Slope Dynamics Project Report: Holderness Coast - Aldbrough, Drilling & Instrumentation, 2012-2015

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Slope Dynamics Project Report: Holderness Coast - Aldbrough, Drilling & Instrumentation, 2012-2015

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Aldbrough test site: cable percussion drilling (2012)

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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., 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., Kirkham, M.P. & Morgan, D.J.R. (2016) Geotechnical laboratory testing of glacial deposits from Aldbrough, Phase 2 boreholes. *British Geological Survey, Open Report* No. OR/15/056.

Whilst this report is focused on the drilling and instrumentation programme, it should be read in conjunction with the reports listed above, which provide further details on survey and monitoring, and the geotechnical properties of the underlying geology. A series of reports will follow presenting the updated drilling and instrumentation 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.

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1 Summary

This factual report describes research work carried out at BGS's Aldbrough 'Coastal Landslide Field Observatory' between March 2012 and December 2015. The work forms part of the 'Slope Dynamics' task of the 'Landslides' project which lies within the Shallow Geohazards and Risk theme of the Engineering Geology programme. It continues from reported work on the North Norfolk coast (Hobbs *et al*., 2008), and survey, monitoring and slope stability analysis between 2001 and 2013 at BGS's Aldbrough coastal landslide 'field observatory' (Hobbs et al., 2013). The latter report has shown that 'soft' cliff recession, and the geomorphological processes that result in it, can be accurately monitored and quantified over a sustained period; the work has continued in 2014, 2015 and 2016.

In March 2012 a drilling and instrumentation programme (referred to as Phase 1) was initiated whereby four 20 m deep boreholes, aligned in two pairs, were installed with instrumentation to measure pore pressures and deformation and a weather station. Subsequently, in January 2015 a second phase of drilling and instrumentation (Phase 2) was carried out. This involved a further pair of 20 m deep boreholes in-line with the Phase 1 pairs. A Tromino (surface) geophysical survey was also carried out at the site. Laboratory geotechnical tests were carried out on the borehole cores in addition to samples taken at the cliff.

The unprotected cliffs of the Holderness coast are cut into Devensian tills laid down between 18,500 and 13,000 years ago. The cliff at the BGS's Aldbrough test site, recently accorded 'coastal landslide field observatory' status, is 16 - 17 m high and amongst the highest on the 'soft' cliffed Holderness coast. It consists of a sequence of glacial deposits, which are here considered typical of the entire 50 km long Holderness coastline. The test site is approximately 300 m in length. Cliff recession figures in historic times have exceeded 2 m annually, whereas the data described in Hobbs et al. (2013) have shown an average recession rate at the test site of 2.7 m per year over a 12 year monitoring period (2001 to 2013). It has also shown that cliff recession, and the geomorphological processes that result in cliff recession, are capable of being accurately monitored, leading to both quantification of the processes and also a better understanding of them.

This report describes the Phase 1 and Phase 2 drilling, the instrumentation installed in the boreholes, geotechnical testing of borehole core from Phase 2 and the preliminary results obtained from these to date. Work is ongoing at the site, both in terms of the borehole instrumentation and geodetic surveying. The purpose of the 'monitoring' part of the task is to measure ground deformations, pore pressures and geophysical parameters using data from the borehole instrumentation, combined with the geodetic surveys and environmental data. At some points in the future the receding cliff and its associated landslides will approach and finally intercept the boreholes and their instruments; the latter providing continuous data building up to these events.

The purpose of the task is to develop a 4D ground model that can be applied elsewhere in similar scenarios and which can provide quantitative and temporal data for coastal erosion modelling practice in general. Clearly, such ground models have to be refined as further data are collected. This report, which provides sub-surface and environmental data and interpretation to meet this end, reflects the 'state of play' at the time of writing. Part of the work is to investigate the hypothesis (Dixon & Bromhead, 1991) that 'rapid' stress-relief allows negative pore pressures in clay-rich cliff-forming materials to increase the effective strength, thus enabling steep slopes to be formed, albeit in a transitory state of stability.

These research findings will be presented in a subsequent report.

2 Introduction

This report describes the Slope Dynamics task's first subsurface dataset for BGS's Aldbrough 'coastal landslide field observatory' on the Holderness coast of eastern England, spanning the period 2012 to 2015. The task forms part of the BGS's 'Shallow Geohazards and Risk' project. The location of the Aldbrough test site is shown in Figure 1. The overall purpose of the project is to examine and quantify landslide processes, their influence on cliff recession and pre-cursors to the slope failure of the cliff.

The geology at Aldbrough consists of a relatively simple and persistent succession of glacially emplaced deposits dominated by tills (Evans & Thomson, 2010; Catt, 1991). The cliff recession at the site is rapid. Hobbs et al. (2013) reported an average annual recession rate for the cliff top of 2.7 m per year for the period September 2001 to June 2013. Calculations from parts of 16 Terrestrial LiDAR Survey (TLS) datasets, selected from a total of 23, over a near-12 year period produced a material loss of 40,500 m^3 for the 100 m cliff length sub-set examined (centred approximately 60 m south of Seaside Road); that is, 36,820 m^3 per 100 m length or 368 m^3 per metre length, or 31 m^3 per metre per year.

This report describes two phases of drilling and borehole instrumentation at the Aldbrough test site (March 2012 and January 2015), and the results obtained up to March 2015. This report does not describe geodetic and geomorphological surveying carried out between 2001 and 2013 or results from the BGS weather station at Aldbrough (refer to Hobbs et al., 2013). In March 2012 two pairs of boreholes were drilled at 10 m and 20 m from the cliff top. Each pair was completed by installing inclinometer tubing in one (the 'a' hole) and a digital piezometer array in the other (the 'b' hole). *Undisturbed core was not obtained from the 2012 drilling. However, a small number of disturbed samples were obtained.* In January 2015, a further pair of 20 m deep boreholes was drilled, nominally 28 m from the cliff top and in line with the first two pairs. The arrangement of the boreholes relative to the cliff (as at 2013) is shown in Figure 2 and Figure 3.

3 Aldbrough test site

The BGS's coastal landslide field observatory is located at Aldbrough, East Riding of Yorkshire [centred: NGR 525770, 439605; 17 m AOD], near the midpoint of the 50 km Holderness coast. Aldbrough is situated about 10 km southeast of Hornsea and 2 km southeast of the Building Research Establishment (BRE) 'lowland clay till' geotechnical research site at Cowden (Powell & Butcher, 2003). The 300 m stretch is centred approximately on Seaside Road on the property of Aldbrough Leisure Park (Figure 2). The cliff at the test site faces northeast and is 16 m to 17 m in height throughout. It consists of glacial deposits, mainly till, and is actively receding, both by rotational (primary), toppling / rock-fall (secondary) and translational / flow (tertiary) landslide mechanisms.

The East Riding of Yorkshire Council (ERYC) has monitored cliff recession along the Holderness coast since 1951 (Lee, 2011) and has shown that at Aldbrough the total recession between 1954 and 2004 was 95 m (a rate of 1.9 m per year), and between 1990 and 2004 was 33.9 m (a rate of 2.4 m per year) (Lee, 2011; Quinn *et al*., 2010).

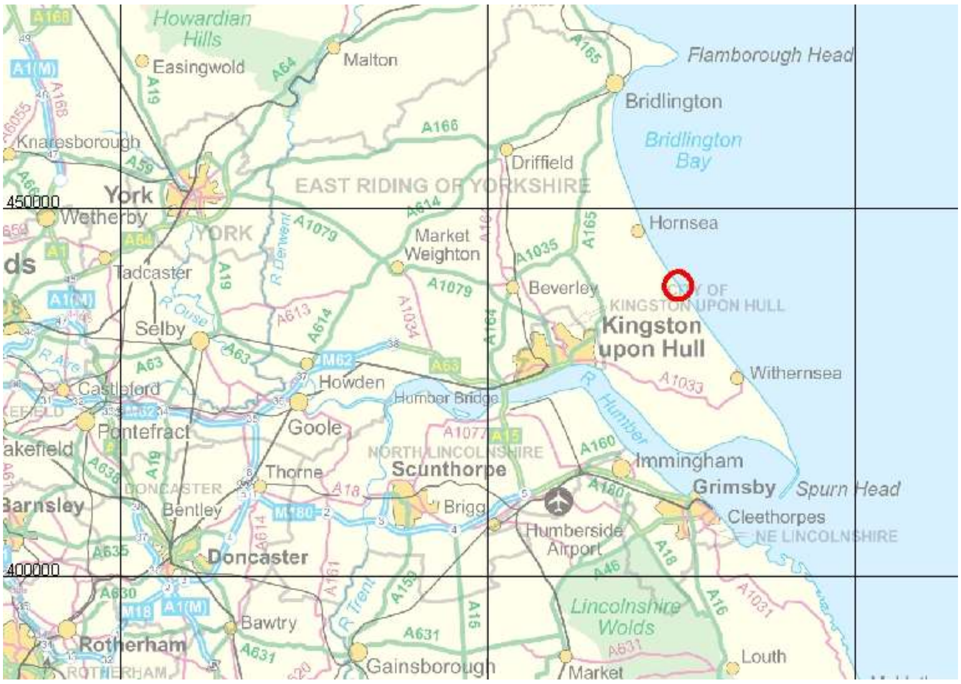

Figure 1 General location of Aldbrough test site

Figure 2 Approximate location of BGS boreholes NOTE: approximate cliff-top position (red line) as at 2013.
NOTE: Boreholes 1A, 1B, 2A & 2B drilled in March 2012, boreholes 3A & 3B drilled in January 2015.
NOTE: Properties marked with X have been demolished (as at Jan 2015)

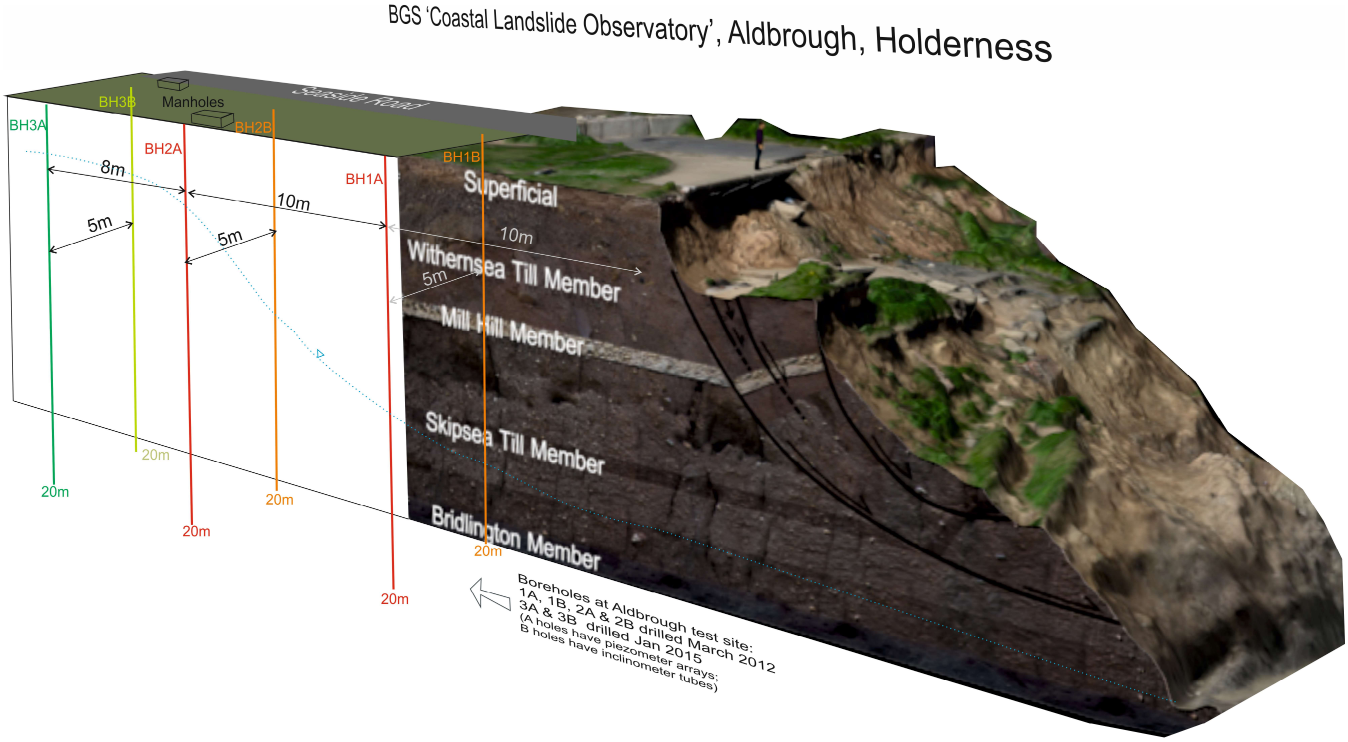

Figure 3 Block diagram showing location of boreholes relative to cliff and inferred geology

4 Geology

Aldbrough is on BGS 1:50,000 (Provisional Series) 'solid & drift' Hornsea Sheet 73 (BGS, 1998). The glacial deposits at Holderness belong to the Holderness Formation (McMillan et al. (2001), part of the North Sea Coast Glacigenic Group, and are mostly Late Devensian Dimlington Stadial (18,500 to 13,000 years old) and probably represent the products of more than one glacial regime and more than one till-forming process. The units recognised on the Holderness coast are shown in. Table 1 (McMillan et al., 2001) and Figure 4. Minor variations have been found between boreholes, but all the formations shown appear to be present but with different thicknesses. A more detailed account of the geology at Aldbrough is given in Hobbs et al. (2013). The glacial deposits at Aldbrough and the Holderness coast are underlain generally by chalk bedrock of the Early Cretaceous (Campanian to Maastrichtian) Rowe Chalk Formation, consisting of white flint-bearing chalk with marl bands (estimated depth -27 m to -29 m amsl).

Table 1 Formations present at Aldbrough test site (from McMillan et al., 2001)

Member/Formation	*Lithology*	*Age*
Hornsea Member (Holderness Formation)	Sand & gravel	Late Devensian (18,000 – 13,000BP)
Withernsea Member (Holderness Formation)	Till	Late Devensian (18,000 – 13,000BP)
Mill Hill Bed (Holderness Formation)	Sand & gravel	Late Devensian (18,000 – 13,000BP)
Skipsea Till Member (Holderness Formation)	Till (with laminated clays)	Late Devensian (18,000 – 13,000BP)
Dimlington Bed (Holderness Formation)	Laminated silt	Late Devensian (18,500BP)
Bridlington Member (Holderness Formation)	Till	Wolstonian (300,000 – 175,000BP)
Rowe Chalk Formation	Chalk	Late Cretaceous (83 - 65 Ma)

The Withernsea Member is a matrix-dominant brown till with a variety of clast lithologies. The Mill Hill Bed is a thin bed of sand and gravel. The Skipsea Till is a matrix-dominant red-brown and grey till with mainly chalk clasts containing a thin, discontinuous (?) layer of laminated clay (un-named). The

Dimlington Bed, beneath the Skipsea Till Member, is a thin grey bed of clayey (laminated) silt. The Bridlington Member is a dark grey, matrix-dominant glaciotectonically sheared till.

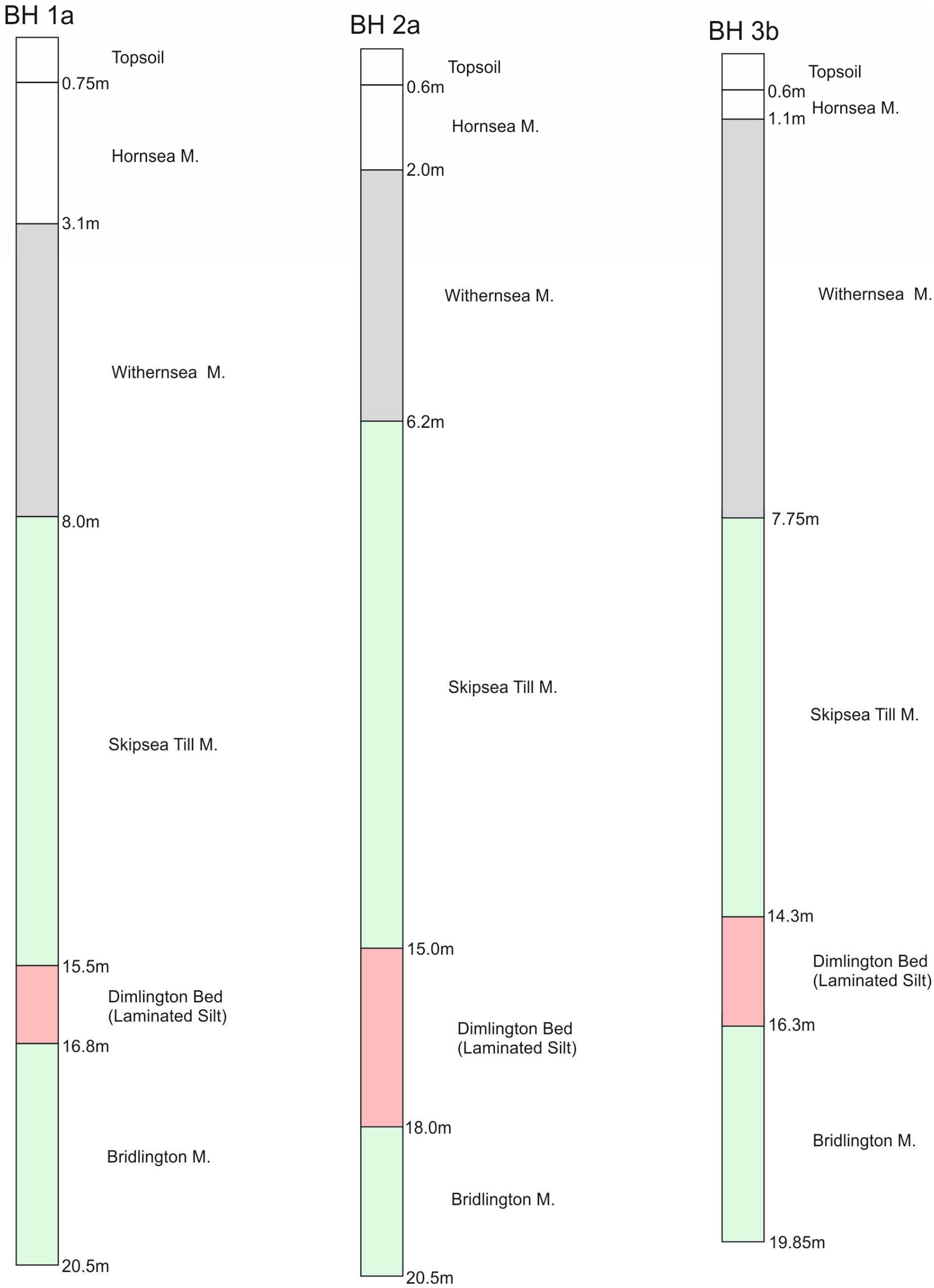

Figure 4 Summary stratigraphy for the Aldbrough test site

Summary stratigraphic data derived from boreholes drilled at the Aldbrough test site are shown in Figure 4. The depths have been adjusted for GPS elevation. *It should be noted that the stratigraphy for boreholes 1a and 2a is approximate and derived from drillers' log only.*

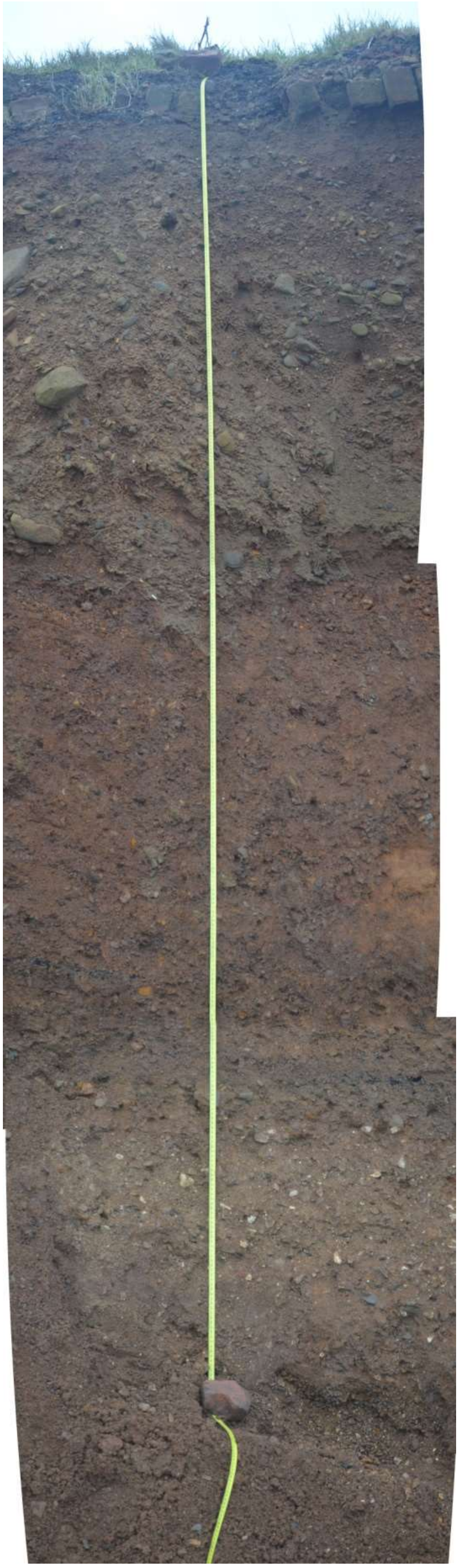

Figure 5 Uppermost cliff section revealed in landslide backscarp (section is 3 m high), Jan 2015.
NOTE: Upper 2 m is considered to represent the Hornsea Member (Holderness Formation)

The upper part of the succession is shown in Figure 5. This was revealed in the backscarp of the landslide (central embayment) in January 2015 and represents the uppermost 3 m of the succession; the upper 2 m of which is assumed to be a thin remnant of the Hornsea Member of the Holderness Formation. It is notable that the layer from 1 to 2 m appears to be oxidised.

