Coastal landslide monitoring at Aldbrough, East Riding of Yorkshire, UK

P. R. N. Hobbs[*], **L. D. Jones, M. P. Kirkham, C. V. L. Pennington, D. J. R. Morgan & C. Dashwood**

British Geological Survey, Keyworth, Nottingham NG12 5GG, UK

P R NH, 0000-0001-7225-5852; C V LP, 0000-0002-3560-9030

[*] Correspondence: prnh@bgs.ac.uk

Abstract: The paper describes results to date of a continuing monitoring study of coastal 'soft cliff' recession at the British Geological Survey's (BGS's) Coastal Landslide Observatory (CLO) on the east coast of England at Aldbrough, East Riding of Yorkshire. The cliffed site, part of the 50 km long Holderness coast, consists of glacial deposits, and is one of the most rapidly eroding coastlines in Europe. This rapid rate of erosion provides an ideal opportunity for observation and process understanding because it facilitates the collection of data over periods of time encompassing significant new landslide events at the same location. The results of two approaches are reported: first, terrestrial Light Detection and Ranging (LiDAR) surveying (TLS); second, the installation of instrumented boreholes. The aim of the research is to combine these to investigate the role of landslides and their pre-conditioning factors and the influence of geology, geotechnics, topography and environmental factors on cliff recession. To date, an average recession rate of 1.8 m a^{-1} and a maximum rate of 3.4 m a^{-1} have been recorded for the site. The establishment of the CLO and its conceptual geological–geotechnical model are described in a related paper.

Received 18 December 2018; **revised** 24 April 2019; **accepted** 12 May 2019

This study follows that of Dixon & Bromhead (2002), which monitored deep-seated rotational landsliding in the London Clay Formation at Warden Point, Isle of Sheppey, Kent; in particular, their observations (since 1971) of first-time movements and the extensive use of piezometers. More recently, the value of the application of terrestrial-based Light Detection and Ranging (LiDAR) techniques to monitoring cliff recession is now widely recognized (Hobbs *et al.* 2002, 2013; Rosser *et al.* 2005; Poulton *et al.* 2006; Young & Ashford 2006; Quinn *et al.* 2010). The Holderness coast has been the subject of intensive study for many decades (Valentin 1971; Pringle 1985; Butcher 1991; Pethick 1996; Prandle *et al.* 1996; Lee & Clark 2002; Newsham *et al.* 2002; Brown 2008; Lee 2008, 2011; Quinn *et al.* 2009, 2010) and recently 'process-response' modellers have focused on this coastline (Walkden & Dickson 2008; Ashton *et al.* 2011; Walkden & Hall 2011; Castedo *et al.* 2012, 2015). Holderness is reported to have the fastest receding coastline in Europe at 2 m a^{-1} overall (Bird 2008; Castedo *et al.* 2015). The British Geological Survey's (BGS's) Coastal Landslide Observatory (CLO) is situated 10 km SE of Hornsea (Fig. 1) and 2 km SE of the Building Research Establishment's (BRE) Cowden 'lowland clay till' geotechnical research site (Marsland & Powell 1985).

That part of the study described here is based on the conceptual model outlined by Hobbs *et al.* (2019) and seeks to refine it further. The nature of landsliding at the CLO has been observed to be primarily deep-seated rotational with secondary toppling and mudflow. Deep-seated landslides occur episodically within established embayments, topples occur frequently both within land-slipped masses and on unslipped promontories, whereas mudflows occur less frequently on the peripheries of landslide masses. The tills are jointed and there is evidence of stress relief in the tills forming the cliff causing fresh discontinuities and opening of existing ones. Erosion at the cliff toe is virtually continuous throughout the year but is affected by the presence (or otherwise) of a sandy beach, the thickness, content and location (on the platform)

of which vary throughout the seasons. The precise morphology of the rotational landsliding is influenced by the complex disposition of the various glacial deposits forming the cliff and the results of several stages of glacial advance and retreat (Evans 2017). Fortuitously, a fresh landslide event (14 February 2017) occupying the greater part of the central embayment was observed by ground staff at the leisure park and reported to the authors. This was arcuate in plan with an initial vertical displacement of 50 mm and occupying about 80% of the embayment's length.

The Aldbrough CLO encompasses three landslide embayments, which have persisted throughout the monitoring period. Surveys have been carried out at 3 or 6 month intervals, although the precise interval has varied from 2001 to the present. The boreholes are aligned with, and landward of, the central embayment and are perpendicular to the coast. Details of the project's survey and monitoring (2001–2013) have been given by Hobbs *et al.* (2013), drilling and instrumentation (to 2015) by Hobbs *et al.* (2015a) and geotechnical laboratory testing by Hobbs *et al.* (2015b).

