glacial velocities exceeding 50–100 m/year would be sufficient to erode an existing till (Boulton & Paul, 1976). It is likely that tills have been reworked and redeposited a number of times during successive periods of glaciation, such that many of the deposits identified today include remnants of previous glaciations laid down during the last glacial period. Thus deformation till may contain remnants of earlier till including glaciolacustrine and fluvioglacial deposits, that is, intraformational sands, gravels and laminated clays that have been deposited in subglacial or englacial meltwater channels and lakes (Eyles & Sladen, 1981). As the ice advances, the subglacial till is increasingly mixed and deformed, leading to lodgement till (Hughes *et al.*, 1998). There is anecdotal evidence that the fines content of tills increases towards the coast in the principal direction of the ice flow (see Fig. 1). A number of pore pressure regimes could have existed, depending on whether the glacier was formed of temperate or cold ice (Boulton *et al.*, 1976), on the permeability of the underlying rock and the temperature profile through the till. Thus till is a complex deposit, which contains material from sources remote from the place of deposition.

Since their deposition, tills will have undergone subsequent processes of ageing and weathering, leading to changes in their properties. The effects of weathering decrease with depth, and are influenced by any extensive lenses of more permeable material that might have acted as barriers to the process of weathering.

In conclusion, till may have been gravitationally compacted, sheared, possibly reworked and weathered. Till can contain a range of particle sizes, from clays to boulders, and can vary from clay-matrix-dominant till, which contains discrete granular particles, to gravel dominated tills, which contain fines. Tills can be fissured and laminated. The implication for the construction industry is that glacial till is a challenging material, as it is difficult to predict the characteristics of the till. A statistical approach linked to empirical and theoretical models may provide a framework to select design parameters.

TILLS OF NORTH EAST ENGLAND

It is generally accepted in the UK that there is often a tripartite succession of till, and in the North East of England this is an upper till separated from a lower till by discontinuous layers of gravels, sands and lacustrine clays (Fig. 3). The upper till is divided into an uppermost mottled till and a red till, while the lower grey till is, in places, divided into a grey till and an underlying dark grey till. The tills have been considered as two or more separate lodgement tills (Beaumont, 1968), a lodgement till overlain by a melt-out till (Carruthers, 1953), a single lodgement till with a weathering profile down to the discontinuity between the two tills (Eyles & Sladen, 1981), or deformation till (Hughes *et al.*, 1998).

These tills are typically stiff to very stiff sandy clay with gravel, containing some boulders and lenses of sand and gravel and laminated clay. Laboratory tests are carried out mostly on the clay matrix because of the difficulty of sampling the more granular component of the till. The implication of this is that the results obtained may be the strength and stiffness of the 'softer' component of the till, and may represent the characteristic design values. In situ the till may appear 'stronger', which implies that the baseline values will exceed the characteristic values.

Characteristic values are cautious estimates of the design values, and are derived from field and laboratory tests complemented by experience (Eurocode 7, 2004). Baseline values form part of a contract specification, and are used to provide information on the ground conditions likely to be encountered at a site, allowing risk to be managed more effectively between the contractor and the client (Randall, 1997).

Fifteen investigations covering an area of about 200 km^2 provided a database of test results from over 5500 samples from a number of sites in North East England (Fig. 4). These ground investigations have been conducted over a number of years as part of the enabling work for opencast sites. This has allowed fresh faces of till to be studied to place the results of the laboratory tests in context. The data have been interrogated to produce typical classification data for the subglacial tills. These are compared with classification data for other tills.

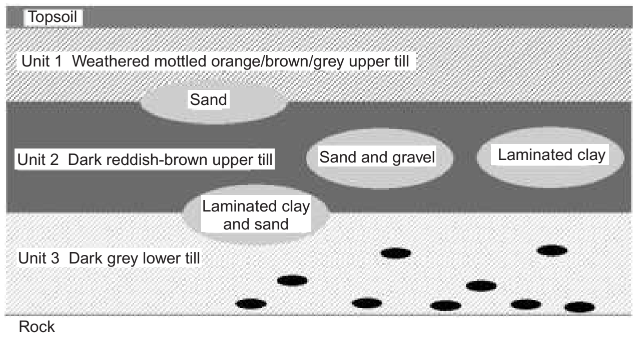


Fig. 3. A geological model for the tills of North East England (after Robertson *et al.*, 1994) that shows, diagrammatically, the materials present in each till and at the boundaries between the tills