5 Borehole drilling and instrumentation

5.1 DRILLING (PHASE 1)

In March 2012 two pairs of boreholes were drilled on the cliff top at the Aldbrough test site. These were each drilled to a nominal depth of 20 m by Geotechnics Ltd of Coventry using a cable percussion rig (Figure 4) and a truck-mounted rotary rig using air/water mist flush Figure 5. The arrangement of the boreholes is shown in Figure 8. Each pair consisted of a cored hole used for piezometer array installation and an open-holed borehole used for inclinometer tubing. The first pair (1a and 1b) was located at 10 m from the cliff edge (at the time) and the second pair (2a and 2b) at 20 m from the cliff edge (at the time); the alignment of the pairs being perpendicular to the coastline. Each pair had a separation, parallel with the coastline, of 5 m. The ground between the (then) cliff edge and the borehole locations showed no sign of subsidence or landsliding at the time of drilling. The piezometer arrays contained five sensors in each borehole and were wired to form a single cable. At the time of drilling (19^{th} – 22^{nd} March, 2012) the test area had recently undergone significant landsliding (see cover photo). This was centred closely on the borehole alignment and the slipped masses produced are likely to protect that section of cliff against further recession for several months. Currently BGS is carrying out three-monthly monitoring of borehole instrumentation (piezometers and inclinometers) and at the same time continuing with six-monthly TLS.

Figure 6 Cable percussion drilling rig at borehole 1a (Geotechnics Ltd.), 19^{th} March 2012

Figure 7 Unimog-Klemm rotary drilling rig at borehole 1b (Photo: C. Spalton, MGS-Geosense)

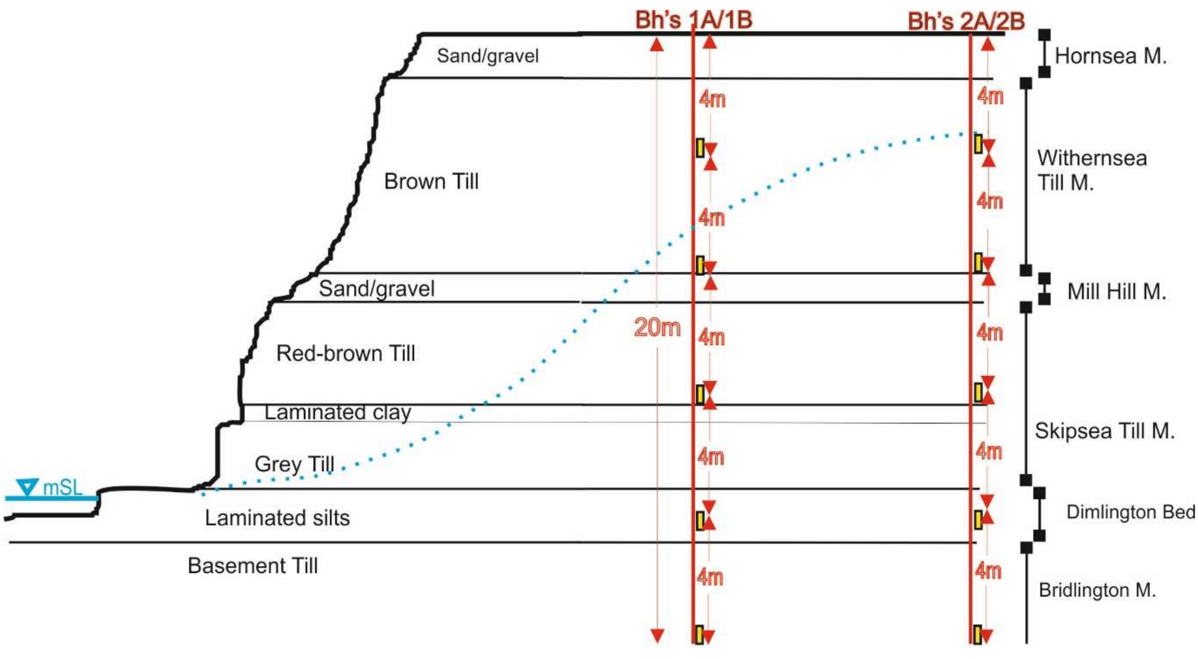

Figure 8 Cross-section at Aldbrough showing location of boreholes and piezometric sensors (Phase 1).
NOTE: Water table (blue line) conceptual

Difficulties were experienced with the rotary drilling when the air/water mist under pressure broke through to the adjacent piezometer holes and expelled part of the partially set bentonite/cement grout from the hole. This was despite casing to 6.0 m. The problem caused the termination of rotary drilling and replacement with cable percussion on borehole 2b.

Table 2 Summary of boreholes, installations and dGPS survey locations at Aldbrough test site in April 2012 (Phase 1)

Borehole No.	*BH Depth (m bGL)*	*Location (Easting, Northing), Ht. (aMSL.)*	*Method*	*Instrumentation*	*Instrument depths (m bGL)*
1a	20.5	525684.3, 439529.7, 16.52	Cable percussion (sampled)	VW Piezo array (x5)	4.0, 8.0, 12.0, 16.0, 20.0
1b	20.5	525681.4, 439533.7, 16.56	Rotary (open-holed)	Inclinometer casing (70mm, QJ)	0.0 – 20.0
2a	20.5	525676.5, 439523.6, 16.18	Cable percussion (sampled)	VW Piezo array (x5)	4.0, 8.0, 12.0, 16.0, 20.0
2b	20.5	525673.4, 439527.5, 16.41	Cable percussion	Inclinometer casing (70mm, QJ)	0.0 – 20.0
Survey pin No.		*Location / ht. (aMSL.)*	*Description*		
X1 pin		525690.6, 439537.7, 16.70	Pin with yellow disc on kerb	Campsite Road	
Pin 1		525676.9, 439539.9, 16.40	Pin in road parallel to BH's 1A and 1B	Seaside Road	
Pin 2		525667.7, 439534.7, 16.33	Pin in road parallel to BH's 2A and 2B	Seaside Road	

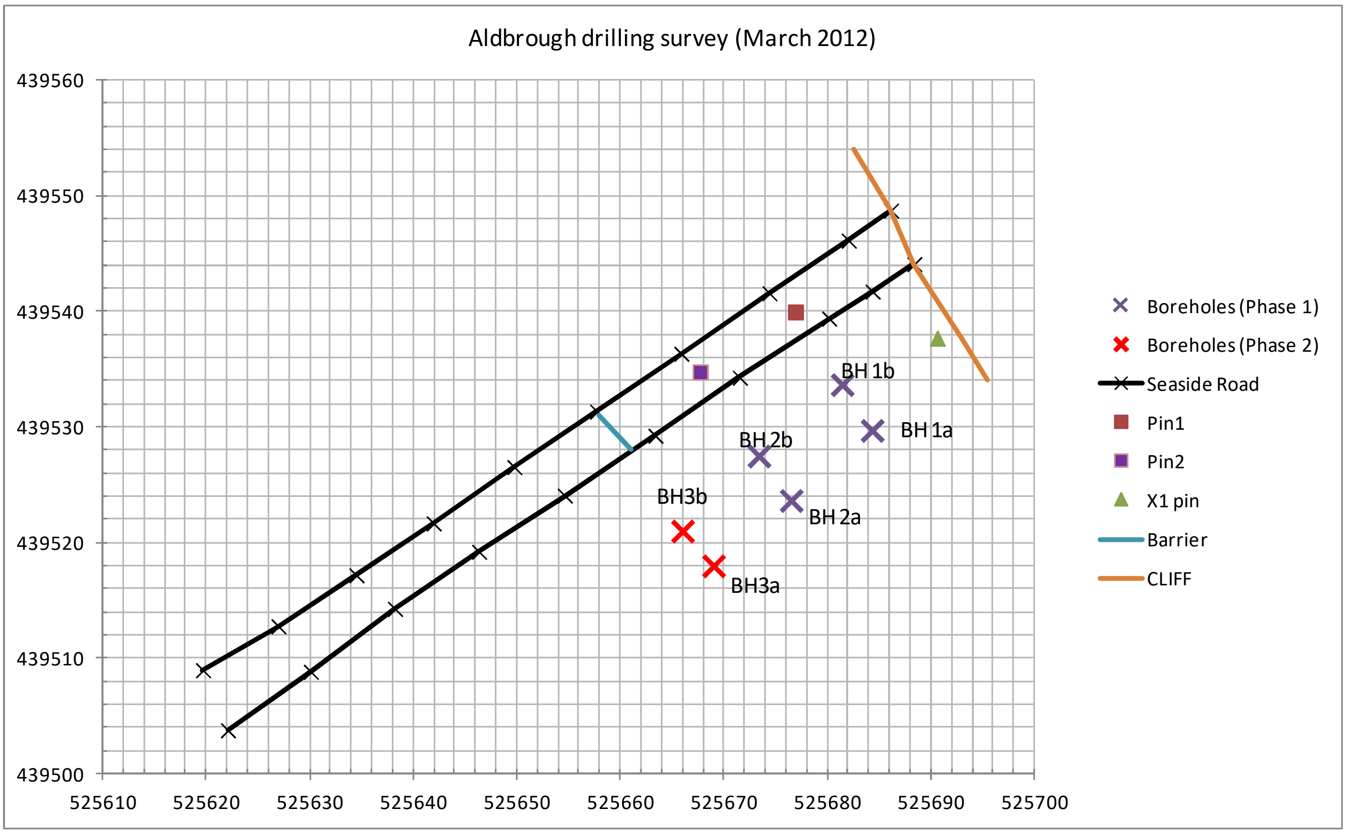

Figure 9 Location of boreholes, survey pins and positions at Aldbrough test site (baseline survey: Apr 2012) ***Note: Phase 2 boreholes included***

6 Commissioning and monitoring of instrumentation

6.1 PIEZOMETERS

Two sets of piezometer arrays were installed by Geosense/Marton Geotechnical Services (MGS-Geosense) for BGS in boreholes 1a and 1b as part of Phase 1. The piezometer arrays are of multi-point vibrating-wire type (G-51 series, VWP-3001) manufactured by RST and MGS-Geosense and supplied by (MGS) Ltd of Bury St. Edmunds; that for borehole 1a is 35 m in length (20 m of which sub-surface) and for borehole 2a is 25 m in length (20 m of which sub-surface). Each array has five ceramic sensors (Figure 8) 4 m apart. The cable is grouted permanently into the borehole using a mix of bentonite and cement. The cables terminate in a manhole adjacent to borehole 2a and flush with the ground surface and connect to a single battery-powered ten-channel vibrating-wire datalogger (RST Instruments DT2055). The sensors are each calibrated from -70 kPa to +345 kPa. The installations (Phase 1) were carried out by Geosense and are monitored at regular intervals by BGS. The piezometers measure water pressure in 'metres of water' (or kPa) and temperature at the sensor. Prior to installation the sensors were soaked in water for several hours. *It should be noted that no sand 'pockets' were provided in the grout column; that is, the sensors are in direct contact with the grout*. This follows the procedure recommended by McKenna (1995), Mikkelsen and Green (2003) and Ridley et al. (2003) for the installation of multi-point downhole piezometers. These advocate surrounding of the array with a medium of similar permeability to the host rock, hence the use of a bentonite/cement grout for a clay host. The mix used was 150 l of water / 50 kg cement / 15 kg bentonite powder. This mix also provides protection from drying out of the sensor (Mikkelsen and Green, 2003). Unfortunately, the grout mix cannot be 'customised' to the lithostratigraphy, and is thus a compromise to suit the succession as a whole.

Problems of compressed air break-through from borehole 1b to 1a and 2a, during the drilling of 1b, may have produced some voids within the grout which was partially cured at the time. At present, it is not clear whether this has compromised the piezometer array in borehole 1a. It is thought that borehole 2a was only slightly affected.

The daylighting piezometer installation is shown in Figure 10. The two cables from the arrays installed in boreholes 1a and 2a terminate in a datalogger installed in a manhole. Interface with the datalogger is achieved via a mini-USB cable to either a laptop or a palm-PC (*NOTE: The thermistor channels from the sensors were not utilised in Phase 1 but were subsequently utilised in Phase 2*).

Figure 10 BGS monitoring piezometer arrays - Surface installation for piezometer arrays datalogger for boreholes 1a and 2a.

6.1.1 Piezometer results

The initial 'baseline' set of readings (22nd March to 15th April 2012) was retrieved on 16th April 2012. The progress of equilibration and post-equilibration behaviour to 19th December 2014 is illustrated in Figure 11 and Figure 12. These show a rapid fall in pore pressures over the first few days immediately following installation, reducing exponentially towards equilibrium values. It is notable that the sensors at 12 m and 20 m (within the mid and lower tills) in BH1a have apparently required over 9 months to equilibrate, whereas those at 8m and 16 m took less than 3 months. In fact, the sensor at 20 m in borehole 1a had still not fully equilibrated after 15 months and has remained relatively unresponsive to the present. This is a result of these sensors being situated within clay-rich till horizons. The sensor at 4 m depth in borehole 1a is notable for showing negative pore pressures immediately after installation, continuing up to 28th January 2016 with the exception of a short period between 26th and 29th November 2012 when the pore pressures went slightly positive. The latter appears to be a direct response to almost 45mm of rainfall recorded over a 48 hour period between 26th and 27th November 2012. A corresponding peak was not recorded in borehole 2a. Also in Borehole 2a the 4 m sensor went slightly negative only between July 2014 and April 2015; it remaining positive for the remainder of the monitoring period. The sensors in BH 2a appear to have equilibrated within about 3 months.

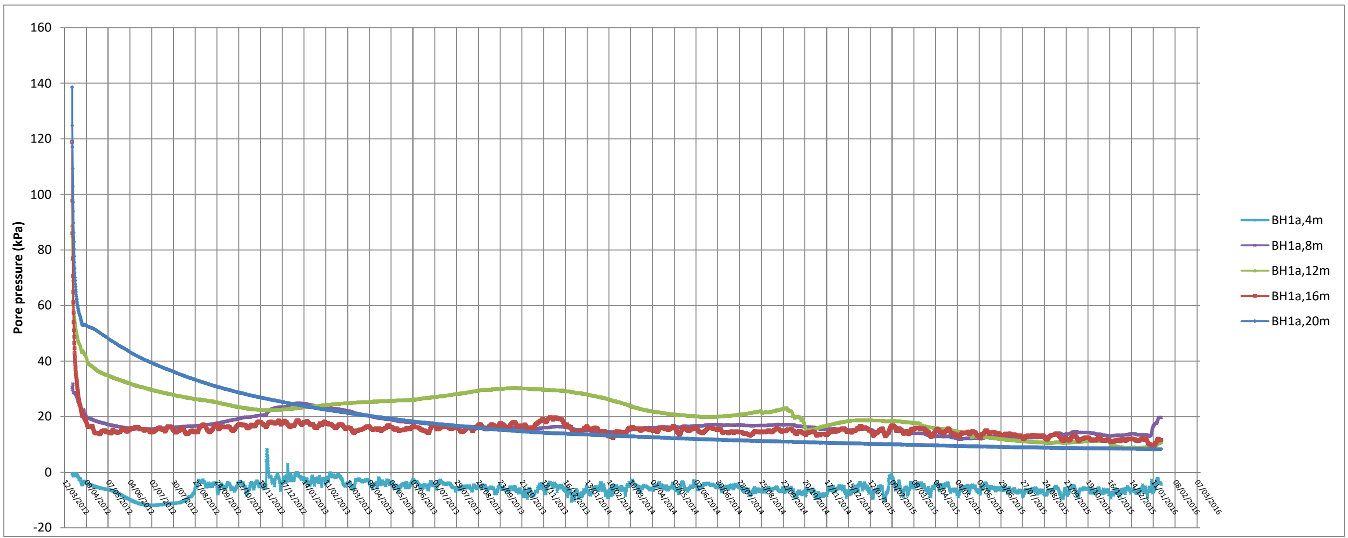

Figure 11 Plot of pore pressure vs. elapsed time for piezometers BH 1a (*21st March 2012 to 21st January, 2016* = 1398 days)

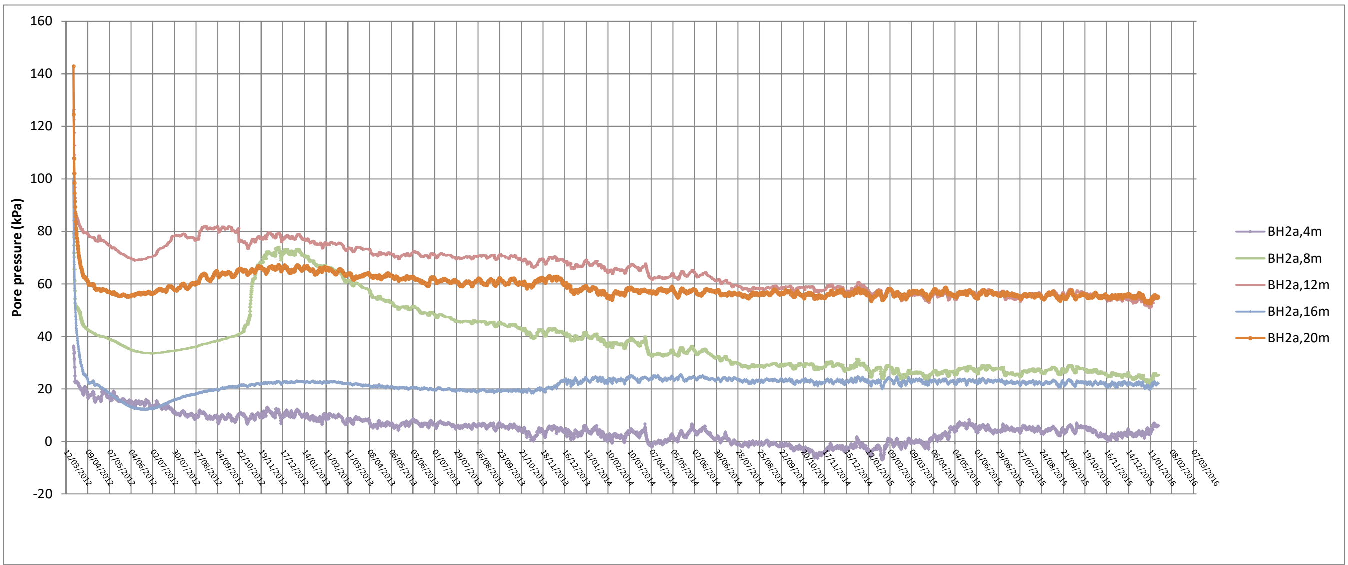

Figure 12 Plot of pore pressure vs. elapsed time for piezometers BH 2a (*21st March 2012 to 21st January, 2016* = 1398 days)

It is notable that the sensors in BH's 1a and 2a show similar trends with the exception of those at 12m which show a large difference (approx. 45 kPa). Some, but not all, of the sensors 'bottom out' between early and mid-June, followed by a gradual increase to December. However, the sensor at 8 m in BH2a shows an unusual and sharp additional upward trend starting around 26th October 2012 and dropping away gradually for the next 8 months. The reason for this is unclear and the trend is not duplicated by any other sensor, except for a slight pore pressure rise in borehole 1a at 8 m. It is interesting to note that the shapes of the curves for the sensors in borehole 1a at 16 m and borehole 2a at 20 m are almost identical. The reason for this is unclear.

It is notable that by the end of 2015 all the BH1a sensors below 4 m had coalesced around 10 kPa whereas the equivalents in BH2a had retained a wide range (20 to 55 kPa). This apparent equalisation process in BH1a is possibly due to the presence of vertical stress relief fissures close to the cliff, whereas further from the cliff at BH2a there are insufficient fissures to provide the same hydraulic connectivity throughout the geological sequence.

