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The geotechnical properties of some till deposits occurring along the coastal areas of eastern England

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Abstract

Deposits of till are found along the coastal areas of eastern England from Northumberland to East Anglia. The geotechnical properties of tills from three areas, namely, north Norfolk, Holderness and Teesside have been investigated. The dominant clay minerals in the fine fraction of the tills are kaolinite and illite. As would be expected, quartz is the other dominant mineral in the fine fraction of the tills.

Deposits of till occur in the Anglian and Devensian stages of the Quaternary succession in Norfolk. All these tills are matrix-dominated, with clay generally forming less than a third of the matrix. They are either firm or stiff with low or intermediate plasticity and have relatively low values of shear strength. The tills are either inactive or have normal activity and all have low sensitivity. Their consolidation properties are characteristic of stiff clays.

The glacial deposits of Holderness consist primarily of tills. Except for the oldest of these tills, which is Wolstonian, the others are of Devensian age. The fine fraction usually constitutes up to 60–80% of the deposits. These clays have a low plasticity. The tills of Holderness have a low sensitivity and a relatively low unconfined shear strength. Their values of shear strength are reduced from peak values, to residual values primarily by a reduction in the cohesion parameter. Like the tills from the other two areas, the pore water pressures on testing in, consolidated, undrained conditions rose rapidly to a peak which was followed by a gradual falling off as failure was approached.

The glacial deposits of the Teesside area are of Late Devensian age. These lodgement tills were products of successive ice sheets. The tills are thickest in the north and west of the area, and are characteristically unsorted and matrix dominated. They are of low to intermediate plasticity, and vary in consistency from firm to hard, generally being stiff to very stiff. The results of triaxial tests indicate a reasonably wide range of strength.

Keywords: Lodgement till; Particle size distribution; Atterberg limits; Compressibility; Shear strength

1. Introduction

During Pleistocene times, a maximum of approximately 30% of the land surface of the Earth was covered by ice. As a consequence, glacial deposits are of particular importance to geotechnical engineers and engineering geologists in northern Europe, northern Asia and North America. Also of geotechnical significance is the fact that tills represent one of the most variable of sedimentary deposits. This variation is brought about by the variety of materials of which tills may be composed, by the various means by which the materials have been incorporated into the ice, by the way in which they were transported and what happened to them during transport, and to how

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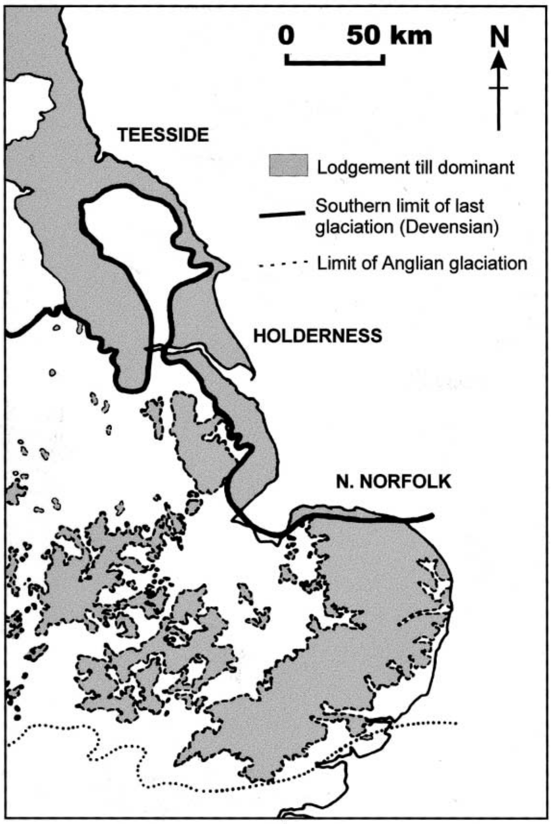

Fig. 1. Distribution of till, deposited by the Anglian and Devensian glacial advances along the east coast of England.

they were deposited. Hence, they can range from extremely dense non-plastic tills to weak plastic clay tills.

Till has been recently defined by Hambrey (1994) as a poorly sorted mixture of clay, silt, sand, gravel, cobble and boulder-sized material deposited directly from glacier ice. As such, Hughes et al. (1998) correctly pointed out that in terms of soil mechanics, till is a non-textbook material, in that it is characteristically neither clay nor sand and does not conform to the depositional models upon which, much of soil mechanics is based. Furthermore, lack of appreciation of the effects of depositional and post-depositional processes on the geotechnical properties of tills can lead to engineering difficulties.

In the past, tills often have been regarded as heavily overconsolidated deposits, and indeed many tills are. For example, Klohn (1965) and Radhakrishna and Klym (1974) have described such tills from North America. Heavily overconsolidated tills, being relatively incompressible, undergo relatively little settlement when loaded. However, not all tills behave in this way, and less stiff tills can deform when loaded with heavy structures associated with many industrial plants, bridge piers and the like. Therefore, the more geotechnical data there are available on till deposits the better, as this can only lead to more effective understanding of their engineering performance.

In eastern England, the maximum extension of ice during the Pleistocene occurred during the Anglian (Lower Illinoian) stage, when it spread southwards almost to the Thames estuary (Fig. 1). The extension of ice during Late Devensian (Wisconsin) times was restricted to northern England, with a lobe extending along the east coast southwards to northwest Norfolk (Catt, 1991). Accordingly, only a very small area of East Anglia was glaciated during Late Devensian times. In addition, Late Devensian glacial activity removed nearly all traces of Anglian deposits from those areas covered by this later ice. Most of the tills deposited in eastern England are regarded as lodgement tills. Lodgement tills are derived from rock debris carried at the base of a glacier and are the predominant type of till which occurs in glaciated lowland areas. Generally, because of glacial abrasion and grinding, the proportion of silt and clay in lodgement till is relatively high.

Glacial deposits, notably tills, occur extensively along the eastern coastal areas of England, from Northumberland in the north extending southwards into East Anglia (Fig. 1). The tills frequently are well exposed in cliff sections, as in north Norfolk and Holderness, two of the study areas. Unfortunately, the till deposits around the Tees estuary, the third study area, are not well exposed over this flat and rather featureless area. Furthermore, large parts of this industrial area are built over. With the exception of some of the tills in Northumberland which have been investigated by Eyles and Sladen (1981), Robertson et al. (1994), Hughes et al. (1998), and Clarke et al. (1998), little investigative work on the geotechnical properties of the tills of the east coast of England has been reported in the literature. Accordingly, the three areas referred to were chosen from which to collect samples. Their geotechnical

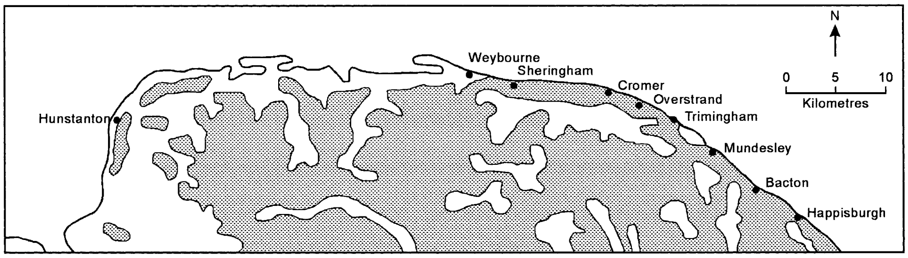

Fig. 2. Distribution of till deposits, shown stippled, in north Norfolk.

properties were determined and compared with those of the tills from Northumberland.

The samples from north Norfolk and Holderness were obtained mainly from coastal exposures, except that some were taken from abandoned clay pits. They were all block samples, which were wrapped and sealed before being packed in containers. The samples from Teesside were obtained from a dozen boreholes by a light cable and tool rig, the samples being retrieved by U100 sampling tubes. All the boreholes were less than 16 m in depth, except one which extended to 26.5 m.

In Norfolk, glacial deposits overlie earlier sediments of marine, estuarine and freshwater origin. The area was invaded more than once by ice sheets but just how many advances and interglacial stages occurred, has been keenly debated (Mitchell et al., 1973; Lewis, 1999). Hence, the stratigraphical succession has not been worked out to the satisfaction of everyone. This is to be expected because of the complicated nature of some of the stratigraphy of the glacial deposits in this area. By comparison, the glacial deposits of the other two areas are simpler in terms of their stratigraphy.

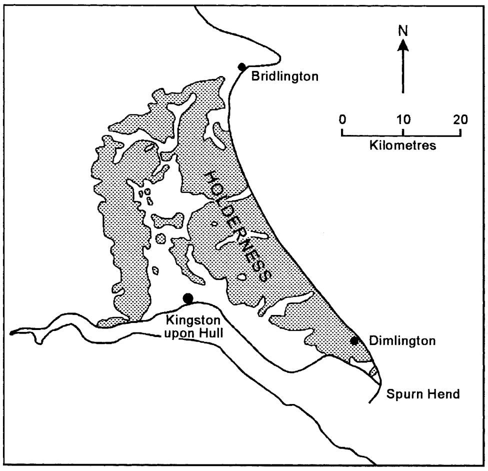

Fig. 3. Distribution of till deposits, shown stippled, in Holderness.