Engineering geology

The lithostratigraphy at the site is summarized in Figure 2; a fuller description has been provided by Hobbs *et al.* (2019). From an engineering geology viewpoint the major till units, belonging to the Withernsea, Skipsea Till and Bridlington Members of the Holderness Formation, represent fissured, lightly to heavily over-consolidated materials having similar geotechnical properties that are in general agreement with descriptions by Bell & Forster (1991), Bell (2002) and Powell & Butcher (2003). However, the laminated, silty, clayey (and glacitectonized) Dimlington Bed between the Skipsea Till and Bridlington members, at around 15 m depth, combines low strength and high average permeability with high plasticity and compressibility. Evidence from exposure on the cliff, when compared with the borehole logs, suggests that the Dimlington Bed is prone to liquefaction and may have undergone
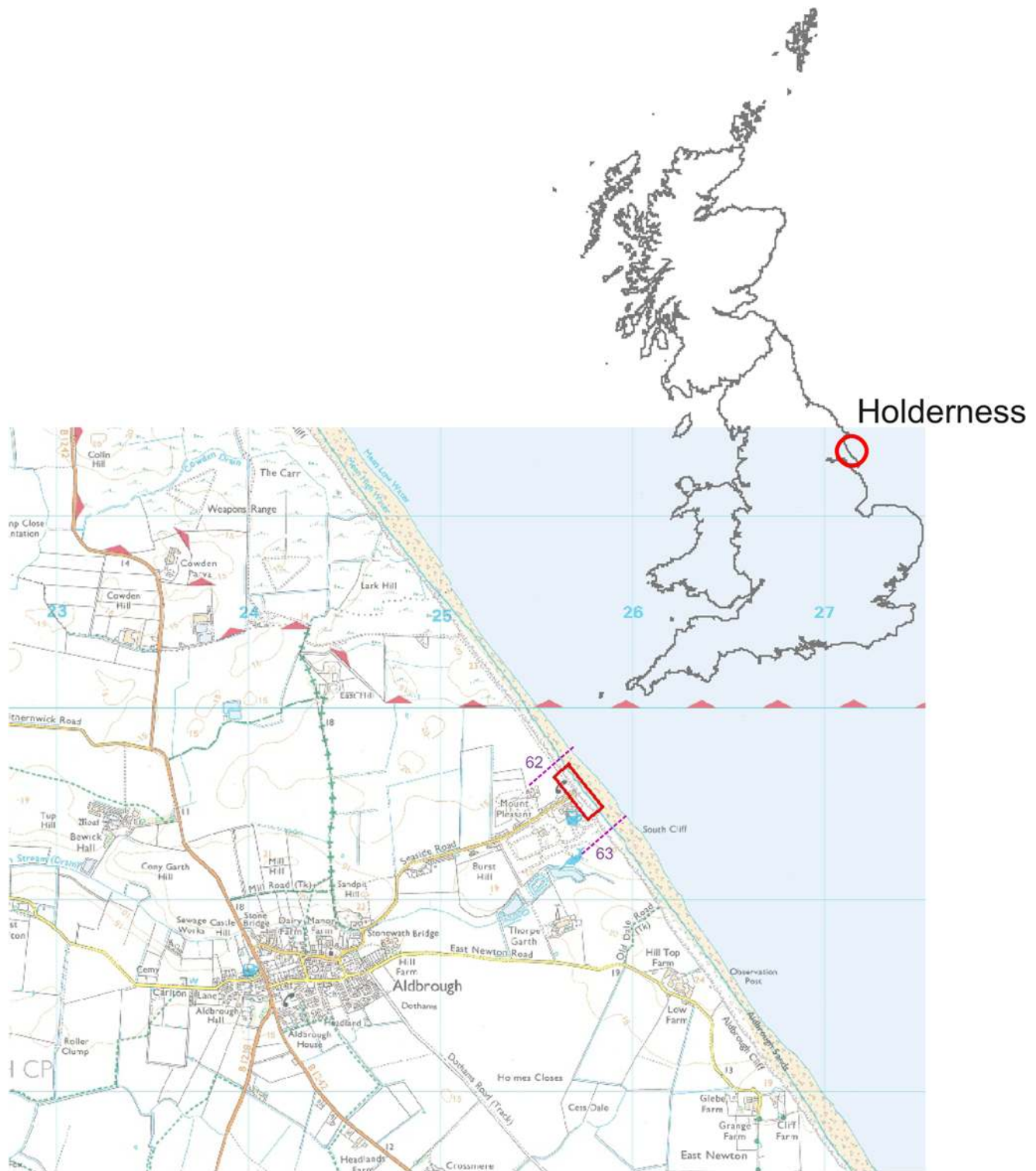
Fig. 1. Map showing location of Aldbrough Coastal Landslide Observatory, CLO (box) (BGS©UKRI). Contains Ordnance Survey data © Crown Copyright and database rights 2018.

extrusion and thus thinning of the bed at the cliff. It is unclear whether or not minor observed (pre-landslide event) subsidence close to the cliff edge can be attributed to this.

Geotechnical laboratory testing, described in detail by Hobbs *et al.* (2019), has revealed the following at the Aldbrough CLO: (1) the Dimlington Bed has 'high' plasticity, higher clay and silt contents and higher water content and shrinkage limit than the tills and is weaker, more permeable and more compressible than the tills; (2) the tills have a 'low' to 'intermediate' plasticity, well-graded particle-size distribution and 'medium' shrinkage limit; (3) the upper part of the Withernsea Member shows features attributable to weathering; (4) the effective peak shear strength behaviour and densities of the tills are similar; (5) residual strengths for the till members are very similar whereas that for the Dimlington Bed is much lower; (6) residual friction angles for the till members are high owing to significant sand content (the strength sensitivity of the tills is likely to be small (Reeves *et al.* 2006), although specimen size and preparation need to be taken into account); (7) geotechnical

Fig. 2. Schematic stratigraphy with photograph of central (100 m) embayment (not to scale) (BGS©UKRI). M, Member.

differences between tills are minor and are in general agreement with published values.

The landslide and hydrogeological processes within the CLO cliff slope are in dynamic equilibrium, in the sense of 'competing' processes tending to cancel each other out, but only temporarily, thus resulting in episodic activity (Chandler & Brunsden 1995). For example, the zone of partial saturation increases in depth towards the cliff, as evidenced by established negative piezometric pore pressures; these marginally reduce vertical stress and increase intact effective strength in that part of the cliff; at the same time stress relief reduces mass strength. Significant groundwater has been observed being discharged from the Mill Hill Bed to the cliff, and a much smaller amount by the silt laminae within the Dimlington Bed. However, the dynamic equilibrium is affected by the initiation, and progress, of fresh rotational landslides on the cliff as groundwater pathways are partially blocked under certain conditions of landslide displacement. Overall, pore pressures measured in the borehole piezometer arrays are much lower than hydrostatic. There is evidence of increased saturation and consequent softening of the tills immediately adjacent to the Mill Hill and Dimlington Beds. Factors in the hydrological regime are a possible lack of continuity of some strata and the presence of stress-relief fissures close to the cliff. Although all formations are believed to persist throughout the CLO, poor borehole core recovery has not allowed this to be confirmed.

A further factor in the hydrogeology regime is the spacing and persistence of joints within the tills and the consequent increase in the mass permeability of the formations. Trial drilling in Phase 1 using air-flush suggested the presence of persistent open joints within the Withernsea Member, although their influence may have been exaggerated by near-surface desiccation cracks. Examination of Phase 2 borehole core, initially 28 m landward (in 2015) of the cliff, revealed few joints and fissures compared with those exposed on the cliff. It is likely that, close to the cliff, vertical transmission of groundwater is greatly enhanced by stress relief fissures.