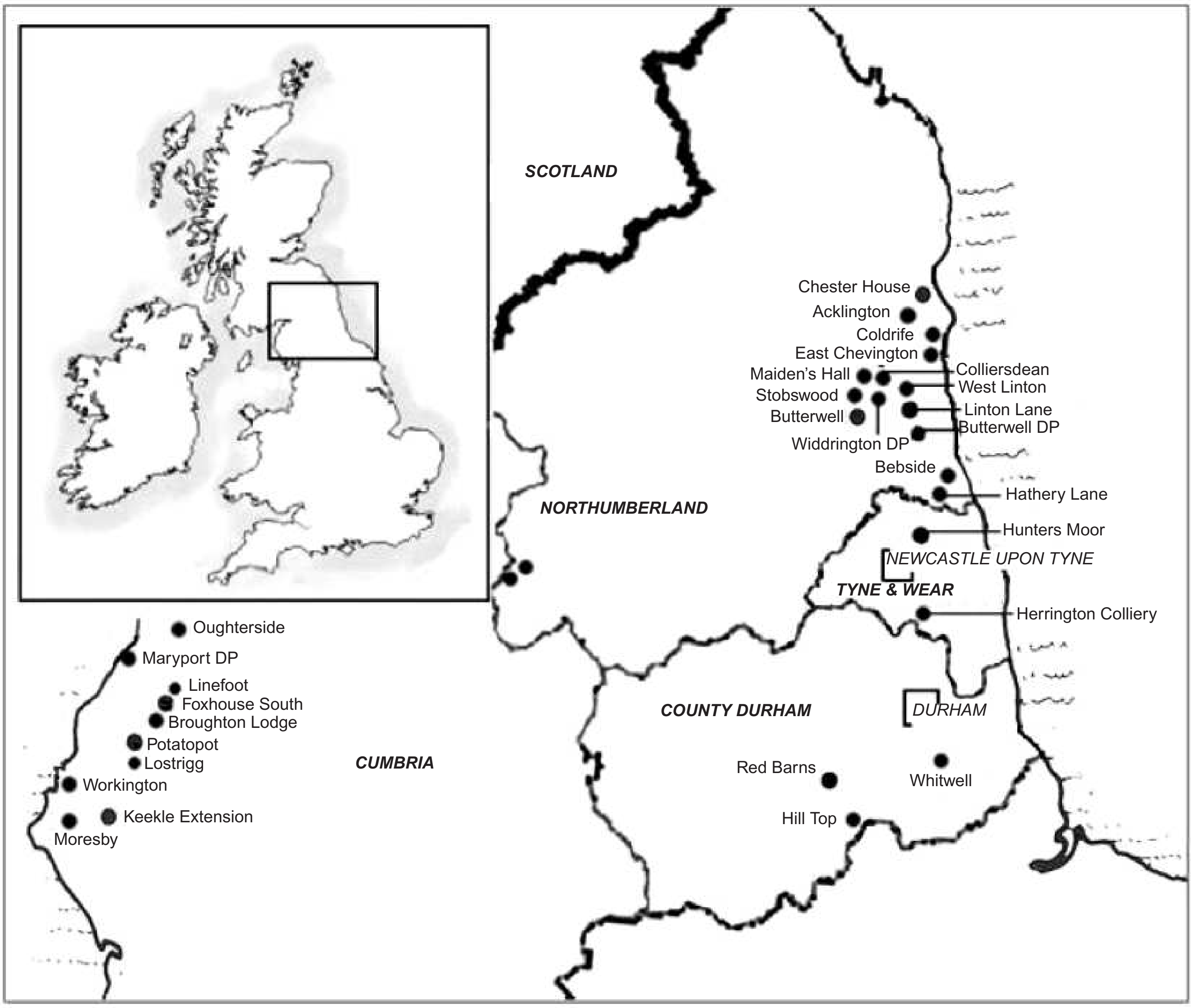


Fig. 4. Location of opencast pits in the North of England (after Hashemi *et al.*, 2006). This paper used the data from the sites in Northumberland

CLASSIFICATION

The samples are separated into five units of till: upper red till, lower red till, and lower grey till, which are distinguished by their colour; laminated clays by their fabric; and sands and gravels. All of these materials are a form of till, but this paper focuses on the first three, which form the majority of the deposits. Therefore any future reference to till refers to these three tills. The laminated clays are distinct lenses and layers of laminated clays that have little or no granular material. These are found within the tills, particularly the red tills, and between the tills. The till matrix is also laminated in places, but this material is distinguished from the laminated clays by the degree of laminations and the presence of granular material.

Colour is used as the prime means of distinguishing between one till and another, because classification data on their own cannot be used to separate the clay-dominant tills because of the spatial variability, which leads to considerable overlap in the results (e.g. Fig. 5).

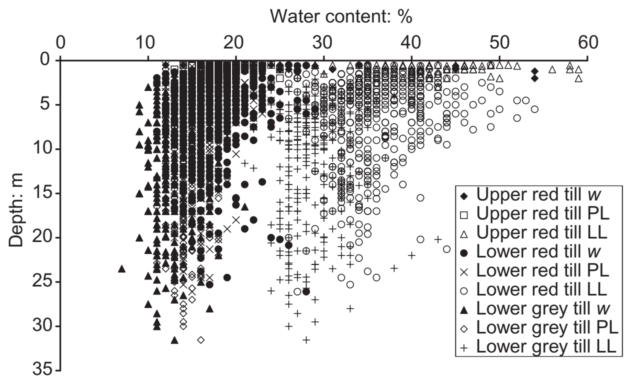


Fig. 5. Profile of Atterberg limits and water content for a site in North East England

Atterberg limits

Figure 5 highlights the difficulty in assigning characteristic values to this spatially variable soil and identifying the differences between the tills. Note that the amount of data available reduces with depth. The data from all the sites in this study have been plotted on the Casagrande plot in Fig. 6. Soils of similar composition tend to lie on lines parallel to the A-line; Boulton (1976) suggested that clay-matrix-dominant tills of the UK cluster about the T-line. Fig. 6

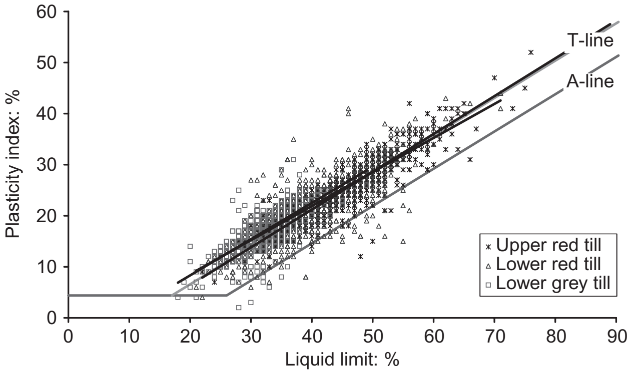


Fig. 6. Casagrande plot for the tills, showing the relationship between their limits and the T-line, a line parallel to the A-line (the best-fit lines for each till are shown as dashed lines)

shows that both these statements apply, which suggests that the three tills have a similar composition, though the particle distribution differs between the tills.