The glacial deposits of the north of Norfolk (Fig. 2) rest on the Cromer Forest Bed Formation, the Weybourne Crag or directly on the Chalk. The earliest till deposits belong to the Cromer Till, which occurs in the lower part of the Anglian stage. The Anglian stage extended from 500,000 to 350,000 years BP. Mitchell et al. (1973) recognised three divisions of the Cromer Till, namely, the First, Second and Third Cromer Tills, although this subdivision is not universally agreed. The Third Cromer Till includes the Contorted Drift (Reid, 1882), which occurs around Trimingham. Around Weybourne, the till deposits include much chalky material and consequently have been referred to as the Chalky Boulder Clay by Baden-Powell (1948). According to Mitchell et al. (1973), the Chalky Boulder Clay marks the end of the Anglian stage. No further till deposits occur in north Norfolk until Late Devensian times when the Hunstanton Till was laid down. It occurs in small patches in northwest Norfolk.

The till deposits of Holderness are well displayed along the coast from Bridlington to Dimlington (Fig. 3). Four units have been recognised, namely, the Basement Till (referred to as the Bridlington Till by Lewis, 1999), the Skipsea Till, the Withernsea Till and the Hessle Till. The Basement Till was considered to have been deposited during the Wolstonian (late Illinoian) glaciation by Mitchell et al. (1973). This stage occurred between 300,000 and 175,000 years BP. The other tills are of Late Devensian age, being deposited between 18,000 and 13,000 years ago (Penny et al., 1969. However, Madgett and Catt

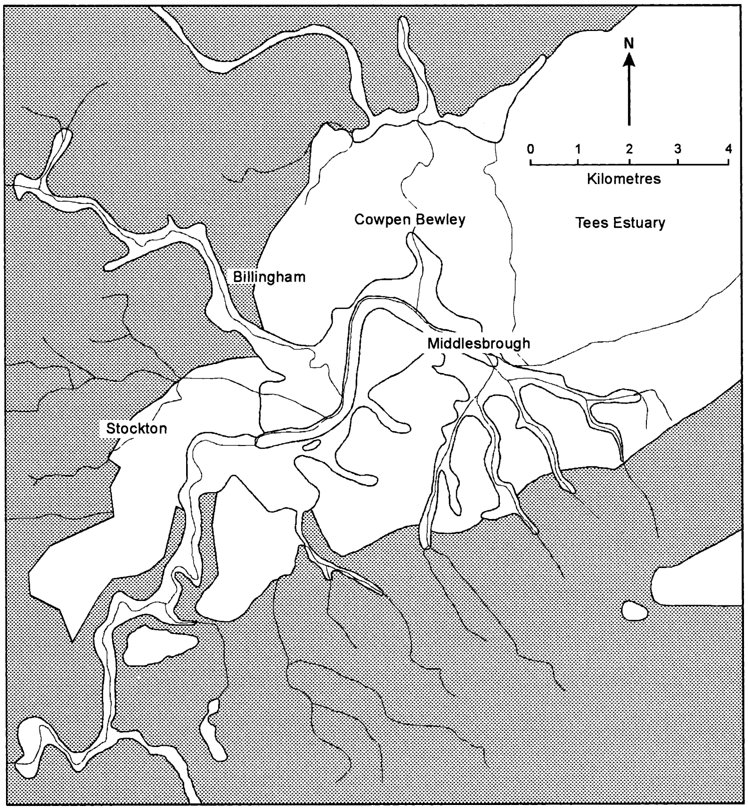

Fig. 4. Distribution of till deposits, shown stippled, at Teesside.

(1978) concluded, on the basis of colour, mineralogical composition and particle size distribution, that the Hessle Till was not a discrete till unit but was composed of both weathered Skipsea Till and weathered Withernsea Till.

Two tills have been recognised in the Teesside area, i.e. the Lower Boulder Clay and the Upper Boulder Clay (Fig. 4). These two tills are separated by sands (Agar, 1954). Smith (1981) maintained that the two tills had significantly different erratic suites and clast fabrics. This tripartite division also has been recognised in the glacial deposits of east Northumberland, Durham and northeast Yorkshire (Hughes et al., 1998). These tills are of Late Devensian age (Thomas, 1999).

2. The character of the tills

The First and Second Cromer Tills occur between Happisburgh and Cromer. According to Funnell and Wilkes (1976), their maximum thickness is about 30 m. The First Cromer Till is a stiff fissured grey to dark grey silty till which, in places, possesses a chalky matrix (i.e. a matrix dominated till). It contains pebbles of flint, quartzite, schist, gneiss and igneous rocks, which are of Scottish and Scandinavian origin. Generally, the pebbles are less than 50 mm in length and are of irregular shape. The matrix is fairly homogeneous in character although patches of sand occur. The Second Cromer Till also is a stiff fissured grey coloured silty till but, unlike the lower till, it may consist of up to 40% chalk pebbles which vary in size from a few millimetres up to 50 mm (Kazi and Knill, 1969). The larger erratics may range up to 0.2 m in diameter. West (1964) suggested that the contortions in the Contorted Drift could have been produced by melting of dead ice associated with a down-melting ice sheet causing slumping of englacial and supraglacial material or by movement of ice at the margin of an ice sheet. This is a grey or brown matrix dominated till, containing boulders of local derivation, notably chalk. It is found between Happisburgh Overstrand.

The Chalky Boulder Clay is a matrix-dominated pale grey or light brown till which contains locally derived pebbles of chalk, flint, Red Chalk and Carstone which may exceed 100 mm in diameter, as well as pebbles of quartzite. Sandy layers also occur in the till as well as blocks and large masses of chalk. The pale grey colour of the till frequently weathers to a brown colour due to oxidation of the iron compounds present. Decalcification has occurred in places. The till typically is less than 30 m thick, although the maximum thickness is reported as 60 m (Funnell and Wilkes, 1976).

The Hunstanton Till is a reddish-brown sandy till, which is not widely distributed. In the Hunstanton area, its maximum thickness is around 6 m. Being deposited by Devensian glacier ice, the clast content differs from that of the tills previously deposited in north Norfolk. In particular, it contains practically no chalk but pebbles of igneous rocks similar to those found in the Cheviot Hills are present, as are pebbles of limestone, sandstone and quartzite. The till also contains occasional lenticular beds of sand.

The Basement Till of the Holderness area has a grey clay matrix containing cobbles and boulders derived mainly from northeast England. However, a few of these clasts, such as larvikite and rhomb porphyry from Norway, were picked up from older tills in the North Sea or derived from contemporary Scandinavian ice. Structural evidence, such as grain orientation and minor folds, suggests that the ice sheet originated from the northeast (Penny and Catt, 1967).

The Skipsea Till has a brown clay matrix containing clasts derived from the Carboniferous rocks of the Pennine area and much locally derived chalk. The Withernsea Till contains a dark brown clay matrix with a variety of clasts from northern England including Triassic sandstone, but less chalk than the Skipsea Till. The Skipsea and the Withernsea Tills both contain a few clasts of Norwegian origin, possibly incorporated from the underlying till. The tills also contain random fluvial cross-bedded lenses of sand. The time interval in which the Skipsea and Withernsea Tills were deposited, about 5 000 years, appears very short for them to have been formed from two separate glacial advances (Madgett and Catt, 1978). It is possible that they are the result of deposition from a composite glacier composed of two glaciers originating from different parts of northern Britain. The mode of formation of the tills is still a matter for discussion and it is possible that their deposition included lodgement, flow and melt-out processes (Marsland and Powell, 1985).

The Lower and Upper Boulder Clays of the Teesside area were regarded by Smith (1981) as products of successive Late Devensian ice sheets. The first deposited lodgement till and outwash as it retreated and these deposits subsequently were overridden by the second ice sheet, which left behind its own lodgement till and outwash. The Lower Boulder Clay is brown in colour and contains clasts from the western Southern Uplands and the Lake District, as well as some from Scandinavia. The sands which separate the Lower from the Upper Boulder Clay are regarded as outwash deposits (Agar, 1954). The lower part of the Upper Boulder Clay is chocolate brown in colour and merges upwards into a reddish coloured till. The brown till does not appear to be continuous throughout the area and the reddish till never exceeds 2 m in thickness. The Upper Boulder Clay contains clasts from the Cheviot Hills and eastern Southern Uplands. Again some clasts were derived from Scandinavian ice. The tills are thickest in the north and west of the area where they reach some 30 m, thinning out to the south and east to as little as one tenth of this figure. A proglacial lake formed in the Teesside area as the ice retreated. The Tees Laminated Clay was deposited in this lake and rests directly upon the Upper Boulder Clay (Fig. 5).