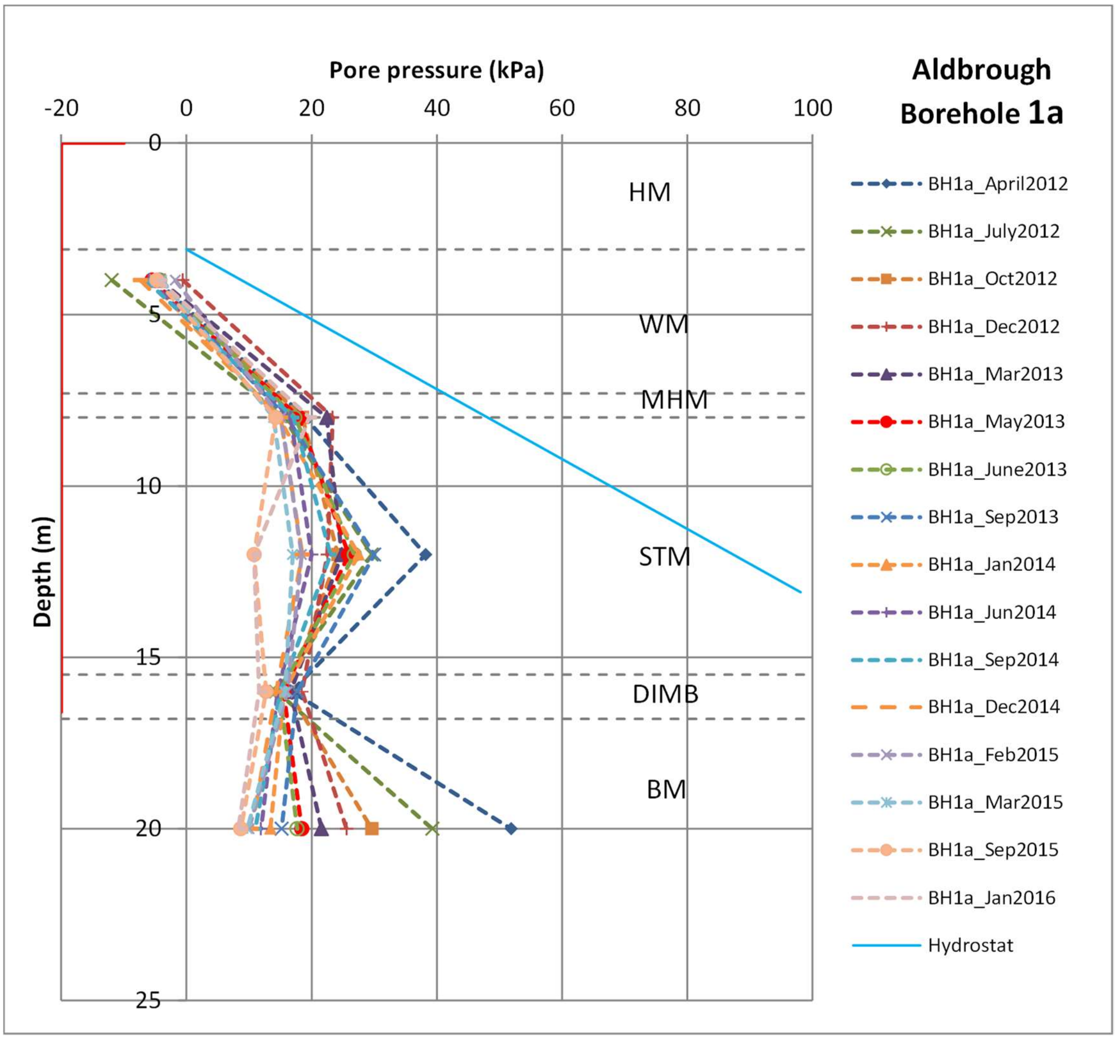

Figure 13 Plot of pore pressure vs. depth for BH 1a piezometer array (April, 2012 to Jan 2016)
NOTE: Lines connecting sensor points are conjectural; red line (top left) indicates approximate cliff elevation

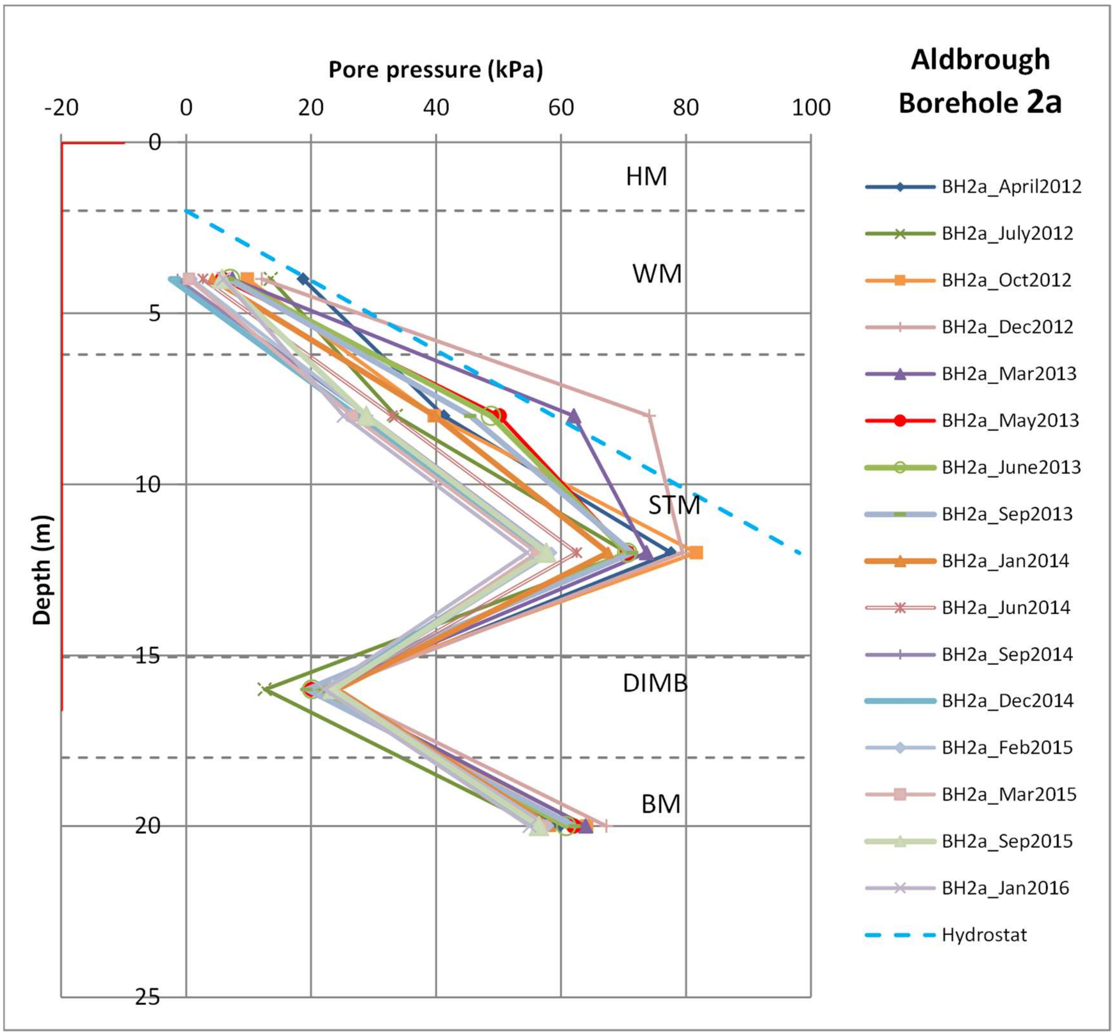

Figure 14 Plot of pore pressure vs. depth for BH 2a piezometer array (April, 2012 to Jan 2016)
NOTE: Lines connecting sensor points are conjectural; red line (top left) indicates approximate cliff elevation

Plots of pore pressure vs. depth are shown in Figure 13 and Figure 14. These appear to show that between 4 m and 12 m in borehole 2a a less than hydrostatic, but increasing, pore pressure profile is found, whereas for borehole 1a there is a reduction below hydrostatic at 12 m. At 16 m depth the results for both boreholes coincide at around 20 kPa throughout the monitoring period. At 20 m depth the widest scatter is found, particularly for borehole 1a; the overall range for both boreholes being 10 to 67 kPa. It is notable that the pore pressure for borehole 1a at 20 m depth has steadily but significantly reduced over the monitoring period, whilst in contrast it has remained constant (at only slightly above zero) at 12 m depth. The data when viewed together with the lithostratigraphic interpretation (Figure 13) suggest the following:

- The materials at 4 m depth in borehole 1a are subject to a small suction, particularly in the summer, though the overall trend is for a steady reduction.
- Natural hydraulic continuity exists between boreholes 1a and 2a at 16 m; that is, within the Dimlington Beds. This is likely to continue through to the cliff face, excepting the presence of landslide deposits on the cliff slope.
- The Dimlington Beds (mainly laminated silts) are probably under-draining the overlying tills.
- Pore pressures in borehole 1a appear to be much lower than hydrostatic* (solid blue line in Figure 13), at least to a depth of 16m (approximate cliff height).
- Pore pressures in borehole 2a at 8 m, 12 m and 20 m depth are significantly higher than their borehole 1a equivalents.
- Pore pressures in borehole 2a were approaching hydrostatic* (dashed blue line in Figure 14) to a depth of 12 m during the winter of 2012 / 2013. The gradient of pore pressure from 16 m to 20 m depth in borehole 2a matches that from 4 m to 12 m depth and is close to hydrostatic*.

**The hydrostatic line has been taken from the base of the Hornsea Member.* Pore pressures at 20 m depth in borehole 1a decrease at a slowing rate throughout the period from the start of monitoring in April 2012 to Dec 2014. This is in contrast to the situation at16 m depth where readings are effectively constant (to within 3 kPa) after mid-April, 2012.

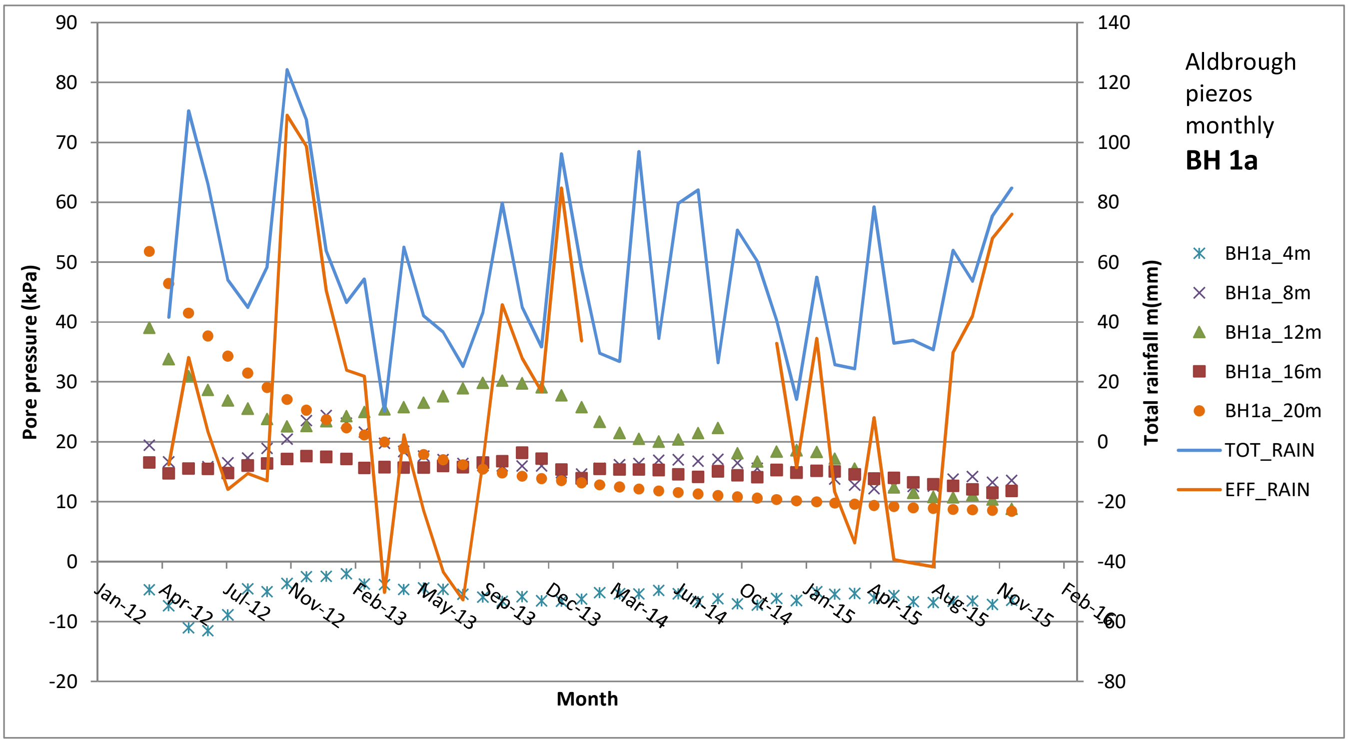

Figure 15 Plot of pore pressure vs. elapsed time for piezometers BH 1a (*21st March 2012 to 19th December, 2015 =* 1003 days) showing total & effective rainfall (BGS Aldbrough weather station, Hobbs et al, 2013)

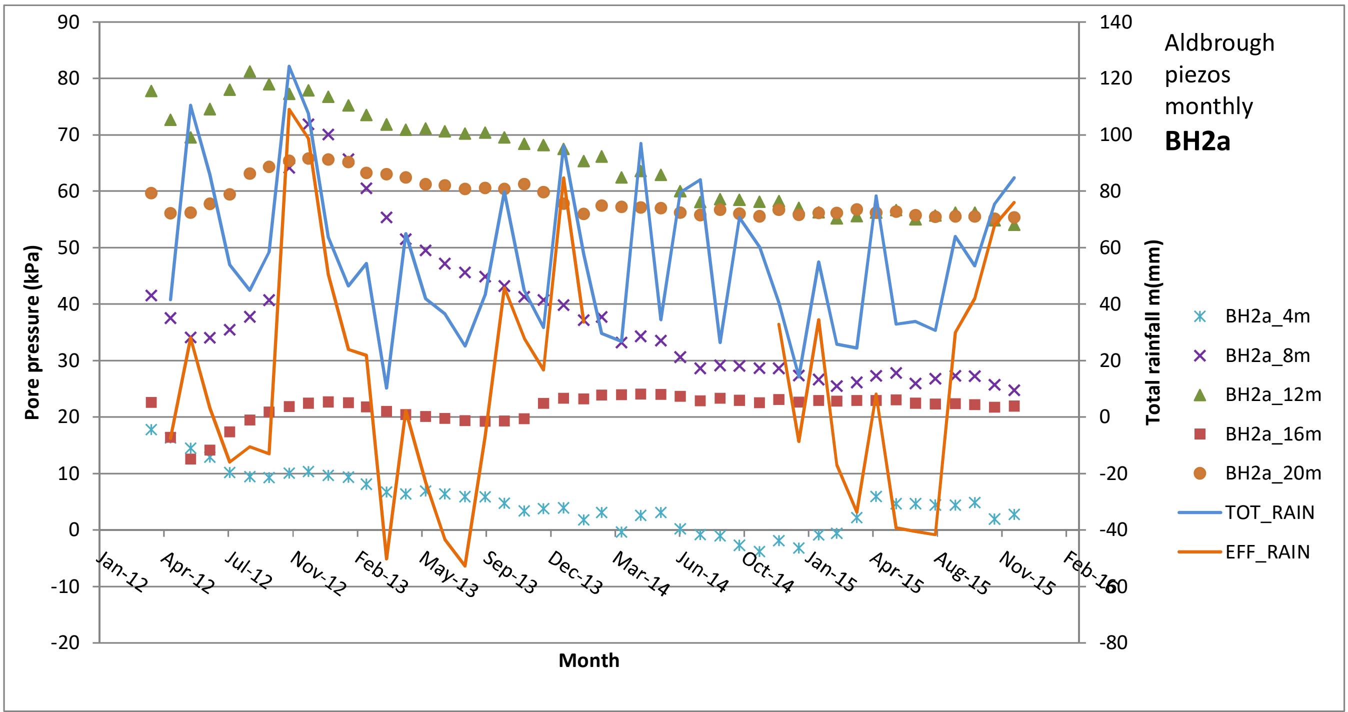

Figure 16 Plot of pore pressure vs. elapsed time for piezometers BH 2a (*21st March 2012 to 19th December, 2015 =* 1003 days) showing total & effective rainfall (BGS Aldbrough weather station, Hobbs et al, 2013)

Plots of pore pressure vs. elapsed time for piezometers in BH's 1a & 2a are shown, with total & effective rainfall (BGS Aldbrough weather station, Hobbs et al., 2013), in Figure 15 and Figure 16. The principal rainfall induced response appears to be at 8 m depth in BH 2a for the winter of 2012/13. *Data for effective rainfall between March and December 2014 were unavailable due to weather station sensor malfunction.* With this exception, there appears little or no response from the other sensors to total or effective rainfall either for the winter of 2012/2013 or that of 2013/2014. The dominant response is one of continual decline in pore pressures irrespective of season or rainfall. This would tend to indicate a 'stress-relief' causation. Alternatively, there may be the contribution of a reducing drainage path length to the cliff, though this is discontinuous and probably cannot be investigated over the short time frame of piezometer monitoring at the time of reporting. The plot for the sensor at 8 m in Borehole 1a appears to be inverse to that for 12 m which may suggest an approximately 9-month lag in the 12 m sensor. It is notable that all the sensors for BH1a, except for that at 4 m, virtually coalesce around 10 kPa by 2015 whereas, over a similar time scale, the sensors at 8 m and 16 m in BH2a have coalesced at around 25 kPa, as have 12 m and 20 m at around 55 kPa. This is presumably due to the isolation of the low and high permeability layers relative to one another and the drainage of each layer towards the cliff.

The overall pore pressure profiles indicate an underlying increase with depth from about 1 - 2 m below ground level to 20 m depth but well below hydrostatic and with major deviations at the more permeable horizons with drainage presumably towards the cliff. Powell & Butcher (2003) reached the same conclusions from their data at nearby Cowden regarding the uppermost 20 m, but also prognosed 'underdrainage' to the chalk below this.

6.2 INCLINOMETERS

A 70 mm diameter QJ type plastic inclinometer casing was installed for BGS by MGS-Geosense Ltd in boreholes 1b and 2b (closest of the two pairs to Seaside Road) to a depth of 20.5 m and 20.0 m, respectively below ground level. This consisted of standard 3 m snap-fit sections supplied by MGS-Geosense. This installation is intended for use with the 30 m (cable length) long, 0.5 m wheelbase RST Instruments MEMS-G30-001 digital inclinometer probe (Figure 17) supplied by MGS-Geosense; the cable for which is marked out at 0.5 m intervals. This will deal with a minimum casing curvature of 1.88 m. The data are logged via a remote palm computer ('field PC') with Bluetooth connectivity. Data are retrieved and analysed using RST's 'Inclinalysis' software. The casing is aligned in the boreholes so that the 'A' direction is facing (approximately) towards the cliff and the 'B' direction parallel with it. The precise orientation of the top of the casing is recorded (Figure 25) and, where appropriate, corrections made to indicate azimuth.

The procedure at Aldbrough is as follows:

1. Run probe to base of hole in A+ direction (upper wheel towards A+, i.e. approximately seaward).
2. Allow equilibration of temperature (approx. 15 mins.)
3. Raise probe in 0.5 m increments taking readings at each interval.
4. Repeat steps 1 to 3 in A- direction (upper wheel towards A-, i.e. approximately landward)

NOTE: *The sign convention is that* <u>*positive*</u> *deviation is in the direction of the upper wheel.*

For reasons of cost, the thermistor sensors incorporated in the piezometer probes were not logged as part of the Phase 1 installations. However, those installed as part of Phase 2 were logged (section 6.3.6).

Figure 17 RST inclinometer equipment (cable reel, probe & Field-PC datalogger)

The procedure is illustrated in Figure 18.

Figure 18 Borehole inclinometer monitoring - Insertion of inclinometer probe into borehole 1b (A- direction, landward)

6.2.1 Inclinometer results

The maximum deviation from vertical of the boreholes as installed (as shown by 'absolute' inclinometer datasets) was 150 mm (Borehole 1b) and 280 mm (Borehole 2b). The monitoring data are described below using 'cumulative' datasets; that is, the sum of the displacements since the first set of readings (*NOTE: none of these data reflect the shape of the borehole itself*). This interpretation is satisfactory provided that cumulative errors are small. To date, errors (indicated by the 'checksum' dataset) are low and consistent between surveys.

The initial (baseline) set of readings was retrieved on 16th April 2012. Subsequent sets taken in July, October and December are shown as cumulative changes from the baseline set in Figure 19 and Figure 20, where the baseline data are represented by the central vertical grey line with zero cumulative displacement. Thus the bottom of the borehole (nominally 20 m) is taken as a fixed datum. *NOTE: these plots do not illustrate the 'shape' of the borehole.* Additional plots ('polar' and 3D 'cumulative') show alternative representations of the displacements.