The average Atterberg limits from samples obtained at 0·5 m intervals (upper red till) and 1 m intervals (lower tills) have been plotted in Fig. 7, which also shows that other tills from the UK lie on or adjacent to the T-line. Boulton & Paul (1976) showed that the Atterberg limits tended to fit on a line parallel to the A-line, known as the T-line. The fact that soils from across the country appear to have the same composition is, in part, due to the fact that reworking the tills during successive periods of glaciation has ensured that source material has been widely distributed.

The volume of data allows a statistical analysis to be undertaken to establish whether the data from different sites have the same characteristics of the master set, and whether a characteristic range of values can be identified. Atterberg limits for the three tills are presented in the form of histograms in Fig. 8. The three sets of data create overlapping but distinctly skewed distributions. There are a significant number of outliers shown in Fig. 8, which are defined as those that are less than or greater than twice the standard deviation from the mean. Cherbyshev's rules imply that 85% of the results will lie within two standard deviations of the mean. Removing the outliers improves the normality of the data.

Box plots (Fig. 9) are a visual means of assessing the normality of the data. The median is the data point in the middle of a box that represents the samples between the first and third quartile. The extensions from the boxes represent the limits to the data used in subsequent analyses. Note that less than 4% of the data, which have been removed, were outliers.

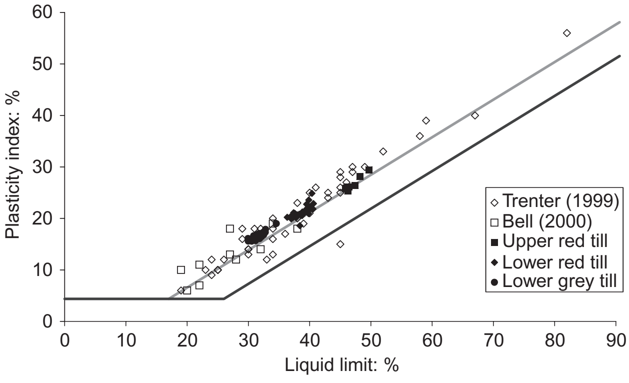


Fig. 7. Casagrande plots for UK tills, showing they tend to align with the T-line

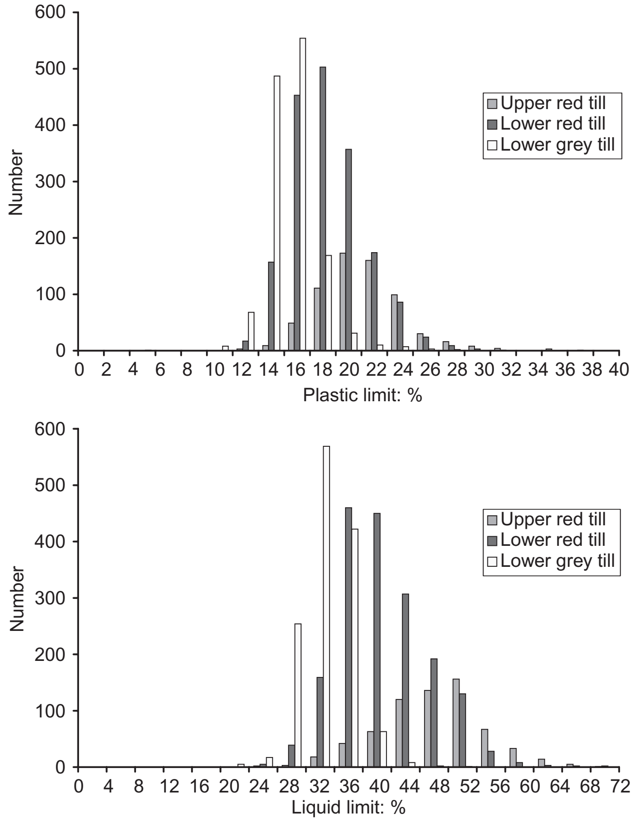


Fig. 8. Distribution of (a) plastic limit and (b) liquid limit for upper and lower red tills and grey till

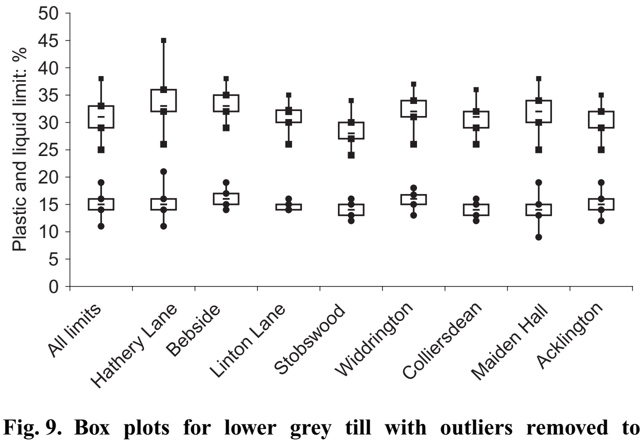


Fig. 9. Box plots for lower grey till with outliers removed to highlight the engineering significance of the data from the various sites

Table 1 lists the descriptive statistics for the three tills. This includes the mean and range, and description of the distribution of that range for the unit weight, water content, Atterberg limits and undrained shear strength. The range is expressed in terms of the mean, and first and third quartiles. The description of the distribution is expressed in terms of the standard deviation and variance. Skew and kurtosis have been used to determine the appropriate statistical techniques to be used to produce the characteristic and baseline values.