The two principal clay minerals in the fine fractions of these tills, as determined by X-ray diffraction, are illite and kaolinite. Kaolinite tends to be the dominant clay mineral in the Hessle Till and this was attributed by Madgett and Catt (1978) to the influence of weathering. Quartz usually occurs in varying amounts in the fine fraction of the tills, i.e. between 5 and 30%. The carbonate content of the matrix material, especially in the chalky tills from north Norfolk can exceed 50%. However, it generally is less that 10% in the other tills but over 20% has been recorded in the Skipsea Till. By constrast, some samples of Hessle Till have been either completely or almost decalcified. Eyles and

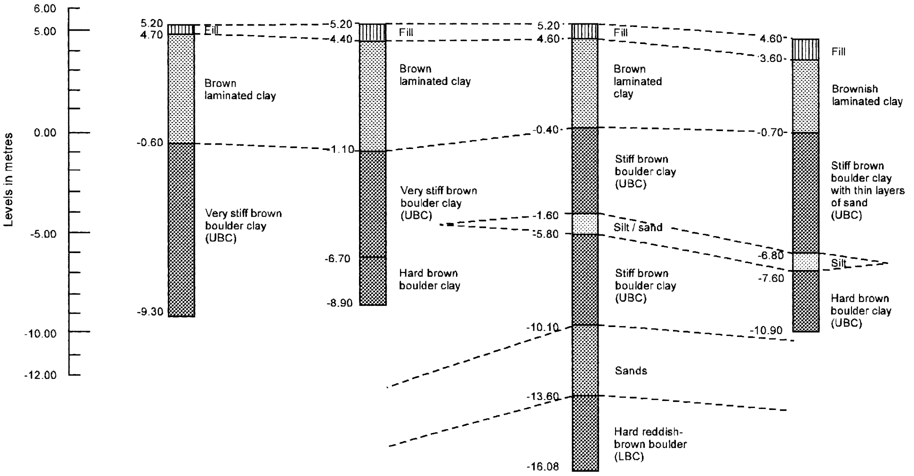

Fig. 5. Borehole logs showing the succession of tills, sands and laminated clay in the Teesside area. Note that the boreholes are not set out to a horizontal scale.

Sladen (1981) maintained that a notable decrease in carbonate content is one of the indications of a weathered till. Nonetheless, over 20% carbonate content has been found in some Hessle Till material suggesting that it could have been derived from the Skipsea Till while the low content of calcareous material could represent weathered Withernsea Till.

3. Particle size distribution and consistency limits

Tills are characteristically unsorted, consisting of a clast and a fine fraction or matrix, their particle size distribution being influenced by their source rocks and, especially in the case of lodgement tills, by the distance of transport travelled. The clast size consists principally of rock fragments and composite grains, and presumably was formed by frost action and crushing by ice. Single grains predominate in the matrix. The range in the proportions of clast and fine fractions in tills dictates the degree to which the properties of the fine fraction influence the properties of the composite soil. The variation in the engineering properties of the fine soil fraction is greater than that of the coarse fraction, and this often tends to dominate the behaviour of the till.

The clast fraction of the tills which occur in north Norfolk accounts for less than 40% of the deposits and usually is less than 20%. Hence, they are matrix-dominated tills, the approximate proportions of sand, silt and clay varying as shown in Table 1 and Fig. 6. The till with the most clay size material in the matrix is the Chalky Boulder Clay. In fact, a large proportion of the fine material in the Chalky Boulder Clay often consists of chalky material as can be seen from the following chemical analysis, which is compared with another from the Hunstanton Till:

Table 1
Sand, silt and clay fractions of till from north Norfolk

	Cromer Till (%)	Contorted Drift (%)	Chalky Boulder Clay (%)	Hunstanton Till (%)
Sand	38–64	26–40	15–45	34–58
Silt	32–18	54–48	30–23	36–27
Clay	30–18	20–12	55–32	30–15

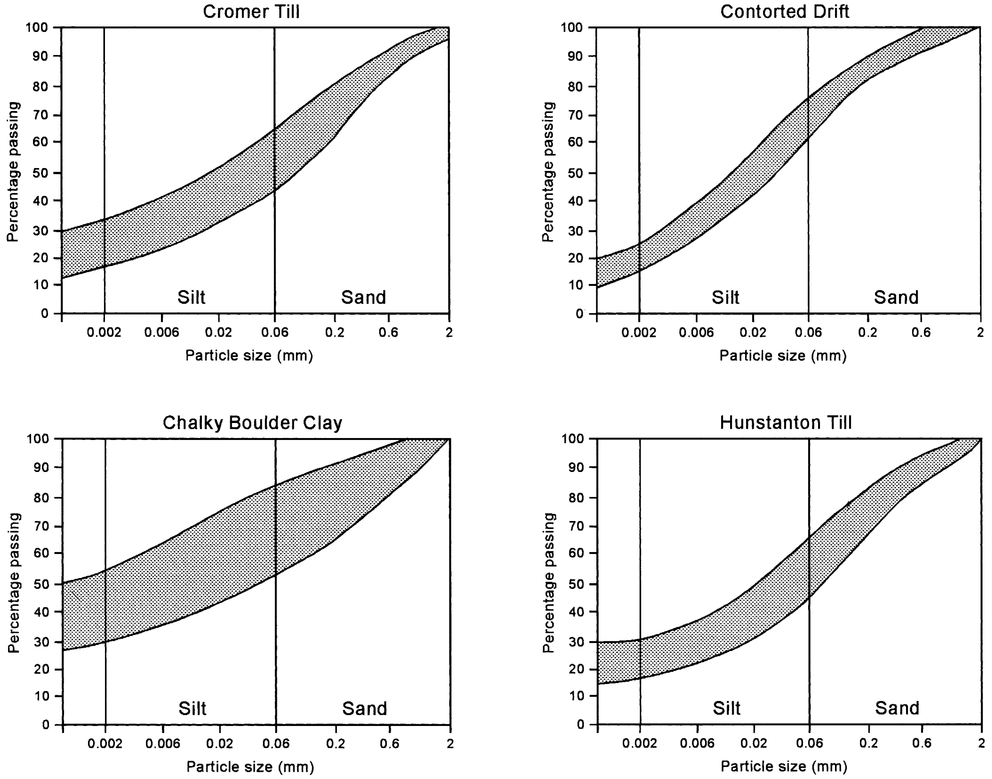

Fig. 6. Particle size distribution of the fine fractions of tills of north Norfolk.

	Chalky Boulder Clay (%)	Hunstanton Till (%)
SiO_2	19.6	62.4
Al_2O_3	14.3	15.1
Fe_2O_3	2.2	4.4
MgO	1.1	1.5
CaO	36.4	2.5
CO_2	26.7	6.3

The smallest clay size material occurred in the Contorted Drift, most of this consisting of silt. Sand tended to form the major component of the matrix in the Cromer and Hunstanton Tills.

A similar particle size distribution occurs in the tills of Holderness. Here the fine fraction of the tills generally is over 60% and frequently over 80% of the individual deposits. Therefore, they similarly are all matrix-dominated tills. However, the particle size distribution of the sand–silt–clay fractions of these tills does indicate differences between them. The Basement Till is the finest, containing the largest amount of clay size material, usually between 22 and 40% (Fig. 7). The proportion of silt tends to vary from 27 to 35% and fine sand from 15 to 20%. The remaining proportion of sand is always less than 15%. It can be seen from Fig. 7 that the cumulative curves for the Skipsea Till are somewhat steeper, especially in the fine sand fractions than they are for either the Basement or Withernsea Tills. Nonetheless, the overall particle size distribution of the Skipsea Till is not appreciably different from that of the Basement Till, and it has been suggested that the former picked up and reworked large quantities of the Basement Till (Madgett and Catt, 1978). In fact, in the Skipsea Till the fine sand fraction can range between 20 and 30%, while medium and coarse sands together do not account for more than 15% and frequently for less than 10%. The silt fraction varies between 30 and 40%, while that of clay fraction constitutes between

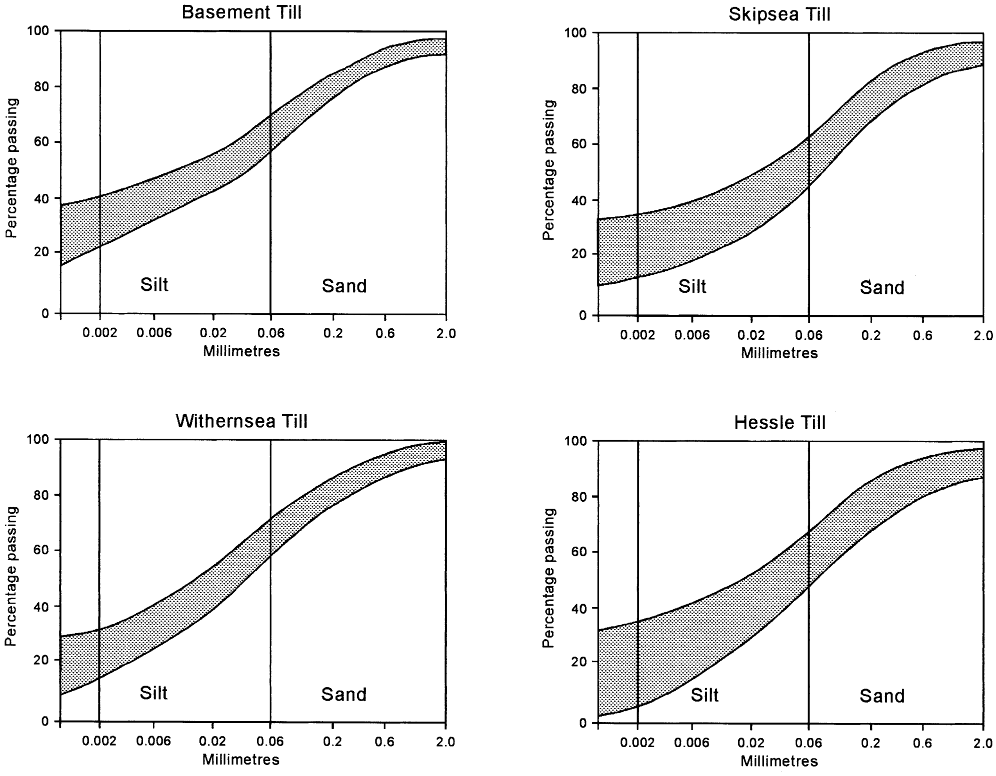

Fig. 7. Particle size distribution of the fine fraction of the tills of Holderness.