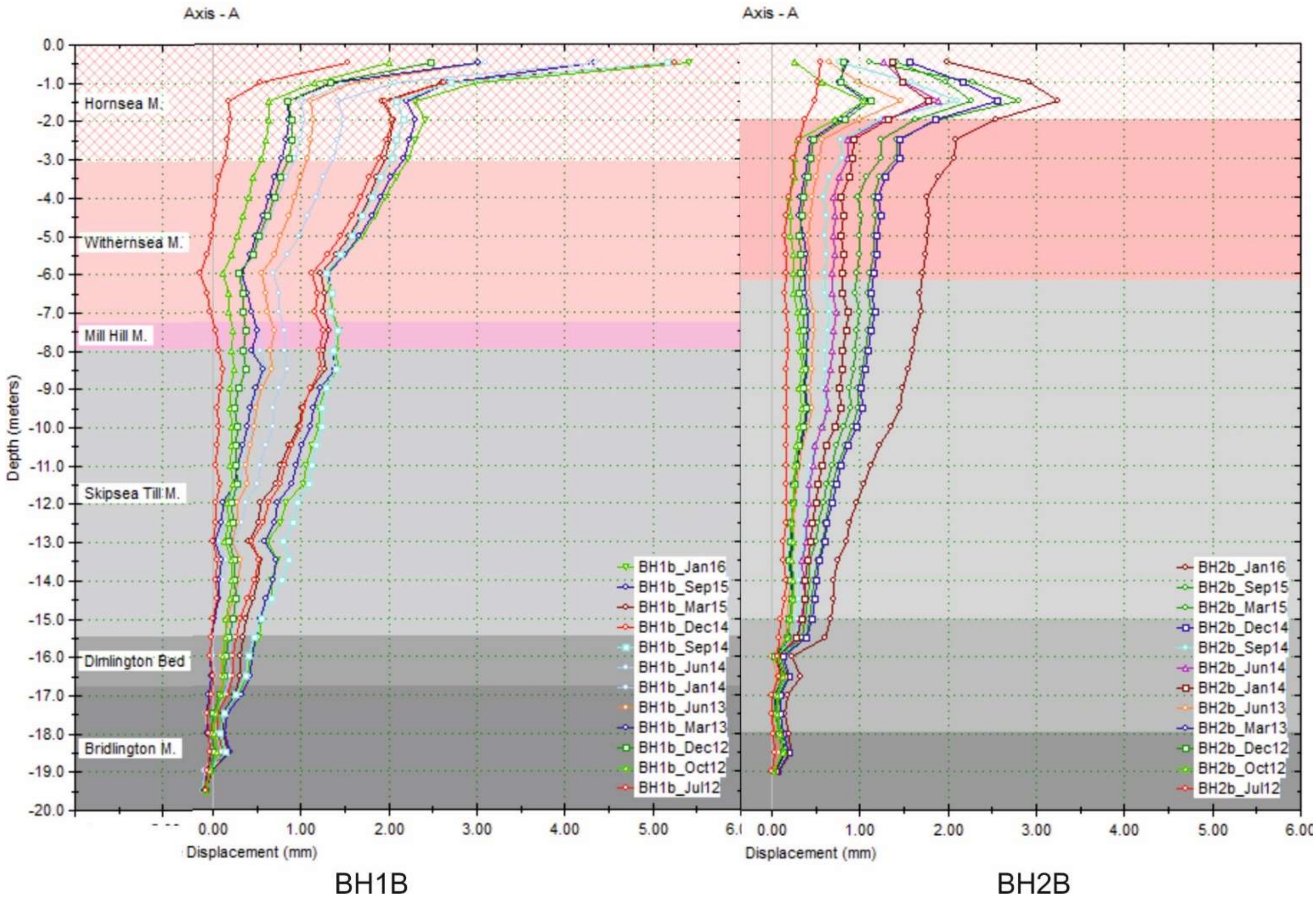

Figure 19 Cumulative inclinometer profiles (compared to April 2012 baseline: *zero*) for Boreholes 1b & 2b [Axis A].
NOTE: X-axis deviation (m), Y-axis Depth (m); A+ azimuth = N78 degr (BH1a) and .N13 degr (BH2b). *NOTE: 20 m depth assumed fixed*

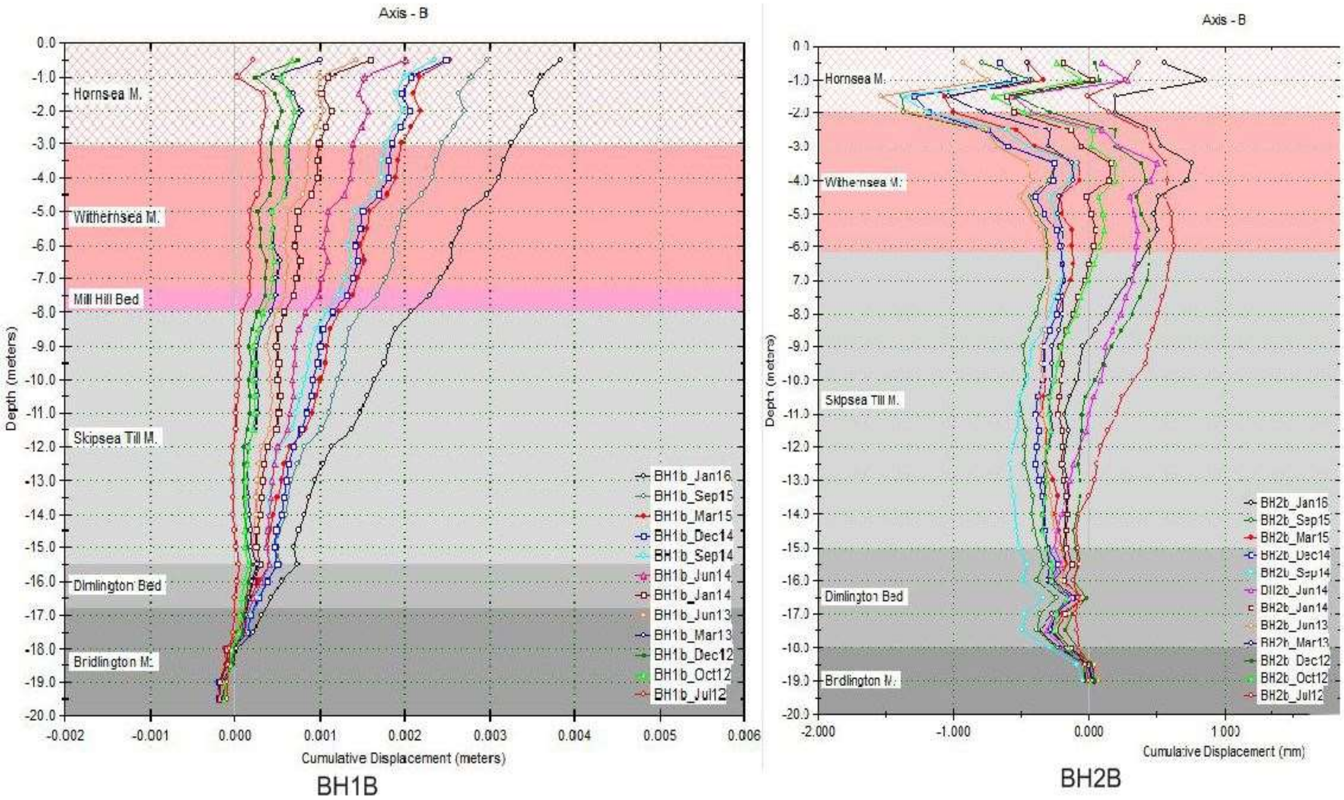

Figure 20 Cumulative inclinometer profiles (compared to April 2012 baseline: *zero*) for Boreholes 1b & 2b [Axis B].
NOTE: X-axis deviation (m), Y-axis Depth (m); A+ azimuth = N78 degr (BH1a) and .N13 degr (BH2b). *NOTE: 20 m depth assumed fixed*

The interpretation of the results to date for Borehole 1b is as follows:

- Small displacements have taken place, particularly in the upper 8 m, and more so in the upper 1.5 m (Figure 19 and Figure 20).
- Displacements have reached a maximum of 5.5 mm in the A+ direction at 0.5 m depth and 3.9 mm in the B+ direction over the monitoring period to January 2016.
- Displacements in the B direction have increased linearly from 20 m depth upward to 1.5 m depth. Above this, the displacements have increased markedly to 0.5 m depth. Displacements in the A direction are more zonal with a different trend between 1.5 m and 6.0 m.
- The displacement vectors indicate net movement in a general seaward direction over the monitoring period to January 2016, at least to a depth equivalent to the cliff height, though this appears not to be perpendicular (approx. N25°) to the cliff line (approx. N145°) as might be expected.

The interpretation of the results to date for Borehole 2b is as follows:

- Small displacements have taken place, most notably above 2.5 m depth (Figure 20).
- Displacements have reached a maximum of 3.2 mm in the A+ direction and 1.5 mm in the B- direction at 1.5 m depth over the monitoring period.
- Displacements in both A and B directions have tended to increase linearly from 16 m depth upward to 2.5 m depth. Above this, the displacements have increased markedly to 1.5 m depth, then reduced up to a depth of 0.5 m
- It is unlikely that the displacement vectors indicate net movement in any particular direction over the monitoring period. Movement apparently initiates within the Dimlington Bed, above the Bridlington Member.

The overall trend is for displacement to be to the northeast (seaward) for Borehole 1b and to the northwest or north for Borehole 2b. Both boreholes show movements increasing with time, although minor reversals occur apparently at random. Both boreholes show movements increasing up-hole over most of their depth, though again there are minor exceptions.

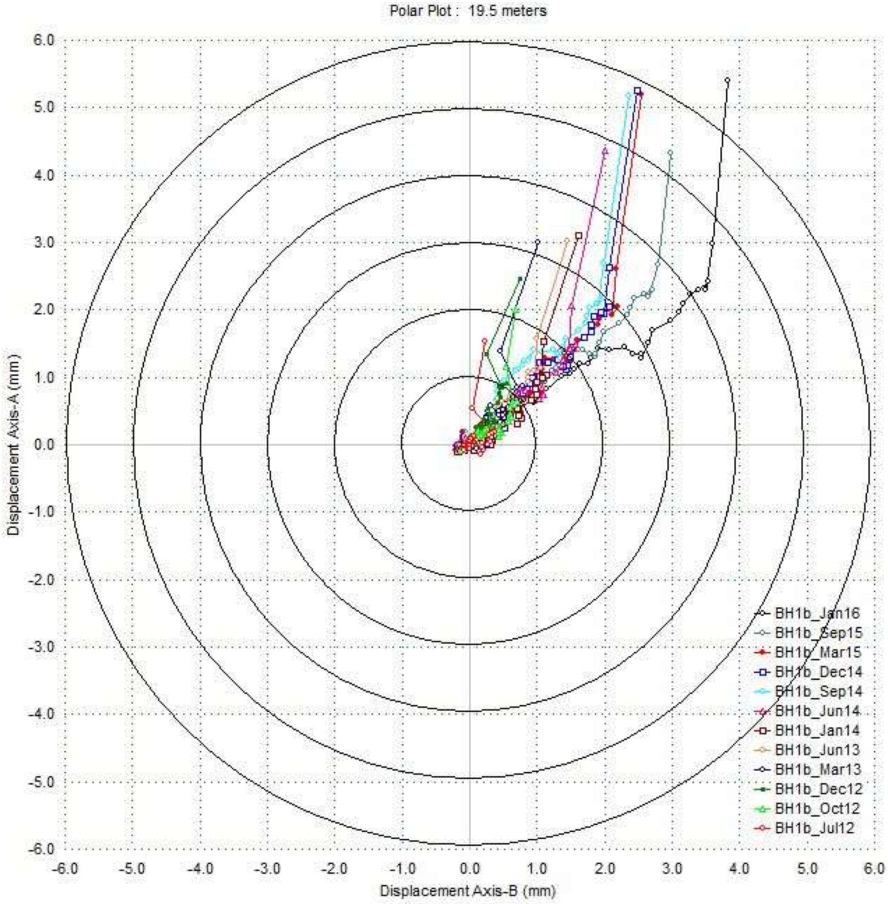

Figure 21 Polar cumulative plot for Borehole 1b (full depth)
NOTE: Corrected for azimuth (78 degr.); i.e. plot oriented North (top)

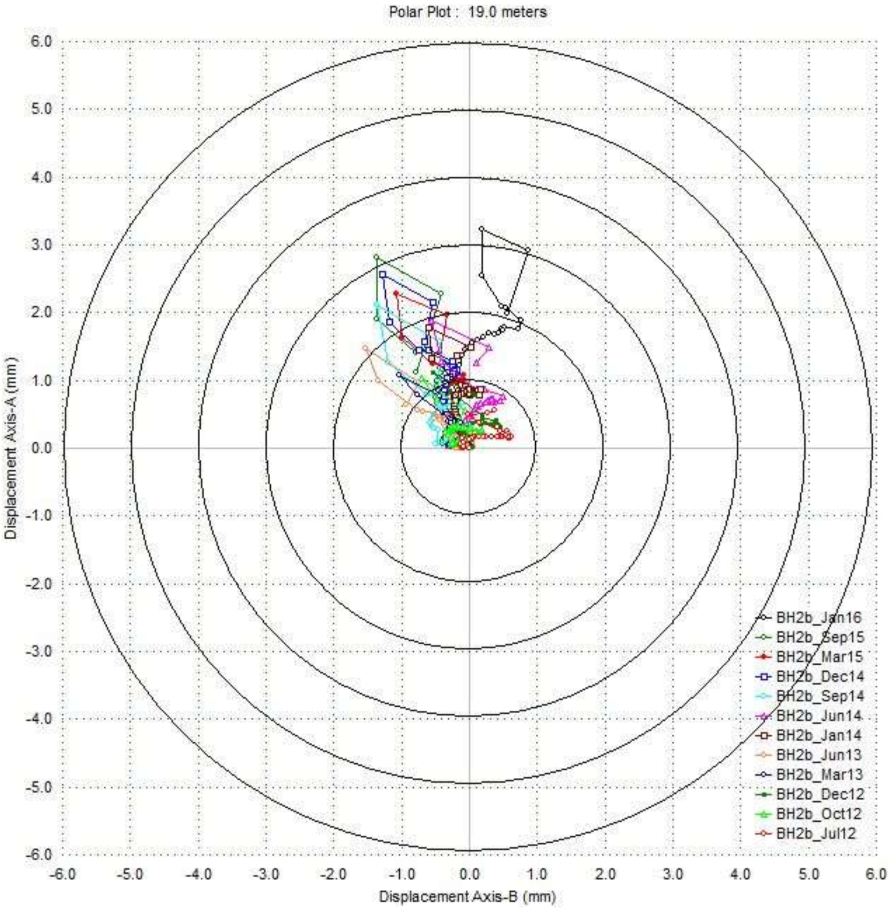

Figure 22 Polar cumulative plot for Borehole 2b (full depth)
NOTE: Corrected for azimuth (13 degr.); i.e. plot oriented North (top)

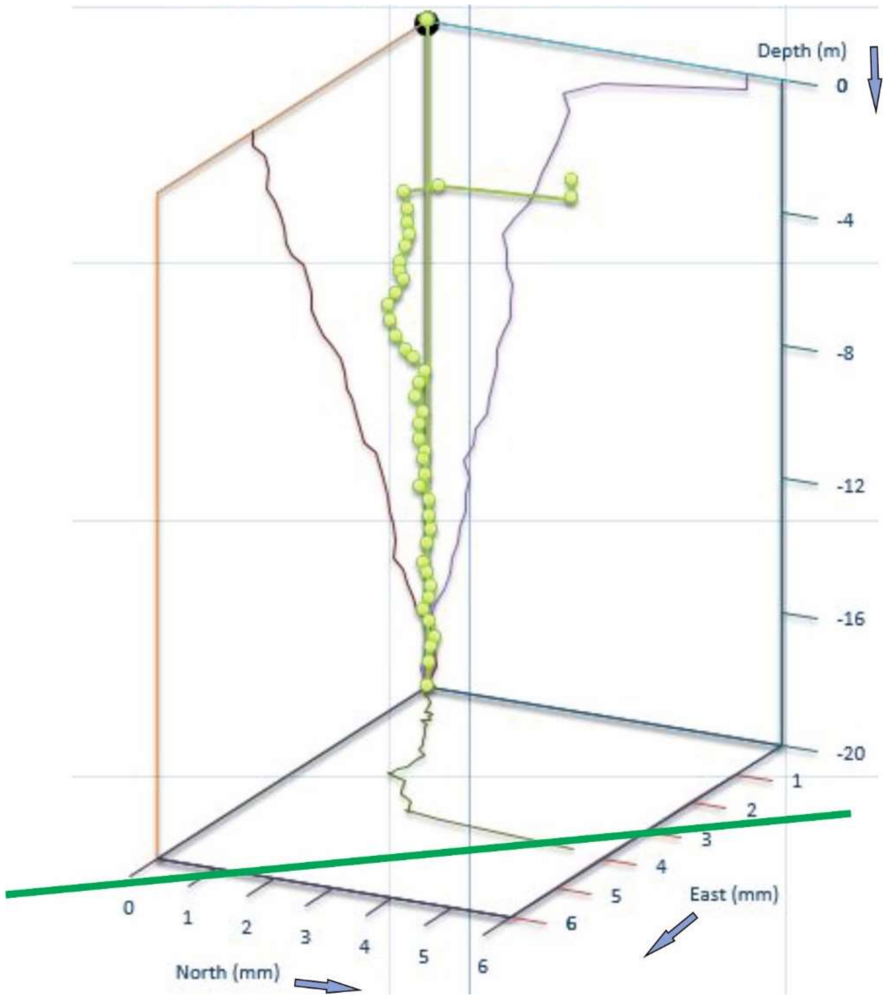

Figure 23 3D plot of cumulative displacement for BH1b to Jan 2016
NOTE: approximate orientation of cliff-top shown in dark green (not to scale)

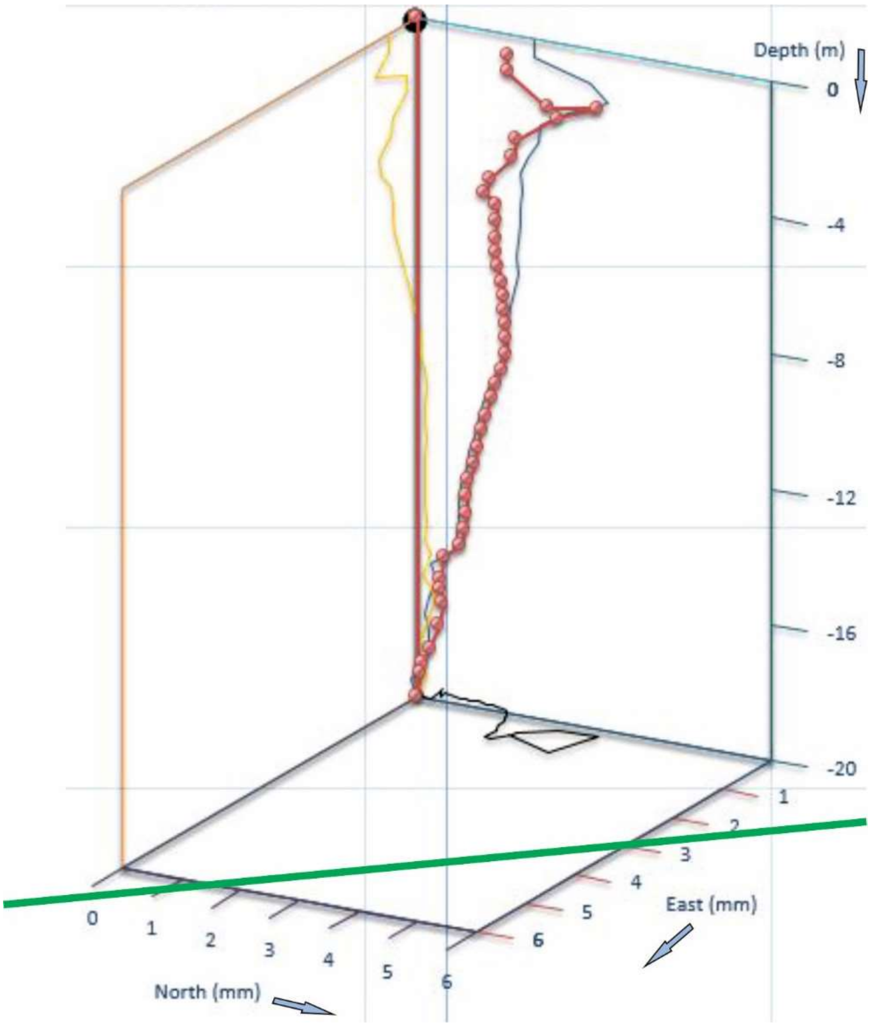

Figure 24 3D plot of cumulative displacement for BH2b to Jan 2016
NOTE: approximate orientation of cliff-top shown in dark green (not to scale)

The 3D plots shown in Figure 23 and Figure 24 illustrate the northward and eastward components of the cumulative inclinometer displacements for boreholes 1b and 2b up to January 2016. The approximate orientation of the cliff-top is also shown (not to scale). In the case of BH1b the movement is seen to be north-easterly with the exception of the very near-surface. In the case of BH2b the movement is northerly below about 9 m and varies between northerly and north-easterly above this.

The site plan (Figure 25) is a schematic representation of the inclinometer data relative to the road and cliff-top. In this diagram the boreholes and the road are accurately located whereas the cliff-top was taken at a specific point in time using dGPS. The red arrows show the most significant directions of displacements, albeit minor to date, measured during monitoring. *It is not possible to show a unique vector of displacement on a plan view as these vary downhole.*

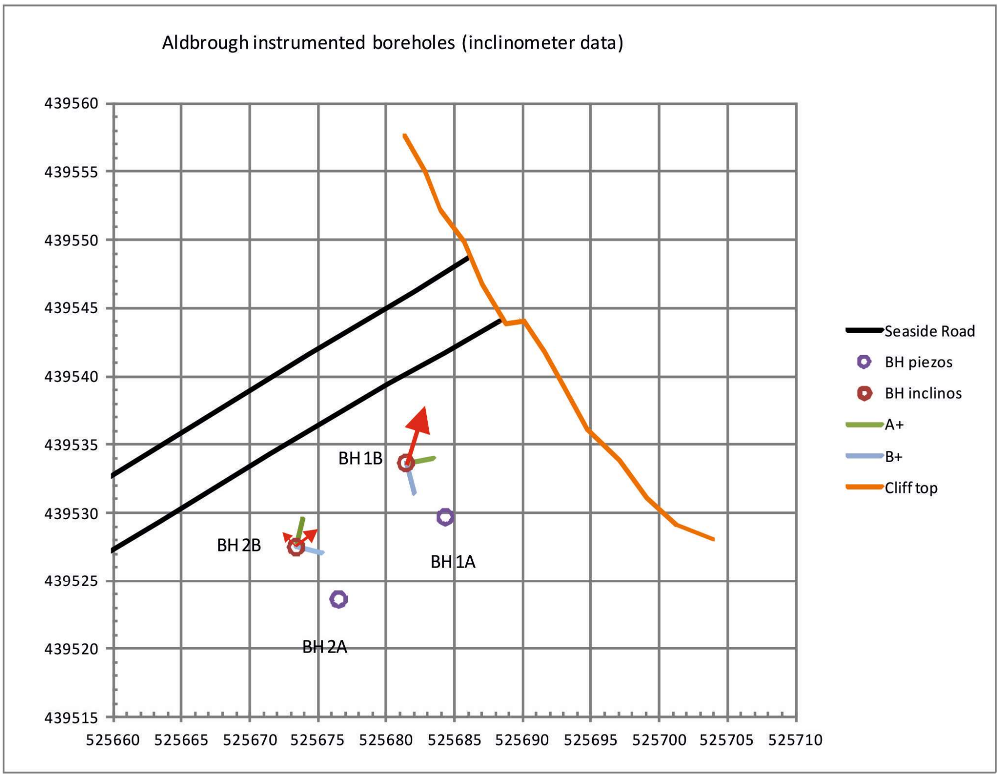

Figure 25 Site plan showing location of boreholes relative to road, cliff-top and inclinometer casing azimuths. Displacement vector trend (red arrows). Valid to Jan 2016

NOTE: Azimuth for A+ in BH1b = N78°, azimuth for A+ in BH2b = N13° (at ground level)

6.3 DRILLING (PHASE 2)

6.3.1 Introduction

A second phase of drilling was carried out between 26 Jan and 4 Feb, 2015. This added a third pair of boreholes to the two pairs drilled in Phase 1 (Section 5.1). These boreholes (3a & 3b) were installed 8 m landward of boreholes 2a and 2b (Figure 3); that is, approximately 28 m from the (2012) cliff-top. Boreholes 3a and 3b were drilled to depths of 19.90m and 19.85m, respectively using a triple-barrel wireline method (Geobore-S) with the aim of obtaining A1-quality core and full core recovery, and installing a piezometer array and inclinometer casing as per Phase 1. In addition, arrays of PRIME electrodes were installed in both boreholes. This BGS-developed system (Figure 34), Proactive Infrastructure Monitoring and Evaluation (PRIME), provides cross-borehole, and surface to borehole, time-lapse electrical resistivity tomography (ERT). This method is used to characterise changes in resistivity with time; this being closely related to lithology and changes in water content. The borehole arrangement is shown in Figure 28.