It shows that the average plastic limits in the area are 20·3% (±6·6%), 17·6% (±5·4%) and 14·8% (±4·1%) for the upper and lower red tills and grey till respectively, excluding those values that fall outside two standard deviations from the mean. Fifty per cent of the results fall within 2·3%, 1·6% and 1·1% of the mean. The values for liquid limit are 46·5% (±15·5%), 38·7 (±12·3%) and 31·3% (±6·7%), with

Table 1. Descriptive statistics for the regional database after all outliers removed

Parameter	Range				Description of distribution					
	Mean	Number of data points	1st quartile	2nd quartile	Standard deviation	Variance	Skew	Standard error of skew ×2	Kurtosis	Standard error of kurtosis ×3
Upper red till										
γ_b: Mg/m^3	2·06	596	1·95	2·05	0·076	0·038	0·372	0·201	0·150	0·401
w: %	21·5	706	19·0	23·7	3·519	0·164	0·267	0·184	0·096	0·369
PL: %	20·3	641	18·0	22·0	2·757	0·135	0·082	0·193	0·340	0·387
LL %	46·5	637	42·0	51·0	6·630	0·143	0·150	0·194	0·386	0·388
c_u: kPa	99	526	65	125	45	0·456	0·439	0·214	−0·047	0·427
Lower red till										
γ_b: Mg/m^3	2·06	2024	2·01	2·12	0·078	0·038	−0·09	0·109	−0·51	0·218
w: %	18·1	2157	16·0	20·0	3·157	0·174	0·164	0·105	−0·62	0·211
PL: %	17·6	2000	16·0	19·0	2·412	0·137	0·237	0·110	0·566	0·219
LL %	38·7	1978	35·0	42·0	5·335	0·138	0·263	0·110	0·469	0·220
c_u: kPa	100	1879	68	127	45	0·437	0·194	0·113	−0·219	0·226
Lower grey till										
γ_b: Mg/m^3	2·18	1185	2·13	2·22	0·063	0·029	0·082	0·142	0·171	0·285
w: %	12·5	1341	11·3	13·6	1·53	0·122	0·090	0·134	−0·45	0·268
PL: %	14·9	1296	14	16	1·563	0·105	0·179	0·136	0·077	0·272
LL %	31·3	1293	29	33	3·009	0·096	0·035	0·136	0·621	0·272
c_u: kPa	172	1121	111	231	83	0·483	0·487	0·146	−0·404	0·293

50% of the results falling within 4·5%, 3·7% and 2·3%. The mean value of plastic limit for each of the sites is within 2·8%, 2·1% and 1·9% of the overall mean; and the values for the liquid limit are within 4·9%, 6·7% and 2·7%. These data show that the spatial variability of the lower grey till is less than that of the upper tills, which is consistent with increased deformation prior to deposition. From an engineering point of view the differences in Atterberg limits between the sites are not significant: hence the mean values of plastic limit and liquid limit in the area are 20·3% : 46·5%, 17·6% : 38·7% and 14·8% : 31·6% for the upper and lower red till and grey till respectively.

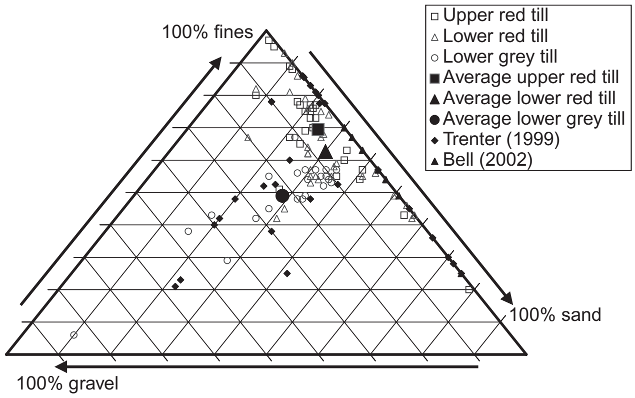
Particle size distribution

Clay-dominant subglacial tills are generally well graded. Fig. 10 shows ternary diagrams for the percentages of fines, sands and gravel (Fig. 10(a)) and clay, silt and coarse particles (Fig. 10(b)). Note that cobbles are removed either in the sampling process or in preparing the specimen. The gradings confirm that the tills are dominated by fine-grained particles. The averages show that the tills are distinctly different. Fig. 10(b) shows that, on average, the clay content decreases and the sand content increases with depth. Data from Trenter (1999) and Bell (2002) are included to show the variation in gradings of UK tills.

Water content

The average water content at intervals of 1 m for the lower tills and 0·5 m for the upper red till tends to be constant with depth (Fig. 11). This graph shows that the average water content is greater than the plastic limit for the upper red till; approximately equal to the plastic limit for the lower red till; and lower than the plastic limit for the lower grey till.

The average water contents in the area are 21·5% (±10·4%), 18·1% (±7·2%) and 12·5% (±3·9%) for the upper and lower red tills and grey till respectively (Table 2),



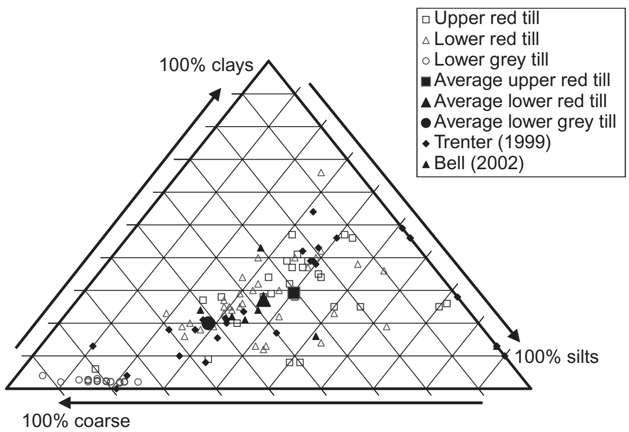


Fig. 10. Ternary plots for UK glacial tills highlighting variation in the tills according to: (a) fines; (b) clays

excluding those values that fall outside two standard deviations from the mean. Fifty per cent of the results fall within 2·5%, 2·1% and 1·2% of the mean. The outlying values are attributed to local pockets of wetter materials, and sample