Cliff recession monitoring

Since 2001, cliff monitoring has been maintained at the Aldbrough test site using Terrestrial LiDAR Surveying (TLS) (Hobbs *et al.* 2002, 2013, 2015*a*; Poulton *et al.* 2006; Miller *et al.* 2007; Buckley *et al.* 2008), more recently augmented by unmanned aerial vehicle (drone) photogrammetry. The data from the TLS are used to construct digital elevation models (DEMs), examples of which are shown in Figure 3. These were compared and used to characterize landslide processes and to calculate volume changes between surveys. Up to November 2017, 38 surveys had been carried out at Aldbrough, 27 of which have been used in volume calculations. The data obtained from the monitoring surveys have allowed geomorphological assessments and multiple cross-sections for slope stability analyses to be derived. Volumes lost from the cliff have been calculated directly from the TLS models for the period September 2001 to November 2017 (Table 1; Fig. 4), these representing a potentially useful calibration dataset for coastal process modelling (Pethick 1996; Walkden & Dickson 2008). The data shown have been extracted from the central 100 m of the study site retreating along the line of recorded migration of the central embayment.
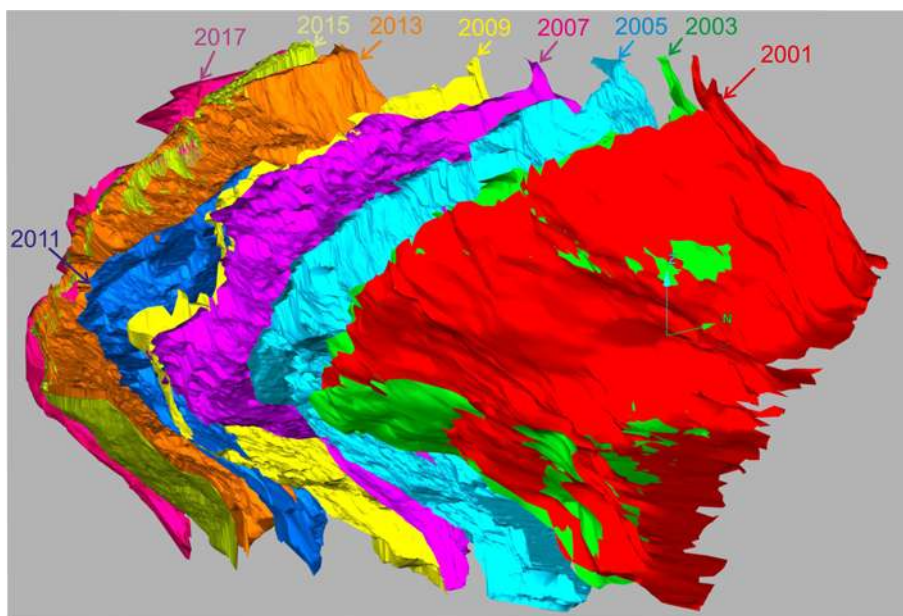

Fig. 3. Selected biennial digital elevation models (DEMs) for CLO cliff (central embayment) (BGS©UKRI). Intermediate DEMs are omitted for clarity. Width of DEM is 100 m.

Table 1. *Table of cliff recession derived from selected TLS surveys, September 2001 to November 2017. (BGS©UKRI)*

Date	Period start	end	Increm. time (days)	Cumul. time (days)	Increm. loss /100 m (m³)	Cumul. loss /100 m (m³)	Cumul. loss/m (m³)	Increm. loss /100 m (tonnes)	Cumul. loss /100 m (tonnes)	Cumul. loss/m (tonnes)	12 mnth incr. loss /100 m (m³)	Mean recess. rate (m/yr.)
01-09-2001		Sep-01				0		0	0			
18-04-2002	Sep-01	Apr-02	229	229	1700	1700	17	3570	3570	36		
18-09-2002	Apr-02	Sep-02	165	394	800	2500	25	1680	5250	53	2500	1.5
10-10-2003	Sep-02	Sep-03	375	769	1500	4000	40	3150	8400	84	1500	0.9
07-04-2004	Sep-03	Apr-04	180	949	3100	7100	71	6510	14910	149		
19-08-2004	Apr-04	Aug-04	134	1083	700	7800	78	1470	16380	164	3800	2.4
18-09-2005	Aug-04	Sep-05	395	1478	6800	14600	146	14280	30660	307	6277	3.4
06-09-2006	Sep-05	Sep-06	353	1831	3100	17700	177	6510	37170	372	3100	1.8
30-08-2007	Sep-06	Aug-07	358	2189	1200	18900	189	2520	39690	397	1200	0.8
28-04-2009	*Aug-07*	*Apr-09*	*607*	*2796*	*7200*	*26100*	261	*15120*	*54810*	*548*	*4320*	*1.5*
22-10-2009	Apr-09	Oct-09	177	2973	3200	29300	293	6720	61530	615		
03-03-2010	Oct-09	Mar-10	132	3105	1900	31200	312	3990	65520	655	5100	3.3
27-07-2010	Mar-10	Jul-10	146	3251	1900	33100	331	3990	69510	695		
08-02-2011	Jul-10	Feb-11	196	3447	1100	34200	342	2310	71820	718	3000	1.9
22-03-2012	Feb-11	Mar-12	408	3855	3600	37800	378	7560	79380	794	3600	2.0
25-06-2013	Mar-12	Jun-13	460	4315	2700	40500	405	5670	85050	851	2160	1.0
20-01-2014	Jun-13	Jan-14	178	4493	1700	42200	422	3570	88620	886		
23-09-2014	Jan-14	Sep-14	238	4731	500	42700	427	1050	89670	897	1886	1.0
03-02-2015	Sep-14	Feb-15	129	4860	600	43300	433	1260	90930	909		
18-05-2015	Feb-15	May-15	105	4965	800	44100	441	1680	92610	926		
15-07-2015	May-15	Jul-15	58	5023	200	44300	443	420	93030	930		
28-09-2015	Jul-15	Sep-15	77	5100	500	44800	448	1050	94080	941	2100	1.1
21-01-2016	Sep-15	Jan-16	115	5215	1500	46300	463	3150	97230	972		
06-07-2016	Jan-16	Jul-16	169	5384	1400	47700	477	2940	100170	1002		
19-10-2016	Jul-16	Oct-16	96	5480	2300	50000	500	4830	105000	1050	5200	2.6
01-03-2017	Oct-16	Mar-17	120	5600	1800	51800	518	3780	108780	1088		
18-05-2017	Mar-17	May-17	138	5738	600	52400	524	1260	110040	1100		
23-11-2017	May-17	Nov-17	101	5839	600	53000	530	1260	111300	1113	3000	1.6
TOTALS	**Sep-01**	**Nov-17**		**5839**		**53000**	**530**		**111300**	**1113**		

TLS data are unavailable for 2008. Mean recession rate is here calculated from incremental volumetric loss for each monitoring period by normalizing the monitoring period to 12 months and dividing by cliff height (17 m) and test section width (100 m). Whilst being an approximation in terms of cliff height, this is not a cliff-top recession rate.