Figure 26 Map showing approximate position of Phase 2 boreholes 3a and 3b.
NOTE: properties marked with X have been demolished
NOTE: Cliff line (March, 2013) shown as red line

6.3.2 Drilling method

Drilling was carried out by Environmental Scientifics Group (ESG), under contract A5007-16, using a Beretta T41 track-mounted drill. This was used with a Geobore-S rotary wireline system producing a 147 mm diameter hole and 109 mm core. The drill bits used were tungsten. Flush was provided by pumped water obtained from a nearby hydrant. Borehole completion was made using a grout mix of cement and bentonite (150 litres water: 50 kg cement: 15 kg bentonite powder). This work was carried out over 8 working days between 26th January and 6th Feb 2015. The BGS team carried out preparatory and completion work over a further 2 days. The decision to use rotary coring was based largely on the need to maximise core recovery. As pointed out by Powell & Butcher (2003) this drilling method may lead to increased water content in these materials. The outer few millimetres of the core comprised disturbed material and was removed during laboratory preparation. The problem is greatest for material with lower clay content. Triaxial strength tests on rotary cored and high-quality thin-walled ‘pushed’ samples gave similar results overall (section 7.1).

Figure 27 ESG's Beretta T41 drill on borehole 3b at Aldbrough

Table 3 Summary of boreholes, installations & dGPS survey locations at Aldbrough test site, Jan/Feb 2015 (Phase 2)

Borehole No.	*BH Depth (m bGL)*	*Location (Easting, Northing), Ht. (aMSL.)*	*Method*	*Instrumentation*	*Instrument depths (m bGL)*
3a	19.90	525670.1, 439518.8, 16.1	Geobore-S triple barrel wireline	VW Piezo array (x6) PRIME array	1.7, 3.7, 7.7, 11.7, 15.7, 19.7m 1 m intervals 0.9 - 19.9m
3b	19.85	525667.3, 439522.8, 16.3	Geobore-S triple barrel wireline	Inclinometer casing (70mm, QJ) PRIME array	0.0 – 19.85m 1 m intervals 0.85 - 19.85m
				PRIME array (surface)	1 m intervals over 23 m
Survey pin No.		*Location / ht. (aMSL.)*	*Description*		
X1 pin		525690.6, 439537.7, 16.7	Pin with yellow disc on kerb	Caravan Road	
Pin 1		525676.9, 439539.9, 16.4	Pin in road parallel to BH's 1A and 1B	Seaside Road	
Pin 2		525667.7, 439534.7, 16.3	Pin in road parallel to BH's 2A and 2B	Seaside Road	
Pin 3		525659.8, 439529.8, 16.23	Pin in road	Seaside Road	

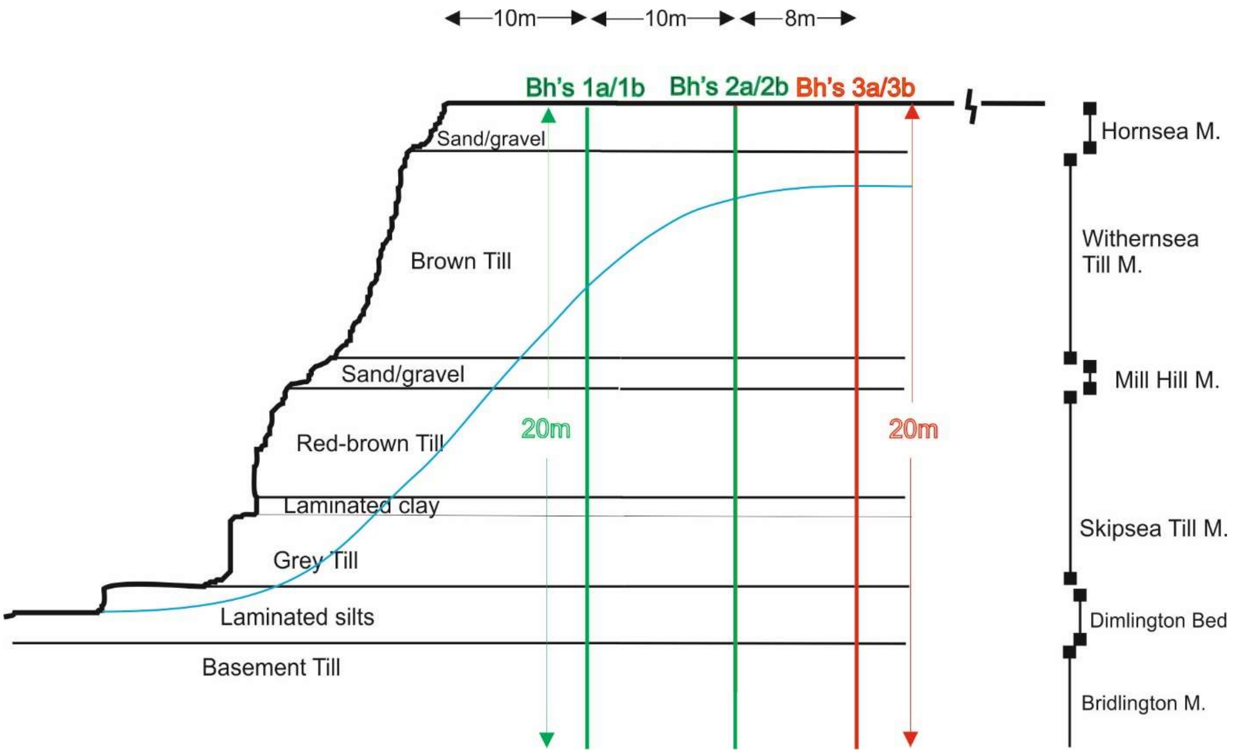

Figure 28 Cross-section at Aldbrough showing location of all boreholes (Phase 2 shown in red, Phase 1 in green)
NOTE: Water table (blue line) conceptual
NOTE: Borehole depths are nominal

6.3.3 Drill core

Core recovery was disappointing: 83 % on borehole 3b followed by 67 % on borehole 3a; giving a combined value of 70 %. This was considered to be due to:

1. Cobble-size clasts jamming in the bit on several occasions.
2. An intermittent jamming wireline latch problem.
3. Overdriving the drill and over-pressuring the flush water (?).

Items 1 & 2 were reported by the drill crew. It was unfortunate that a common size of clast within the tills seemed to match the internal dimeter of the core barrel! Item 3 was inferred by the authors from observations in field and lab.

Core of (nominal) diameter 109 mm was supplied, contained in transparent plastic liner, in 1.5 m lengths and placed in wooden core boxes, each containing a maximum of 3 m of core. In practice, many core runs were devoid of plastic caps, and none of those with plastic caps were sealed in any way, for example by PVC tape or by waxing (Figure 31). This led to some water content loss, particularly at both ends, during the period between drilling and opening the core at BGS, Keyworth, a period of about 3 weeks.

Figure 29 Example of core as supplied by ESG

The missing caps were replaced at BGS and all caps then sealed with PVC tape.
Core runs from the two boreholes featured significant gaps (Table 4):

Table 4 Gaps in core runs

Borehole	3a	3b	Combined
	0.00 to 1.60 m	0.00 to 1.20 m	0.00 to 1.20 m
	1.74 to 1.95 m	4.70 to 6.15 m	4.70 to 6.15 m
	3.45 to 4.88 m	12.10 to 12.33 m	12.10 to 12.33 m
	5.68 to 7.90 m	12.70 to 13.85 m	19.14 to 19.90 m
	10.10 to 10.90 m	18.80 to 19.85 m	
	11.65 to 12.40 m		
	15.16 to 15.40 m		
	17.90 to 18.40 m		
	19.14 to 19.90 m		

If the cores recovered are considered together (Table 4) a 'synthesized' total core recovery of 82 % was achieved. The fact that the boreholes were only 5 m apart, as well as evidence from the cores themselves, indicates that this is a reasonable conclusion.

6.3.4 Inclinometer

A 70 mm diameter 'Quick Joint' (QJ) inclinometer casing, of the same type used for Phase 1 (Boreholes 1b & 2b), was installed in borehole 3b to a depth of 19.85 m. This was set in a cement/bentonite grout as used in borehole 3a and the Phase 1 boreholes. A cap fitted to the base of the casing prevented ingress of grout during installation, but required partial filling with water in order to prevent flotation in the grout. *NOTE: The presence of this water which remains in the casing does not affect the use of the inclinometer probe.* The orientation (A+) of the installed and grouted inclinometer casing was measured to be N58 degr at ground level. Use of the inclinometer probe is described in section 6.2. The maximum deviation from vertical of borehole 3b as installed (as shown by 'absolute' inclinometer datasets) was 150 mm.

The PRIME borehole resistivity array was taped to the outside of the inclinometer casing (Figure 30). Refer to section 6.3.7.

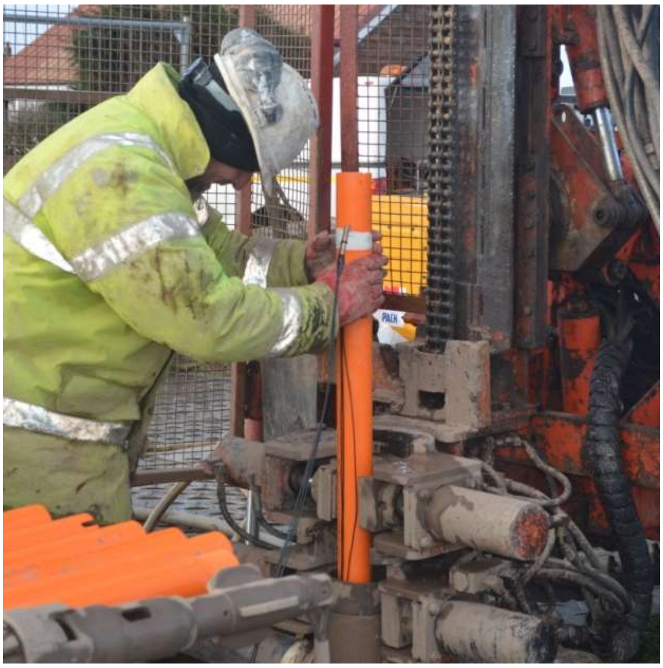

Figure 30 Inclinometer tube segment, with PRIME borehole resistivity array attached, being lowered in Borehole 3b

6.3.5 Piezometers

A Geosense 'fully-grouted' VWP-3001 multipoint vibrating-wire piezometer array was installed in Borehole 3a. This consisted of 6 sensors allowing pore pressure and temperature measurement mounted on a 20 m section of cable having a total cable length of 35 m; that is, with a further 15 m of trailing cable. These were positioned at depths of 1.7 m, 3.7 m, 7.7 m, 11.7 m, 15.7 m and 19.7 m **(**Figure 35**).** The piezometer array was connected via 15 m of trailing cable to a DT2055B 10-channel datalogger and a DT-2011B single channel datalogger; the former being the same as that used for Phase 1. However, in this case two channels were used for each sensor in order that borehole temperature could be recorded. The dataloggers were installed in the existing manhole which contains the datalogger from Phase 1.

Immediately prior to borehole installation the piezometer sensors were saturated in buckets of water for 2 hours so that the filter tips (Figure 31) were fully de-aired and the 'zero' readings could be recorded (in air) for subsequent calibration. Calibration procedures were carried out after borehole installation using data provided by Geosense, via laptop to the dataloggers. The calibration pressure range was -70 kPa to +345 kPa.

Table 5 Details of piezometer sensors (borehole 3a)

Ser. No.	Type	Depth (mBGL)	Wire colours	Terminal No.	Terminal block
331518	Piezo / thermistor	1.7	Red,black / green,black	P1	1A,1B / 2A,2B
332701	Piezo / thermistor	3.7	Blue,black / white,black	P2	1A,1B / 2A,2B
332720	Piezo / thermistor	7.7	Yellow,black / orange,black	P3	1A,1B / 2A,2B
332744	Piezo / thermistor	11.7	Brown,black / green,red	P4	1A,1B / 2A,2B
332823	Piezo / thermistor	15.7	Blue,red / white,red	P5	1A,1B / 2A,2B
332777	Piezo / thermistor	19.7	Yellow,red / brown,red	P6	1A,1B / 2A,2B

Figure 31 Piezometer sensor showing push-on cap containing high air-entry sintered alumina filter

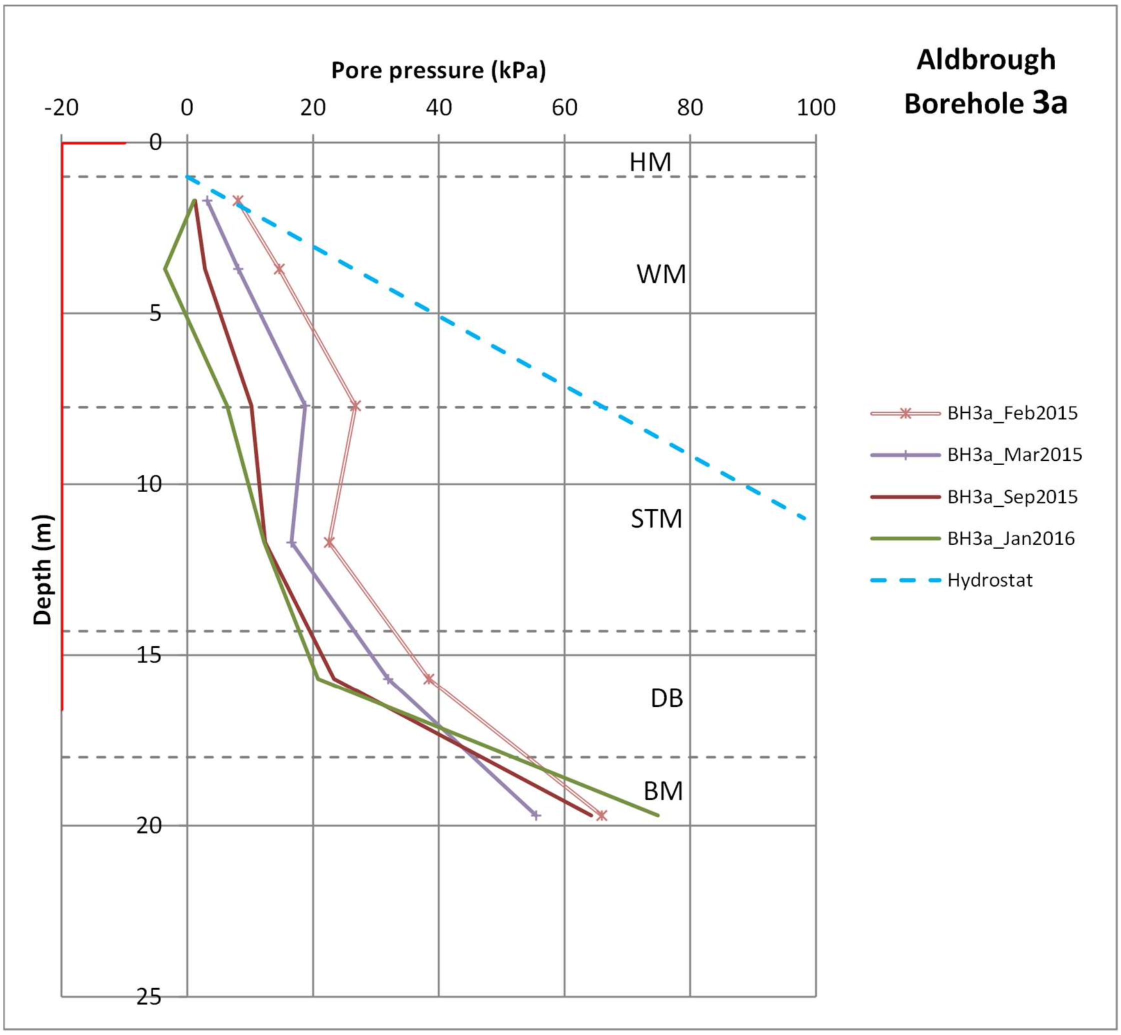

Figure 32 Plot of pore pressure vs. depth for BH 3a piezometer array (February 2015 to Jan 2016)
NOTE: Lines connecting sensor points are conjectural; red line (top left) indicates approximate cliff elevation
NOTE: Pore pressures have not equilibrated

It is too early to draw any conclusions from the piezometer data in borehole 3a, though at present they are lower than expected, particularly within the Skipsea Till Member.

6.3.6 Thermistors

The piezometer array installed in Borehole 3a contains, in addition to pore pressure sensors, thermistors which record temperature. *These were not available for the Phase 1 boreholes because all datalogger channels were allocated to piezometric sensors.* A time plot of the results from the thermistors is shown in Figure 33. Reductions in temperature over the first few days are probably due to the curing of the bentonite/cement grout in which the array is encased. The overall trend is for the temperature to be more constant with depth; the temperature at 19.7 m maintaining 10.5 degrees (+/- 0.5 degr.) throughout the year. With each increment of increasing depth the plot becomes flatter and less susceptible to seasonal temperature changes. There is also a distinct 'delay' in the seasonal response which increases with depth. For example, when the shallowest sensor (1.7 m) is approaching peak values in August the sensor at 7.7 m is only just starting to rise from its lowest value. The three lowermost sensors produce little or no seasonal variation in temperature; all values lying between 10.5 and 11 degr. It is also noted that, as expected, the shallowest sensor (1.7 m) has the least smooth curve; that is, it is more responsive to variations in air temperature.

These data will be used to correct the PRIME resistivities to a common temperature datum. Temperature corrections to the piezometer readings themselves are not considered practical with this type of installation.

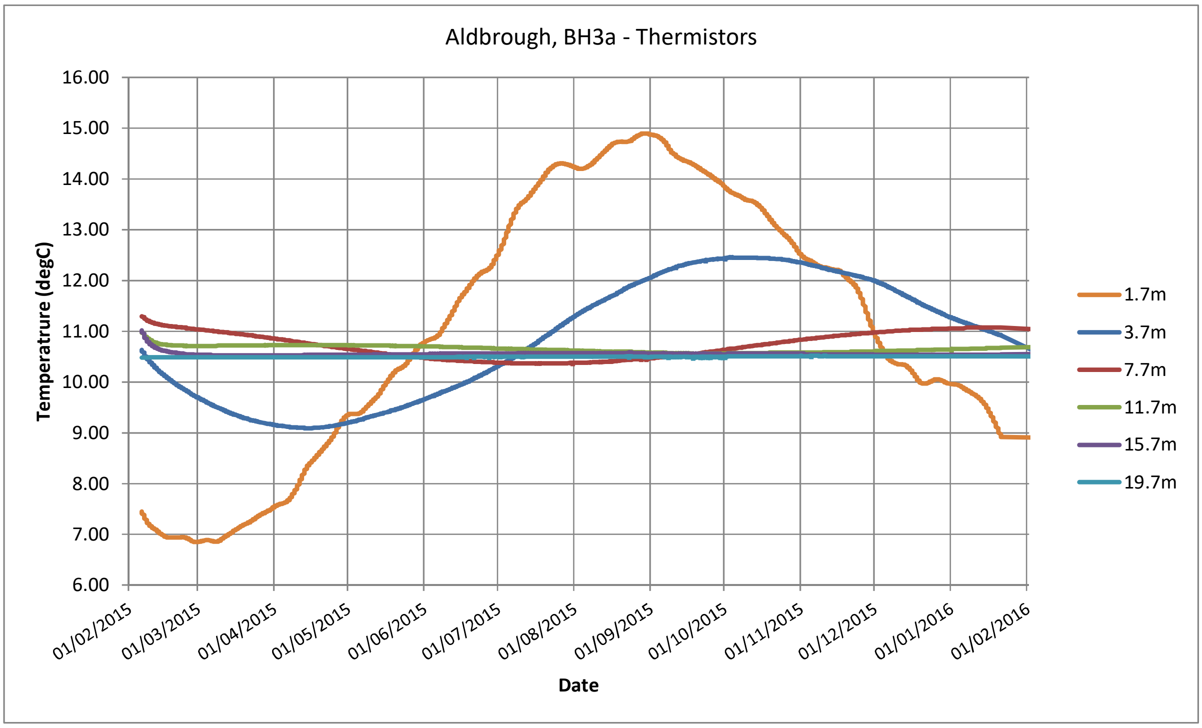

Figure 33 Plot of downhole temperature with time (BH 3a)

6.3.7 PRIME system

The Proactive Infrastructure Monitoring and Evaluation (PRIME) system, designed by BGS, is a new version of time-lapse Electrical Resistivity Tomography (ERT) which is used to generate images of the resistivity distribution in the subsurface, and can be deployed in the form of linear arrays, either downhole or on the surface (Figure 34) (Chambers et al, 2015). A pair of adjacent downhole arrays should allow fine-scale 'cross-hole' tomography to be employed with time-lapse data captured automatically and streamed in near real-time via a web interface. Resistivity is sensitive to both lithology and water content. Thus, in time-lapse mode it can detect changes in water content in 3D and 4D. Recent research at BGS's (inland) landslide field observatory at Hollin Hill, North Yorkshire (Uhlemann et al., 2017), has shown that the system may also be interpreted to measure ground movement. *It is not clear at present whether this technique can be used with the Aldbrough installations*. Previous studies of resistivity tomography as a tool for detecting cliff instability applied to chalk cliffs was described in Busby & Jackson (2005). The PRIME system is low cost compared with conventional ERT systems. The electronics are low-power and feature digital signal processing.