15 and 35%. The Withernsea Till contains between 20 and 45% silt and between 10 and 27% clay (Fig. 7). The fine sand fraction is between 15 and 20%, and the remaining sand amounts to between 12 and 18%. As can be seen from Fig. 7 a wider range of particle size distribution occurs in the Hessle Till than the other three tills. The proportion of clay size material varied from 6 to 37%, of silt from 28 to 32% and of fine sand from 17 to 21%. Medium and coarse sand can comprise from 9 to 18%. This wide spread of particle size distribution can be attributed to the fact that the Hessle Till is the weathered product of the Skipsea and Withernsea Tills. Like all tills, these are characteristically unsorted.

Table 2
Content of clay, silt and sand in the tills of Teesside

	Clay	Silt	Sand
Lower Boulder Clay			
Max	30	48	58
Min	16	31	25
Mean	21	36	44
Upper Boulder Clay			
Max	38	50	53
Min	17	32	24
Mean	24	39	40

The tills of the Teesside area are also characteristically unsorted and matrix-dominated with the clast fractions generally accounting for less than 20%. As shown in Table 2, the principal material in the fine fraction of the Lower and Upper Boulder Clays is sand, and clay generally constitutes the smallest amount of the fine fraction in both. Fig. 8 shows the relative proportions of sand, silt and clay in these tills.

The particle size distributions of the tills of these three areas do not differ radically from each other and are similar to those of the unweathered tills of east Northumberland, as determined by Eyles and Sladen (1981). However, as would be expected, they are very

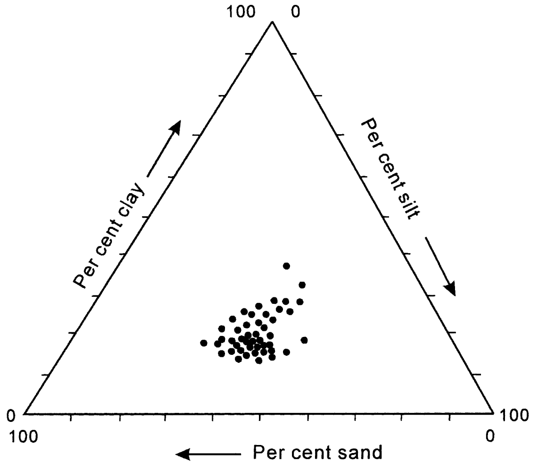

Fig. 8. Sand, silt and clay content of the tills of Teesside.

different from the particle size distributions of some tills found in North America, notably in parts of Ontario and Ohio, referred to by Sladen and Wrigley (1981).

Table 3 indicates that the moisture contents of some of the tills are notably higher than those of others. For instance, the Chalky Boulder Clay in north Norfolk has an average moisture content of 23.6%, which is at least 6% higher than those of the other tills of north Norfolk. This may be due to the chalky content, which can hold significant amounts of pore water. Similarly, the Hessle Till in Holderness has a higher moisture content than the other tills. Presumably, this is because it is a weathered derivative of the tills beneath and so generally has a higher clay fraction. However, in the Teesside area the natural moisture content of both tills does not vary appreciably. In the case of the Upper Boulder Clay, it ranges from 4 to 21%, although all except one sample are 10% or above. The average value is 14%, one per cent higher than that of the Lower Boulder Clay. The latter exhibits a more restricted range.

The consistency limits of tills are dependent upon moisture content, grain size distribution and the properties of the fine grained fraction. For instance, the higher the non-clay fraction is, then the lower are the plastic and liquid limits. As this tends to affect the liquid limit more than the plastic limit, the result is that the plasticity index is reduced. Generally, however, the plasticity indices of tills are small and such soils are firm to stiff. The Atterberg limits influence many other geotechnical properties such as the degree of consolidation and strength.

The lowest plastic and liquid limits of the tills of north Norfolk occur in the Contorted Drift, averaging 14 and 25%, respectively (Table 3). All samples had a low plasticity. The highest values of these two consistency limits were obtained in the Chalky Boulder Clay, in which the average plastic limit was 20% and that of the liquid limit was 37%. Most of the samples from the latter till are of intermediate plasticity (Fig. 9). There is little difference between the plastic and liquid limits of the Cromer and Hunstanton Tills. The highest plasticity index of all these tills is 26% and occurs in the Chalky Boulder Clay (Table 3).

In the case of the tills from Holderness, both the Skipsea and Withernsea Tills possess low plasticity, the respective average plastic and liquid limits being 16 and 30%, and 18 and 34% (Table 3). On the other hand, many of the samples of the Basement Till are of intermediate plasticity (Fig. 10). The difference in plasticity between the two former tills and the Basement Till may be explained by the fact that the latter contains more clay size material in its fine fraction than do the other two. Some of the samples of the Hessle Till have a high plasticity, although most are in the intermediate range. The higher plasticity of this material may be attributable to it being the weathered derivative of the two tills beneath.

The range of plastic limits in the Teesside area is a little greater in the Upper Boulder Clay than the Lower Boulder Clay, 11–20% compared with 9–16%, with the average of the Lower Boulder Clay being lower than that of the Upper Boulder Clay (Table 3). Of the 46 samples of Upper Boulder Clay tested, 30 had a low plasticity, the remainder being of intermediate plasticity (Fig. 11). Again, the average liquid limit of the Upper Boulder Clay is slightly higher than that of the Lower Boulder Clay (Table 3). However, the range of liquid limits of the Upper Boulder Clay is notably higher than that of the Lower Boulder Clay, i.e. from 22 to 49% compared with 27–38%, respectively. But, as illustrated in Fig. 11, two of the liquid limit values are much higher than the rest. When compared with the lodgement tills from east Northumberland examined by Eyles and Staden (1981), it would seem likely that these two

Table 3

Natural moisture content (*m*), plastic limit (PL), liquid limit (LL), plasticity index (PI), liquidity index (LI), consistency index (CI), and activity (A) of tills from north Norfolk, Holderness and Teesside (Liquid limit: L = low plasticity, less than 35%; I = intermediate plasticity, 35–50%; H = high plasticity, 50–70% (Anon, 1999). Consistency index: VS = very stiff, above 1; S = stiff, 0.75–1; F = firm 0.5–0.75 (Anon, 1986). Activity: I = inactive, less than 0.75; N = normal, 0.75–1.25; A = active, over 1.25 (Skempton, 1953))