The cumulative volume loss for the study period to date (1 September 2001 to 23 November 2017; i.e. 16.2 years) was 53 000 m³ per 100 m along coast; giving an estimated gross weight of 111 300 tonnes. This translates to a total of *c.* 27 m linear recession. Twelve month volumetric losses from the cliff (Table 1) in the central embayment of the CLO range from 1.2 to 6.3 m³ m⁻¹ (along coast); the average being 3.3 m³ m⁻¹. These figures equate to sediment yield, if sediment retained on the beach is included (Prandle *et al.* 1996; Newsham *et al.* 2002). The average equivalent cliff recession of the study site over the monitoring period, derived from TLS, is 1.9 m a⁻¹. This agrees with historical average recession rates for Holderness as a whole, obtained from point data, of 0.80–2.0 m a⁻¹ determined by Pethick (1996) and Castedo *et al.* (2015), but greater than the 1.3 m a⁻¹ average of Quinn *et al.* (2010).

Landslide processes

The conceptual geological–geotechnical model for the CLO is shown in Figure 5. This has been derived from data described by Hobbs *et al.* (2019).

The primary type of landsliding at the CLO is observed to be deep-seated rotational. These landslides daylight 1–3 m above the cliff toe, a position largely determined by the undulating boundary between the Bridlington Member and the Dimlington Bed. This compares with a deeper-seated landslide at nearby Cowden cliff

described by Butcher (1991) as having a 'compound' slip surface, rather than a simple rotational one, extending to several metres below sea-level. Indeed, such landslides have been observed to the south of the CLO daylighting beneath beach level and also on the north Norfolk coast at Sidestrand (Hobbs *et al.* 2008). Dixon & Bromhead (2002) in their study of London Clay landslides at Warden Point, Isle of Sheppey, Kent, noted that bedding-related features 'controlled the location of the basal part of the slip surface' and that this was normal in stiff plastic clays. Major rotational landslide events at the CLO result in cliff-top recessions of up to 7 m at mid-embayment (Fig. 6a and d) with near-vertical backscarps fully exposing the Hornsea Member. Pickwell (1878) emphasized the role of the 'boulder clay' (Bridlington Member) in providing the base of the landslips and a 'revetment' against erosion of the overlying deposits and landslide debris, depending on its elevation locally. He also illustrated types of rotational and composite landslides on the Holderness coast, including at 'Aldborough' (Pickwell 1878, fig. 6) and gave detailed accounts of losses of land from the period. He added that 'Almost the whole length of the cliff in this parish [Aldbrough] may be considered as one huge landslip from end to end'.

Secondary landslides tend to occur within the slipped mass (Fig. 6b and c), although toppling of Withernsea Member blocks (typical volume 3–5 m³) also occurs from the over-steepened promontories separating embayments. Toppling has also featured, but on a much larger scale, at Warden Point (Dixon & Bromhead
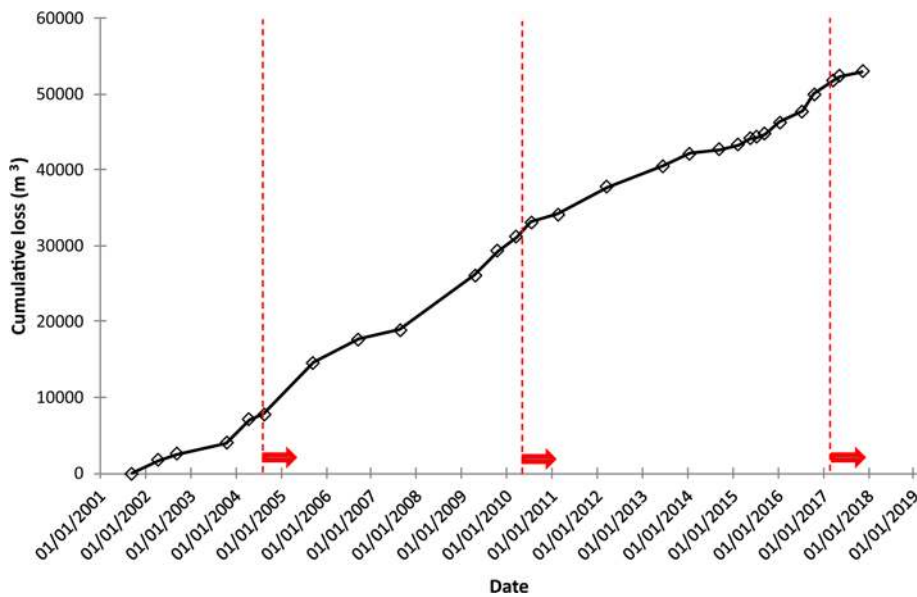
Fig. 4. Plot of date v. cumulative volume loss from cliff (per 100 m) at CLO (September 2001 datum) (BGS©UKRI). Dates of major fresh landslide events in central embayment are shown as dashed red lines with arrows.

2002). At the CLO, toppling has been observed either where a vertical rotational landslide back-scarp undergoes degradation and secondary movement or where the upper part of a vertical (or near-vertical) inter-embayment promontory partially collapses. Toppling may also be promoted by minor pre-failure subsidence of the cliff top resulting in a seaward tilt or where a graben-like feature has developed at the rear of an already rotated slip mass. Mudflows tend to occur on the peripheries of rotated slip blocks in response to the amount of surface water on the slope resulting from seepage and/or direct rainfall and where the slipped masses have had time to degrade sufficiently.

Examination of TLS-derived cross-sections revealed an overall minimum slope angle of 45° and a maximum of 66°, although steeper and temporarily near-vertical slopes have been observed at the site, particularly at promontories. There have been many instances where slope stability analyses have returned factors of safety less than unity for 'stable' cliff slopes, probably owing, at least in part, to long-term partial saturation within the main bodies of the tills and the Hornsea Member close to the cliff face (Butcher 1991; Hobbs *et al.* 2013).

The monitoring has shown that the cycle of major landslide events at the CLO is every 6–7 years, this being based on three events identified since September 2001 (i.e. August 2004, March 2010 and February 2017; Figs 4 and 7). This compares with a cycle of around 30–40 years for the 40 m high London Clay cliffs at Warden Point, Isle of Sheppey, Kent (Dixon & Bromhead 2002). As was the case at Warden Point, the embayments at the CLO have retreated along the same heading (due west in this case) and maintained their dimensions over the monitoring period. This is at odds with the suggestion of Pethick (1996) that embayments migrated southward at Holderness. Pickwell (1878) observed 3–4 year cycles of landslide activity at Tunstall (10 km SSE of Aldbrough).

The relationship between incremental volume loss and total rainfall is also shown in Figure 7 (total rainfall refers to that since the previous survey). This shows a broad-scale agreement between rainfall and volume loss from the cliff (calculated from TLS) with peaks in volume loss following the major landslide events. (It should be noted that pre-2012 rainfall data are averages taken from three East Riding of Yorkshire stations within a 23 km radius of the CLO.)

