British
Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Geotechnical laboratory testing of glacial deposits from Aldbrough, Phase 2 boreholes

Engineering Geology Programme

Internal Report OR/15/056

BRITISH GEOLOGICAL SURVEY

ENGINEERING Geology PROGRAMME

INTERNAL REPORT OR/15/056

Geotechnical laboratory testing of glacial deposits from Aldbrough, Phase 2 boreholes

Peter R.N. Hobbs, Mathew P. Kirkham & David J.R. Morgan

Contributor/editor

V. Banks

Keywords

Landslide, coastal, laboratory, testing, triaxial, till.

National Grid Reference

485720, 507513

Map

Sheet 999, 1:99 000 scale, Map name

Front cover

100 mm triaxial test specimen with Hall-effect strain gauges & mid-plane pore pressure take-off.

Bibliographical reference

HOBBS, P.R.N., KIRKHAM, M.P. & Morgan, D.J.R.(2015). Geotechnical laboratory testing of glacial deposits from Aldbrough, Phase 2 boreholes. *British Geological Survey Internal Report*, OR/15/056. 33pp.

Keyworth, Nottingham British Geological Survey 2015

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report is a published product of an ongoing study by the British Geological Survey (BGS) of the coastal change at Aldbrough on the Holderness coast, East Riding of Yorkshire, UK. The test site at Aldbrough has been selected as one of the BGS Landslide Observatories because it is representative of the high rates of coastal recession along this stretch of the east coast. The Aldbrough Landslide Observatory is operated under the BGS ‘Slope Dynamics’ task within the BGS’s ‘Landslide’ project of the ‘Shallow Geohazards and Risk’ team. As well as providing new insights with respect to the volumetric rates of recession and the near surface processes, it is a focus for the trialling of new surface and subsurface monitoring technologies. The establishment of the Aldbrough observatory and the initial research findings are reported in a series of reports in addition to this report. These are:

Hobbs, P.R.N., Jones, L.D. and Kirkham, M.P. (2015) Slope Dynamics project report: Holderness Coast – Aldbrough: Drilling & Instrumentation, 2012-2015. *British Geological Survey, Internal Report* No IR/15/001.

Hobbs, P. R. N., Jones, L. D., Kirkham, M. P., Pennington, C. V. L., Jenkins, G. O., Dashwood, C., Haslam, E. P., Freeborough, K. A. and Lawley, R. S. (2013) Slope Dynamics Project Report: Holderness Coast – Aldbrough: Survey & Monitoring, 2001 - 2013 *British Geological Survey, Open Report* No. OR/11/063.

Whilst this report is focused on the geotechnical laboratory testing programme, it should be read in conjunction with the reports listed above, which provide further details on drilling and instrumentation and on survey and monitoring. A series of reports will follow presenting the updated survey and monitoring reports, and their publication will be announced through the BGS project web page. Readers of these reports will probably also be interested in the context for this research, which can be found in:

Hobbs, P.R.N., Pennington, C.V.L., Pearson, S.G., Jones, L.D., Foster, C., Lee, J.R., Gibson, A. (2008) Slope Dynamics Project Report: the Norfolk Coast (2000-2006). *British Geological Survey, Open Report* No. OR/08/018.

Acknowledgements

The authors would like to acknowledge the contribution to the project of Mr. Paul Allison of Shorewood Leisure UK for permitting access to Shorewood's property and allowing the drilling, from which the samples described in this report, were obtained. The authors would also like to acknowledge the contributions of Lee Jones (BGS) and Chris Wardle (formerly BGS).

Contents

FIGURES

Summary

This report describes the results obtained from a programme of geotechnical laboratory testing to determine geotechnical properties of glacial deposits, including till, sampled from boreholes drilled at the BGS's 'Coastal Landslides Field Laboratory' test site at Aldbrough, Holderness, East Riding of Yorkshire in 2015. Tests include triaxial strength & consolidation, shear box strength, ring shear strength, oedometer consolidation & swelling, shrinkage and other index parameters. The tests were carried out at the BGS's 'physical properties' laboratories in Keyworth, Nottingham. The results are used to characterise the materials tested and to examine relationships relevant to their engineering behaviour and slope stability properties.

1 Introduction

The Slope Dynamics task of the Shallow Geohazard & Risk (SGR) project of the Engineering Geology (EG) theme at the British Geological Survey (BGS) has been monitoring and modelling coastal landslide activity at a specially established 'Coastal Landslide Field Observatory' at

Aldbrough on the Holderness coast of the East Riding of Yorkshire. Previous work on this project, going back to 2001, is described in Hobbs et al. (2013) and Hobbs et al. (2015). Phase 2 of this work commenced in January 2015 by the drilling of two 20 m deep boreholes, adding to the four previously drilled during Phase 1 in 2012. Core from these two boreholes (BH3a & BH3b) was logged and samples taken for geotechnical laboratory testing at BGS, Keyworth. The location of the boreholes and their relationship to the lithostratigraphy and the cliff is shown in Figure 1.

The geotechnical properties of tills on the east coast of England have been investigated (Bell & Forster, 1991; Bell, 2002; Powell & Butcher, 2003; Reeves et al., 2006) and in a previous 'Slope Dynamics' study (Hobbs & Freeborough, 2006). The present study provides additional data relevant to slope stability analyses, in particular effective stress parameters, for each of the formations present at Aldbrough and sampled during Phase 2 drilling operations. These include triaxial, ring shear, shear box and oedometer consolidation tests in addition to index tests.

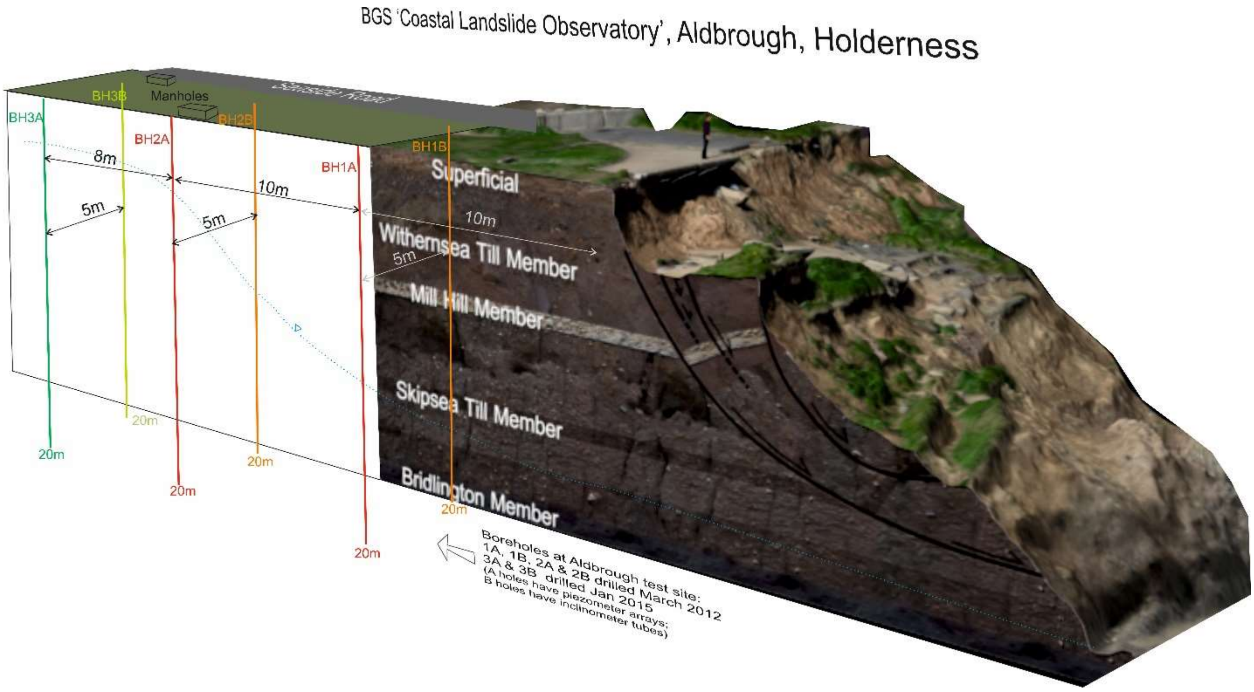

Figure 1 Block model showing borehole locations in relation to cliff (2013) and lithostratigraphy

The stratigraphic units present at the test site belong to the Quaternary Holderness Formation. These members are shown as Figure 1 and attributed to samples in Table 1. *For sample descriptions refer to Hobbs et al. (2015)*. Core was obtained by rotary wire-line drilling (Hobbs et al., 2015) in contrast to the Phase 1 boreholes which were mainly cable percussion and which did not provide undisturbed samples. Six sampling points were identified from borehole BH3b and five from borehole BH3a. Samples were obtained during core logging at BGS and sub-sampled for index and strength tests. All triaxial and shear box strength tests, and the shrinkage limit tests using the SHRINKiT apparatus (Hobbs et al., 2014), were carried out on undisturbed specimens. All other tests were carried out on remoulded or disaggregated samples. All tests, with the exception of the shrinkage limit tests, were carried out according to BS1377 (1999) and Head (1992).

Table 1 Laboratory test schedule

Bore hole	Sample	Depth (m)	Lithostrat.	Triaxial (multi-CIU)	Shear Box	Ring Shear	SHRINKiT	Oedom consol.	Index
BH3b	Geotech 1	2.23 -2.73	WM	✓	✓	✓	✓	✓	✓
	Geotech 2	6.41 - 6.70	WM	✓	✓	✓	✓	✓	✓
	Geotech 3	10.3 - 10.80	STM	✓	✓	✓	✓	✓	✓
	Geotech 4	14.1 - 14.60	STM/DB	✓	✓	✓	✓	✓	✓
	Geotech 5	16.1 - 16.60	DB/BM	✓			✓	✓	✓
	Geotech 6	18.35 - 18.74	BM	✓				✓	✓
BH3a	Geotech 7	4.78 – 5.28	WM	✓				✓	✓
	Geotech 8	8.15 – 8.65	WM					✓	✓
	Geotech 9	12.65–13.50	STM					✓	✓
	Geotech 10	15.40-15.90	DB	✓		✓		✓	✓
	Geotech 11	18.40-18.90	BM	✓				✓	✓

WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

The results of laboratory tests are discussed in separate sections according to test, starting with the effective stress tests and ending with the index tests, and finally in the conclusions and recommendations.

2 Strength tests

2.1 TRIAXIAL TESTS

Multi-stage isotropically-consolidated undrained (CIU) triaxial tests with pore pressure measurement were carried out, following procedures described in BS1377 (1999) and Head (1992), on nine 100 x 200 mm specimens. Specimens were saturated prior to consolidation and saturation checked with B-tests. Isotropic consolidation parameters m_{vi} and c_{vi} were recorded. Effective and total strength parameters c', ϕ', c_u & ϕ_u were recorded. The results are given in

Table 2 and Figure 2. *Sample Geotech 5 contains within it the lower boundary of the Dimlington Bed and the Bridlington Member and thus a significant lithology change.*

Table 2 Results of multi-CIU triaxial tests for BH3b

BH 3b			Effective		Total		Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Sample	Depth (m)	Lithostrat	c' (kPa)	ϕ' (degr.)	c_u (kPa)	ϕ_u (degr.)	c_{vi} m^2/yr	c_{vi} m^2/yr	c_{vi} m^2/yr	m_{vi} (m^2/MN	m_{vi} (m^2/MN	m_{vi} (m^2/MN
Geotech 1	2.73	WM	8.0	34.2	8.0	24.8	13.57	3.87	5.55	x	1.84	0.07
Geotech 2	6.70	WM	28.3	25.8	28	18.1	4.97	3.28	3.06	0.80	0.14	0.06
Geotech 3	10.80	STM	17.0	25.2	25.0	24.7	0.96	0.31	x	0.14	0.10	0.37
Geotech 4	14.50	DB	25.0	26.4	26.0	17.4	0.37	0.33	0.13	0.46	0.09	0.06
Geotech 5	16.60	DB/BM	10.0	28.3	19.0	18.9	1.24	0.73	0.48	0.17	0.05	0.03
Geotech 6	18.74	BM	0.0	32.7	5.0	21.1	0.28	0.2	0.12	0.19	0.06	0.03
BH 3a												
Geotech 7	5.28	WM	10	30.4	x	x	66.2	31.1	25.5	0.8	0.21	0.1
Geotech 10	15.9	DB	16.0	25.6	19	16.1	0.53	0.49	0.29	2.29	0.71	0.42
Geotech 11	18.9	BM	0	31.6	0	17.4	0.22	0.15	0.12	0.52	x	x

WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member
c' = Effective cohesion
ϕ' = Effective friction angle
c_u = Total cohesion
ϕ_u = Total friction angle
c_{vi} = Isotropic coefficient of consolidation
m_{vi} = Isotropic coefficient of volume compressibility