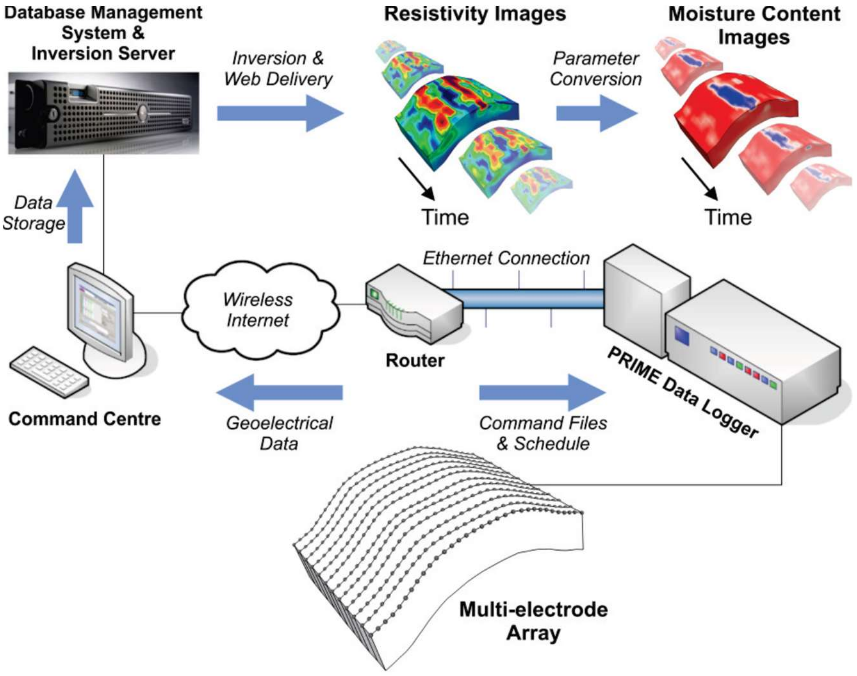

Figure 34 Proactive Infrastructure Monitoring and Evaluation (PRIME) system components for completed installation

The PRIME system at Aldbrough (Drilling Phase 2) was arranged as two borehole arrays (one each in Boreholes 3a & 3b) and one surface array. The electrodes resemble 15 cm long brass 'nails' which are hammered into the ground (surface array) or grouted in place (borehole array). The borehole arrays were taped to the inclinometer casing (BH 3b) in 3 m long sections which clipped together, and to sacrificial tremie pipe (BH3a) assembled in 3 m long sections which screwed together (Figure 35). These two arrays were positioned so that they faced each other in a NW-SE alignment (i.e. approximately parallel to the cliff line). Each downhole array has 20 brass electrodes spaced at 1 m intervals running from just below ground level to within 0.3m of the bottom of each hole. The absolute elevation difference between the arrays in Boreholes 3a and 3b is estimated to be about 0.25 m (3b being the higher), based on borehole depth record and dGPS ground surface measurements (Feb 2015).

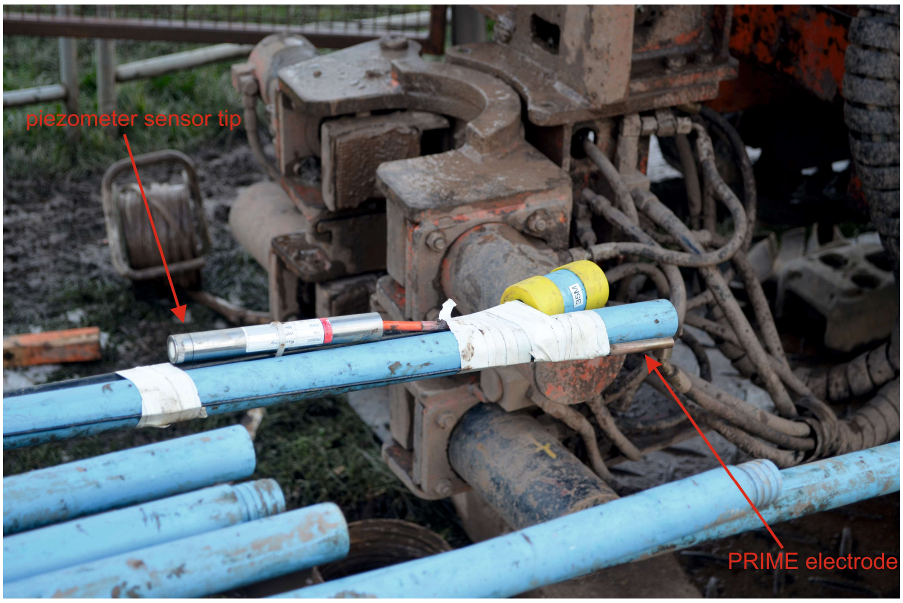

Figure 35 Lowermost PRIME resistivity array electrode taped to bottom section of sacrificial tremie pipe (blue) prior to installation in Borehole 3a

NOTE: lowermost stainless steel piezometer sensor (with orange cable & yellow junction) also taped to tremie pipe.

In Borehole 3b the PRIME resistivity array was attached to the outside of the (orange) inclinometer casing using tape (Figure 30); the lowermost electrode installed at a depth of 19.85 m in BH3b and the remaining electrodes at 1 m intervals up the hole to a depth of 0.85 m. The orientation of the array was towards BH3a. Trailing cables for the borehole arrays were installed in a shallow trench and fed through plastic conduit pipes (Figure 36).

Figure 36 Trench containing PRIME surface resistivity array and borehole resistivity array trailing cables emerging from Borehole 3b.
NOTE: capped borehole inclinometer casing for borehole 3b.

In Borehole 3a the PRIME resistivity array was attached to the outside of the (blue) sacrificial tremie pipe using tape (Figure 35). The lowermost electrode was installed at a depth of 19.90 m in BH3a and the remaining electrodes at 1 m intervals up the hole to a depth of 0.90 m. The orientation of the array was towards Borehole 3b.Trailing cables were installed in a shallow trench and fed through plastic conduit pipes (Figure 36). *The use of a bentonite/cement grout mix in borehole 3a (as for Phase 1 boreholes) has hopefully contributed to isolation of the PRIME system electrodes from the piezometer sensors, which otherwise may have interfered with each other electromechanically.*

The PRIME surface array has 24 electrodes (numbered RS01 to RS24) spaced at 1 m intervals. The arrangement of the surface array relative to boreholes 3a and 3b is shown in Figure 37.

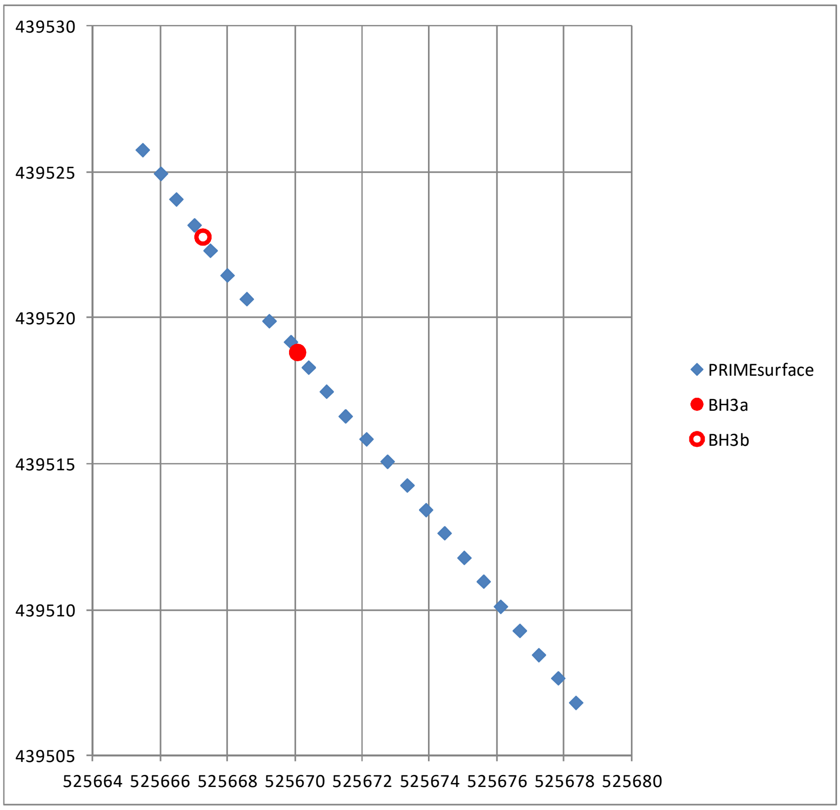

Figure 37 Location of PRIME surface array electrodes (RS01 at top; RS24 at bottom) and Boreholes 3a and 3b

7 Laboratory testing

7.1 GEOTECHNICS

Geotechnical samples have been taken from Boreholes 3a and 3b and the results summarised in Table 6. The tests and test results are described in Hobbs et al. (2015). The test schedule to date is summarised as follows:

- Triaxial strength/deformability: multi-stage, CIU (isotropically consolidated undrained)
- Shear box strength (peak)
- Ring shear strength (residual)
- 1-D oedometer consolidation & swelling pressure
- Index (Liquid, plastic and shrinkage limits, water content, particle density, particle-size)

Table 6 Geotechnical samples from Boreholes 3a and 3b

Bore hole	Sample	Depth (m)	Formatn. /Member.	Triaxial (multi-CIU)	Shear Box	Ring Shear	Oedom	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	BM/DB	✓	✓	✓	✓	✓
	Geotech 6	18.35 - 18.74	BM	✓			✓	✓

BH3a	Geotech 7	4.78 – 5.28	WM	✓			✓	✓
	Geotech 8	8.15 – 8.65	STM				✓	✓
	Geotech 9	12.65 – 13.15	STM				✓	✓
	Geotech 10	15.40 – 15.90	DB	✓		✓	✓	✓
	Geotech 11	18.40 – 18.90	BM	✓				✓

The test results, for which a detailed account is given in Hobbs et al. (2015), show that, in general, the tills' geotechnical behaviour is in keeping with data published elsewhere for Holderness tills (e.g. Powell & Butcher, 2003; Bell, 2002). Triaxial effective shear strength ranges from ϕ'= 25.2 to 34.2° and c' = 0 to 28.3 kPa; samples Geotech 1 and Geotech 6 being the strongest over the range of applied stress. Shear box tests gave a range ϕ' = 24.9 to 32.6° and c' = 0.6 to 17.3 kPa. Ring shear tests gave a range of ϕ_r' = 24.4 to 25.7° and c_r' = 4 to 10.0 kPa. The results are plotted in normal vs shear stress space in Figure 38. A dashed line representing combined effective CIU Triaxial results from Powell & Butcher (2003) from BRE's Cowden test site is also shown on the plot. It will be noted that the data from all three test types fall within a narrow envelope, at least until higher stresses are reached. However, the strength results for the till samples are within the envelope of published data for UK tills. An exception is the ring shear result for Geotech 10 which falls well below this envelope throughout the stress range.

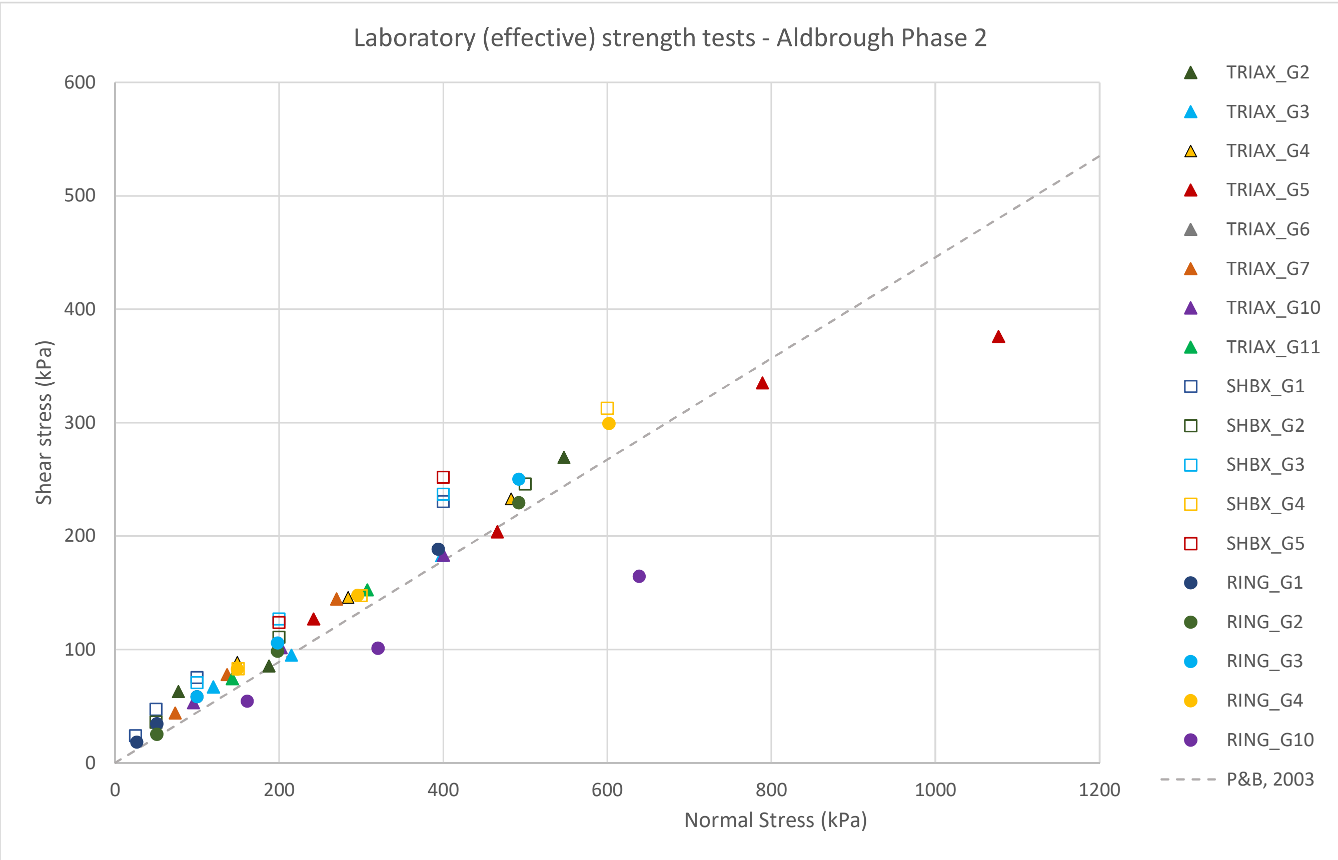

Figure 38 Plot of normal stress vs. shear stress for Triaxial (TRIAX), Shear box (SHBX) and Ring shear (RING) tests (BH's 3a & 3b) NOTE: P&B 2003 (Powell & Butcher, 2003)

If the strength data are converted to 'estimated effective shear strength', s' using the Mohr-Coulomb relation for soils and estimated overburden stresses based on measured density values, these are then plotted against depth in Figure 39.

Shear modulus data from cross-hole seismic tests carried out at Cowden (Powell & Butcher, 2003) show an overall increase with depth, but with constant modulus between 13 and 20 m. The change in behaviour at about 20 m was correlated with a gravel layer at that depth. Laboratory shear wave tests gave higher values of shear modulus with greater scatter compared with the field tests.

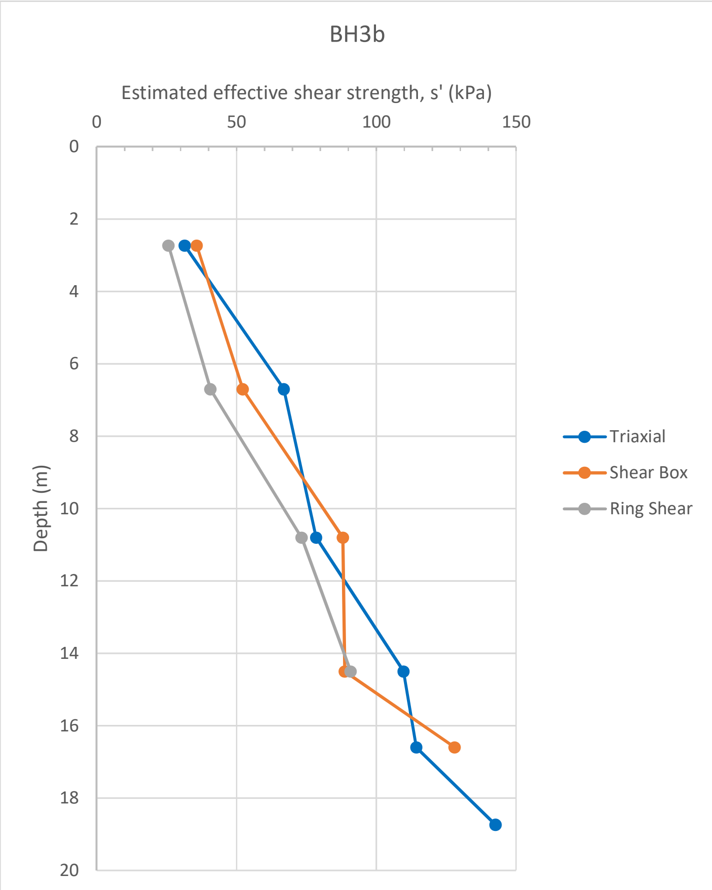

Figure 39 Plot of Estimated effective shear strength, s' vs. Depth for BH3b

The oedometer consolidation results are summarised in

Table 7 and Figure 40. These are taken from Hobbs et al., 2015. They include the maximum swelling pressure, P_{sw} and the over-consolidation ratio, OCR. *Note: Samples Geotech 6 and Geotech 11 have anomalous initial degree of saturation values; i.e. significantly greater than 100%.* The Bridlington Member sample (Geotech 6) plots below the rest on the e-logP (Figure 40), having a lower voids ratio overall. The Dimlington Bed samples (Geotech 5 and Geotech 10) plot above the rest having the highest voids ratios overall; Geotech 10 being notably separated from the remainder. The coefficients of volume compressibility, m_v do not vary significantly across the board, showing exponential decay with increasing applied stress and major reduction with increasing applied stress (below 250 kPa). The coefficients of consolidation, c_v are generally low at applied stresses greater than 250 kPa with the exceptions of Geotech 5 and Geotech 8 which are much higher across the range of stresses. The over-consolidation ratio (OCR) decreases with depth, as expected, from 4.0 to 0.5 (BH3b).