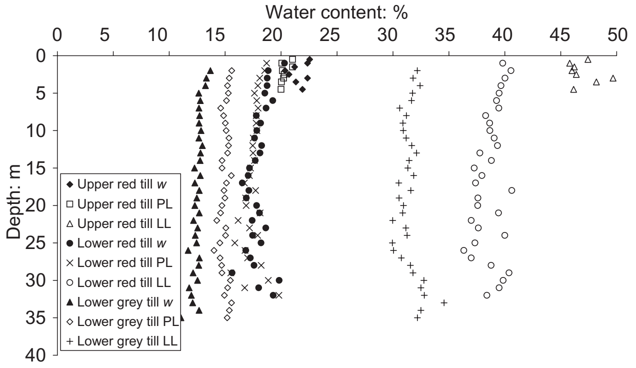


Fig. 11. Variation of average water content and Atterberg limits with depth

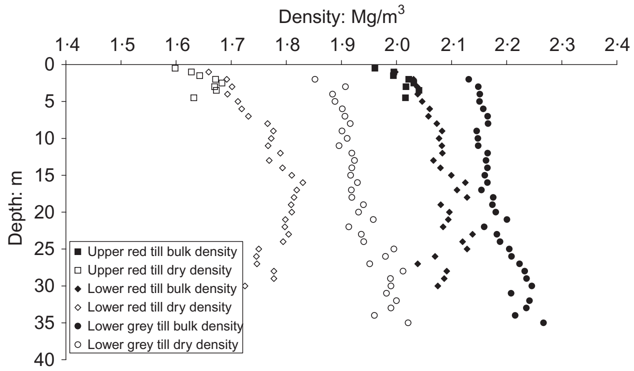


Fig. 12. Variation of average bulk and dry density with depth

disturbance. The average water contents for each site are within 1·7%, 2·5% and 0·5% of the mean of all sites, suggesting that the average values of water content in the area are 21·5%, 18·1% and 12·5%.

Density

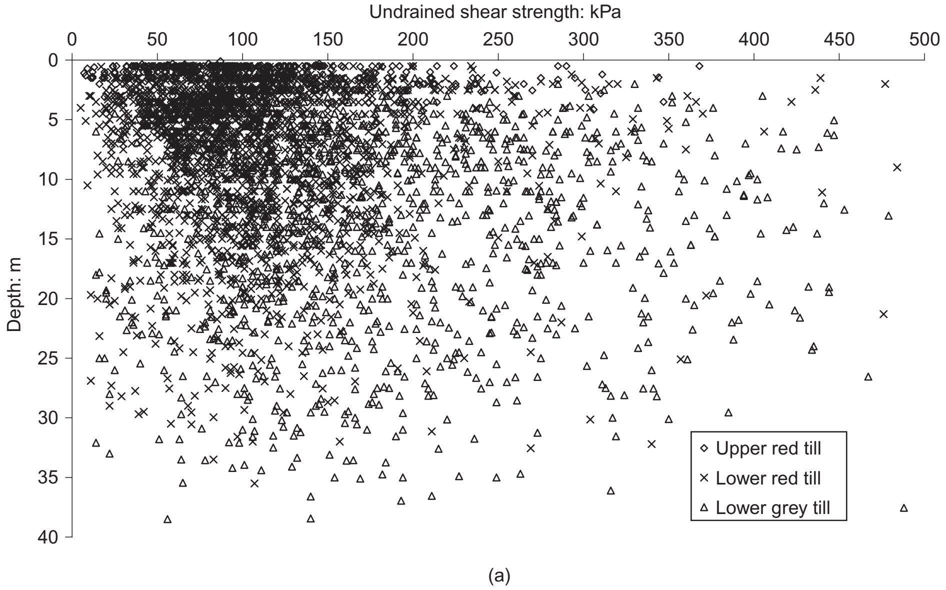
There is a trend of increasing average density with depth, though the increase over the full profile is about 10% of the average value for each till (Fig. 12). The average bulk densities in the area are 2·00 Mg/m^3 (±0·20 Mg/m^3), 2·06 Mg/m^3 (±0·18 Mg/m^3) and 2·18 Mg/m^3 (±0·17 Mg/m^3) for the upper and lower red tills and grey till respectively (Table 2), excluding those values that fall outside two standard deviations from the mean. Fifty per cent of the results fall within 0·05 Mg/m^3 of the mean for all the tills. The outlying values are attributed to local pockets of wetter materials, sample disturbance and significant gravel content. The average bulk densities for each site are within 0·08 Mg/m^3, 0·27 Mg/m^3 and 0·07 Mg/m^3 of the mean of all sites, suggesting that the average values of bulk density in the area are 2·00 Mg/m^3, 2·06 Mg/m^3 and 2·18 Mg/m^3, though in the 10 m where the majority of construction takes place the average values are 2·00 Mg/m^3, 2·05 Mg/m^3 and 2·15 Mg/m^3.

Shear strength

The derived undrained shear strength is considered here as a classification parameter. Fig. 13(a) shows that the strength is spatially variable. The scatter in the data is due to the variation in composition, water content, fabric (e.g. the tills are fissured and, in places, weakly laminated) and sample disturbance, as well as in situ effective stress. The average values at a given depth (0·5 m intervals for the upper red till and 1 m intervals for the lower tills) have been plotted in Fig. 13(b), provided there were at least five samples tested at that depth. The alternative was to consider the average strength of adjacent samples in each borehole, assuming that the random distribution was localised. This removed those