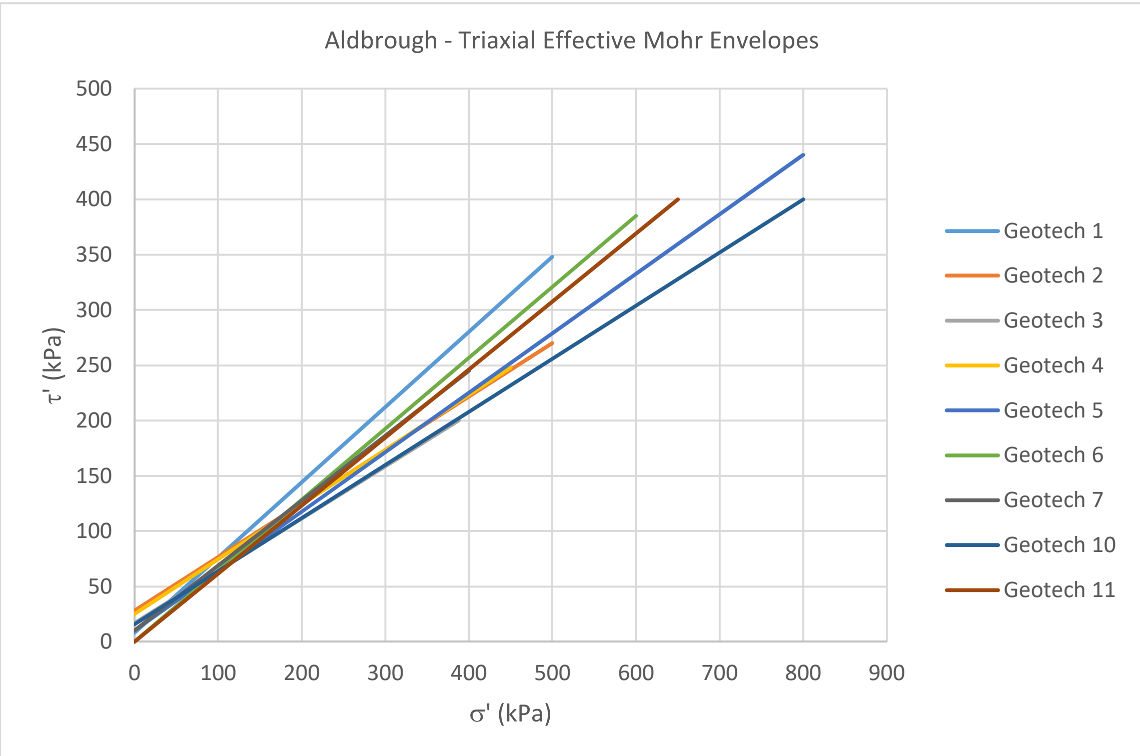

Figure 2 Combined Mohr envelope plots for CIU triaxial (effective) tests for all samples (BH3b and BH3a)

The results reported here compare favourably with those reported by Powell & Butcher (2003) and Zdravkovic et al. (2015) who quoted an overall CIU and CD Triaxial strength result of c' = 0 and ϕ' = 27.6° for Holderness Formation tills at Cowden, to the north of Aldbrough.

The multi-stage CIU triaxial data set was also examined for stiffness. The 'initial tangent' Young's Modulus of Elasticity, E_{TAN} was calculated. The results are plotted in Figure 3. This shows the divergent behaviour of Geotech 1 and the higher stiffness of the Bridlington Member samples (Geotechs 5, 6 & 11) at stresses above 400 kPa. Higher stiffness tends to pertain to the stronger samples and the values for the till samples are in line with stiff, low to medium plasticity tills reported elsewhere (Obrzud & Truty, 2012). *It should be noted that the 'small-strain stiffness' Hall-effect apparatus was unavailable and results were obtained with conventional triaxial strain measurement techniques. This has introduced scatter to the data.* It has been noted that density and stiffness are functions of the mode of deposition and not necessarily due to consolidation and that tills may behave as a 'drained' material because of the stiffness even though they are of low permeability (Clarke, 2011).

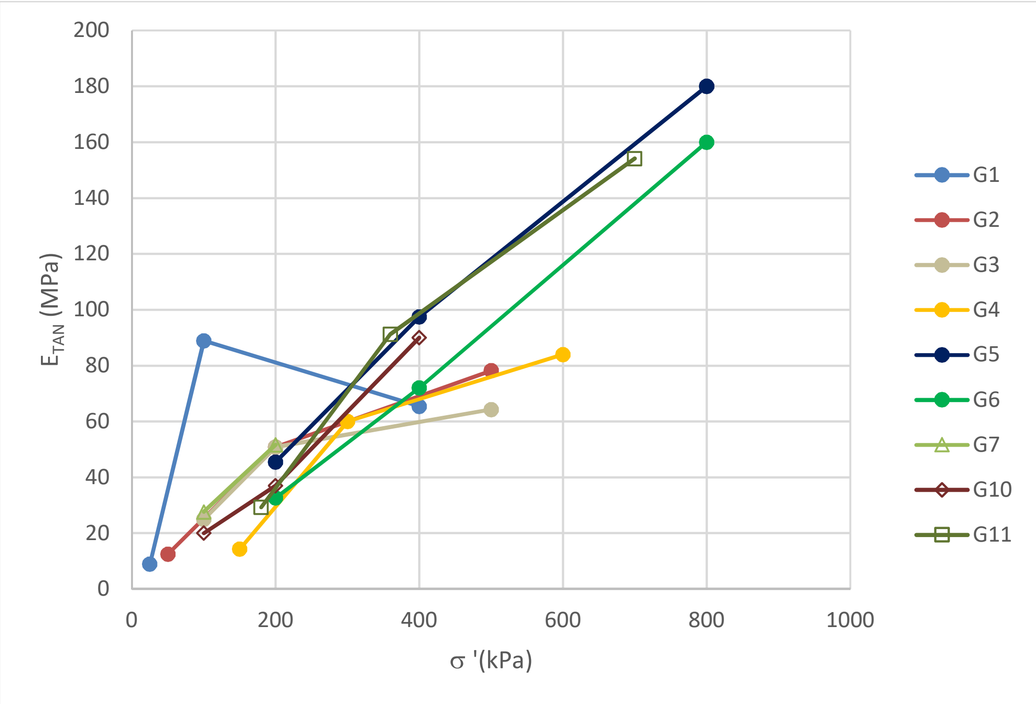

Figure 3 Plot of 'initial tangent' Young's Modulus, E_{TAN} vs Applied nett stress, σ' (Triaxial compression stages)

Strengths are generally higher than those reported in Bell (2002) though, as pointed out in that paper, Bell's Holderness samples were small and taken at surface. Specimens tested here tended to exhibit barrelling-type failures rather than shear-type failures, though low-angled shear were noted as a secondary mode of failure. This suggests that they are more plastic than brittle and are not heavily over-consolidated.

2.2 SHEAR BOX TESTS

Shear box strength tests were carried out, following procedures described in BS1377 (1999) and Head (1992), on four of the six samples taken from borehole BH3b. The test specimens were 60 x 60 mm square and 25 mm thick. The results are given in

Table 3.

Table 3 Results of Shear Box tests for BH3b

Sample	Depth (m)	Strat.	c′ (kPa)	ϕ' (degr.)
Geotech 1	2.73	WM	17.3	27.5
Geotech 2	6.70	WM	15.0	24.9
Geotech 3	10.80	STM	16.0	28.9
Geotech 4	14.50	STM	0.6	27.3

C′ = Cohesion
ϕ' = Friction angle
WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

The results of the shear box tests are shown combined on a single normal vs shear stress plot in Figure 4. These results are good quality and cluster in a narrow range and lie within an acceptable range for tills (Powell & Butcher, 2003; Bell & Forster, 1991; Bell, 2002).

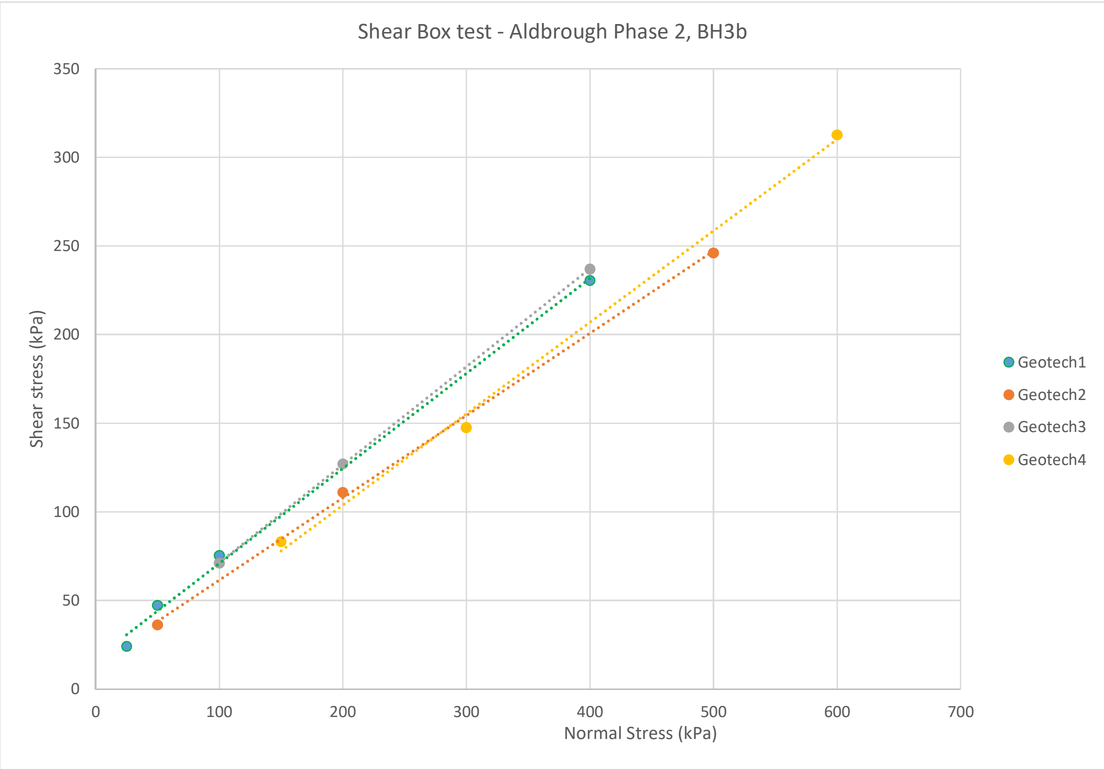

Figure 4 Plot of Normal stress vs. Shear stress for shear box tests for BH3b

2.3 RING SHEAR TESTS

Ring shear tests were carried out, following procedures described in BS1377 (1999) and Head (1992), on five samples using a Bromhead apparatus with a 100 mm specimen diameter. The 'remoulded' samples were prepared by passing through a 1.18 mm sieve and mixing to a water content below the liquid limit. The results are given in Table 4.

Table 4 Results of Ring Shear tests

Sample	Depth (m)	Strat.	c'$_r$ (kPa)	ϕ'$_r$ (degr.)
Geotech 1	2.73	WM	10.0	24.4
Geotech 2	6.70	WM	4.0	24.7
Geotech 3	10.80	STM	9.3	26.1
Geotech 4	14.50	STM	22.5	26.6
Geotech 10	15.9	DB	8.7	15.1

WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member
C'$_r$ = Residual cohesion
ϕ'$_r$ = Residual friction angle

The results of the ring shear test for samples Geotech 1 to Geotech 4 gave a close agreement overall. The residual friction angles are quite high and reflect the particle-size distribution. The results are shown combined on a single normal vs shear stress plot in Figure 5. Data compare well with Powell & Butcher (2003) and Bell (2002), reported in Reeves et al. (2006) and summarised in Table 5. However, the Dimlington Bed sample (Geotech10) shows a different behaviour having a much lower angle of internal friction and higher cohesion. This is probably due to its higher fines content and lower sand content compared with the other samples (refer to section 4.3). *The 'Basement Till' in Table 5 refers to the Bridlington Member (BM).*

Table 5 Residual strength data for Holderness tills (Bell, 2002)

Name	Average	Range
	ϕ'$_r$ (degr.)	ϕ'$_r$ (degr.)
'Withernsea Till'	21	18 - 27
'Skipsea Till'	25	19 - 35
'Basement Till'	23	18 - 30