Table 7 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	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

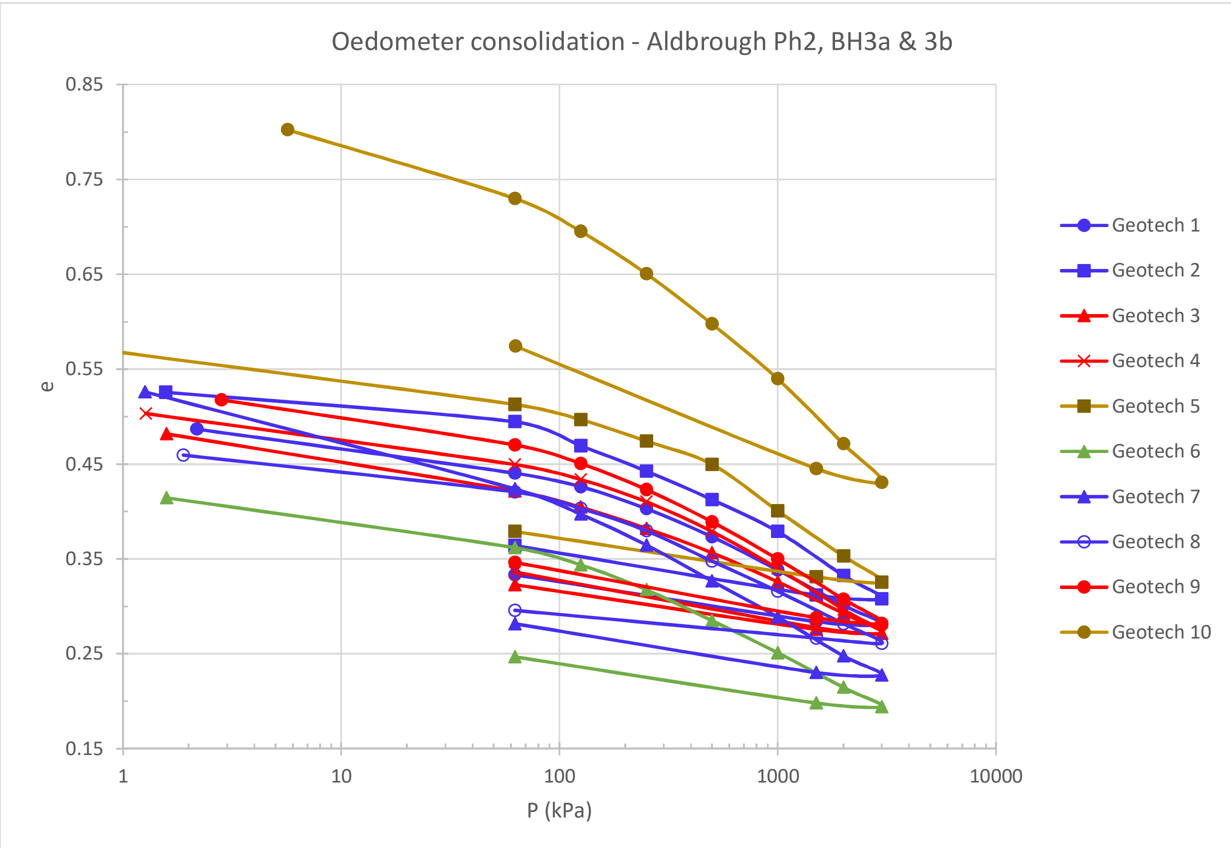

Figure 40 Plot of Applied stress, P vs. Voids ratio, e for oedometer consolidation test
NOTE: Blue = WM; Red = STM; Brown = DB; Green = BM

A summary of index test results is given in Table 8. These are taken from Hobbs et al. (2015). The Atterberg (plasticity) results show that the samples were clustered close to the 'Intermediate' and 'High' boundary and above the A-line on the Casagrande plot. These data lie approximately in the lower half of those reported by Powell & Butcher (2003) and Bell, 2002. Clay (fraction) contents again cluster between 25.4 and 38.2 %. Shrinkage limit tests, carried out on undisturbed samples, gave values for w_s ranging from 11.2 to 13.5 % with Geotech 2 having the greatest amount of volumetric shrinkage (ΔV = 10.9 %).

Table 8 Summary of index test results

Sample	Depth (m)	Strat.	w_0	γ_b	w_L	w_P	I_P	LS	w_s	Clay	Silt	Sand	Grav
			(%)	(Mg/m³)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)
Geotech 1	2.23 -2.73	WM	15.9	2.29	37	20	17	10.0	12	37.5	33	22.9	6.6
Geotech 2	6.41 - 6.70	WM	17.8	2.14	36	17	19	11.0	11.4	35.4	36	22.1	6.4
Geotech 3	10.3 - 10.80	STM	16.7	2.27	32	16	16	10.0	11.2	30.3	37.2	26.2	6.3
Geotech 4	14.1 - 14.60	STM/ DB	18.4		31	16	15	9.0	13.1	31.8	35.6	22.4	10.1
Geotech 5	16.1 - 16.60	BM/D B	21.8	2.15	31	16	15	9.0	13.5	33.8	41.5	19.2	5.5
Geotech 6	18.35 - 18.74	BM	14.3	2.3						25.4	24.2	28.6	21.8
Geotech 7	4.78 – 5.28	STM	14.9	2.22	33	17	16	10.0		29.8	30.9	22.5	16.8
Geotech 8	8.15 – 8.65	STM	15.7	2.12	26	15	11	7.0		27.7	29.3	33.9	9.1
Geotech 9	12.65 – 13.15	STM	18.8	2.10	34	17	17	9.0		31.8	32.9	24.0	11.3
Geotech 10	15.40 – 15.90	DB	26.2	1.96	54	23	31	12.0		38.2	57.6	4.1	0.0
Geotech 11	18.40 – 18.90	BM	15.0	2.22	30	14	16	9.0		25.4	28.1	34.2	12.4

w_0 = Water content

γ_b = Bulk density (Triax)

w_L = Liquid limit

w_P = Plastic limit

I_P = Plasticity index

LS = Linear shrinkage

w_s = Shrinkage limit

NOTE: The shrinkage limit tests were carried out using BGS's 'SHRINKiT' apparatus (Hobbs et al., 2014). This is a non-standard method

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). Elsewhere, geotechnical testing has been carried out on Holderness deposits.

Extensive geotechnical testing has been carried out over many decades by the Building Research Establishment (BRE), and others, at the 'lowland clay till' geotechnical research site at RAF Cowden situated at TA 245 403, approximately 2 km north of Aldbrough and 500 m from the coast. It was established in 1976 (Powell & Butcher, 2003; Marsland and Powell, 1985). Large-scale plate-loading tests were carried out in addition to extensive drilling, sampling, down-hole testing and laboratory testing. Piezocone, self-boring pressuremeter, dilatometer and vane tests were carried out and evaluated as part of the programme. These data were used to estimate over-consolidation ratio (OCR) and K_0 for the tills. Analysis of in-situ stresses indicated that vertical and horizontal stresses were virtually identical through most of the profiles (Powell & Butcher, 2003). A 'weathered zone' was identified between 4 and 5 m depth within which macro fabric discontinuities were found and where strength and stiffness increases with depth were not established. Only micro crack fabrics were identified below the weathered zone. Strength results from triaxial tests on high quality ('pushed') core samples were found to be close to those from the plate-bearing tests; the latter being considered to have produced the best results. In general, scatter of strength data was large when taken across all test methods and sample qualities, though good agreement tended to be shown for the 'high quality' sampling/testing methodologies. Other geotechnical appraisals include those of Bell (2002) and Bell & Forster (1991).

7.2 GEOPHYSICS

Following transport to BGS, Keyworth, and temporary storage at the NGDC there, drill core from BH3a and BH3b was logged and sampling locations selected. Prior to this, non-contact resistivity (NCR) measurements, using BGS/Geotek equipment (Figure 41), were made on the whole core prior to removal of the liner. The purpose of this was to help identify any deterioration of the cores, help with selection of sampling locations within it and to compare 3a with 3b prior to opening them up.

Figure 41 Non-contact resistivity (NCR) table with 1.5 m long core run (BGS, Keyworth)

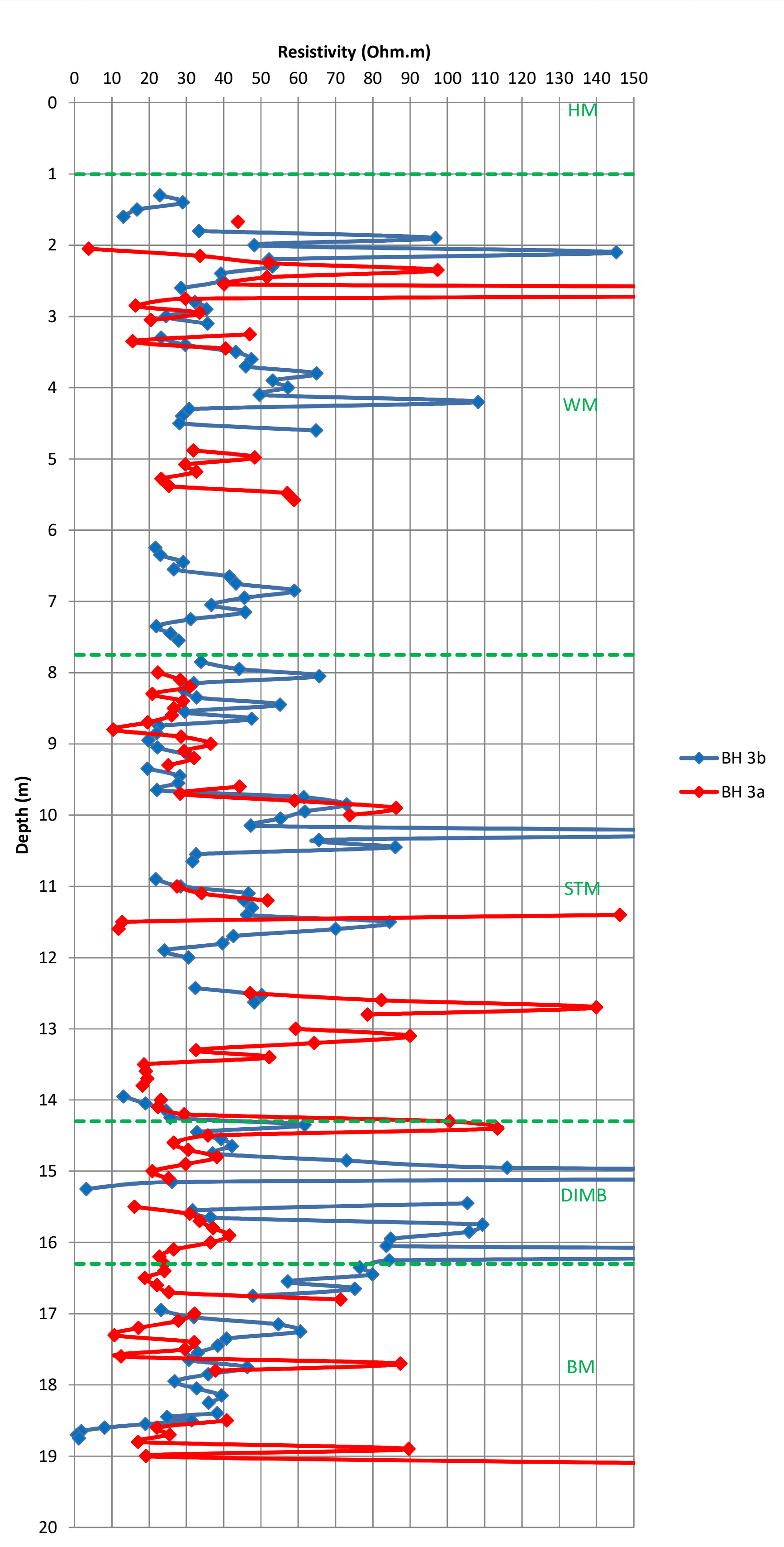

Figure 42 Non-contact resistivity test results for lined borehole core (NOTE: stratigraphy shown in green)

The results (Figure 42) show that resistivity averaged 49 ohm m (both boreholes combined) when the uppermost and lowermost readings were removed from each core run. A few very high values (>200 ohm m) are likely to represent air gaps due to separation of the core inside the liner. Alternatively, these may be due to fissures within the core, though none were observed during inspection of the core. The results for both boreholes show reasonably good agreement with the notable exception of the Dimlington Bed (14.2 m to 16.2 m), within which Borehole 3b resistivities are much higher. Between 2.0 and 2.8 m there are very high values in both boreholes but not at coincident depths; even allowing for the difference in borehole elevation of 0.18 m.

The relationship with stratigraphy is not clearly defined (Figure 42), though a general decrease in value is seen with depth for the Bridlington Member in BH3b. The average values, combining both boreholes, for each stratigraphic unit are: Withernsea M. (50.0 ohm m), Skipsea Till M. (43.1 ohm m), Dimlington Bed (66.3 ohm m) and Bridlington M. (38.0 ohm m). The high values for the Dimlington Bed probably reflect the (relatively) high porosity and partial saturation (due to poor core handling) within this layer. Further core logging for magnetic susceptibility will be carried out in due course.

8 Field geophysics

The Tromino is a portable geophysical device for rapidly analysing passive environmental seismic signals in the ground. The instrument has a 3-axis seismometer. A Tromino survey was carried out on 23 January 2015, immediately prior to Phase 2 drilling operations. The main purpose was to check the position of the chalk bedrock underlying the till, so that any risks of artesian conditions resulting from penetrating the chalk could be avoided. One interpretation of the result of the Tromino survey is given in Figure 43. This shows results from a section aligned perpendicular to the coast and extending beyond the borehole locations at either end. The velocity at which the model has been processed is 450 m/sec; this having been based on an initial assessment of the surface wave data at the lower end of the velocity range for this section. The ratio H/V is determined from curve fitting. The scale is dimensionless.

Interpretation of the Tromino profile (Castellaro S., & F. Mulargia, 2009) for a velocity of 450 m/sec indicates that the chalk lies at a depth of about 25m below mean sea level; that is about 37 m below ground level at the Aldbrough test site (this depth increases, however, if a velocity of 600 m/sec is selected). This marks a transition from resonance (log H/V) values less than 0.25 for the glacial deposits to greater than 0.25 for the chalk. The profile may also suggest a low resonance layer at about 20 m depth which may equate to the Dimlington Beds or the Bridlington Formation. The chalk depth inferred from the Tromino data appears to fit with regional estimates from geological evidence (Foster et al., 1976).

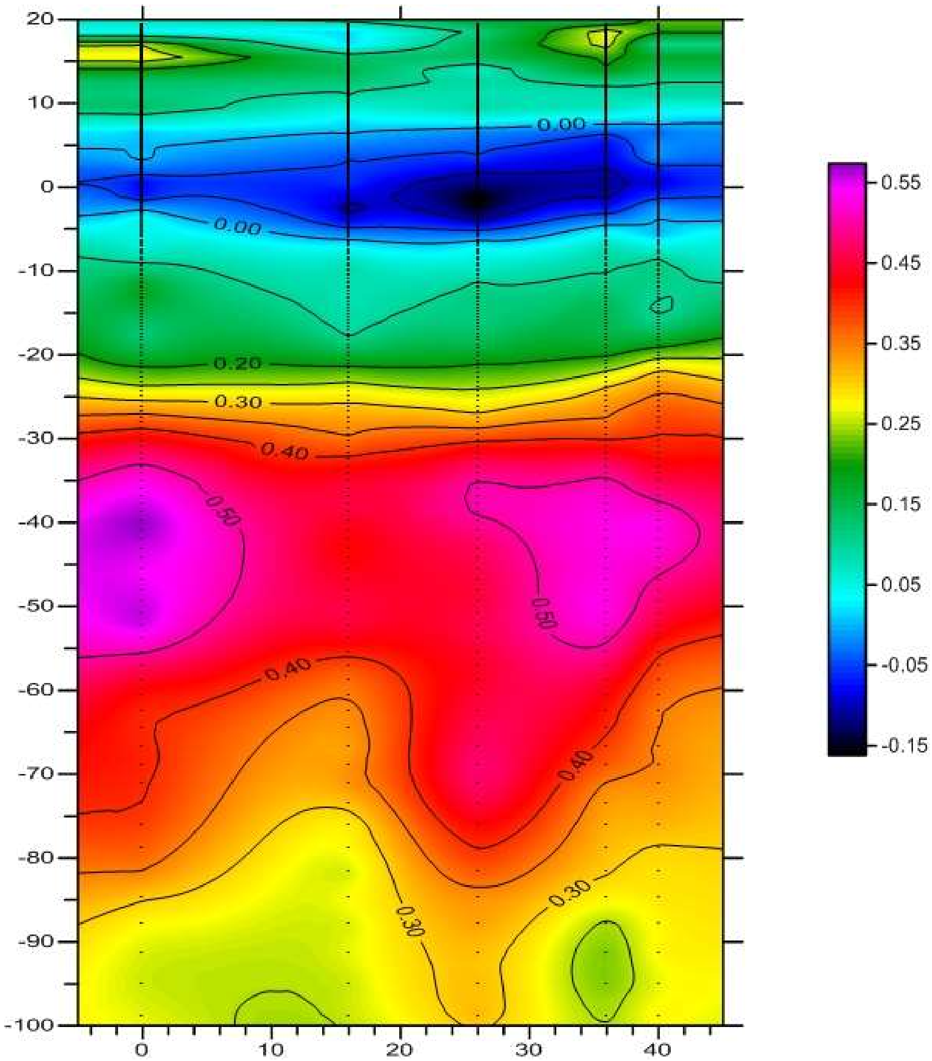

Figure 43 Tromino section showing interpretation of profile of resonance (log H/V) for Vs = 450m/sec

Cross-hole and surface-wave seismic measurements made at the BRE's 'lowland clay till' geotechnical research site at Cowden were described in Powell & Butcher (2003); The purpose of these was to obtain values of small-strain shear modulus and to obtain relationships with over-consolidation from the ratio of horizontal to vertical stiffness (see also Section 7.1).

9 Conclusions

The report describes the results of the 'drilling and instrumentation' component of a major study of coastal erosion and landsliding on a test section of the Holderness coast at Aldbrough between 2001 and 2015. The work has been carried out principally by the BGS's 'Slope Dynamics' task, within the 'Landslides' project, and has recently been developed to become a BGS 'coastal landslide field laboratory' to coincide with the introduction (Phase 1 in 2012 and Phase 2 in 2015), of six instrumented boreholes landward of the cliff at (initial) distances of 10, 20 and 28 m from the cliff-top (central embayment), to enable pore pressures and borehole displacement to be measured. It is anticipated that continuing cliff recession will interact progressively with these installations until ultimately slope failure occurs at each location; the process having been continuously monitored. The intention is for these installations to focus on precursors to slope failure and landslide cyclicity both on the cliff and landward of it, and to investigate the possibility of geotechnical variations related to stress relief and pore pressures. To date, the piezometer and inclinometer data from Phase 1 have shown small responses, apparently to cliff recession (reasonably oriented), and suggest that resolution of pore pressures and displacement will be good, in preparation for an anticipated major phase of landslide activity (central embayment) in 2016 and 2017.

<u>Borehole logs:</u>

It was not possible to obtain high quality continuous core in Phase 1, and this has been only partially achieved in Phase 2; the till lithologies in particular having proved unexpectedly difficult to core. The borehole logs for Borehole 3a and 3b (Phase 2) indicate that the sequence of glacial deposits at Aldbrough, modelled from the Phase 1 boreholes and from observations on the cliff, remains valid in all but minor detail. For example, the Mill Hill Member, consisting of sands and gravels, appears to be absent in the Phase 2 boreholes, and may also be absent from Boreholes 2a and 2b. The laminated silts, clays and sands of the Dimlington Bed were found between 14.5 and 16.5 m in Borehole 3b. This bed registered a sharp, and possibly anomalous, increase in the non-contact resistivity log. The tills are typically described as 'firm' to 'very stiff', whereas the laminated silts and clays are 'very soft' to 'soft'.

<u>Piezometers:</u>

It has been noted that, over the monitoring period for Phase 1 installations, the pore pressures have shown an overall reduction, including negative pressures in the 4 m sensor in Borehole 1a and intermittent negative pore pressures at the shallowest sensors in boreholes 2a and 3a. The piezometer array installed in BH3a (Phase 2) has required several months to equilibrate, as was the case for the Phase 1 arrays in BH's 1a and 2a. However, the pore pressure profile for Borehole 3a already resembles the initial profiles for BH's 1a and 2a though exhibiting lower pressures which, in common with BH's 1a and 2a, are markedly lower than hydrostatic throughout. The pore pressure profiles in both boreholes are significantly affected by the reduced pore pressures recorded within the Dimlington Beds. These have very similar values in both boreholes. There is also a notable and persistent reduction in pore pressure with time in BH1a at 20 m. The coalescence with time of pore pressures in BH1a suggests the presence near the cliff of vertical stress-relief fissures allowing equalisation through the strata. The instrumentation and monitoring of boreholes has provided useful data to support the project's main aims.

<u>Inclinometers:</u>

Overall, displacement vectors have continued in a consistent manner, suggesting a genuine reflection of ground movement; the trends being towards the northeast (seaward) for Borehole 1b and to the northwest or north for Borehole 2b. Both boreholes show movements increasing with time, although minor reversals occur apparently at random. Both holes show movements increasing up-hole over most of their depths, though again there are minor exceptions. Displacements in Borehole 1b have been up to 6 mm, while in Borehole 2b they have been up to 5 mm. The greatest displacements have been in the upper 0.5 to 1.5 m in each hole; that is within the Hornsea Member. The main difference between the boreholes to date has been that the trends in displacement with time in Borehole 1 have been constant whereas in Borehole 2b they have not.

NOTE: At the time of reporting, data for Borehole 3b are insufficiently established to make any interpretation.

NOTE: All displacements are small compared with the resolution of the inclinometer system. Future major landslide events may alter the trends observed to date.

<u>'PRIME' resistivity arrays</u>

The PRIME resistivity system consists of two borehole arrays (3a & 3b) and one surface array which were installed in Jan/Feb 2015 as part of the Phase 2 drilling programme. Telemetric monitoring of the arrays began in late 2015. At the time of writing 'good quality' data are being logged but as yet have not been analysed.

It is now possible, via the 'Slope Dynamics' methodology to accurately quantify coastal recession, changes in landslide morphology and cyclicity, and to provide 3D models at each stage of development, though confined, at present, to quarterly increments. The continuation of monitoring at Aldbrough is essential to build up what will be a unique dataset as far as British coastal landsliding is concerned and to span more than one 'cycle' of cliff development. It is believed that at the time of writing we are approaching this point. It is regrettable that continuous CCTV observation has not been possible at this site and hence daily observations and 'responsive' monitoring regimes have not been possible. Several strands of innovation have been brought to the task and it is hoped that these will develop into reliable analytical methods for sub-surface characterisation and monitoring.