Oceanographic and meteorological factors

Coastal processes, such as storms, and the energy provided by high waves at the coast, play a major role in coastal erosion around Britain and these are found to be particularly enduring on the east coast north
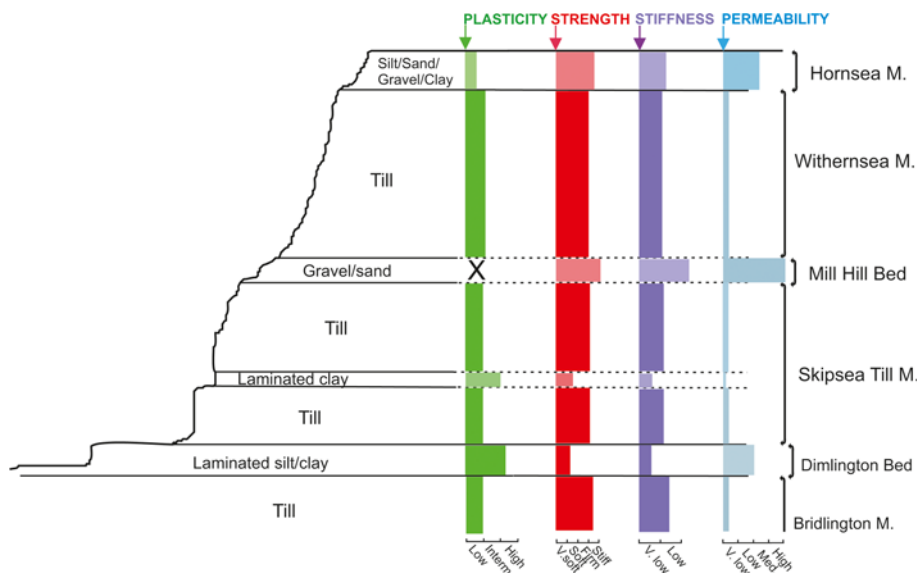

Fig. 5. Conceptual geological–geotechnical model for the CLO. (BGS©UKRI).

Fig. 6. Examples of different stages of deep-seated rotational landsliding in the central embayment of the CLO: (**a**) August 2004; (**b**) February 2011; (**c**) November 2011; (**d**) November 2017. All cliff access was carried out with a full risk assessment (BGS©UKRI).

of the Humber (median duration >13 h) with the likelihood of spanning High Water (Dhoop & Mason 2018); for example, an anticyclonic storm on 18 December 2009 lasted 19.5 h at Hornsea. A storm surge, described by the Environment Agency as the most serious for 60 years, hit the east coast of England on 5 December 2013, causing severe coastal flooding and erosion, most notably in East Anglia. During this event the high tide levels (predicted) at Bridlington and Spurn Point were 6.15 m at 17.54 h and 7.25 m at 18.53 h, respectively. This compares with estimated mean high-water spring (MHWS) and mean low-water spring (MLWS) of 6.44 m and 1.14 m, respectively, at Aldbrough. Wave height recorded by the Channel Coastal Observatory (CCO) for the 'Hornsea' buoy, belonging to the East Riding of Yorkshire Regional Coastal Monitoring Programme (ERYRCMP 1995), peaked in the early hours of 6 December with waves in excess of 6 m, accompanied by a maximum wind speed of 20.8 m s^{-1} (Force 8–9) recorded at the nearby BGS weather station. However, in terms of wave energy alone, higher peaks were recorded on 24 March and 10 October 2013, a maximum wave height of 7.4 m having been recorded on 23 March. Another notable 'storm' year (since June 2008) was 2010. Wave direction was predominantly and consistently from the NNE and NE. 'Onshore' waves (defined here as derived from compass points N340° to N140°) represent >80% of the total. This highlights the vulnerability of the Holderness coast to the erosive wave energy, which predominantly emanates from an average angle of incidence 42.5° to the current average coastline at Aldbrough (CCO 2017). Notable rainfall events included 12–15 and 24–25 June 2007; this

month had over four times the average rainfall, equivalent to a 200 year return event at Holderness (Hanna *et al* 2008).

The occurrence of storms, as defined by CCO (2017) and recorded at the Hornsea buoy from 2009, is plotted against incremental volume loss for 100 m of cliff (calculated from TLS) in Figure 8. It should be noted that a storm event is indicated using the 'peaks-over-threshold' method (CCO 2017) where the 'wave height threshold' was variously defined over the monitoring period from 3.00 to 3.75 m and based on 0.25 year return periods. A comparable long-term trend is shown but the number of storms does not appear to have a causal effect on cliff volume change. However, a closer agreement is evident after 2013 where TLS surveys are more frequent.

A plot of average wave-climate energy v. incremental volume loss for 100 m of cliff (calculated from TLS) is shown in Figure 9; the wave data for which were provided by the Hornsea buoy (CCO 2017). The 'wave-climate' energy, P was calculated here as follows (Dexawave, http://www.dexawave.com):

$$P = 0.57 \times (H_S)^2 \times T_P$$

where P is wave energy (kW m^{-1}), H_S is significant wave height (m) (half-hourly data) and T_P is time period between each wave crest (s).