	m	PL (%)	LL (%)	PI (%)	LI	CI	A
North Norfolk							
Hunstanton Till (Holkham)							
Max	18.6	23	40 (I)	23	0.07	0.97 (S)	1.00 (N)
Min	16.8	15	34 (L)	15	−0.19	0.89 (S)	0.75 (N)
Mean	17.6	18	37 (I)	20	−0.02	0.92 (S)	0.85 (N)
Chalky Boulder Clay (Weybourne)							
Max	25.2	21	45 (I)	26	0.48	0.85 (S)	0.50 (I)
Min	22.4	18	32 (L)	14	0.15	0.50 (F)	0.40 (I)
Mean	23.6	20	37 (I)	18	0.32	0.68 (F)	0.45 (I)
Contorted Drift (Trimingham)							
Max	18.9	18	29 (L)	13	0.33	0.86 (S)	0.80 (N)
Min	13.2	9	19 (L)	8	0.07	0.72 (F)	0.65 (N)
Mean	15.6	14	25 (L)	11	0.16	0.78 (S)	0.75 (N)
Cromer Till (Happisburgh)							
Max	15.8	20	40 (I)	24	−0.16	1.16 (VS)	0.95 (N)
Min	11.9	14	27 (L)	13	−0.18	0.98 (S)	0.65 (N)
Mean	13.2	17	35 (I)	19	−0.17	1.09 (VS)	0.80 (N)
Holderness							
Hessle Till (Dimlington, Hornsea)							
Max	26.6	26	53 (H)	32	0.072	1.147 (VS)	2.10 (A)
Min	18.5	20	38 (I)	17	−0.02	0.794 (S)	0.06 (N)
Mean	22.6	22	47 (I)	25	0.044	0.972 (S)	1.24 (N)
Withernsea Till (Dimlington)							
Max	19.3	21	39 (L)	20	−0.28	1.016 (VS)	1.21 (N)
Min	12.3	15	22 (L)	12	−0.1	0.828 (S)	0.72 (I)
Mean	16.9	18	34 (L)	17	−0.16	0.986 (S)	0.93 (N)
Skipsea Till (Dimlington)							
Max	18.2	19	36 (I)	18	−0.29	1.288 (VS)	0.67 (I)
Min	13.5	14	20 (L)	9	−0.04	0.978 (S)	0.51 (I)
Mean	15.5	16	30 (L)	14	−0.19	1.108 (VS)	0.56 (I)
Basement Till (Dimlington)							
Max	20.4	23	42 (I)	22	−0.16	1.081 (VS)	0.59 (I)
Min	15.6	16	28 (L)	12	−0.03	0.984 (S)	0.53 (I)
Mean	17	20	36 (I)	19	−0.13	1.009 (VS)	0.55 (I)
Teesside							
Upper Boulder Clay							
Max	21	20	49 (I)	34	0.23	1.77 (VS)	1.50 (A)
Min	5	11	22 (L)	10	−0.46	0.42 (S)	0.57 (I)
Mean	14	15	33 (L)	19	−0.04	1.23 (VS)	0.97 (N)
Lower Boulder Clay							
Max	17	16	38 (I)	23	0.32	1.92 (VS)	1.22 (N)
Min	10	9	27 (L)	13	−0.31	0.71 (F)	0.63 (I)
Mean	13	13	31 (L)	18	−0.03	1.13 (VS)	0.81 (N)

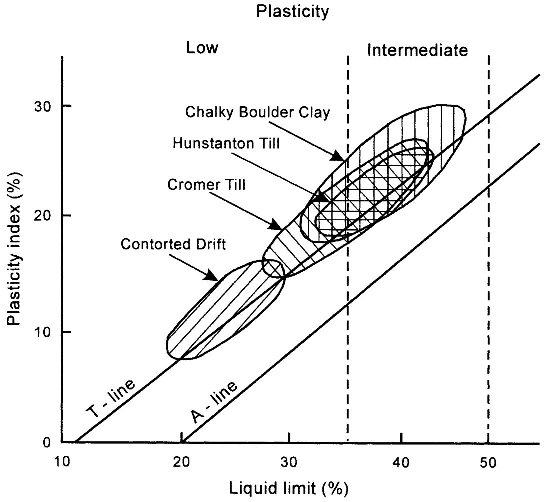

Fig. 9. Plasticity chart of the tills of north Norfolk.

samples are weathered representatives of the Upper Boulder Clay. What must be borne in mind, however, is that these two samples were obtained from boreholes in which they were overlain by the Tees Laminated Clay. The latter was deposited in a proglacial lake more or less immediately after the Upper Boulder Clay (Bell, 1998). Hence, this would appear to rule out the possibility of any weathering of the Upper Boulder Clay in the particular localities concerned. The higher liquid limit presumably is due to the higher clay content. Obviously, to assume that a till is weathered on the basis of one parameter, especially one, which is influenced by mineralogy and particle size distribution, is unwise. The plasticity indices of the Upper Boulder Clay range from 10 to 34%, while the range of the Lower Boulder Clay is between 13 and 23%, i.e. a more restricted range. This again is probably explained by the fact that generally the Upper Boulder Clay has a higher clay fraction than the Lower Boulder Clay. The variation of moisture content and consistency limits for a typical borehole is shown in Fig. 12.

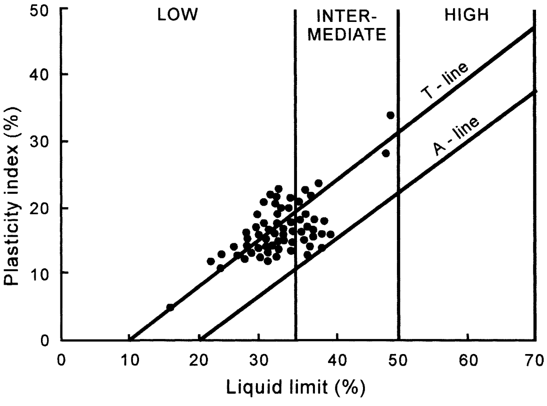

Fig. 11. Plasticity chart of the tills of Teesside.

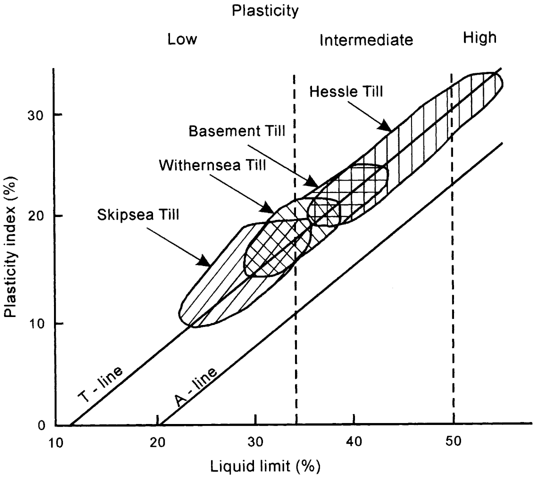

Fig. 10. Plasticity chart of the tills of Holderness.

There is some variation in the plastic and liquid limits of the tills of these three areas. Notably, those of the Contorted Drift of north Norfolk are the lowest. The liquid limits, in particular, are lower than those of the other tills. As a consequence, the Contorted Drift has the lowest plasticity indices. The reason for this is presumably because it has the lowest clay fraction of these tills. The highest Atterberg limits are found in the Hessle Till. All the values of both the plastic and liquid limits of the latter till fall within the ranges quoted by Eyles and Sladen (1981) for the weathered tills of east Northumberland, and so help substantiate the claim of Madgett and Catt (1978) that the Hessle Till is the weathered derivative of the two Devensian tills beneath. Comparison also can be made with some Canadian tills from Alberta, Ontario and Saskatchewan mentioned by Milligan (1976). He referred to plastic limits varying from 12 to 20%, averaging 15%, and liquid limits ranging from 19 to 30%, with a mean value of 26%. Generally, the plastic limits of these Canadian tills are not too different from those of

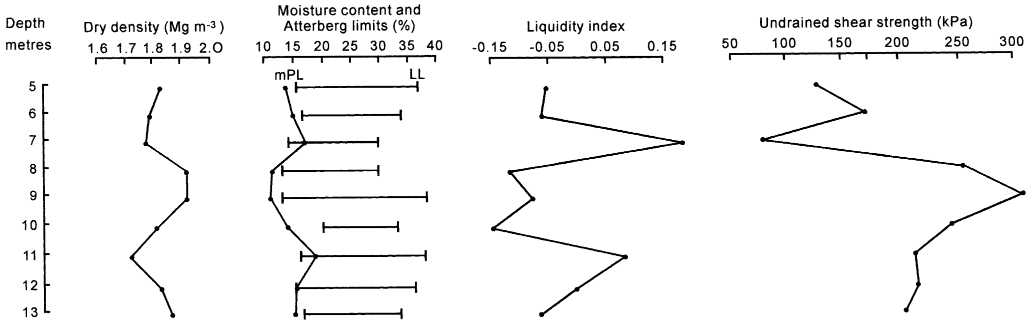

Fig. 12. Variation of density, natural moisture content, plastic limit, liquid limit, liquidity index and undrained shear strength of the Upper Boulder Clay of Teesside. Note the relationship between liquidity index and undrained shear strength.

the coastal areas of eastern England, with the exception of the Hessle Till. However, the liquid limits usually are lower, except for those of the Contorted Drift. Unfortunately, Milligan provided no data on the mineralogy or particle size distribution of these Canadian tills, which might help explain these differences in liquid limits. Nonetheless, this would suggest that the plastic index is less sensitive than the liquid index as far as tills are concerned.

When the plasticity indices of these tills are plotted against their liquid limits they all fall above the A-line on the plasticity chart (Figs. 9–11). In fact, they tend to fall along the T-line of Boulton (1976), indicating the unsorted nature of the tills and that most material of which they consist is usually larger than the clay size. Lodgement tills tend to straddle the T-line. The position of the Hessle Till (Fig. 10) along the T-line further suggests that this is a weathered till (Eyles and Sladen, 1981).