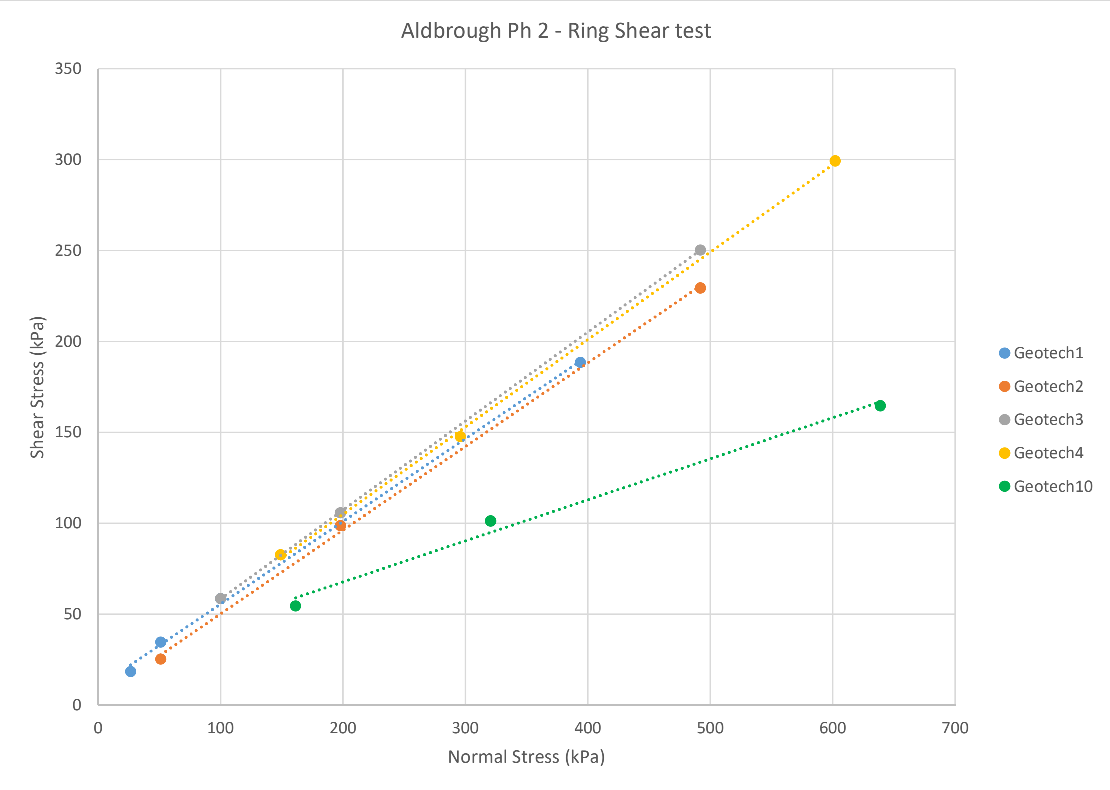

Figure 5 Plot of ring shear tests

The Triaxial, Shear Box and Ring shear data are combined in Figure 6. A dashed line representing combined CIU Triaxial results taken from Powell & Butcher (2003) is also shown. Data from these tests are also shown as 'estimated strength' vs. depth profiles in Figure 7. A difficulty concerning this plot is that the pore pressures recorded in Boreholes 1a and 2a (Hobbs et al., 2015) continue to change with time and those in borehole 3a have not fully equilibrated since installation in Jan 2015. *The 'estimated effective strength' should therefore be treated with some caution at the present time.* The ring shear result for Geotech 10 falls well below all other samples on the plot (Figure 6) due to it being from the Dimlington Bed with high silt content and low density, compared to the till samples. This fact has a significant influence on the slope stability and mode of failure of the cliff (Hobbs et al., 2013).

Though the samples in this study were not subject to remoulding or compaction, Bell (2002) points out that such tills tend to have low strength sensitivity. This is not surprising as the tills have been effectively reworked many times during their formation. However, the Dimlington Bed sample (Geotech10) does not follow this pattern and shows considerable strength sensitivity.

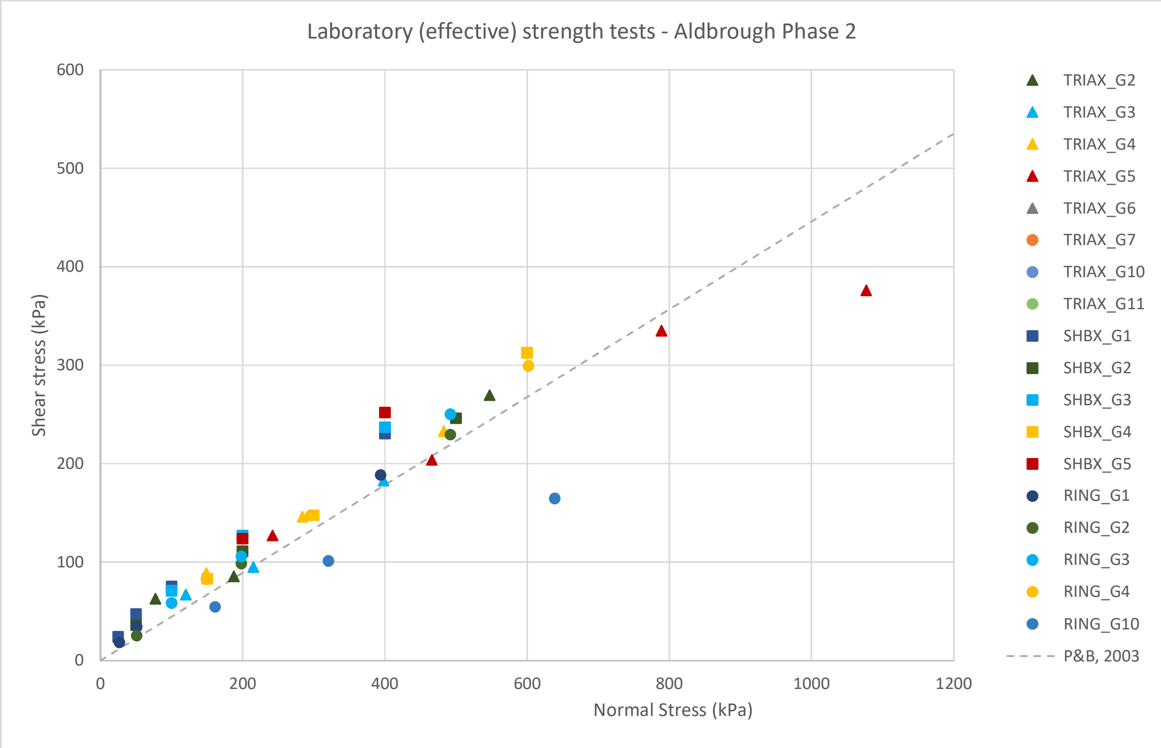

Figure 6 Plot of normal stress vs. shear stress for Triaxial, Shear box and Ring shear tests
Note: P&B, 2003 = Powell & Butcher (2003)

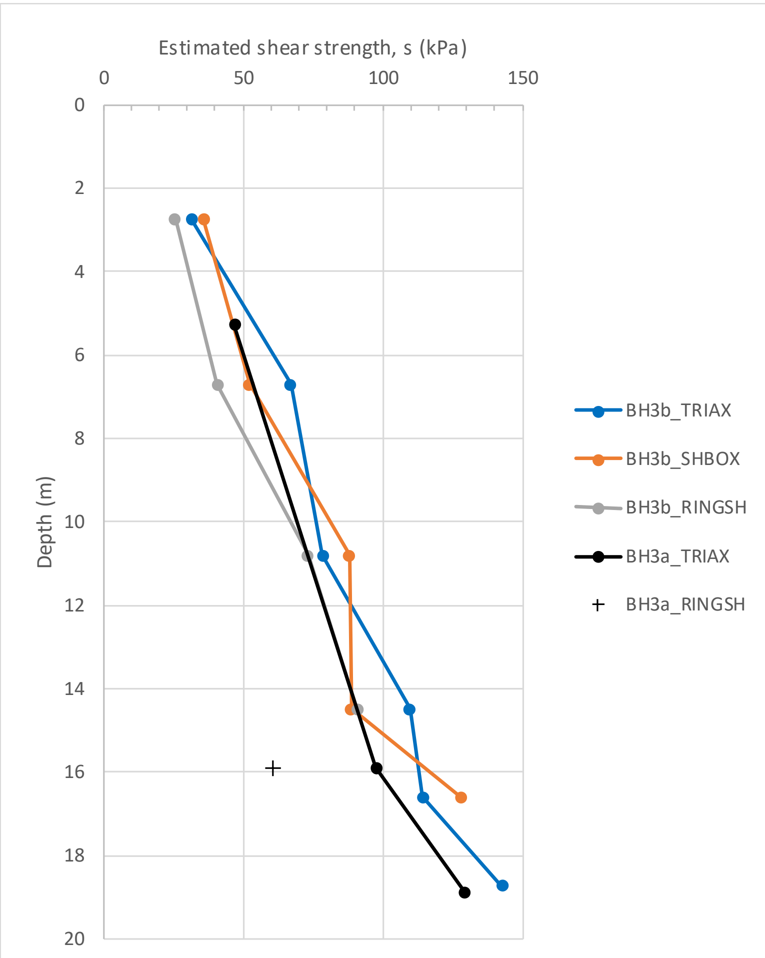

Figure 7 Plot of estimated effective shear strength vs. depth

2.4 STRENGTH 'INDEX' TESTS

The Torvane 'pocket shearometer' is a simple and small hand-operated device which measures undrained shear strength at the surface of a soil sample and may be considered an 'index' test. A number of Torvane tests were carried out (perpendicular to bedding) on core from Borehole 3a. The tests were carried out after surface drilling disturbance (e.g. 10 mm) had been removed from the outer surface of the core. These results are shown plotted against depth in Figure 8. This shows an overall decrease in undrained shear strength with depth which corresponds well with an increase in water content with depth. The plot also shows the relationship to current strength classification descriptions. The results fall largely within the range 'medium' to 'high', but are 'low' between 16.90 and 17.50 m with one 'very high' value at 11.10 m. The low values around 17.00 m suggest a softening of the upper part of the Bridlington Member, probably due to higher water contents within the overlying Dimlington Bed. The strength classification shown in Figure 8 is taken from British Standards Institution (2004). The relationship between (estimated) undrained shear strength and water content is shown in Figure 9. This shows a reasonable inverse correlation.

It should be noted that 'index' strength and water content are both influenced by drilling disturbance and a have been affected by a period of incorrect storage immediately following recovery from site. These tests also apply stress to a very small volume of sample and, as such, cannot be considered truly representative of strength overall, particularly where tills are concerned because they are inherently variable.

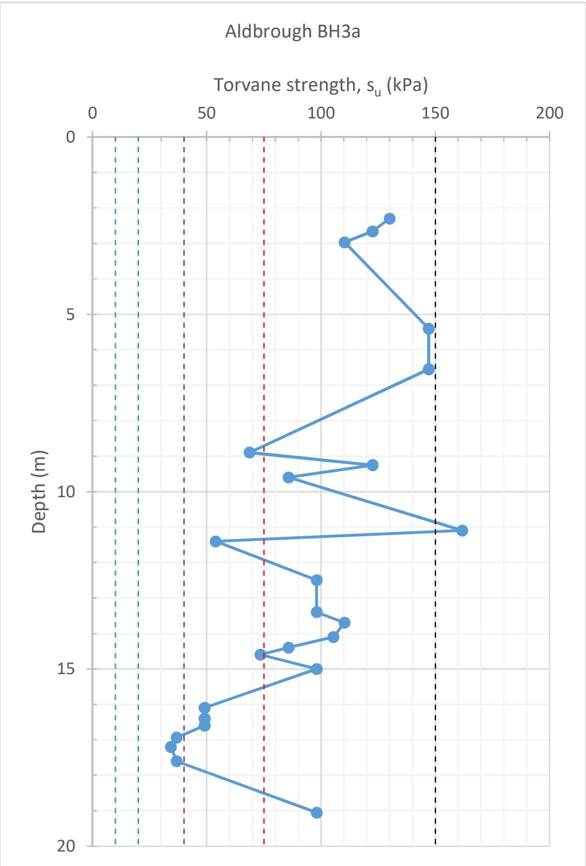

Figure 8 Plot of undrained shear strength, s_u (Torvane) vs Depth for core from Borehole 3a NOTE: Strength classification boundaries are: 'extremely low' (0-10 kPa), 'very low' (10-20 kPa), 'low' (20-40 kPa), 'medium' (40-75 kPa), 'high' (75-150 kPa) & 'very high' (150-300 kPa), taken from BS EN ISO 14688-2:2004, 5.3, Table 5.