The plot shows similar trends with time for cliff volume loss and wave energy, particularly when taken over several years. However, a causal effect is not indicated.
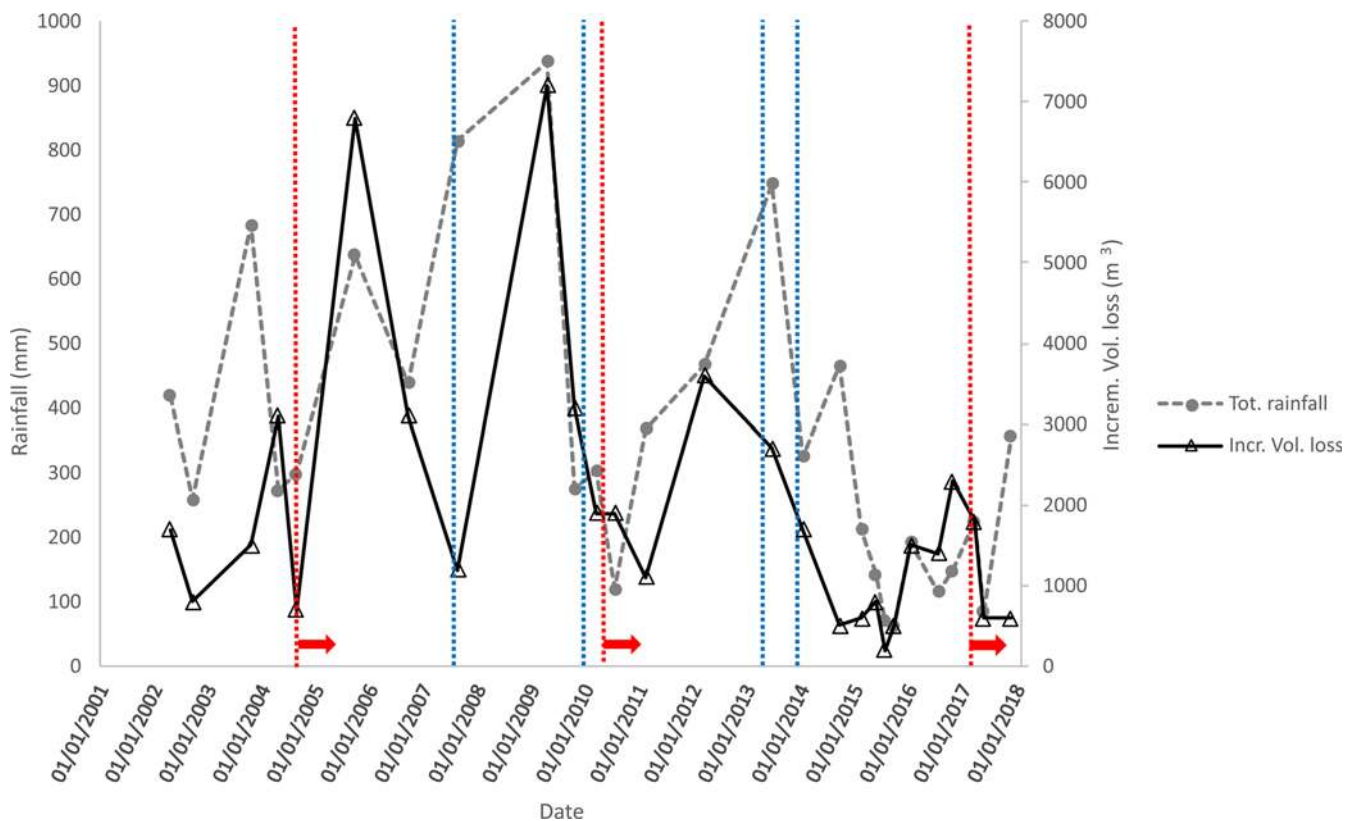
Fig. 7. Plot of date v. total rainfall and incremental volume loss (per 100 m) from cliff. Includes Met Office data (2001–2011) (BGS©UKRI). 'Total rainfall' refers to total rainfall since last survey. Dates of major fresh landslide events in central embayment are shown by dotted red lines with arrows; notable storms are shown by dotted blue lines.

The 'Holderness Experiment' carried out between 1993 and 1996 monitored the processes of sediment transport along the rapidly retreating Holderness coastline, which provides the largest single coastal source of sediments to the North Sea (Prandle *et al.* 1996). Various processes have an impact on sediment transport including tides, storm surges and waves. Breaking waves in particular have an important impact on the beach and the nearshore zone (Wolf 1998). Pethick & Leggett (1993) indicated that high-energy waves with long return periods (e.g. 8–15 months) are responsible for almost all the net southerly sediment transport and that these are also responsible for offshore bar development. A detailed account of

available wave and wind data for the CLO (to 2013) has been givenby Hobbs *et al.* (2013).

The Phase 1 borehole installation post-dated a major landslide event in March 2010. More recently, a fresh event occurred on 14 February 2017 at the same embayment in line with the boreholes and was 'captured' by the borehole instrumentation on 1 March 2017 primarily in the form of significantly accelerated borehole displacement of up to 30 mm (cumulative). The timing of this latest event, heralding the start of a new landslide cycle, allowed the piezometers to equilibrate and a substantial precursory inclinometer dataset to be established.
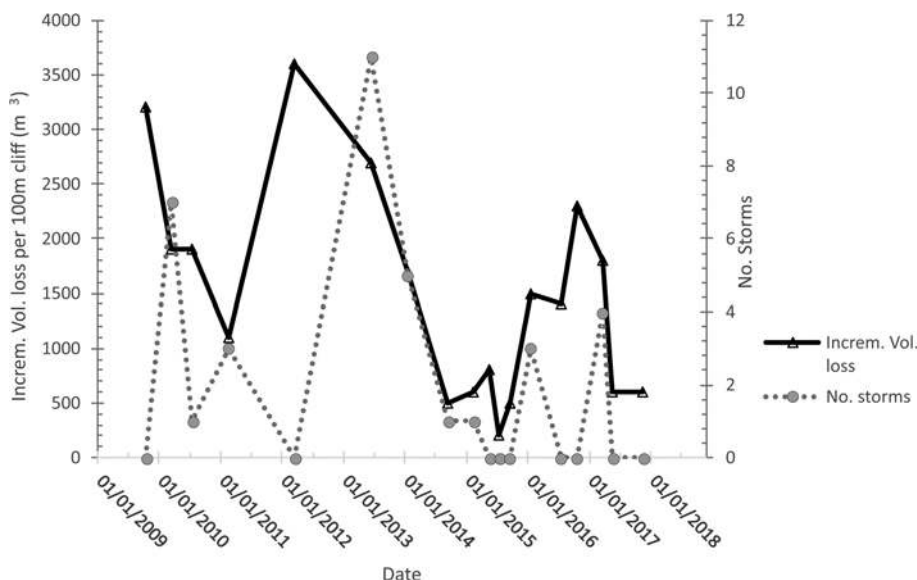

Fig. 8. Plot of date v. incremental volume loss from cliff (per 100 m) and number of storms since last survey (Hornsea buoy) ERYRCMP (1995). Includes data from CCO (BGS©UKRI).
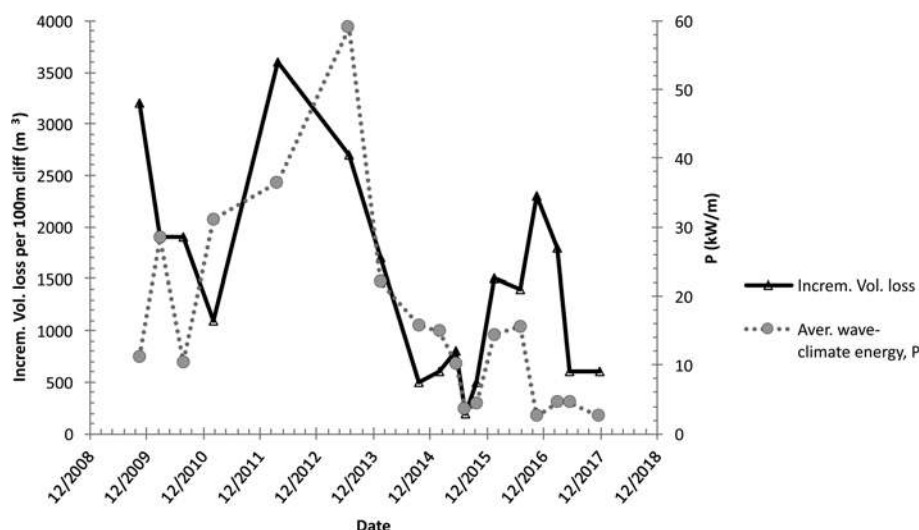
Fig. 9. Plot of date v. incremental volume loss from cliff (per 100 m) and average wave-climate energy (Hornsea buoy) ERYRCMP (1995). Includes data from CCO (BGS©UKRI).