It can be seen from Table 3 that the Cromer, Hunstanton, Basement, Skipsea and Withernsea Tills have natural moisture contents which are in general, slightly below the plastic limits and hence they commonly have negative liquidity indices. The reverse situation is true for the Contorted Drift, Chalky Boulder Clay and Hessle Till. As far as the Chalky Boulder Clay is concerned, the high content of chalky material may help explain the fact that it possesses a high natural moisture content, which exceeds the plastic limit. On the other hand, this situation in the Contorted Drift may be attributable to its low plasticity. Eyles and Sladen (1981) suggested that the liquidity index could indicate whether or not a till had been subjected to weathering. For example, they maintained that the natural moisture content in heavily overconsolidated unweathered lodgement tills, usually is rather low and slightly above that of the plastic limit. Hence, the liquidity indices of such tills are negative and typically lie within the range −0.1 to −0.35. The frequent positive liquidity index values of the Hessle Till suggest, along with its plasticity indices, that this till probably is a weathered derivative of the two tills below it. Of the 46 values of Upper Boulder Clay, 23 have negative values which vary between −0.05 to −0.46. Eighteen have positive values, extending from 0.06 to 0.23, the rest having zero values. This would suggest that the Upper Boulder Clay has been weathered, at least in part. However, the position of this till on the plasticity chart, with the exception of the two samples referred to above, suggests that it is unweathered. In addition, the Upper Boulder Clay in the Teesside area, as noted above, tends to be covered by the Tees Laminated Clay. Similarly, with the exception of three samples of Lower Boulder Clay which have values of liquidity index of nought, half of the remainder have positive, while the other half have negative values. The same argument against the Lower Boulder Clay being weathered applies. It therefore appears that the use of the liquidity index an indicator of weathering of tills should be treated with caution.

The consistency index is the ratio of the difference between the liquid limit and natural moisture content to the plasticity index. It can be used to classify the different types of consistency in cohesive soils, i.e whether they are soft, firm, stiff, very stiff or hard. The consistency indices of the tills from north Norfolk indicate that these tills range from firm to very stiff, the stiffest being the Cromer Till, followed by the Hunstanton Till, the Contorted Drift and the Chalky Boulder Clay. The stiffness is due to their mineral composition and their degree of overconsolidation. The consistency indices of the tills of Holderness suggest that all are either stiff or very stiff, the Basement and Skipsea Tills being slightly stiffer than the Withernsea Till (Table 3). This presumably reflects the differences in composition, grading and degree of overconsolidation. In this case of the tills of Teesside, 39 out of the 46 samples of Upper Boulder Clay prove to be very stiff, 6 are stiff and 1 soft. As far as the Lower Boulder Clay is concerned, 12 are very stiff, 8 are stiff and 1 is firm. The ranges and mean values of consistency indices for these tills are given in Table 3.

The activity of most of these tills is either inactive or normal (Table 3). For example, the matrix material of the tills from north Norfolk consists of rock flour in the form of finely ground quartz or carbonate material and inactive clay minerals. This, in turn, is reflected in their activity. In particular, the Chalky Boulder Clay, which contains significant amounts of chalky material (see above), is notably inactive. The others either are inactive or just fall within the normal category. The Basement and Skipsea Tills also are typically inactive while the Withernsea Till varies from inactive to normal. In fact, unweathered lodgement tills are generally inactive. Some exceptions occur in the Hessle Till of Holderness and the Upper Boulder Clay of the Teesside area. Only 8% of the samples of Upper Boulder Clay are active and a somewhat higher figure is recorded for the Hessle Till. The higher activity of the Hessle Till may be attributable to weathering.

4. Compressibility and strength of tills

The compressibility and consolidation characteristics of tills are principally determined by their clay content. There is a general tendency for the coefficients of volume compressibility, m_v, and consolidation, c_v, of the tills from north Norfolk to decrease with increased loading. This can be seen from the following example of the coefficients of consolidation for Hunstanton Till:

Load (kPa)	c_v (m^2 y^{-1})
86	4.48
172	3.58
344	3.32
688	3.16

For comparative purposes values of m_v and c_v at one particular loading, i.e. 344 kPa, for the tills from north Norfolk are given in Table 4. These values are the characteristic of firm to stiff clays with medium to low compressibility. The range of values for these two coefficients for the tills from Teesside, tested at the same loading, also is given in Table 4. These values indicate that the tills of the Teesside area are firm to stiff, that is, of medium compressibility. The range of compressibility of these tills more or less corresponds with the descriptions attributable to the consistency indices.

In the case of tills, it frequently has been claimed that the reason for their overconsolidation is the load attributable to the overlying ice and that this overburden pressure can be deduced by the determination of the preconsolidation pressure (Gass, 1961). However, Boulton and Paul (1976) demonstrated from studies of the deposition of till from modern glaciers that many are not laid down subglacially, and that drying and wetting in the proglacial environment may give rise to appreciable changes in stress. Even if the tills are deposited in a subglacial environment, the development of pore water pressures can lead to effective pressures which are not directly related to the thickness of the overlying ice. Boulton

Table 4
Values of coefficients of volume compressibility, m_v, and consolidation, c_v, for tills from north Norfolk and Teesside (L = low compressibility, 0.05–0.1 m^2 MN^{-1}; M = medium compressibility, 0.1–0.3 m^2 MN^{-1} (Head, 1982))

	m_v (m^2 MN^{-1})	c_v (m^2 y^{-1})
North Norfolk		
Hunstanton Till	0.188–0.120 (M)	1.25–3.32
Chalky Boulder Clay	0.241–0.145 (M)	0.84–3.01
Contorted Drift	0.182–0.094 (L–M)	0.94–3.81
Cromer Till	0.164–0.127 (M)	1.30–2.79
Teesside		
Upper Boulder Clay	0.144–0.117 (M)	2.64–4.82
Lower Boulder Clay	0.138–0.110 (M)	3.32–5.41

and Paul maintained that relatively high pore water pressures can exist in tills, the pore water being derived from melting ice. This explains why lodgement tills, which may have been deposited under considerable thicknesses of ice may not be heavily overconsolidated. In such circumstances, the determination of the preconsolidation pressure may be of little value. Indeed, Milligan (l976) contended that if drainage is inhibited, then high pore water pressures can develop so that only a minor degree of consolidation occurs due to the weight of overlying ice. None of the tills studied are heavily overconsolidated as none of them have values of coefficient of volume compressibility of less than 0.05 m^2 MN^{-1}

The strength of the tills sampled were determined by the unconfined compression test, the shear box test and the triaxial test. In the latter case, quick-undrained and consolidated-undrained tests were carried out. In the quick-undrained tests increments of 100 kPa were used for the cell pressures. The rate of strain was 2% per minute which is equivalent to a strain of 1.5 mm per minute. Each test was continued until the specimen had failed or until a value of 20% strain was reached. In the consolidated-undrained tests, the specimens were allowed to consolidate under the cell pressure for 24 h. A back pressure of 200 kPa was applied to the specimens prior to testing to ensure full saturation. Cell pressures were applied at intervals of 150 kPa.

In the undrained conditions, most of the tills did not behave as ideal cohesive materials, some recording an angle of friction. In the consolidated-undrained tests, the pore water pressures were monitored and on testing tended to undergo a rapid rise to a peak which was followed by a gradual falling off towards failure. This decrease in pore water pressure presumably accompanies the dilatancy experienced by overconsolidated tills during shear.

In the case of the tills from north Norfolk, except for the material from the Chalky Boulder Clay, most of the samples tested in unconfined compression proved to be stiff. Those belonging to the Chalky Boulder Clay were firm (Table 5). When the same materials were remoulded and then tested again in unconfined compression, there were no significant losses in strength. Indeed, the ratio of undisturbed to remoulded strength showed that every soil tested had a low sensitivity, that is, every value of sensitivity thereby obtained was less than two. Although the lowest value of sensitivity was obtained from a sample of Contorted Drift (1.08), generally the Cromer Till was the least sensitive, closely followed by the Hunstanton Till. Even those values obtained from the Chalky Boulder Clay never exceeded 1.5. This suggests that any changes, which may occur in the fabric on remoulding do not reduce the packing of grains to any appreciable extent.

From the values of the strength parameters obtained from the undrained triaxial tests, it can be seen that these tills are not perfectly cohesive materials (Table 5). Indeed, because of the sand content in some of these tills, a frictional component would be expected. The Chalky Boulder Clay most closely approximates an ideal cohesive soil and, of course, it contains the highest proportion of clay size material. Turning to the effective strength parameters, no till has a value of cohesion greater than 20 kPa, but it is always above 5 kPa. With the exception of the Chalky Boulder Clay, the effective angles of friction for the three other deposits ranged between 25 and 35°.

The behaviour of soils of low plasticity can be sensitive to small changes in moisture content. This is well demonstrated by the Hunstanton Till and the Contorted Drift. Samples were compacted and specimens were taken dry and wet of optimum moisture content and subjected to undrained-triaxial testing. The results are shown in Fig. 13a and b. From Fig. 13a, it can be seen that the Hunstanton Till compacted dry of optimum behaved as a ‘brittle’ material, having an initial steep stress–strain curve with a notable peak strength which reduces to a residual strength. Such specimens failed in diagonal shear while those compacted wet of optimum produced barrel-shaped failures. Furthermore, it can be seen that the load at failure is significantly reduced as the water content is increased, an overall loss of around 85% being brought about by the addition of 8% water. However, the addition of the first 2% water caused a reduction of just over 70% in strength. In the Contorted Drift, the decline in strength with increasing water content also is dramatic, an increase of about 2.5% reducing the strength by almost 70%. Again the stress–strain curve of the driest specimen initially is very steep, however, the curve does not have a marked peak. In both tills those specimens compacted wet of optimum have very much flatter stress–strain curves.