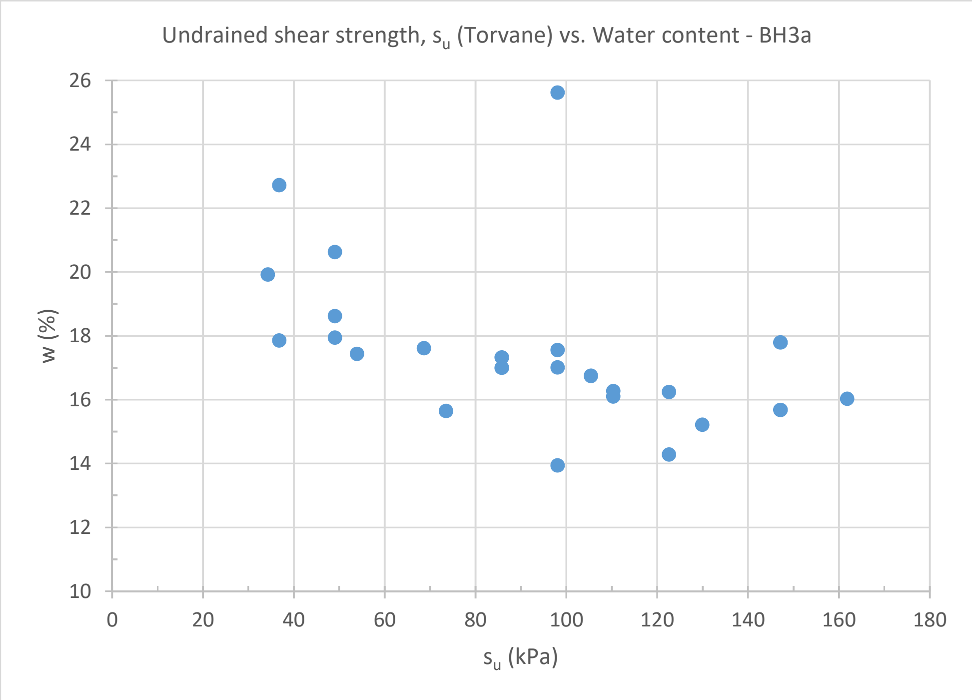

Figure 9 Plot of Undrained shear strength, s_u vs. Water content for core from Borehole 3a

3 Consolidation & swelling

1-D consolidation/swelling tests were carried out, following procedures described in BS1377 (1999) and Head (1992), on specimens of undisturbed glacial deposits from samples Geotech1 to Geotech10 using a GDSAOS automatic oedometer. This apparatus allows a swelling stage (axial strain prevented) to be carried out at the start of the test, immediately after the cell is flooded. Test specimen dimensions were 20 x 65ϕ mm. The tests were started with a single 'swelling' stage followed by 8 'consolidation' stages and finally 2 'unloading' stages. Applied consolidation stresses ranged from 62.5 kPa (initial) to 3000 kPa (final). Loading rates were 0.0002 mm/min. The test results are summarised in Table 6 and initial plots shown in Figure 10 and Figure 11.

Table 6 Summary of 1-D oedometer consolidation / swelling test results, BH's 3a & 3b

Borehole	Sample	Depth (m)	Strat.	w_0	Sn_0	e_0	m_v	c_v	P_{sw}	OCR
				(%)	(%)		(m^2 / MN)	(m^2 / yr)	(kPa)	
BH3b	Geotech 1	2.52	WM	15.9	96.0	0.49	0.53 – 0.03	78.5 – 8.6	2.18	4.0
	Geotech 2	6.45	WM	17.8	96.6	0.53	0.34 – 0.03	7.4 – 4.0	1.57	3.4
	Geotech 3	10.56	STM	16.7	101.0	0.48	0.69 - 0.03	60.7 – 4.2	1.58	1.7
	Geotech 4	14.10	STM	18.4	98.6	0.50	0.60 – 0.03	5.2 – 2.9	1.27	1.2
	Geotech 5	16.26	BM/DB	21.8	101.0	0.57	0.60 – 0.04	39.3 – 29.5	0.95	1.2
	Geotech 6	18.40	BM	12.8	106.7	0.41	0.63 – 0.03	18.3 – 4.1	1.58	0.5
BH3a	Geotech 7	5.04	WM	14.9	99.3	0.53	1.16 – 1.03	128.2 – 5.0	1.26	1.2
	Geotech 8	8.46	WM	15.7	92.9	0.46	0.44 – 0.03	82.8 – 52.5	1.89	1.2
	Geotech 9	13.01	STM	18.8	98.0	0.52	0.54 – 0.03	8.2 – 3.7	2.83	0.5
	Geotech10	15.62	DB	30.6	99.4	0.72	1.03 – 0.03	5.13 – 3.36	5.67	0.6
	Geotech 11	18.90	BM	15.0	107.4					

w_0 = Initial water content
Sn_0 = Initial degree of saturation
e_0 = Initial voids ratio
m_v = Coefficient of volume compressibility (initial consolidation stage to final)
c_v = Coefficient of consolidation (initial consolidation stage to final)
Psw = Maximum swelling pressure (swelling stage)
OCR = Over-Consolidation Ratio
WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

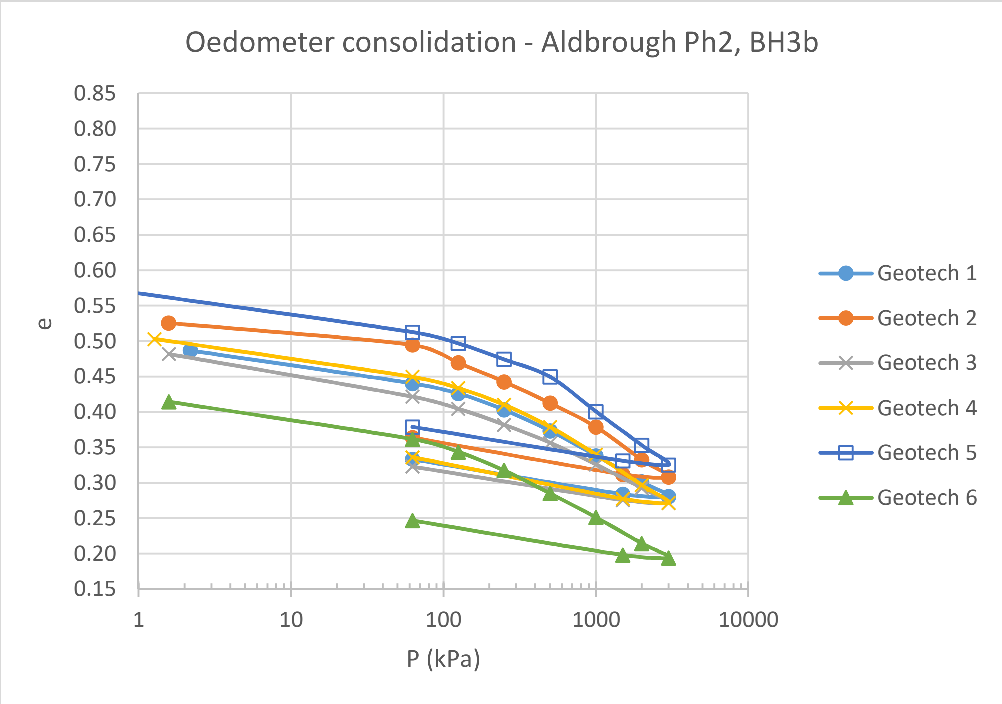

Figure 10 Plot of Applied stress, P vs. Voids ratio, e (log scale) for oedometer consolidation test, BH3b

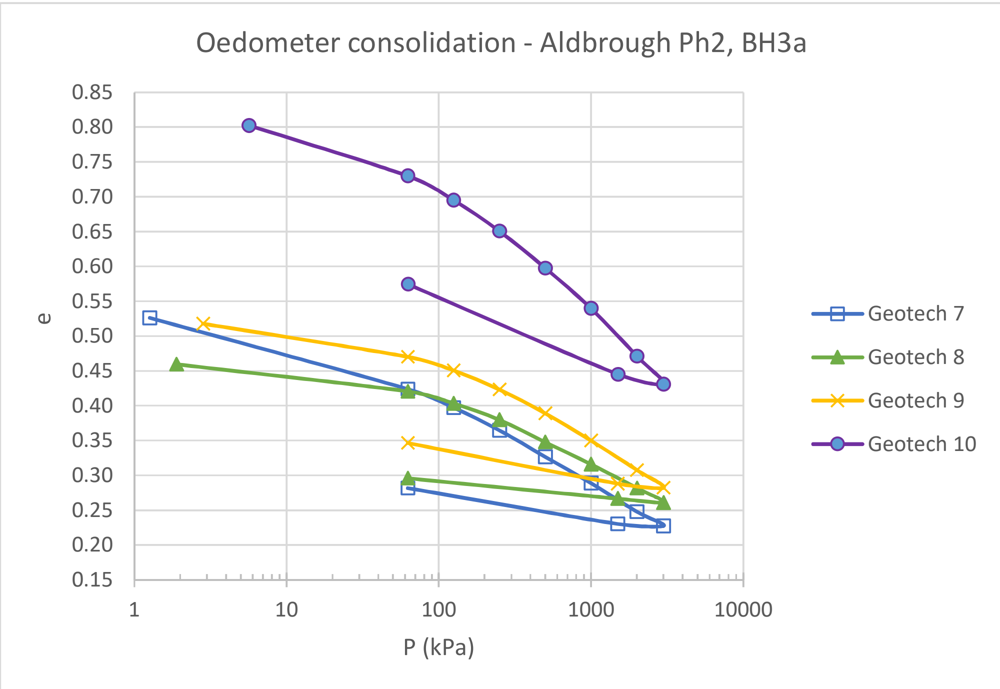

Figure 11 Plot of Applied stress, P vs. Voids ratio, e (log scale) for oedometer consolidation test, BH3a

In summary, the test plots (P vs. e) show differences in behaviour between the Members (Figure 10 & Figure 11), although the Withernsea and Skipsea Till Member samples are similar in position and all the plots have a similar overall shape with the exception of Geotech 6 (Bridlington Member) and Geotech 10 (Dimlington Bed); the former having a lower voids ratio and the latter a significantly higher voids ratio overall than the remainder of the samples. The Skipsea Till Member samples (Geotechs 3, 4 & 9) are notable in being very similar in their compression behaviour. This is also reflected in their particle-size characteristics (Section 4.3). The slightly greater heterogeneity shown by the Withernsea Member samples, compared with the Skipsea Member samples, is probably due to their enhanced weathering state.

The plots of coefficient of volume compressibility, m_v and the coefficient of consolidation, c_v with depth are shown in Figure 16. Only results for the first and last stages of consolidation are shown. The trend is for c_v to reduce with increasing depth as expected. Dimlington Bed sample (Geotech 5) deviates from this trend. Values of m_v show no trend with depth.

The over-consolidation ratio, OCR is calculated using the following equation:

$$OCR = \frac{\sigma'_p}{\sigma'_{vo}}$$

Where: σ'_p = Effective pre-consolidation stress (derived from oedometer consolidation yield point construction)
σ'_{vo} = Estimated present effective overburden stress (derived from BH3b density data)

The OCR ranges from 4.0 to 0.5. The value, as expected, reduces with increasing depth overall. The values for maximum swelling pressure range from 2.18 to 0.95 kPa. The plot of OCR with depth, and its power curve fit, is shown in Figure 17. *It should be noted that the OCR can only be interpreted within the stress range applied and that high stresses may have changed the analysis.*

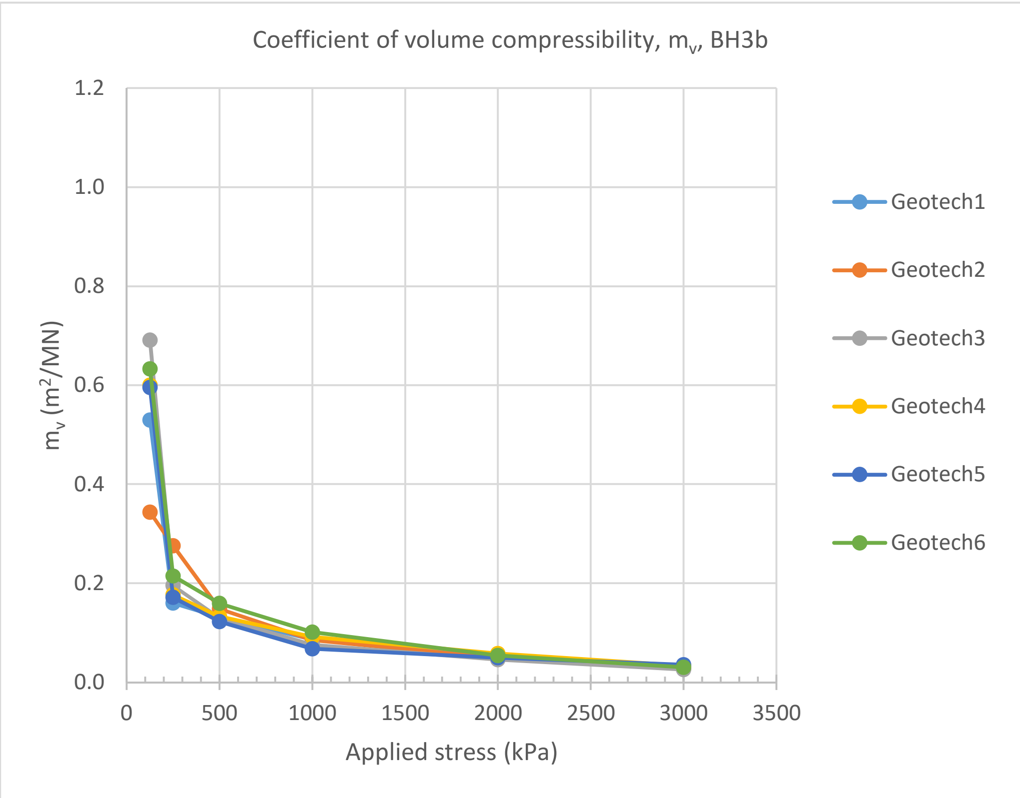

Figure 12 Plot of Applied stress vs. Coefficient of volume compressibility, m_v, for BH3b