Instrumentation results

Inclinometers

Boreholes 1b, 2b and 3b (Figs 10–12) contain inclinometer casing to full depth, which is 'dipped' using a digital probe. The results are shown in the form of a cumulative plot of the northerly and easterly components of lateral displacement for each dated survey, where the temporal datum is the dataset from that borehole's first survey (the plot's centreline) and the displacement datum is at 20 m depth; that is, the bottom of the borehole is assumed to be stable. For comparison the plots are at the same scale. The inclinometer method and detailed analysis of data have been described by Hobbs *et al.* (2015a).

The inclinometer results from Borehole 1b (up to August 2017) are shown in Figure 10 as cumulative lateral displacement, where the left-hand plot (Axis A) represents northward displacement and the right-hand plot (Axis B) eastward displacement. The scale on the *x*-axes (positive) is 0–30 mm (displacement) and on the *y*-axes is 0–20 m (depth). The plots show positive lateral

displacements from a depth of 17.5 m upward within the Bridlington Member, although significant displacements occur only above 12.5 m, within the Skipsea Till Member and overlying deposits, including the major one recorded between October 2016 and August 2017 and attributed to the landslide event of 14 February 2017. Displacements have consistently increased uphole in an overall linear trend, reaching a maximum eastward component (to August 2017) of 28 mm at a depth of 0.5 m in the Hornsea Member. Also, displacements have accumulated in a positive direction throughout. The equivalent maximum northerly displacement is 18 mm.

Prior to the event of February 2017 there has been a precursory (positive) trend starting between September 2015 and January 2016 and accelerating during 2016. This suggests a 'lag' of between 13 and 17 months on the B-axis (east) between initiation of perceptible accelerated movement and the landslide event itself, although the A-axis (north) movement has a shorter lag of between 4 and 7 months. It should be noted that this dataset has a July 2012 baseline.
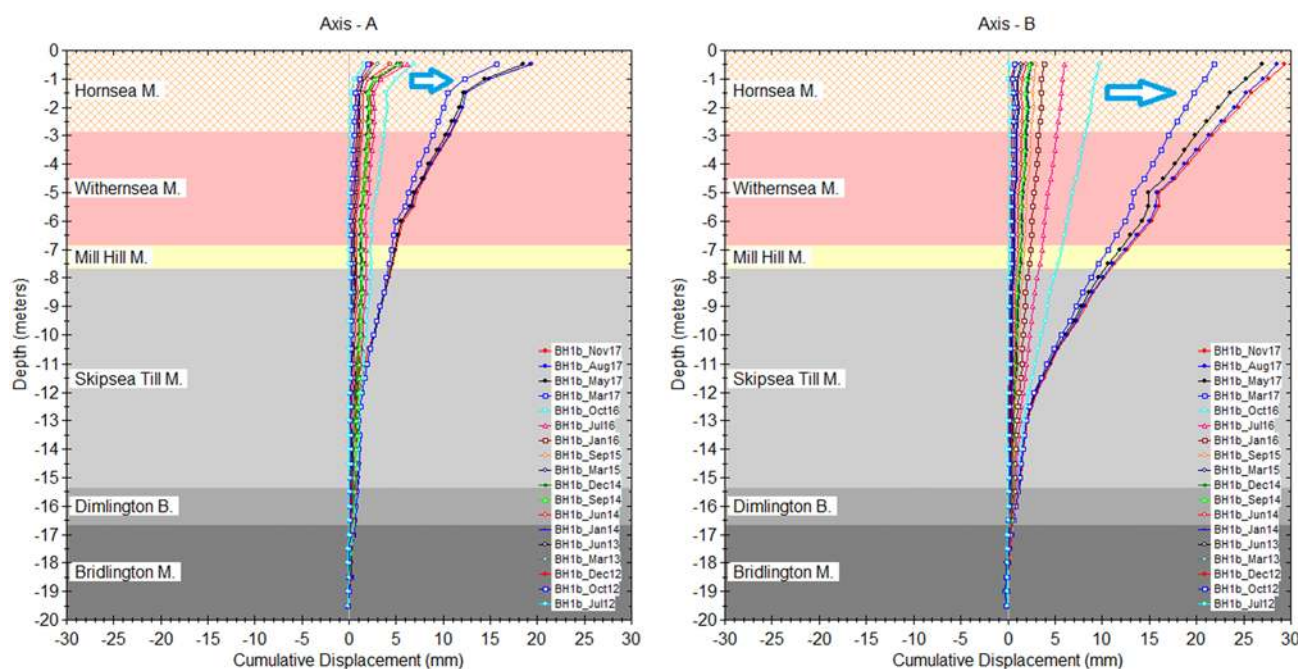