Table 2. Characteristic values from the regional database

Parameter	Mean	Characteristic values					Baseline values			
		Schneider (low)	Cautious mean (low)	Cautious mean (high)	Student-*t* factor for 95%	*k*	Minimum	Maximum	Student-*t* factor for 95%	*k*
Upper red till										
γ_b: Mg/m^3	2·00	1·960	1·993	2·003	1·646	0·067	1·87	2·12	1·64	1·646
w: %	21·5	19·74	21·28	21·72	1·646	0·062	15·7	27·3	1·64	1·645
PL: %	20·3	18·98	20·17	20·53	1·646	0·065	15·8	24·9	1·64	1·645
LL %	46·5	43·18	46·06	46·93	1·646	0·065	35·6	57·4	1·64	1·645
c_u: kPa	99	76	96	102	1·646	0·072	24	173	1·64	1·646
Lower red till										
γ_b: Mg/m^3	2·06	2·023	2·059	2·065	1·646	0·037	1·93	2·19	1·64	1·642
w: %	18·1	16·56	18·02	18·25	1·646	0·035	13·0	23·3	1·64	1·642
PL: %	17·6	16·39	17·51	17·69	1·646	0·037	13·6	21·6	1·64	1·642
LL %	38·7	36·02	38·49	38·89	1·646	0·037	29·9	47·4	1·64	1·642
c_u: kPa	100	78	98	101	1·646	0·038	38	171	1·64	1·642
Lower grey till										
γ_b: Mg/m^3	2·18	2·145	2·173	2·179	1·646	0·048	2·07	2·28	1·64	1·643
w: %	12·5	11·77	12·46	12·60	1·646	0·045	10·0	15·0	1·64	1·642
PL: %	14·9	14·08	14·79	14·94	1·646	0·046	12·3	17·4	1·64	1·643
LL %	31·3	29·78	31·15	31·43	1·646	0·046	26·3	36·2	1·64	1·643
c_u: kPa	172	131	168	176	1·646	0·049	35	310	1·64	1·643



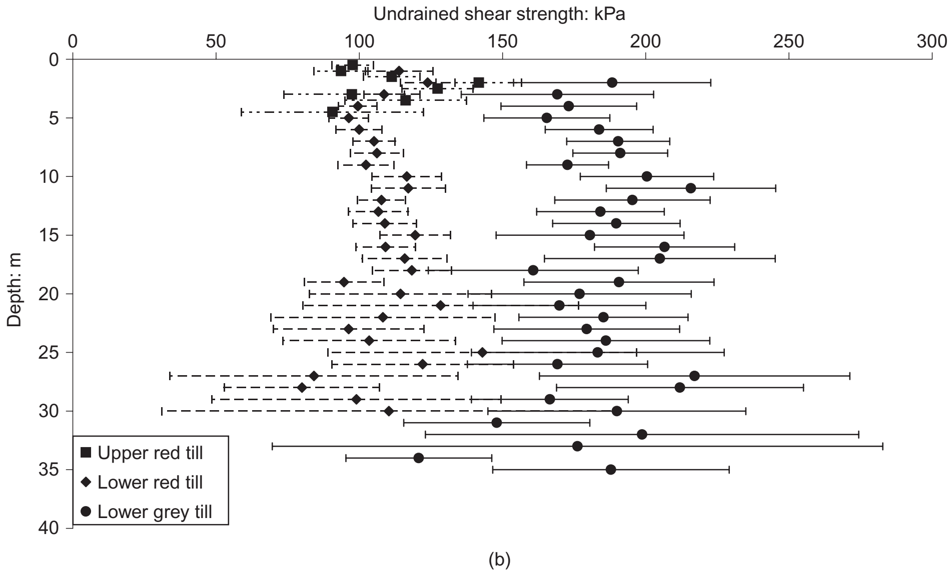


Fig. 13. Variation in undrained shear strength with depth for all sites showing: (a) all data; (b) mean and characteristic strengths at each depth

samples that had no adjacent samples, and reduced the scatter, but there was no significant improvement in the quality of the profile. Both methods showed that there was no clear trend of change of strength with depth.

Table 2 shows that the average undrained strengths for the three tills in the area are 115 kPa, 110 kPa and 185 kPa after the outliers exceeding two standard deviations have been removed. The ranges have not been presented, as the upper bound is more than twice the average strength. Fifty per cent of the results fall within one standard deviation of the average. The mean undrained shear strength for each site is within 25 kPa, 25 kPa and 60 kPa of the mean of all sites.

DISCUSSION

These results can be used to produce characteristic profiles with depth for preliminary designs, characteristic and baseline values for design and construction, and a means of enhancing further investigations.

Modelling of the till

In order to assign characteristic values to the till it is necessary to produce a model to establish whether there is a trend in the data. This can be a deterministic model based on empirical or theoretical relationships, a stochastic model based on a statistical analysis of the data, or a combination of these. The former includes relationships between the Atterberg limits and undrained shear strength of remoulded clays (e.g. Wroth & Wood, 1976; Carrier and Beckman, 1984); in situ strengths of normally consolidated clays, density and Atterberg limits (e.g. Skempton, 1957); and overconsolidated soils and Atterberg limits (e.g. Yilmaz, 2000). Burland (1990) and Chandler (2000) suggested that the intrinsic properties of a soil can provide a framework to characterise clay. This framework is shown in Fig. 14, in which the average shear strength for each till taken from Fig. 13 is plotted against the void index, I_v, given by

$$I_v = \frac{e - e^*_{100}}{C^*_c} \tag{1}$$

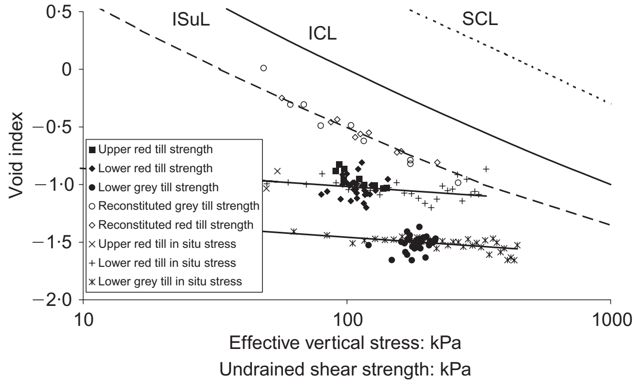


Fig. 14. Relationship between intrinsic compression and strength lines and in situ conditions and shear strength

where e^*_{100} is the void ratio at a vertical effective stress of 100 kPa on the intrinsic compression line, and C^*_c is the slope of the intrinsic compression line. Burland (1990) suggested that these two intrinsic properties are empirically related to the void ratio at the liquid limit e_L by

$$e^*_{100} = 0{\cdot}114 + 0{\cdot}581 e_L \tag{2}$$

$$C^*_c = 0{\cdot}256 e_L - 0{\cdot}04 \tag{3}$$

The intrinsic compression line, ICL, represents the compression curve for reconstituted clays; the intrinsic strength line, ISuL, represents the strength of reconstituted soils (Chandler, 2000). Fig. 14 shows that results of tests on reconstituted tills (Clarke *et al.*, 1998) fit to the ISuL, which suggests that this framework can be used to characterise the tills.