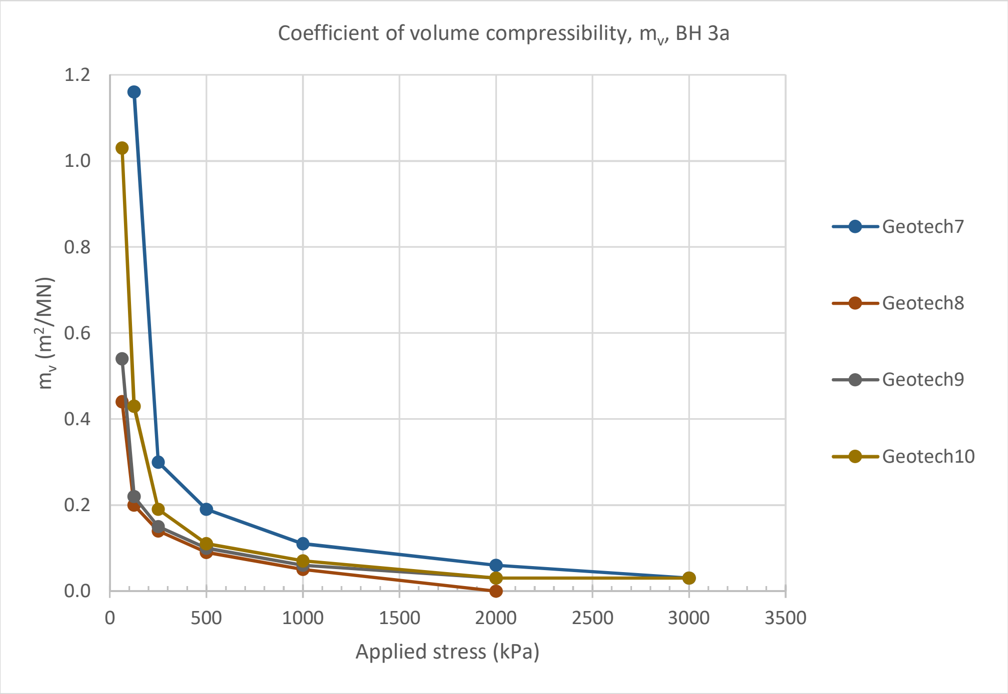

Figure 13 Plot of Applied stress vs. Coefficient of volume compressibility, m_v, for BH3a

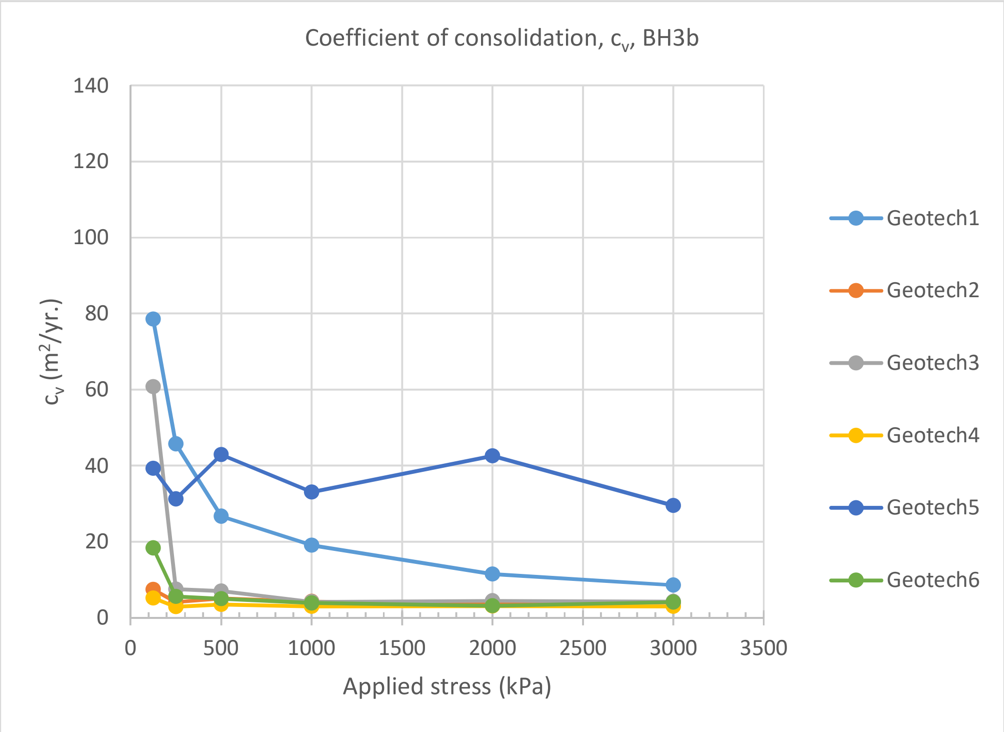

Figure 14 Plot of Applied stress vs. Coefficient of consolidation, c_v, for BH3b

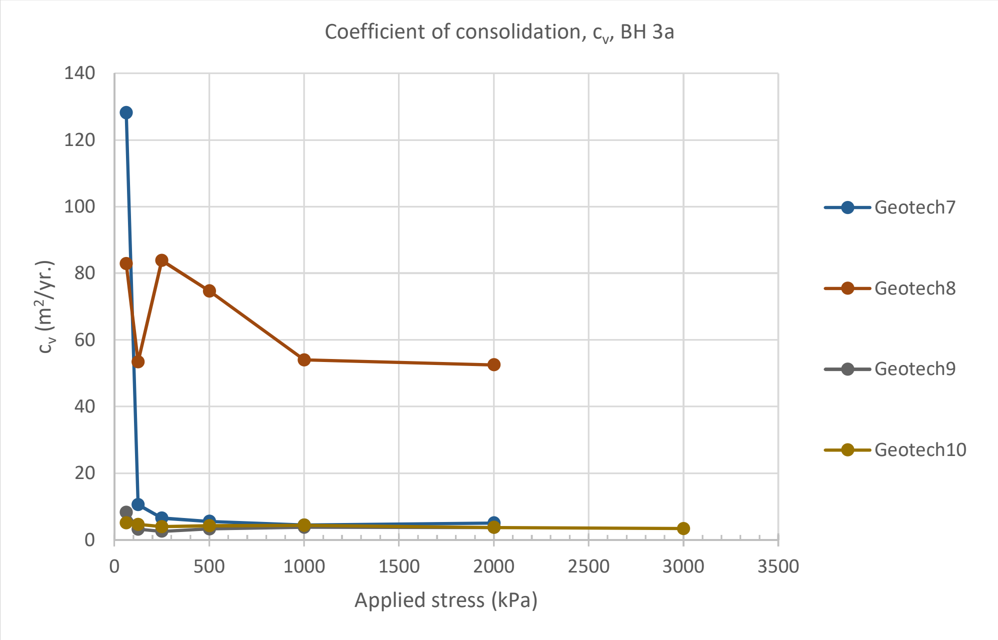

Figure 15 Plot of Applied stress vs. Coefficient of consolidation, c_v, for BH3a

In terms of the coefficient of volume compressibility, m_v, the samples behave in a similar manner with increasing applied stress (Figure 12 and Figure 13). In terms of the coefficient of consolidation, c_v, samples Geotech 1 and Geotech 2 stand out from the others (Figure 14 and Figure 15). In addition, sample Geotech 5, representing the Dimlington Bed, follows a trend with increasing applied stress that is characteristic of silt-rich material. However, this is not the case for Geotech 10 which is also Dimlington Bed material. Plots of m_v and c_v with depth are shown in Figure 16. The results for swelling pressure, P_{sw} range from 0.95 to 2.83 kPa. There is no clear trend with depth (Figure 17) or with other properties. However, Over-Consolidation Ratio (OCR) reduces exponentially with depth as would be expected (Figure 17), though this trend is clearer in BH3b than BH3a.

In summary, the tills can be described as having low compressibility with low to medium consolidation rates. The result for the Dimlington Bed sample (Geotech 10) does not appear to reflect the silty nature of its particle-size distribution (Section 4.3). This may be due to the fact that the index and oedometer samples were taken from different sections of sample Geotech 10 and hence may have had different lithologies.

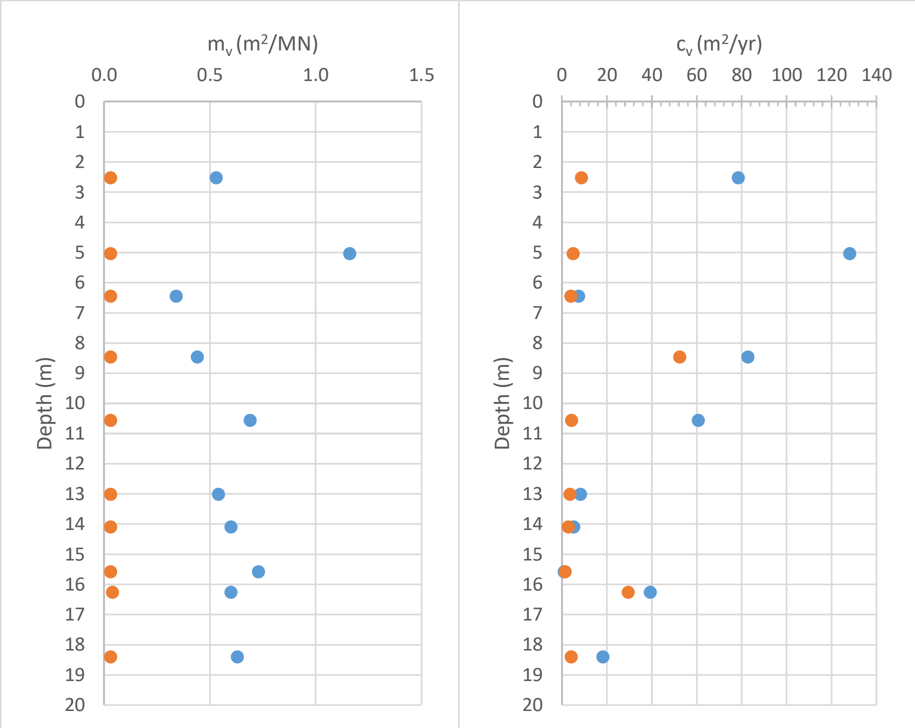

Figure 16 Plots of Coefficient of volume compressibility, m_v and Coefficient of consolidation, c_v vs. Depth, showing results for first (blue) and last (orange) consolidation stages

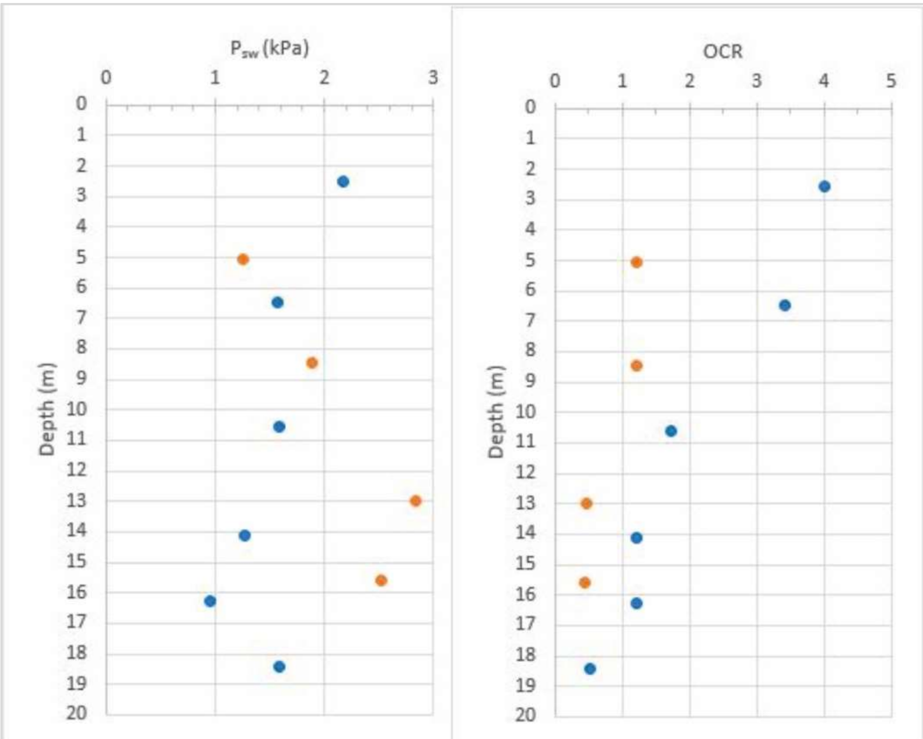

Figure 17 Plots of Maximum swelling stress, P_{sw} and Over-consolidation ratio, OCR vs. Depth BH3a (blue) & BH3b (orange)

4 Index tests

A range of index tests were carried out according to British Standards (BS1377:1999) and Head (1992) plus a shrinkage limit test based on the procedures outlined in Hobbs et al. (2014) and an x-ray sedigraph method for fine-grained particle-size determination (Kirkham & Entwisle, 2017). The index tests included liquid and plastic limit, water content (natural), density (bulk, dry and particle), particle-size and linear shrinkage.