Table 5
Strength of tills from north Norfolk and Holderness (c: cohesion in kPa; ϕ: angle of friction; L: low sensitivity (Skempton and Northey, 1952))

	Unconfined compressive strength (kPa)			Cohesion (kPa)		Angle of friction (°)	
	Intact	Remoulded	Sensitivity	c_u	c'	ϕ_u	ϕ'
North Norfolk							
Hunstanton Till (Holkham)							
Max	184	164	1.22 (L)	43	18	9	34
Min	152	128	1.18 (L)	22	8	3	26
Mean	158	134	1.19 (L)	29	12	5	29
Chalky Boulder Clay (Weybourne)							
Max	120	94	1.49 (L)	49	16	3	28
Min	104	70	1.28 (L)	16	7	0	21
Mean	110	81	1.34 (L)	27	11	1	24
Contorted Drift (Trimingham)							
Max	180	168	1.67 (L)	46	20	10	33
Min	124	76	1.08 (L)	20	6	3	27
Mean	160	136	1.23 (L)	26	11	6	30
Cromer Till (Happisburgh)							
Max	224	188	1.19 (L)	48	19	6	32
Min	154	140	1.10 (L)	26	12	2	26
Mean	176	156	1.13 (L)	35	14	4	29

	Unconfined compressive strength (kPa)			Direct shear				Triaxial			
	Intact	Remoulded	Sensitivity	c	$\phi°$	c_r	$\phi°_r$	c_u	$\phi_u°$	c'	ϕ'
Holderness											
Hessle Till (Dimlington, Hornsea)											
Max	138	116	1.31 (L)	30	25	3	23	98	8	80	24
Min	96	74	1.10 (L)	16	16	0	13	22	5	10	13
Mean	106	96	1.19 (L)	20	24	1	20	35	7	26	25
Withernsea Till (Dimlington)											
Max	172	148	1.18 (L)	38	30	2	27	62	19	42	34
Min	140	122	1.15 (L)	21	20	0	18	17	5	17	16
Mean	160	136	1.16 (L)	26	24	1	21	30	9	23	25
Skipsea Till (Dimlington)											
Max	194	168	1.15 (L)	45	38	5	35	50	21	25	36
Min	182	154	1.08 (L)	25	20	0	19	17	10	22	24
Mean	186	164	1.13 (L)	27	26	1	25	29	12	28	30
Basement Till (Dimlington)											
Max	212	168	1.27 (L)	47	34	2	30	59	17	42	36
Min	163	140	1.19 (L)	23	20	0	18	22	6	19	20
Mean	186	156	1.21 (L)	29	24	1	23	38	9	34	29

Samples of till from Holderness also were tested in unconfined compression. They were first tested in the undisturbed state, and then remoulded and tested again. Again, all the tills proved to have a low sensitivity, giving only a small reduction in strength on remoulding. The highest values of unconfined compressive strengths are obtained from the two lowest tills, that is, the Skipsea Till and the Basement Till (Table 5). Generally, they are at least 20 kPa higher than the values recorded from the Withernsea Till. This difference may be due to the greater degree of overconsolidation experienced by the Basement

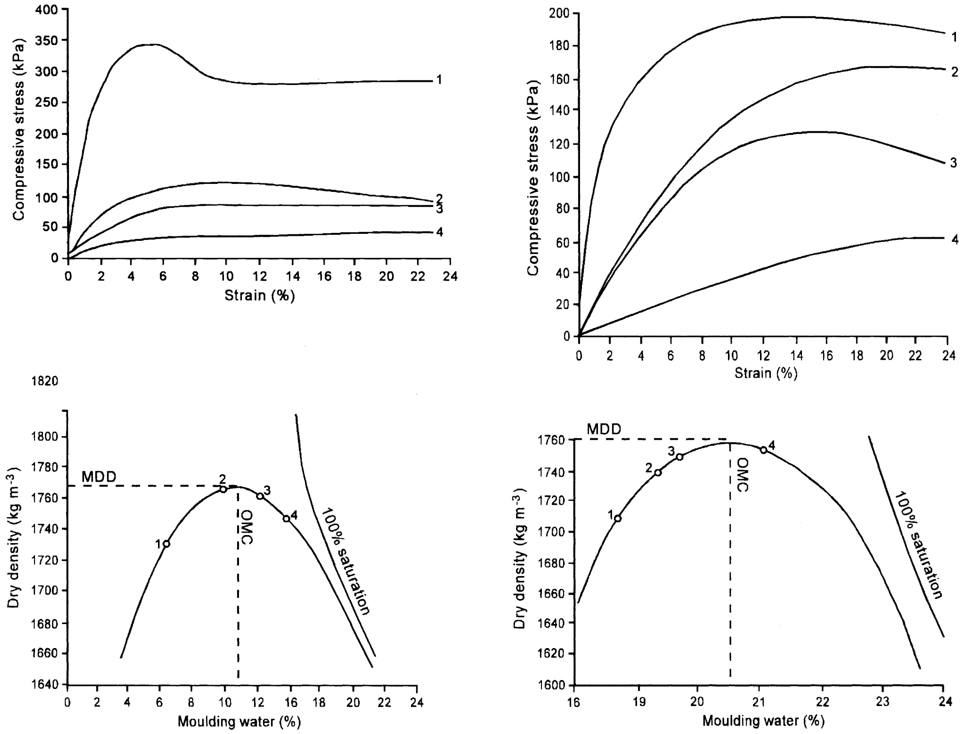

Fig. 13. Stress–strain curves for (a) Hunstanton Till (b) Contorted Drift, tested at different moulding water contents (1–4) wet and dry of optimum moisture content (OMC). MDD = maximum dry density.

and Skipsea Tills but differences in composition and grading also may influence the results. The Hessle Till yielded values of unconfined compressive strength generally some 30–40 kPa lower than those of the Withernsea Till. This, no doubt, is because it is the weathered derivative of the Skipsea and Withernsea Tills.

Direct shear tests were carried to determine both the peak and residual shear strengths. Table 5 shows that the values of shear strength were reduced from peak to residual values, particularly by the reduction in the cohesion parameter. In other words, this was reduced in all tills to only a few kilopascals or even to zero. The reduction in the value of the angle of friction involves a few degrees, generally by one, two or perhaps three degrees.

In the quick-undrained tests the samples of Basement, Skipsea and Withernsea Till exhibited both barrel and shear failures. However, most samples of Hessle Till produced barrel-shaped failures. That these materials are not purely cohesive is illustrated by the values obtained from the quick-undrained tests in that all tests revealed some value of angle of friction (i.e. 5° or higher). The highest angles of friction are found in the Skipsea Till, which is perhaps to be expected since it contains the largest proportions of sand–silt. However, the differences between the total and effective strength parameters of the Basement, Skipsea and Withernsea Till do not appear to be significant (Fig. 14). In the case of the Hessle Till there is a greater range in strength than occurs in the Basement, Skipsea or Withernsea Tills (Table 5). This presumably is because the Hessle Till is the weathered derivative of the latter two tills.

Quick-undrained triaxial tests showed that the tills from the Teesside area behaved as cohesive materials, only a very few tests recording an angle of friction and those never exceeded 4°. The undrained shear strength of the Lower Boulder Clay is notably higher than that of the Upper Boulder Clay, ranging from 63 to

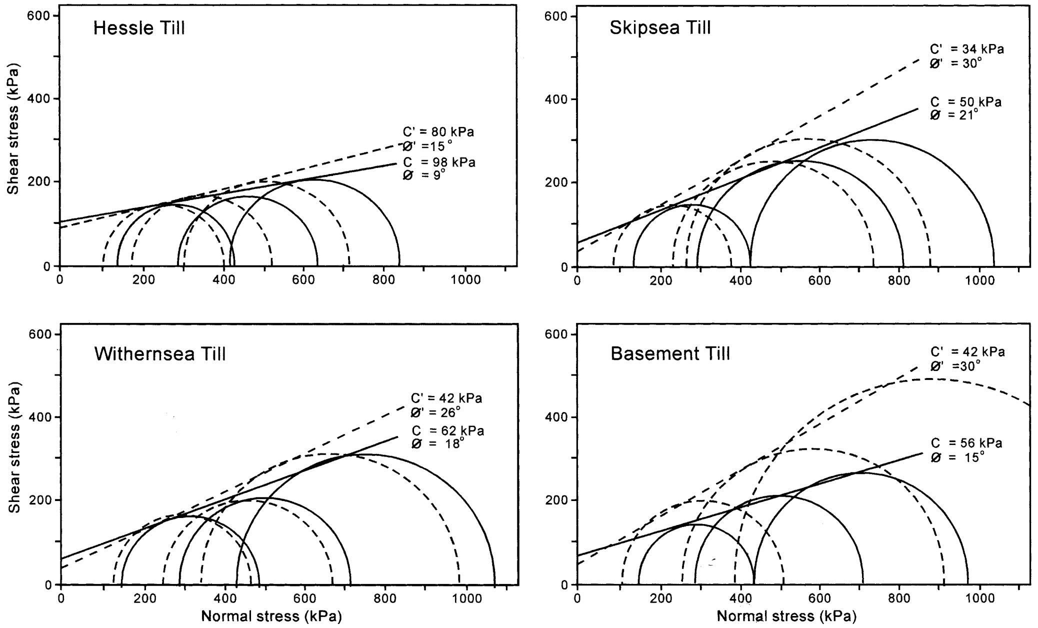

Fig. 14. Mohr circles for total and effective strength of tills of Holderness tested in consolidated-undrained conditions.