The average void index, vertical effective stress and shear strength for the three tills are plotted in Fig. 14. The void indices plotted against the in situ effective vertical stress for the upper and lower red till lie to the left of the ISuL, confirming that they are overconsolidated and, since they lie about a common line, suggests that they have had a similar stress history, leading to the conclusion that they are a single till, the difference being the weathering in the upper red till. The lower grey till is also overconsolidated, but the preconsolidation pressure exceeds that of the red till. The best fit to the data are two lines that are very nearly parallel. The slope of the lines is such that the average void ratio is very nearly constant, which implies that the characteristic shear strength profile could be considered to be vertical (see Fig. 13): hence the reason why the strengths cluster about two points in Fig. 14.

Characteristic values

The evidence from this database is that the classification parameters are random, reflecting the composition and fabric of the tills and depositional and post-depositional processes. Fig. 11 shows that the mean values of Atterberg limits and water content for each till are reasonably uniform with depth, so the values given in Table 2 represent the regional mean values. Note that the apparent trend shown in Fig. 5 is due to the reduction in the amount of data with depth. This is the reason for the increased variation from the mean in Fig. 11.

Figure 12 shows that the regional average density increases with depth. Fig. 13 shows that the regional average shear strength shows no trend with depth: therefore an average value can be used for classification purposes.

This regional database represents a 'global' situation: therefore a cautious mean represents the characteristic value (Frank *et al.*, 2004), with the probability of the worst case occurring being less than 5%. Frank *et al.* (2004) suggest that, if there no significant trend in the data, the characteristic value X_k is given by

$$X_k = X_{\text{mean}}(1 \pm k_n V_x) \tag{4}$$

$X_k > X_{\text{mean}}$ is used when the cautious mean is a high value, for example when calculating active pressures on retaining structures; and $X_k < X_{\text{mean}}$ is used when the cautious mean is a low value, for example when calculating bearing capacity. V_x, the coefficient of variation, is equal to the standard deviation divided by the mean value if there is no trend to the data and there is no *a priori* knowledge. The value of V_x given in Table 2 can be considered as *a priori* known value when characteristic values are being derived from a new investigation in the region. k_n is a statistical coefficient that takes into account the number of samples, the volume of the ground, the type of results, and the level of confidence.

Schneider (1999) suggested that the characteristic value for a new investigation is simply the mean less half the standard deviation, since the regional coefficient of variation is likely to be unknown. Table 2 shows that this can lead to a characteristic value, with about 70% of the results exceeding that value: that is, it is an over-cautious estimate of the mean.

The characteristic values for design may be different from baseline values for construction, since baseline values are established for contractual reasons to limit claims arising from unforeseen circumstances (Randall, 1997). The values are based on an assessment of the subsurface conditions to produce rational limits to the likely worst-case values. Given that these govern construction processes, then the local low (or high) value could be considered. Eurocode 7 (2004) suggests that this is represented by the 5% fractile values

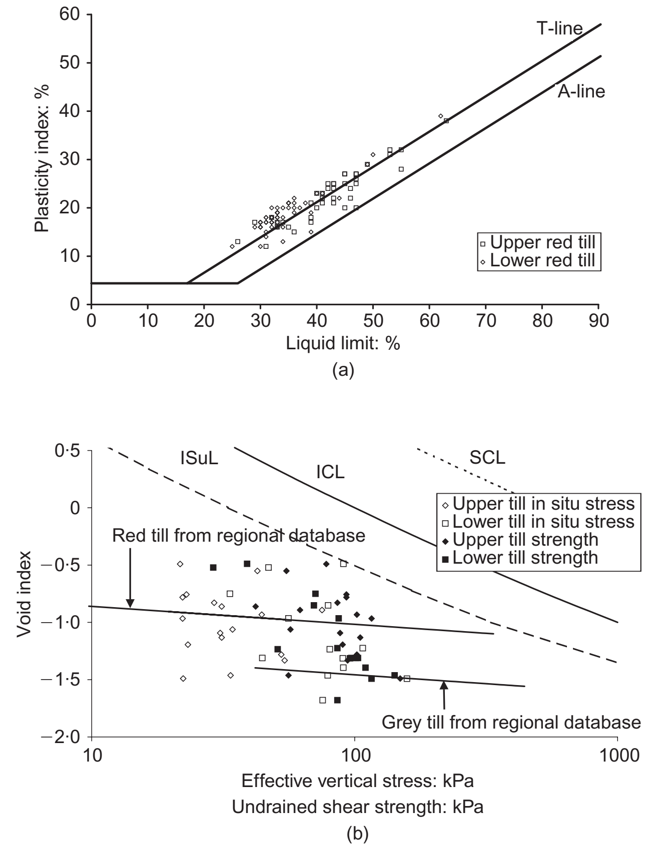


Fig. 15. Relationships between (a) classification data and the T-line and (b) intrinsic compression and strength lines and in situ conditions for the new dataset