4.1 WATER CONTENT AND DENSITY

Water content and density determinations were carried out on core from BH3a and BH3b. The results are synthesised in Figure 18 and Table 7 and plotted in Figure 18. The data include water contents obtained independently from all tests requiring the determination, viz. triaxial, oedometer, shear box and Atterberg. The trends are in general agreement with depth, though there is anticipated variability within the tests. This is partly due to the different sample sizes involved and different sample quality. The water contents remain within the range 15 to 20 % except for the Dimlington Bed (14.8 to 15.9 m in BH3a and 14.3 to 16.4 m in BH3b) and the uppermost Bridlington Member parts of which show higher water contents (w_0 >20 %). However, the Dimlington Bed notably provided the highest water contents (w_0 >25 %), while below 16.6 m there is a sharp decrease in water content within the Bridlington Member to 19.05 m depth.

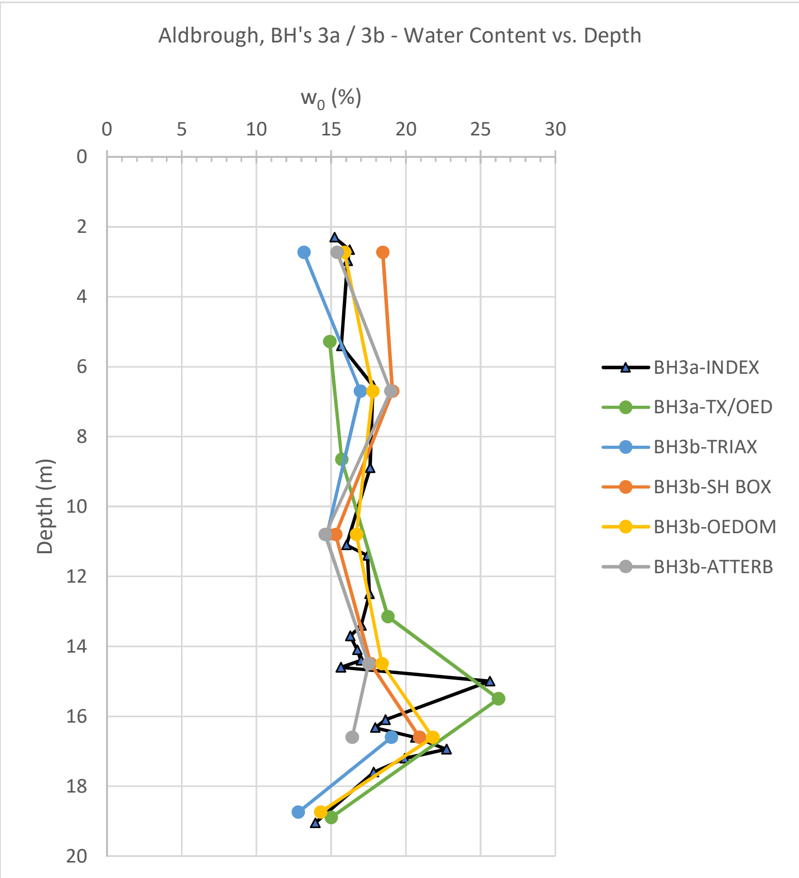

Figure 18 Water content (initial) vs. Depth plot (BH's 3a & 3b)

Table 7 Water content and density results, Boreholes 3a & 3b (data from Triaxial & Oedometer tests)

Borehole	Sample	Depth (m)	Strat.	w_0	γ_b	γ_d	γ_p
				(%)	(Mg/m^3)	(Mg/m^3)	(Mg/m^3)
BH3b	Geotech 1	2.23 -2.73	WM	15.9	2.29	2.03	2.68
	Geotech 2	6.41 - 6.70	WM	17.8	2.14	1.83	2.70
	Geotech 3	10.30 - 10.80	STM	16.7	2.27	1.98	2.71
	Geotech 4	14.10 - 14.60	STM/DB	18.4	2.13	1.80	2.71
	Geotech 5	16.10 - 16.60	DB/BM	21.8	2.15	1.81	2.69
	Geotech 6	18.35 - 18.74	BM	14.3	2.30	2.04	2.68
BH3a	Geotech 7	5.06 – 5.28	WM	14.9	2.04	1.93	2.70
	Geotech 8	8.15 - 8.65	STM	15.7	2.12	1.84	2.67
	Geotech 9	12.65 -13.15	STM	18.8	2.10	1.77	2.68
	Geotech 10	15.40 - 15.90	DB	26.2	1.92	1.54	2.65
	Geotech 11	18.40 - 18.90	BM	15.0	2.30	1.95	2.68

γ_b = Bulk density
γ_d = Dry density
γ_p = Particle density
WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

Density results (initial) obtained from the Triaxial and Oedometer tests (Figure 19) show similar values within the tills and low values of bulk and dry density for the Dimlington Bed (Geotech 10). Values for the tills agree with results from Powell & Butcher (2003). Variations in the densities between triaxial and oedometer tests are due to differences in the sizes of the samples.

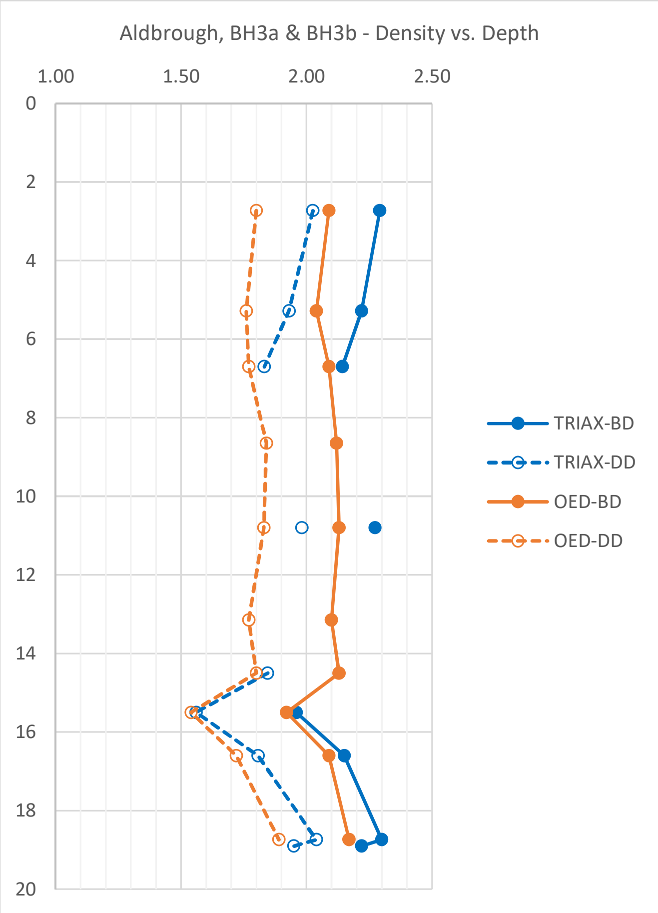

Figure 19 Bulk & Dry density (initial) vs. Depth plot (BH's 3a & 3b)
BD = Bulk density, DD = Dry density

4.2 LIQUID AND PLASTIC LIMITS

Atterberg limit tests for liquid and plastic limit were carried out according to British Standards (BS1377:1999) and Head (1992). Liquid and plastic limit test results are shown in Table 8 and as Casagrande plots in Figure 20 and Figure 21. The results give a 'low' to 'intermediate' plasticity classification for the tills which are broadly similar despite their differing provenances. The Dimlington Bed sample (Geotech 10) differs, however, having a 'high' plasticity. When plotting the Casagrande according to member (Figure 21) the Skipsea Till and Withernsea Members plot according to the envelopes described by Bell (2002) for Holderness samples, whereas the Bridlington Member samples (the 'Basement Till' of Bell, 2002) do not, due to their lower clay contents.

The points on the Casagrande plot all lie well above the A-line as noted by Bell (2002). In fact, they tend to fall along what was referred to by Boulton (1976) as the T-line, indicating (according to Bell, 2002) the unsorted nature of the till. The Dimlington Bed sample, however, also plots on the T-line. Of the samples tested only the uppermost two Withernsea Member samples (Geotech 1 & Geotech 7) gave negative liquidity indices, though other samples, principally above 10 m, had low values. This may be accounted for by the enhanced weathering state of the Withernsea Member.

Table 8 Liquid &plastic limit results

Borehole	Sample	Depth (m)	Strat.	w_0	w_L	w_P	I_P	I_L
				(%)	(%)	(%)	(%)	
BH3b	Geotech 1	2.23 -2.73	WM	15.9	37	20	17	-0.24
	Geotech 2	6.41 - 6.70	WM	17.8	36	17	19	0.04
	Geotech 3	10.30 - 10.80	STM	16.7	32	16	16	0.04
	Geotech 4	14.10 - 14.60	STM/DB	18.4	31	16	15	0.16
	Geotech 5	16.10 - 16.60	BM/DB	21.8	31	16	15	0.39
BH3a	Geotech 7	4.78 – 5.28	WM	14.9	33	17	16	-0.13
	Geotech 8	8.15 – 8.65	STM	15.7	26	15	11	0.06
	Geotech 9	12.65 – 13.15	STM	18.8	34	17	17	0.11
	Geotech 10	15.40 – 15.90	DB	26.2	54	23	31	0.10
	Geotech 11	18.40 – 18.90	BM	15.0	30	14	16	0.06

w_0 = Water content
w_L = Liquid limit
w_P = Plastic limit
I_P = Plasticity index
I_L = Liquidity index
WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

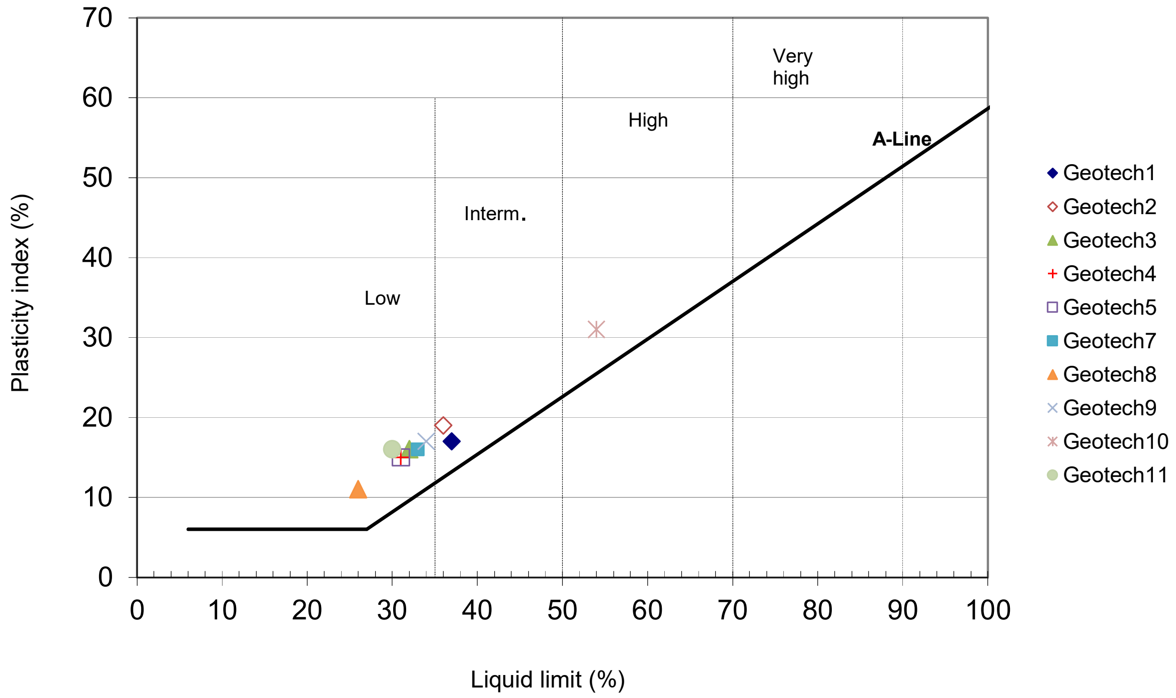

Figure 20 Casagrande plasticity plot – Liquid limit vs. Plasticity index (BH's 3a & 3b)