494 kPa with an average of 226 kPa, compared with a range of 38–352 kPa and an average value of 162 kPa for the Upper Boulder Clay. This possibly could be due to the greater depth of overburden covering the latter, but is more likely because of the higher clay content of the Upper Boulder Clay. Fig. 12 illustrates the variation in undrained shear strength with some other parameters, the most notable variation being with the liquidity index. The influence of dry density (range 1.77–1.99 mg m^3, mean 1.89 mg m^3 for the Lower Boulder Clay; 1.63–1.99 mg m^3, mean 1.83 mg m^3 for the Upper Boulder Clay) and moisture content on the undrained shear strength also is shown in Fig. 15. The respective maximum and minimum values of cohesion and angle of friction for the Lower and Upper Boulder Clays are 35–72 kPa and 32–39°, and 30–67 kPa and 31–37°. Their average values of cohesion and angle of friction are 48 kPa and 36°, and 44 kPa and 34°, respectively.

The undrained shear strengths of the tills of the Teesside area generally are higher than those of the tills of north Norfolk or Holderness. As the other properties of these tills, with certain exceptions, are roughly similar, then the explanation of the difference may lie in sampling. The material from north Norfolk and Holderness was sampled from the surface whereas that from Teesside was obtained from boreholes. In addition, the size of the specimens tested varied. Those taken from block samples were 38.5 mm in diameter (north Norfolk and Holderness) whereas those from the sampling tubes were 100 mm (Teesside), all had a 2:1 axial-diameter ratio. All sample material was tested to determine strength as soon as possible after being obtained. The values of undrained shear strength of the tills of Teesside are similar to those of the lodgement till of Northumberland, as determined by Robertson et al. (1994). The latter ranged from 65 to 410 kPa, with a mean value of 200 kPa. A later investigation by Clarke et al. (1998), however, showed a wider range of 50–640 kPa for lodgement tills from Northumberland, although most of the values were below 300 kPa. The latter authors used the results from boreholes of many site investigations so that their study was much more extensive than the present one or that of Robertson et al. Certainly, the range of undrained shear strength of tills can be much larger than those of the tills of the east coast of England. For instance, Milligan (1976) quoted a range of 107–3437 kPa for tills from Canada, the latter being very heavily overconsolidated.

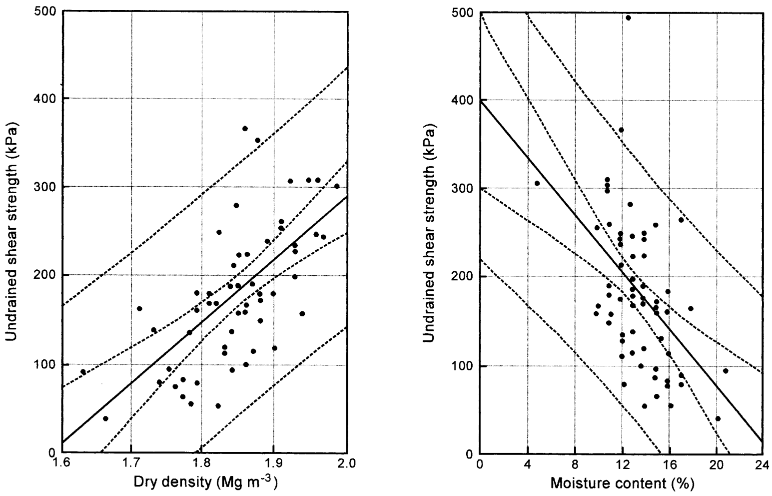

Fig. 15. Relationship between (a) undrained shear strength and dry density (b) undrained shear strength and natural moisture content, of the tills of Teesside.

Similarly, Radhakrishna and Klym (1974) mentioned values of 750–1600 kPa for heavily overconsolidated tills from North America.

5. Summary and conclusions

The till deposits which are extensively distributed over the coastal areas of eastern England obviously have been derived from different sources. They contain locally derived material and some clasts are from the Pennines, the Cheviot Hills, the Southern Uplands or even Scandinavia. X-ray diffraction shows that illite and kaolinite are the two principal clay minerals present in the fine fraction of the tills, quartz being the dominant mineral. Many of the geotechnical properties of these till deposits do not differ widely.

The tills which occur along the north coast of Norfolk were deposited primarily during the Anglian stage. Four tills can be identified in the Anglian stage, namely, the First and Second Cromer Tills, the Third Cromer Till (which contains the Contorted Drift) and the Chalky Boulder Clay. The Hunstanton Till, which occurs in the northwest of the county, was formed during Late Devensian times. The tills of Holderness were deposited during the Wolstonian (Basement Till) and Devensian (Skipsea and Withernsea Tills) stages. The overlying Hessle Till is now regarded as a weathered derivative of the Devensian tills. The Lower Boulder Clay and Upper Boulder Clay in the Teesside area are of Late Devensian age and were deposited by two separate ice sheets, and are separated by sands.

They are all matrix-dominated tills in which sand usually is the major component of the matrix. The size of the clay fraction, in particular, can influence most of the geotechnical properties, notably plasticity and compressibility. With the exception of the Chalky Boulder Clay, clay constitutes less than a third of the matrix materials of the tills of north Norfolk. The particle size distribution of the tills of Holderness differs somewhat one from another. In particular, that of the Hessle Till has an appreciably wider distribution, which embraces the particle size distribution of the Skipsea and Withernsea Tills. This is to be expected if the Hessle Till is derived from these two tills. The tills of north Norfolk are characterised by low or intermediate plasticity (all specimens of Contorted Drift tested had a low plasticity), as were most of those from Holderness and those from Teesside. When the values of the plasticity indices and liquid limits were plotted on the plasticity chart, they tended to occur parallel to and above the A-line, and straddle the T-line. The position of the Hessle Till on the plasticity chart suggests that it is weathered material. Generally, the Contorted Drift and Chalky Boulder Clay have low positive liquidity indices. The other tills from north Norfolk have low negative indices, as have the three tills from Holderness. Most of the liquidity indices of the Hessle Till and many of those of the Lower and Upper Boulder Clays of Teesside suggest that they have been partly weathered. However, in the case of the tills from Teesside, with the exception of two samples of Upper Boulder Clay, these tills occupy a position on the plasticity chart which would indicate that they are not weathered. Moreover, these tills have not been exposed, being covered with a few metres of overburden, which includes low permeability laminated clay. Hence, the use of the liquidity index alone as an indicator of whether or not a till has been weathered should be treated with caution. All the specimens of Chalky Boulder Clay tested were inactive whereas all those of the other tills from north Norfolk were normal. With the exception of some of the samples of Hessle Till and a few of the Upper Boulder Clay of Teesside which were active, the rest of the material tested from these two areas was either inactive or normal.

These tills are not heavily overconsolidated, being firm to stiff, and they generally are of medium compressibility. Normally, the undrained shear strength of the tills from north Norfolk, as assessed in unconfined compression, was less than 100 kPa and when they were remoulded and retested they suffered a small loss in strength. Hence, all these tills have a low sensitivity. Similarly, all the tills from Holderness, which were tested had a low sensitivity. Furthermore, the tills from north Norfolk are sensitive to small changes in moisture content, changing behaviour from relatively brittle to plastic and undergoing appreciable strength reduction. The strength values of the Hessle Till generally are lower than those of the other tills of Holderness which again could be interpreted as due to it being a weathered derivative of the two tills beneath. In fact, the strength values of the tills from Holderness tended to increase with age, the Basement Till normally having the highest values while the Withernsea Till generally recorded the lowest. This could be a reflection of the degree of overconsolidation. Most of the till samples of Teesside are stronger than those of Holderness or north Norfolk. This difference in strength may be explained by the fact that the samples of till from Teesside were obtained from boreholes whereas those from the other two areas were taken from the surface. Also, the specimens of Teesside till tested were larger. The strength of Lower and Upper Boulder Clays is influenced by the dry density and moisture content. The consolidation properties of these tills, like those of strength, are characteristic of firm to stiff soils.

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