Table 3. Descriptive statistics and characteristic values for the new dataset

Parameter	Range				Description of distribution					
	Mean	Number of data points	1st quartile	2nd quartile	Standard deviation	Variance	Skew	Standard error of skew ×2	Kurtosis	Standard error of kurtosis ×2
Upper red till										
γ_b: Mg/m^3	2·11	30	2·06	2·14	0·06	0·03	0·53	0·89	0·00	1·79
w: %	20·8	64	18·0	22·0	5·3	0·25	2·95	0·61	14·4	1·22
PL: %	20·1	43	18·0	22·0	3·6	0·18	0·35	0·75	0·90	1·49
LL %	42·4	43	39·0	46·5	7·3	0·17	0·21	0·75	0·75	1·49
c_u: kPa	89	27	60	104	35	0·40	0·68	0·94	0·15	1·89
Lower red till										
γ_b: Mg/m^3	2·16	29	2·15	2·22	0·09	0·04	1·33	0·91	0·88	1·82
w: %	16·4	107	13·0	19·5	5·81	0·35	1·10	0·47	1·01	0·95
PL: %	15·6	53	14·0	18·0	2·73	0·17	1·35	0·67	1·44	1·35
LL %	34·6	53	31·0	36·0	5·92	0·17	2·56	0·67	8·89	1·35
c_u: kPa	85	20	48	105	50	0·60	1·16	1·09	2·26	2·19
Parameter	Mean	Characteristic values					Baseline values			
		Schneider (low)	Cautious mean (low)	Cautious mean (high)	Bayes mean (low)	Bayes mean (high)	Minimum	Maximum	Bayes minimum	Bayes maximum
Upper red till										
γ_b: Mg/m^3	2·11	2·07	2·09	2·13	2·10	2·11	2·06	2·14	2·05	2·16
w: %	20·8	18·2	19·7	21·9	20·8	20·8	18·0	22·0	17·4	24·2
PL: %	20·1	18·3	19·2	21·0	20·1	20·1	18·0	22·0	17·5	22·7
LL %	42·4	38·8	40·6	44·3	42·5	42·6	39·0	46·5	37·0	48·1
c_u: kPa	89	71	77	100	89	89	60	103	57	120
Lower red till										
γ_b: Mg/m^3	2·16	2·12	2·13	2·19	2·16	2·16	2·01	2·32	2·09	2·23
w: %	16·4	13·6	15·5	17·4	16·48	16·48	6·8	26·0	13·3	19·6
PL: %	15·6	14·3	15·0	16·3	15·7	15·7	11·1	20·1	13·7	17·7
LL %	34·6	31·6	33·2	36·0	34·7	34·7	24·8	44·4	30·3	39·1
c_u: kPa	89	60	65	104	86	86	0	170	49	122

that are given in Table 1. In this case k_n in equation (4) is $1{\cdot}64\sqrt{(1/n+1)}$.

Application to other investigations

An aim of this study is to develop a protocol that could be used to assign characteristic and baseline values to a till. In that case it has to be shown that a set of data from a new site investigation in the region has characteristics that fit those of the regional database. The Atterberg limits for the tills identified at a new site in the region lie about the T-line, confirming the geologist's description of glacial till (Fig. 15(a)). Tests for skew and kurtosis of the local dataset show that normality can be assumed (Table 3). The majority of the data lie to the left of the ISuL and about the trend for the red till from the regional database. The scatter in the data reflects the nature of till, but a combination of the geological history, description and classification characteristics suggests that the till that forms the new dataset is the red till identified in the regional database.

It is therefore possible to use Bayesian statistics to determine the characteristic and baseline values. The mean value, standard deviation and variance of the new database, taking into account the regional database and the local dataset, are derived from

$$\mu_2 = \frac{n_1 x_1 \sigma_0^2 + \mu_0 \sigma_1^2}{n_1 \sigma_0^2 + \sigma_1^2} \tag{5}$$

$$\sigma_2 = \sqrt{\frac{\sigma_0^2 \sigma_1^2}{n_1 \sigma_0^2 + \sigma_1^2}} \tag{6}$$

$$s_2^2 = \frac{1}{1/s_0^1 + 1/s_1^2} \tag{7}$$

where s_2, σ_2 and μ_2 are the variance, standard deviation and mean of the total distribution; s_1, σ_1 and x_1 are the variance, standard deviation and mean of the new data; s_0, σ_0 and μ_0 are the variance, standard deviation and mean of the regional database; and n_1 is the number of new datasets.

The descriptive statistics for the new dataset are given in Table 3, together with the characteristic and baselines values based on the dataset and on *a priori* knowledge. This shows that the inclusion of *a priori* knowledge has resulted in less cautious design and construction parameters and hence a more economic design.

CONCLUSIONS

Glacial tills, which cover some 60% of the UK and are some of the most widely distributed deposits in the world, are difficult to characterise owing to the variation in fabric and composition created by the deposition and post-depositional processes. This is accompanied by the difficulty of obtaining quality samples, which means the samples may not be truly representative of the till. Most of the tills in the UK are lodgement or deformation tills, which are heterogeneous mixtures of clays, silts, sands, gravels, cobbles and boulders. They are clay-matrix-dominant tills such that their behaviour is often considered to be that of clay. The Atterberg limits of the fines content show that the composition of the UK tills is similar, as they lie about a line parallel to the A-line on the Casagrande chart.

In the North East of England there is a tripartite succession of tills that is typical of many UK tills. A study of the intrinsic properties shows that the tills can be considered to be heavily overconsolidated, with the lower grey till being more overconsolidated than the upper red till. The upper red till is divided into two, but a study of the intrinsic properties suggests that the top few metres are weathered red till.

A statistical analysis of a regional database shows that for design and construction purposes the physical characteristics of each till (treating the upper and lower red tills as separate for this purpose) can be assumed to be constant with depth until proven otherwise. The lower grey till is generally denser and stiffer than the upper red till. Both tills can be classed as inorganic clays, with the grey till being less plastic than the red till.

Characteristic values for design for the region have been derived using the method recommended by Eurocode 7 (2004), assuming a 95% probability that these are the worst case likely to be encountered. Baseline values for construction have been developed for the 5% fractile assuming that these would be the worst cases likely to be locally encountered. These data provide *a priori* knowledge for future investigations.

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