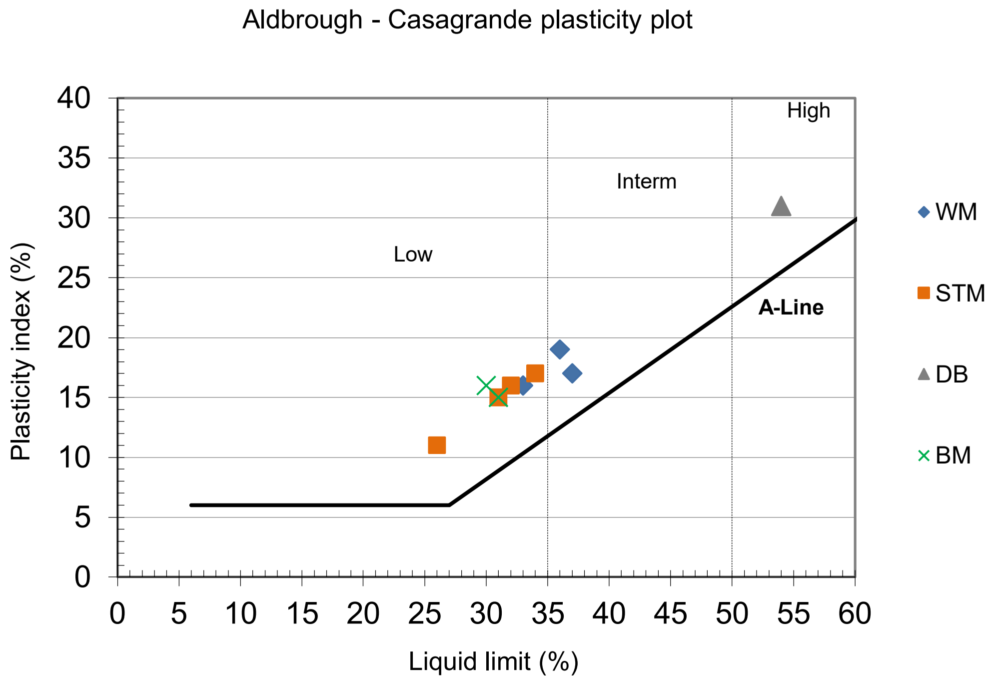

Figure 21 Casagrande plasticity plot – Liquid limit vs. Plasticity index (BH's 3a & 3b) by formation

4.3 PARTICLE SIZE

Particle size analyses were carried out on eleven samples from boreholes 3a and 3b, a summary of which is shown in Table 9 and Figure 22 and Figure 23. These samples were tested using a combination of sieving according to British Standards (BS1377:1999) and Head (1992) combined with X-ray sedigraph (Micromeritics) methods (Kirkham & Entwisle, 2007).

Table 9 Particle size distribution results for BH's 3a & 3b

Borehole	Sample	Depth (m)	Strat.	CLAY	SILT	SAND	GRAVEL
				(%)	(%)	(%)	(%)
BH3b	Geotech 1	2.23 -2.73	WM	37.5	33.0	22.9	6.6
	Geotech 2	6.41 - 6.70	WM	35.4	36.0	22.1	6.4
	Geotech 3	10.3 - 10.80	STM	30.3	37.2	26.2	6.3
	Geotech 4	14.1 - 14.60	STM/DB	31.8	35.6	22.4	10.1
	Geotech 5	16.1 - 16.60	BM/DB	33.8	41.5	19.2	5.5
	Geotech 6	18.35 - 18.74	BM	25.4	24.2	28.6	21.8
BH3a	Geotech 7	4.78 – 5.28	WM	29.8	30.9	22.5	16.8
	Geotech 8	8.15 – 8.65	STM	27.7	29.3	33.9	9.1
	Geotech 9	12.65 – 13.15	STM	31.8	32.9	24.0	11.3
	Geotech 10	15.40 – 15.90	DB	38.2	57.6	4.1	0.0
	Geotech 11	18.40 – 18.90	BM	25.4	28.1	34.2	12.4

WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member
WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member

The particle size distributions for the tills are notably similar and lie within a relatively narrow envelope. However, the sole sample from the Dimlington Bed (Geotech 10) lies outside it, having a higher silt content, very little sand (and notably higher plasticity, section 4.2). Referring to Figure 23 the Skipsea Till Member curves lie within a narrow envelope with the Withernsea Till and the Bridlington Members occupying increasingly wider envelopes, yet retaining a characteristic 'till' signature. The clay contents reflect the 'low' to 'intermediate' plasticity classification obtained for the till samples (section 4.2). Comparison with the results reported in Bell (2002) shows reasonable agreement.

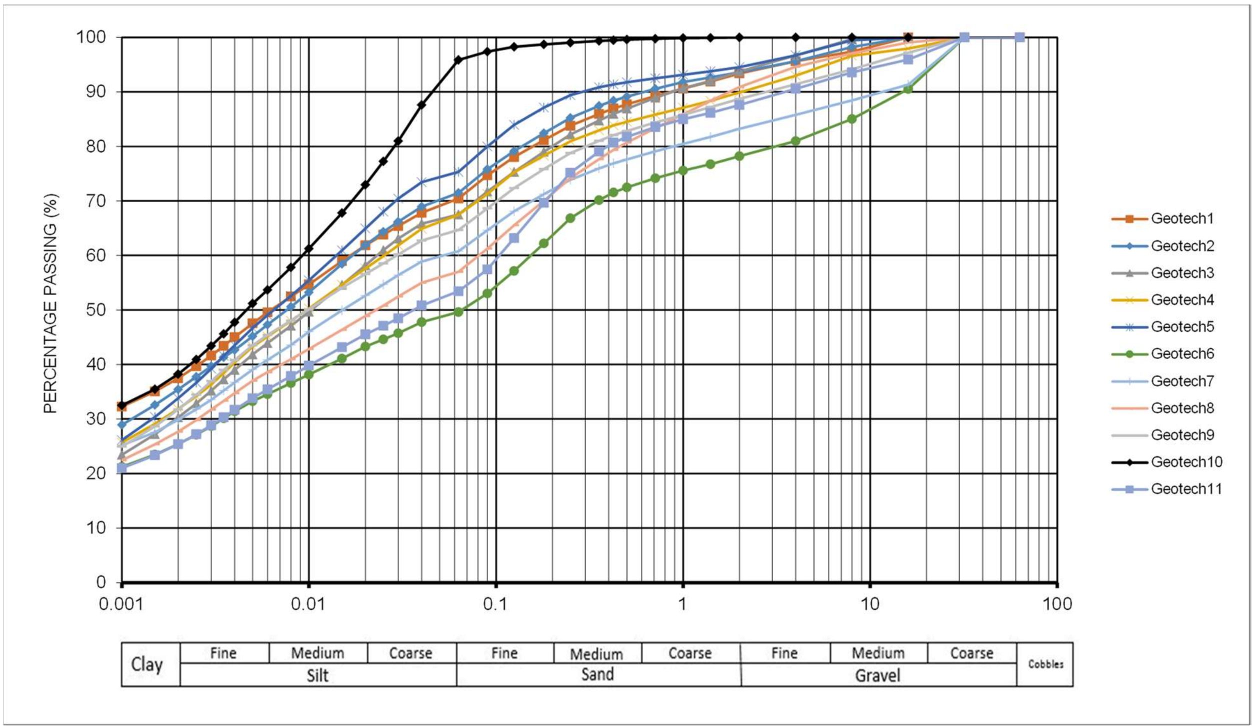

Figure 22 Particle size distribution plot for all data (BH's 3a & 3b)

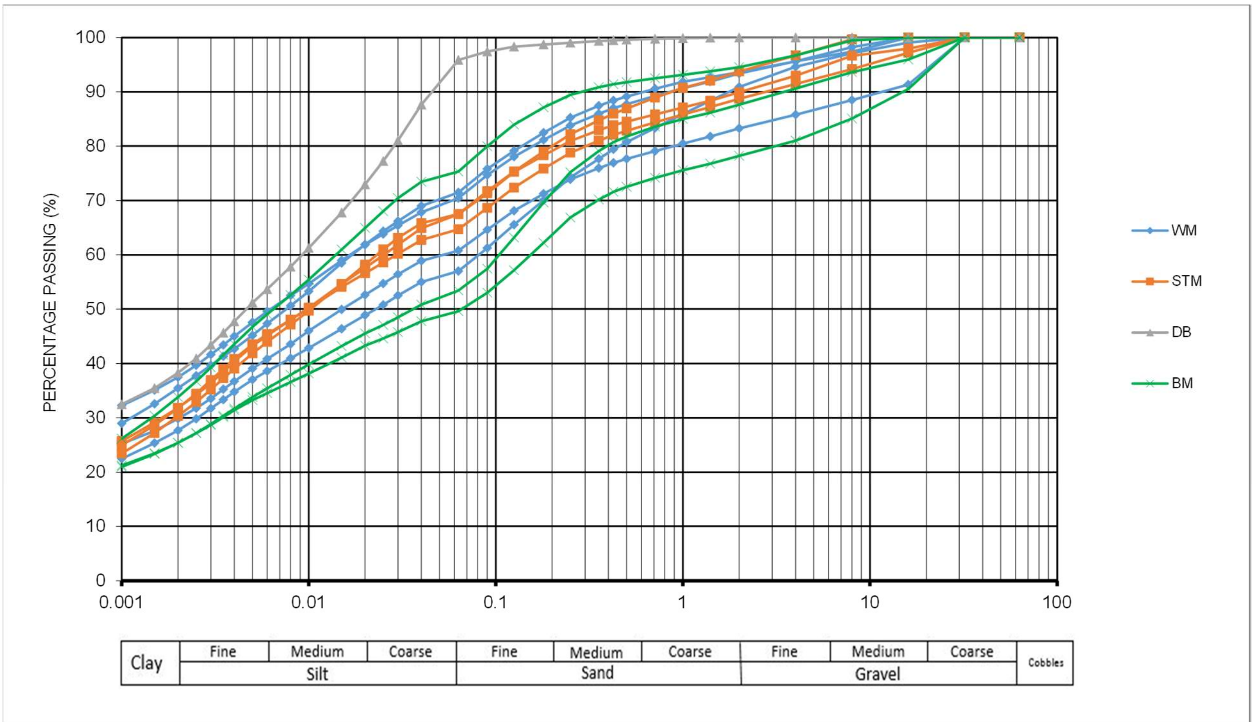

Figure 23 Particle size distribution plot for all data (BH's 3a & 3b) by formation

4.4 SHRINKAGE

4.4.1 Shrinkage limit

The shrinkage limit test was carried out using the SHRINKiT apparatus (Hobbs et al., 2014) on samples Geotech 1 to Geotech 5. All tests were carried out on undisturbed samples. *Sample Geotech 6 contained insufficient material for this test.* The results are shown in Table 10.

Table 10 Shrinkage test results (SHRINKiT)

SHRINKiT		Shrinkage Limit		w_S	ΔV_{tot}	I_S	R_S	Ψ
	Depth	Litho						
Specimen	(m)	strat.	State	(%)	(%)	(%)	(g/cm^3)	
Geotech 1	2.48	WM	U	**12.0**	5.6	8	2.02	0.43
Geotech 2	6.83	WM	U	**11.4**	10.9	5.6	2.06	0.98
Geotech 3	10.5	STM	U	**11.2**	6.9	4.8	2.07	0.71
Geotech 4	14.6	STM/DM	U	**13.1**	8.5	2.9	1.99	1.52
Geotech 5	16.6	BM	U	**13.5**	5.5	2.5	1.98	1.16

WM = Withernsea Member
STM = Skipsea Till Member
DB = Dimlington Bed
BM = Bridlington Member
U = Undisturbed sample
ΔV_{TOT} = Total volumetric strain
I_S = Shrinkage index
R_S = Shrinkage ratio
ψ = Shrinkability index (Hobbs et al., 2014)

The shrinkage limit indicates the water content below which little or no volume change takes place. Values of shrinkage limit, w_s range from 11.2 to 13.5%. The results fall within a smaller range than previous SHRINKiT data from Aldbrough (9.4 to 16.2%) described in Hobbs et al. (2015). The test plots shown in Figure 24 include these earlier data, *Specimen Geotech 4 contained the junction between the Skipsea Till Member (STM) and the Dimlington Bed (DB) at a depth of 16.45m; approximately 80% of the specimen consisting of the former.* A sample of Skipsea Till Member from nearby Mappleton (TA 228 438) gave the following clay mineralogy for the clay fraction: Illite/Mica (26%), Illite/Smectite (41%), Kaolin (29%) and Chlorite (4%); with 20% of the Illite/Smectite classed as 'expansive' (Reeves et al. 2006).