Finally, a brief review of the drilling and instrumentation component of the project to date is given, in terms of benefits and uncertainties, as follows:

Benefits:

- The Phase 1 borehole instrumentation and weather station, installed in 2012, are continuously logged (except for inclinometers which are monitored quarterly) and have proved cost-effective and reliable. These have opened new opportunities for fundamental research at the site.
- Indications are that the Phase 1 borehole instrumentation is responding in a consistent and plausible manner in terms of the early trends in borehole displacement and pore pressure; both apparently affected by stress relief. It is assumed that these processes will continue as the cliff recedes towards the boreholes. A major new phase of landslide activity is anticipated at the test site in 2016/17.
- A deterministic approach has produced plausible models for cliff recession, confirmed by observation, and quantitative data for volumes of material displaced. Such detailed data have not been recorded elsewhere in Great Britain over such a long period. Models are continually augmented and adjusted to match fresh data coming in.
- Phase 2 drilling and installations were successful despite some challenges regarding multiple sensors (piezometer, inclinometer casing and PRIME arrays) combined with borehole casing removal. However, various ad-hoc solutions ultimately proved successful.
- The use of a universal bentonite/cement grout for vibrating-wire piezometer installation instead of sand 'pockets', whilst not novel, is not the traditional method of installing piezometers. It appears to have been successful, though this is difficult to assess analytically.
- Technological development in the fields of surveying and instrumentation during the lifetime of the task (15 years) has been immense. This has allowed for totally new types of data, and their interpretation, to be provided to the coastal modeller and engineering geological researcher. For example: UAV- derived photogrammetry, an exciting development in 3D modelling, and the PRIME resistivity tomography system in a 3D configuration.
- The ongoing technical developments described above have greatly improved the efficiency and data-richness of the 'Slope Dynamics' task.

Uncertainties:

- Core recovery was poor in Phase 1 and the methods used did not allow for 'undisturbed' sampling. Despite using a triple-barrel wireline system for Phase 2, core recovery was again poorer than expected.
- At this point in the study, only the PRIME arrays are scheduled for remote telemetry. This means that regular visits are required to download piezometer data from the 'a' holes and for the 'b' inclinometer holes to be probed. However, this fits well with the current surveying programme, which includes 3 or 6-monthly TLS (laser scanning) and is not considered a major impediment at present.
- During Phase 2 drilling persistent freezing conditions, combined with electrical problems on the rig, led to many interruptions to the work and a 3 day delay in completion overall.
- The monitoring which goes back to 2001 has coincided with major advances in surveying and digital instrumentation. This has meant that data from early in the project were inferior, particular with regard to point-cloud density and positioning, to those derived later. This has led to many issues of compatibility and accuracy. However, this was unavoidable as BGS, through its 'Slope Dynamics' task, has been active at the inception of some of these technologies. Work-arounds have been applied pragmatically to resolve most of these data quality issues.
- Software has been a persistent obstacle to progress in computer modelling, as has the cost of licensing it. A wide variety of software packages have been required to complete even the most basic modelling tasks. Of course, as with other factors, improvements to this situation are ongoing and proliferation of software, a feature of the early days of the task, has lessened.

- The weather station's anemometer suffered from corrosion to the bearings and failed after 4 years use, a situation presumably aggravated by the salty sea air.
- The precise dating of landslide, and other, events has not been possible due to a lack of surveillance, e.g. CCTV.

10 Recommendations

With respect to the 'Slope Dynamics' task it is recommended that:

- Data collection and monitoring are continued on a 3-monthly basis.
- The borehole instrumentation and weather station are maintained.
- Efforts are continued to streamline data processing and improve accuracy and efficiency of surveys. This may include remote telemetry applied to all existing installations.
- Interpretation of the results is maintained and reported in annual reports.

The borehole sensors installed from March 2012 should start to interact significantly with ongoing cliff recession in 2016/17, and the Phase 2 sensors over the following years, assuming processes continue at the measured rate.

The cyclic nature of the cliff recession may result in periods of accelerated change with respect to pore pressures and displacements. The complementarity between the instrumentation components of the project described here and the surveying / geomorphological components (Hobbs et al. 2013) should increase as the datasets become fuller and cover a greater time span.

The dating of specific landslide events has not been possible without some form of CCTV on site. Due to public and business sensitivities to surveillance, this type of monitoring is unlikely to receive approval.

It is recommended that, following successful analysis of the data from the present PRIME installation, that a further surface PRIME array is installed running perpendicular to the cliff line.

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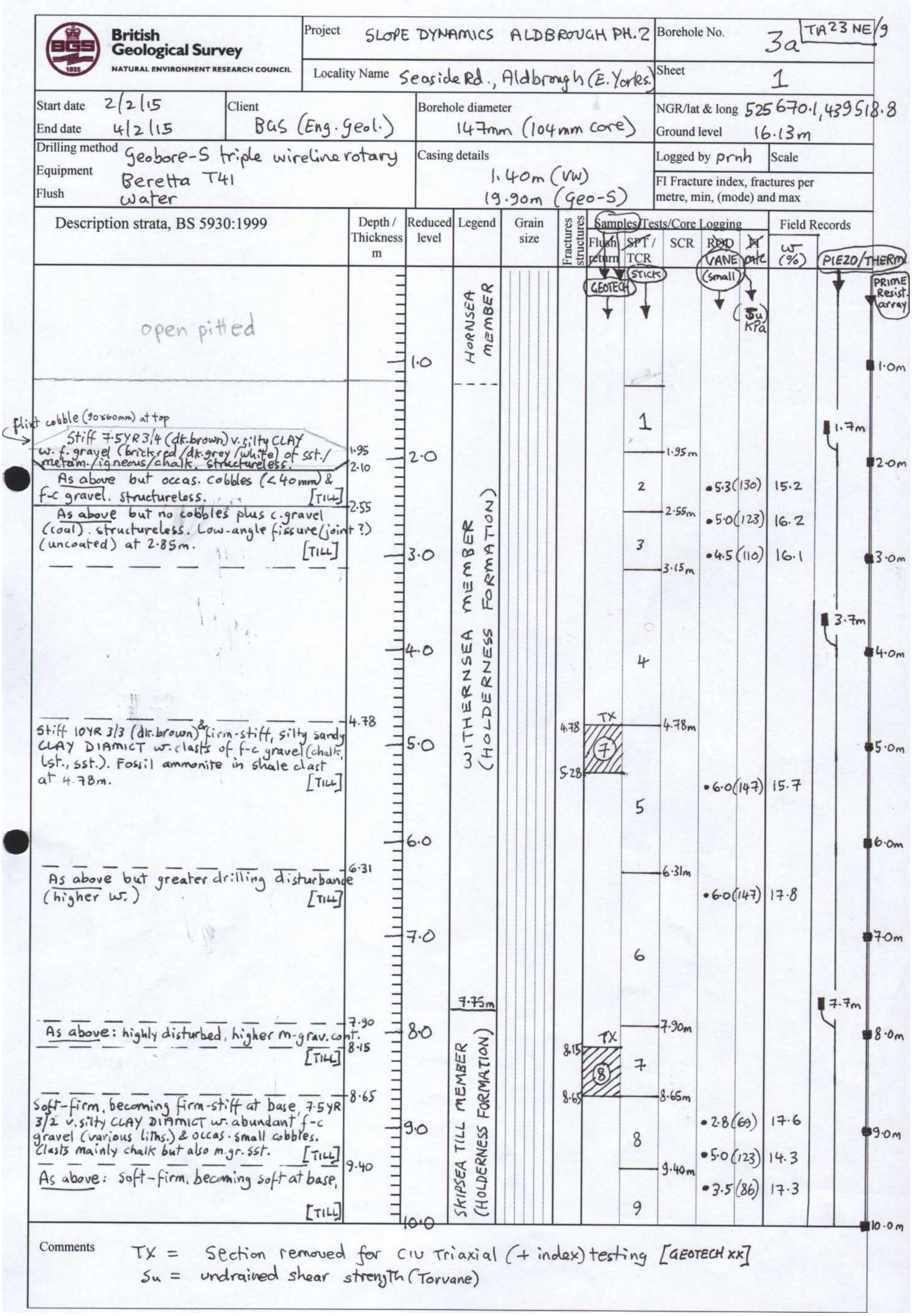
APPENDIX 1

Borehole logs (Phase 2)

Borehole 3a



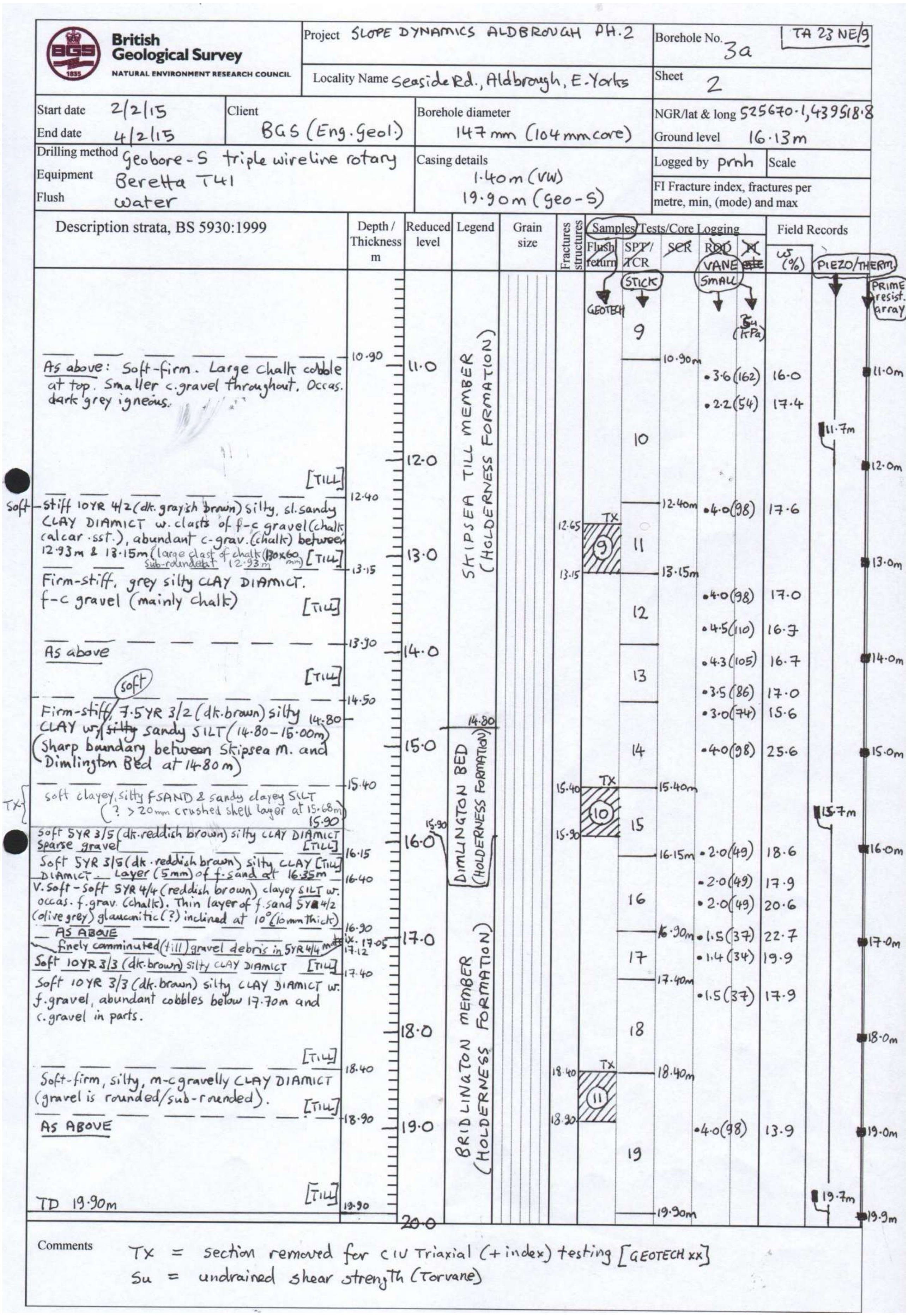
British Geological Survey — Natural Environment Research Council

Project	SLOPE DYNAMICS ALDBROUGH PH. 2
Borehole No.	3a TA23 NE/9
Locality Name	Seaside Rd., Aldbrough (E. Yorks.)
Sheet	1
Start date	2/2/15
End date	4/2/15
Client	BGS (Eng. geol.)
Borehole diameter	147mm (104mm core)
NGR/lat & long	525 670.1, 439 518.8
Ground level	16.13m
Drilling method	Geobore-S triple wireline rotary
Equipment	Beretta T41
Flush	water
Casing details	1.40m (VW); 19.90m (Geo-S)
Logged by	prnh
Scale	
FI Fracture index, fractures per metre, min, (mode) and max	

Description strata, BS 5930:1999	Depth / Thickness m	Legend	Samples/Tests/Core Logging	Field Records: Vane (small) Su kPa	w (%)
open pitted		HORNSEA MEMBER			
Flint cobble (90x60mm) at top. Stiff 7.5YR 3/4 (dk.brown) v. silty CLAY w. f. gravel (brick red/dk. grey/white) of sst./metam./igneous/chalk. Structureless.	1.95	WITHERNSEA MEMBER (HOLDERNESS FORMATION)	1 (to 1.95m)		
As above but occas. cobbles (<40mm) & f-c gravel. Structureless. [TILL]	2.10		2 (to 2.55m)	5.3 (130)	15.2
As above but no cobbles plus c. gravel (coal). Structureless. Low-angle fissure (joint?) (uncoated) at 2.85m. [TILL]	2.55		3 (to 3.15m)	5.0 (123); 4.5 (110)	16.2; 16.1
Stiff 10YR 3/3 (dk. brown) & firm-stiff, silty sandy CLAY DIAMICT w. clasts of f-c gravel (chalk, lst., sst.). Fossil ammonite in shale clast at 4.78m. [TILL]	4.78		4 (to 4.78m); TX sample 7 (4.78–5.28); 5	6.0 (147)	15.7
As above but greater drilling disturbance (higher w.) [TILL]	6.31		6 (from 6.31m)	6.0 (147)	17.8
As above: highly disturbed, higher m-grav. cont. [TILL]	7.90	SKIPSEA TILL MEMBER (HOLDERNESS FORMATION) (from 7.75m)	7 (from 7.90m); TX sample 8 (8.15–8.65)		
Soft-firm, becoming firm-stiff at base, 7.5YR 3/2 v. silty CLAY DIAMICT w. abundant f-c gravel (various liths.) & occas. small cobbles. Clasts mainly chalk but also m.gr. sst. [TILL]	8.65		8 (to 9.40m)	2.8 (69); 5.0 (123)	17.6; 14.3
As above: soft-firm, becoming soft at base. [TILL]	9.40		9	3.5 (86)	17.3

Piezo/therm: 1.7m, 3.7m, 7.7m. PRIME Resist. array: 1.0m – 10.0m.

Comments: TX = Section removed for CIU Triaxial (+ index) testing [GEOTECH XX]
Su = undrained shear strength (Torvane)



Borehole 3a [*SOBI*: TA23 NE/9]

Borehole 3b

British Geological Survey, NATURAL ENVIRONMENT RESEARCH COUNCIL	Project: SLOPE DYNAMICS (ALDBROUGH DRILLING PHASE 2)	Borehole No. 3b
	Locality Name: Seaside Road, Aldbrough (E. Yorks)	Sheet 1
Start date 27/1/15; End date 30/1/15	Client: BGS (Eng. Geol.)	Borehole diameter: 147 mm (104 mm core)
NGR/lat & long: 525667.3, 439522.8	Ground level: 16.31 m	
Drilling method: Geobore-S triple/wireline rotary	Casing details: 1.40 m (UW); 15.35 m (Geo-S)	Logged by: PRNH; Scale
Equipment: Beretta T41 (ESG)		FI Fracture index, fractures per metre, min, (mode) and max
Flush: Water		

Description strata, BS 5930:1999	Depth / Thickness m	Reduced level	Legend	Samples/Tests/Core Logging (TCR)
– open pitted –	1.20	1.0		↓ SAMPLES
Soft-stiff 7.5YR 4/4 (2.5Y 5/4) silty sandy CLAY w. f-c gravel, disturbed in upper 0.15m [TILL]	1.72		WITHERNSEA MEMBER (HOLDERNESS FORMATION)	111
Stiff 5YR 4/4 (reddish brown) silty sandy CLAY w. f-c gravel (sst., chalk, shale) structureless w. weathd sst. clasts (minor) [TILL]	2.23	2.0		109
— Sampled —	2.73			U ① 2.23–2.73m
Very stiff, 5YR 3/3 (dk. reddish brown), v. silty, sandy CLAY w. f-c gravel (chalk, sst, mst) Structureless [TILL]	3.21	3.0		109
Stiff 5YR 4/2 (dk. reddish grey) silty, sl. sandy CLAY w. f-c gravel (chalk, sst, mst) structureless [TILL]	3.96			101
(as above)	4.63	4.0		
(NO CORE RECOVERED) refer to BH 3a	6.15	5.0		7
(as above)	6.41	6.0		108
– sampled –	6.95			U ② 6.41–6.95m
Stiff 7.5YR 4/2 (dk. reddish grey) silty, sl. sandy CLAY w. abundant f-m gravel (dk. grey tabular lst. / rounded chalk / rounded sl. calcar. sst) [TILL]	7.75	7.0		108
Firm to stiff 10YR 3/3 (dk. brown) silty CLAY w. abundant f-c gravel (abundant chalk, rounded to sub-angular / dk. grey tabular lst. / subangular to sub-rounded reddish f.gr sst / subangular to tabular shale) [TILL]	8.50	8.0	SKIPSEA TILL MEMBER (HOLDERNESS FORMATION)	100
Firm to stiff, slightly fissd. 10YR 4/2 (dk. greyish brown) silty CLAY w. abundant f-m gravel (chalk / lst. / sst.), single c. grav clast of sst 10YR 5/8. Occas f-grav. black shale. Some c-sand size chk [TILL]	9.25	9.0		
Stiff .... (as above)	9.67			
Firm .... (as above) ↓		10.0		102

Field Records: INCLINOMETER CASING (QJ 70 mm) 0.0 → 19.85 m; 'PRIME' resistivity array

Comments: [U] = Undisturbed, full-diameter core for geotechnical testing (TX, Consol, Shrinkage, Index)
– – – core stick boundary
——— lithological boundary

Borehole 3b [*SOBI*: TA23 NE/10]

British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL	Project SLOPE DYNAMICS (ALDBROUGH DRILLING PHASE 2)	Borehole No. 3b
	Locality Name Seaside Rd., Aldbrough (E. Yorks)	Sheet 2
Start date 27/1/15 End date 30/1/15	Client BGS (Eng. Geol.) / Borehole diameter 147mm (104mm core)	NGR/lat & long 525667.3, 439522.8 / Ground level 16.31m
Drilling method Geobore-S triple wireline rotary / Equipment Beretta T41 (ESG) / Flush water	Casing details 1.40m (UW) 15.35m (Geo-S)	Logged by prnh / Scale
		FI Fracture index, fractures per metre, min, (mode) and max

Description strata, BS 5930:1999	Depth / Thickness m	Reduced level	Legend	Samples/Tests/Core Logging	SPT/TCR	Field Records
	10.03	10.0			102	'PRIME' resistivity array
(as above)	10.30				10.30	
— sampled —	10.80		SKIPSEA TILL MEMBER (HOLDERNESS FORMATION)	U (3)	10.80	
Stiff 10YR 3/2 (v. dk. greyish brown) v. silty CLAY w. dominantly sub-rounded to sub-angular f-m gravel size chalk, also sub-rounded to tabular lst. and black shale [TILL]	11.52	11.0			105	
(as above)	12.33	12.0				
Stiff 10YR 4/2 & 10YR 3/2 silty CLAY w. sub-rounded to sub-angular clasts (mainly chalk), also of minor black shale and dk. grey lst. [TILL]	13.85	13.0			24	
(as above)	14.10	14.0			14.10	
?-- — sampled —	14.60		--?--	U (4)	14.60	
V. soft 10YR 3/3 (dk. brown) silty f. SAND	14.68		DIMLINGTON BED (HOLDERNESS FORMATION)		101	INCLINOMETER CASING (QJ 70mm)
Soft clayey SILT w. f. sand 10YR 3/3	14.78 / 14.84					
Loose unif. 10YR 4/3 fine SAND 10YR 8/1	15.02	15.0				
Loose lamin. f. SAND w. f. gravel (chalk) 10YR 4/1, 10YR 4/3						
Firm 10YR 4/2 CLAY w. minor lamin. of silts 15.13–15.15m	15.35					
VOID	15.49					
Firm 10YR 4/2 CLAY w. minor lamin of silt	15.75				93	
Firm 10YR 3/3 fissd. thinly laminated CLAY w. silty f. sandy partings.	16.10	16.0			16.10	(P) 110-0121
?-- — sampled —	16.60		--?--	U (5)	16.60	
Firm-stiff 7.5YR 4/4 silty sandy CLAY w. clasts of f-m gravel (mainly chalk, also lst/sst.) [TILL]	16.85		BRIDLINGTON MEMBER (HOLDERNESS FORMATION)			0.00 → 19.85m
Firm-stiff 7.5YR 4/4 & 5YR 4/3 silty sandy CLAY w. sparse clasts of f-m gravel (chalk/lst/sst.) [TILL]	17.06	17.0				
Firm-stiff 10YR 3/3 (dk. brown) silty sandy CLAY w. sparse clasts of f-m gravel (chalk/lst/sst/mst) [TILL]	17.60				113	
Stiff 10YR 3/2 (v. dk greyish brown) & 10YR 3/3 from 17.60 to 17.87m, silty sl. sandy CLAY w. sparse clasts of f-c gravel (chalk/lst/greywacke shale/sst.) [TILL]	18.35	18.0			18.35	
— sampled —	18.74			U (6)	18.74	
(NO CORE RECOVERED)	19.85	19.0 / 20.0			27	

[LAMINATED SILT] (14.60–16.10m, left margin)

TD

Comments: [U] undisturbed, full-diameter core for geotechnical testing (TX, Consol, shrinkage, Index)

— — — Core stick boundary

——— lithological boundary

(P) photo

Borehole 3b [*SOBI*: TA23 NE/10]