The samples 'TILL5' and 'SLIP' with shrinkage limits of 16.2 and 15.0 %, respectively, demonstrate different behaviour from the remainder and have a much higher initial water content. It is believed that the 'SLIP' sample, taken from a basal landslide shear surface exposed at the cliff face, is derived from the Dimlington Bed (DB), as is the 'TILL5' core sample.

Carbonate content was not measured as part of this study. However, a comparable till succession at nearby Cowden showed carbonate contents increasing from 8.5 at 2 m depth to 19.5 % at 9.0 m depth, then decreasing to 12.0 % at 17.0 m depth and increasing again to 26.4 % at 23.5 m depth (Powell & Butcher, 2003). The carbonate content of the Bridlington Member at Aldbrough is likely to be significantly higher than the overlying members due to its chalk clast content.

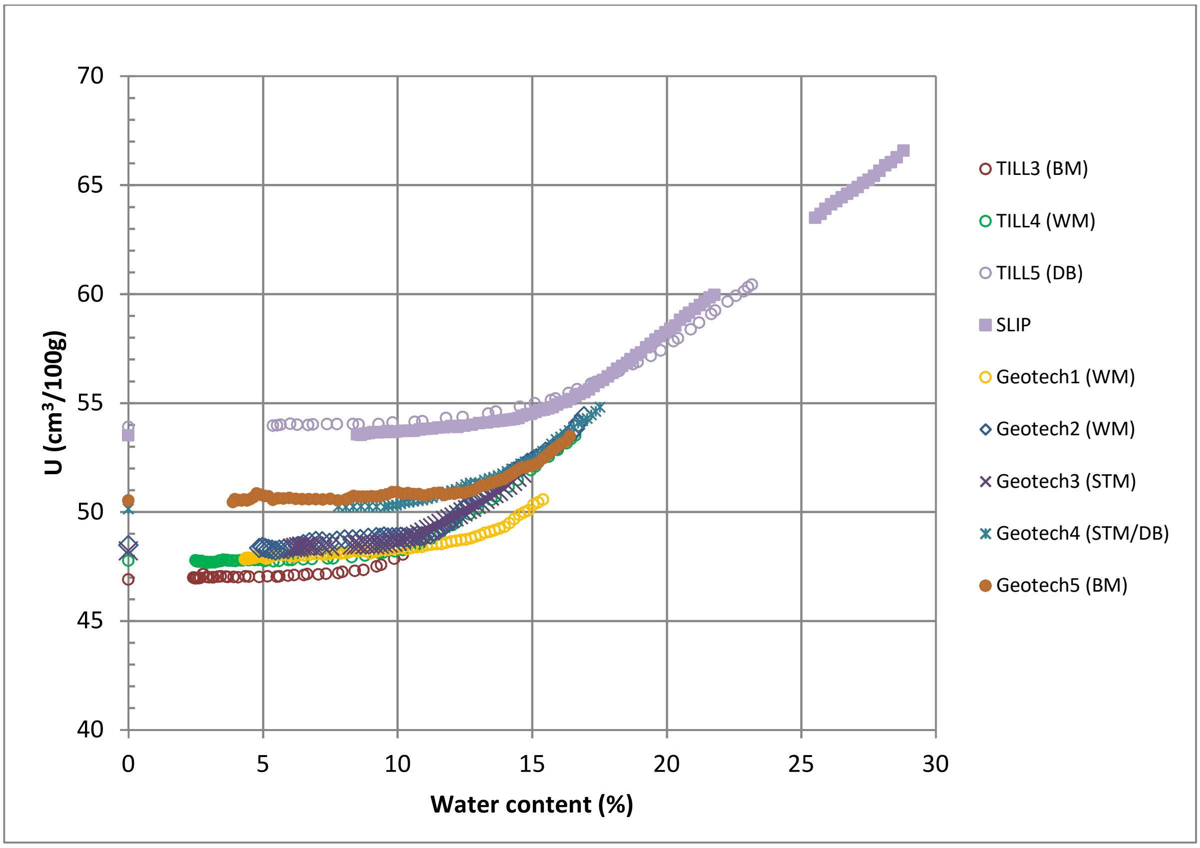

Figure 24 Plot of Water content vs. Unit volume for SHRINKiT shrinkage limit tests

4.4.2 Linear shrinkage

Table 11 Linear shrinkage results

Borehole	Specimen	Depth (m)	Strat.	Linear shrinkage (%)
BH3b	Geotech 1	2.48	WM	10.0
	Geotech 2	6.83	WM	11.0
	Geotech 3	10.5	STM	10.0
	Geotech 4	14.6	STM/DM	9.0
	Geotech 5	16.6	BM	9.0
BH3a	Geotech 7	5.28	WM	10.0
	Geotech 8	8.15	STM	7.0
	Geotech 9	13.15	STM	9.0
	Geotech 10	15.9	DM	12.0
	Geotech 11	18.9	BM	9.0

The linear shrinkage results are shown in Table 11. Values for linear shrinkage (LS) range from 7.0 to 12.0%. There is generally a good correlation between linear shrinkage and liquid limit, though here data are insufficient to demonstrate this. Sample Geotech 10 showed the highest linear shrinkage in keeping with its other index properties.

5 Conclusions

The results of a programme of laboratory geotechnical tests carried out on borehole core from the BGS Aldbrough test site, as part of Phase 2 of the 'Slope Dynamics' project at Aldbrough, show subtle differences contained within the glacial deposit sequence to a depth of 20 m below GL. The data are consistent with the observed lithologies and with published data from sites close to Aldbrough and for the Holderness coast as a whole. Maximum use has been made of a limited budget and relatively poor drilling conditions and core recovery from twin boreholes forming part of the sub-surface investigations at Aldbrough, begun with Phase 1 in 2012.

The effective strength data for each sample are notably similar, despite the fact that they cover three different test methods and specimen types: viz. ring shear, shear box and triaxial (i.e. residual to peak) and the fact that only the ring shear test only was carried out on remoulded samples. The exception to this is the silty Dimlington Bed which has lower strength, higher water content, higher shrinkage limit and higher plasticity compared with the tills. The use of 'multi-stage' triaxial testing, whilst not ideal, has been dictated by the limited core recovery. The method has been optimised to the glacial materials, for example by using the largest possible test specimen, and the results are considered reasonable.

Residual friction angles are quite high (20 – 25 degr.) but not unusual for UK tills, and the strength data generally fall within published ranges for these materials. Index test results are generally similar despite the variations in glacial provenance of the materials tested.

The Dimlington Bed 'SHRINKiT' sample and the 'slip' sample (derived from the Dimlington Bed) showed different shrinkage curves and higher shrinkage limits compared with the other samples, along with higher clay contents and higher plasticities.

The use of pairs of cored boreholes 5 m apart has been successful insofar as the geotechnical results could be compared and/or combined once the stratigraphy in each core had been established. At the same time this provided sufficient separation to avoid interference between various sensors in each hole.

At the time of reporting, the 6-point piezometer array in borehole 3a and the 'PRIME' resistivity arrays in boreholes 3a & 3b and in a near-surface trench are being recorded continuously. The borehole inclinometer data are obtained by 'probing' the borehole (BH3b) during site visits only. The results obtained from these sensors will be reported separately.

The geotechnical test results described in this report have been used in slope stability analyses applied to the Aldbrough site (Hobbs et al., 2013).

6 Recommendations

The Phase 2 drilling programme, while having produced poor core recovery overall, has provided sufficient undisturbed and disturbed samples to allow a reasonably comprehensive programme of geotechnical testing to be carried out. Each persistent member of the Holderness Formation present to 20 m depth has been tested, and comparisons between adjacent Phase 2 boreholes and between Phase 1 and Phase 2 boreholes have been made. The sub-surface installations at Aldbrough now have 3 pairs of instrumented boreholes aligned perpendicular to the coast. These await the first major landslide activity since installation in Feb 2012; the previous major event having been during the winter of 2011/2012; i.e. just before installation.

It is recommended that these borehole installations are monitored continuously where capable (otherwise periodically) and also in response to major storm/rainfall events. Sufficient lead-in time has been available, due to the cyclic nature of slope instability on the Holderness Coast, to allow 'baseline' conditions to be established prior to the next major landslide event at the test site; in other words a 'before and after' scenario. Early indications are that temporal changes, albeit small ones, have also been established with inclinometer deformations vectoring consistently towards the cliff and pore pressures reducing towards the cliff (Hobbs et al., 2015). Early indications from the 'PRIME' surface array are that there is a good response, at least at shallow depth, to rainfall-induced water content increases.

It is recommended that, should a further phase of drilling be contemplated, a different drilling method be considered in order to improve core recovery. On paper the Geobore 'S' triple-barrel method should have produced high quality core and high core recovery, but this was not the authors' experience in this case.

It is recommended that commercially available drilling methods and practice in tills is reviewed in the light of poor core recovery and sample quality obtained as part of this survey. At the time of reporting, further drilling at Aldbrough and further laboratory testing are not anticipated. However, it is planned to install a second surface PRIME array at right-angles to the first so that the ground between Boreholes 3a/3b and the cliff edge can be monitored from 2017.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

British Standards Institution (1990) BS1377:1990 Method of test for soils for civil engineering purposes. *British Standards Institution*, London.

British Standards Institution (2004) BS EN ISO 14688-2:2004 Method of test for soils for civil engineering purposes. *British Standards Institution*, London.

Bell, F.G. (2002) The geotechnical properties of some till deposits occurring along the coastal areas of eastern England. *Engineering Geology*, 63, pp49-68.

Bell, F.G. and Forster, A. (1991) The geotechnical characteristics of the Till deposits of Holderness. *In:* Quaternary Engineering Geology. *Geological Society, Engineering Geology Special Publications,* No. 7. Forster, A., Culshaw, M.G., Cripps, J.C. Little, J.A. and Moon, C.F. (eds.). pp 111-118. London.

Boulton, G.S. (1976) The development of geotechnical properties in glacial tills. *In:* Leggett, R.F. (ed.) Glacial Till – an inter-disciplinary study. *Royal Society Canada*, Ottawa. pp292-303.

Clarke, B. (2011) Geotechnics of glaciogenic deposits. *Geol. Soc., Eng. Geol. Forum*, Univ. of Leeds, 23rd Nov 2011.

Head, K.H. (1992) Manual of soil laboratory testing. Vol. 3, effective stress tests *Wiley*

Hobbs, P.R.N. and Freeborough, K. (2006) Triaxial strength tests on till samples from the Slope Dynamics Project – Happisburgh, Sidestrand, and Aldbrough *British Geological Survey* IR/06/065.

Hobbs, P. R. N., Jones, L. D., Kirkham, M. P., Pennington, C. V. L., Jenkins, G. O., Dashwood, C., Haslam, E. P., Freeborough, K. A. and Lawley, R. S. (2013) Slope Dynamics Project Report: Holderness Coast – Aldbrough: Survey & Monitoring, 2001 - 2013 *British Geological Survey, Open Report* No. OR/11/063.

Hobbs, P.R.N., Jones, L.D., Kirkham, M.P., Roberts, P., Haslam, E.P. and Gunn, D.A. (2014) A new apparatus for determining the shrinkage limit of clay soils. *Géotechnique*, 64, No.3, pp195-203

Hobbs, P.R.N., Jones, L.D. and Kirkham, M.P., (2015) Slope Dynamics project Report: Holderness Coast – Aldbrough: Drilling & Instrumentation, 2012 – 2015. *British Geological Survey*. IR/15/001

Kirkham, M.P. & Entwisle, D.C. (2007) Particle size determinations and statistical analysis of ten samples from Skomer Island, Dyfed, Wales. *British Geological Survey*, CR/07/182.

Obrzud R. & Truty, A. (2012) The hardening soil model – a practical guide, Z-Soil PC 100701 report, revised 31.01.2012

Powell, J.J.M. & Butcher, A.P. (2003) Characterisation of a glacial clay till at Cowden, Humberside. Characterisation and properties of natural soils. Tan et al. (eds.) *Swets & Zeitlinger*, Lisse. p983.

Reeves, G.M., Sims, I., & Cripps, J.C. (eds.) (2006) Clay Materials Used in Construction. *The Geological Society*, Engineering Geology Special Publication. No. 21.

Zdravkovic, L., Taborda, D.M.G., Potts, D.M., Jardine, R.J., Sideri, M., Schroeder, F.C., Byrne, B.W., McAdam, R., Burd, H.J., Houlsby, G.T., Martin, C.M., Gavin, K., Doherty, P., Igoe, D., Muir Wood, A., Kellehave, D., & Skov Gretlund, J. (2015) Numerical Modelling of large diameter piles under lateral loading for offshore wind applications. *Frontiers in Offshore Geotechnics III* – Meyer, V. (ed.), 2015, Taylor & Francis Group, London.