Fig. 10. Cumulative displacements for BH1b up to November 2017 (BGS©UKRI). Axis A is north; Axis B is east. July 2012 baseline. Blue arrows indicate pre-event displacements of winter 2016–2017.
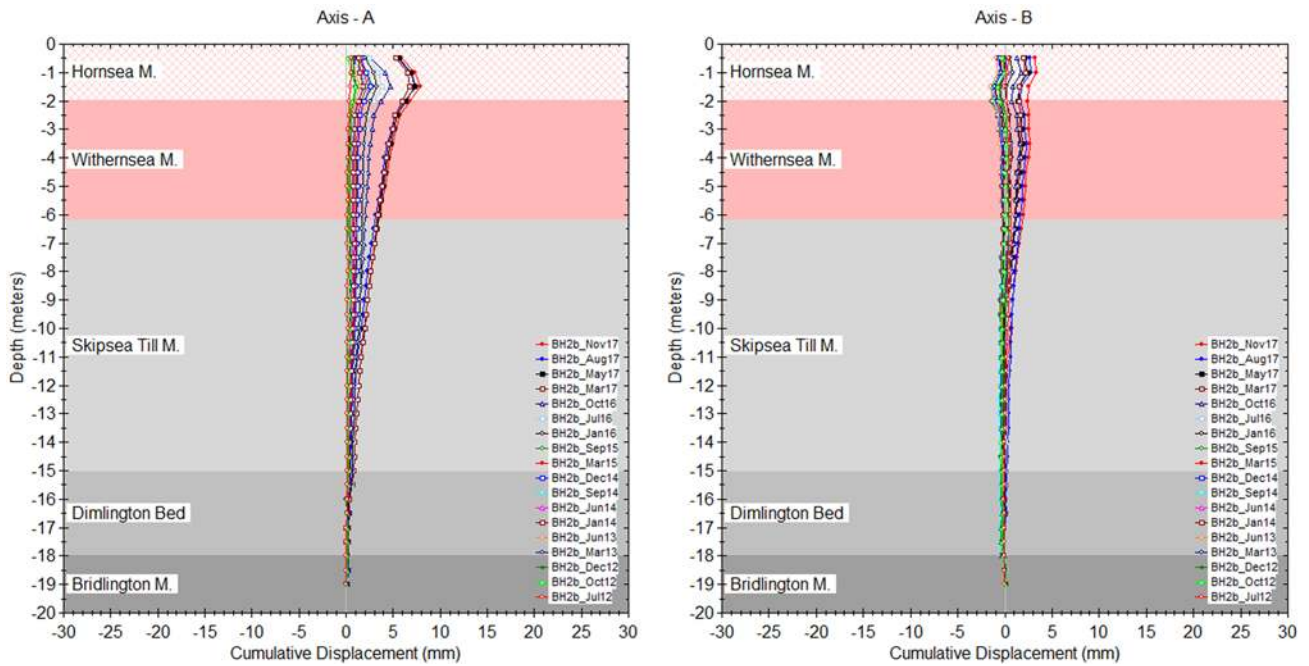
Fig. 11. Cumulative displacements for BH2b up to November 2017 (BGS©UKRI). Axis A is north; Axis B is east. April 2012 baseline.

Equivalent data for Borehole 2b (up to August 2017) are shown in Figure 11, to the same scale. Here displacements were greatly reduced compared with BH1b, a maximum cumulative northerly displacement of 7 mm having been reached at a depth of 1.5 m in the Hornsea Member. Lateral displacements occurred above a depth of 16 m and increased gradually uphole. It is noted that here the A-axis displacement, albeit small, exceeded that of the B-axis when compared with BH1b, possibly indicating some form of stress rotation. This dataset has an April 2012 baseline.

Equivalent data, but over a shorter period, for Borehole 3b (up to August 2017) are shown in Figure 12, to the same scale. Here only very small displacements were seen, initiating above 13.5 m depth and peaking at 3 mm at a depth of 5.0 m within the Withernsea

Member. Displacements on both axes were comparable in amount. This dataset has a March 2015 baseline.

An example of a 'time' plot (BH1a, 4 m depth) is shown in Figure 13. This sigmoidal curve clearly shows detection of the precursory build-up in displacement towards the cliff leading to the landslide event of 14 February 2017 and subsequent decrease in displacement after the event. This inclinometer, closest to the cliff, has thus 'predicted' the landslide event by more than a year. Results for other depths are similar, but reduce proportionately in magnitude to a depth of 12 m, below which there is no response to the landslide event (Fig. 10).

The overall picture is one of consistency in displacement direction throughout the monitoring period and of proportionality in displacement response; that is, a reduction proportionate with
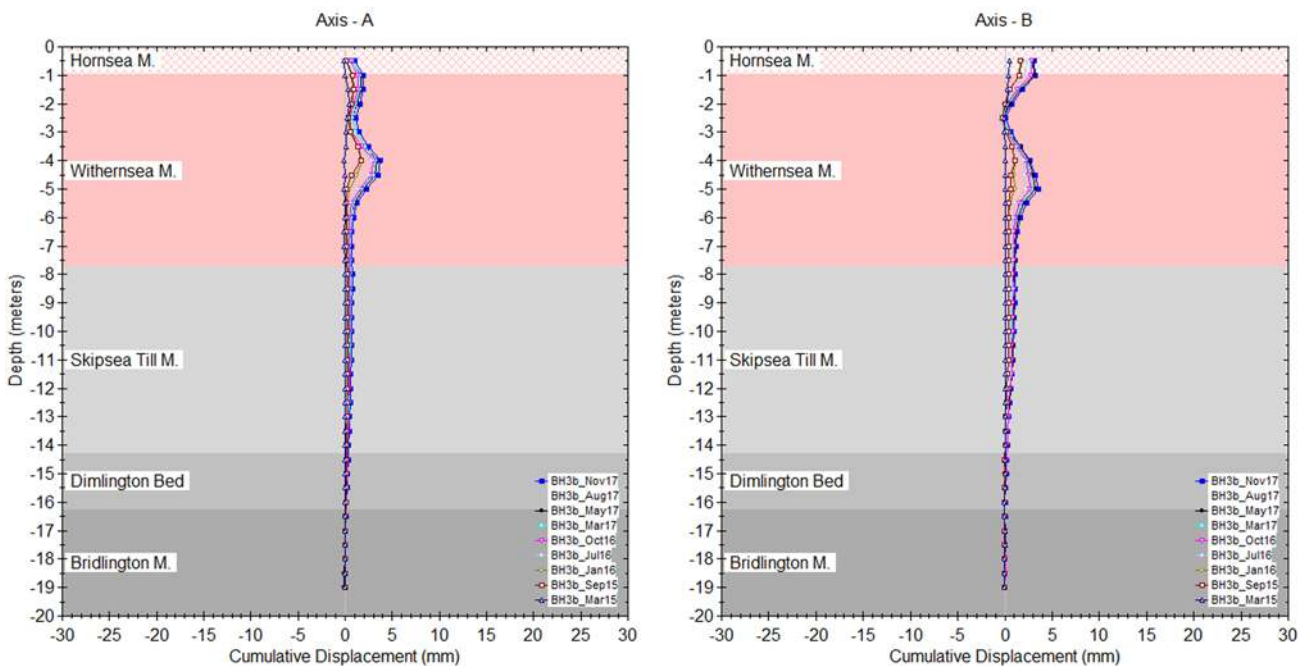

Fig. 12. Cumulative displacements for BH3b up to August 2017 (BGS©UKRI). Axis A is north; Axis B is east. March 2015 baseline.
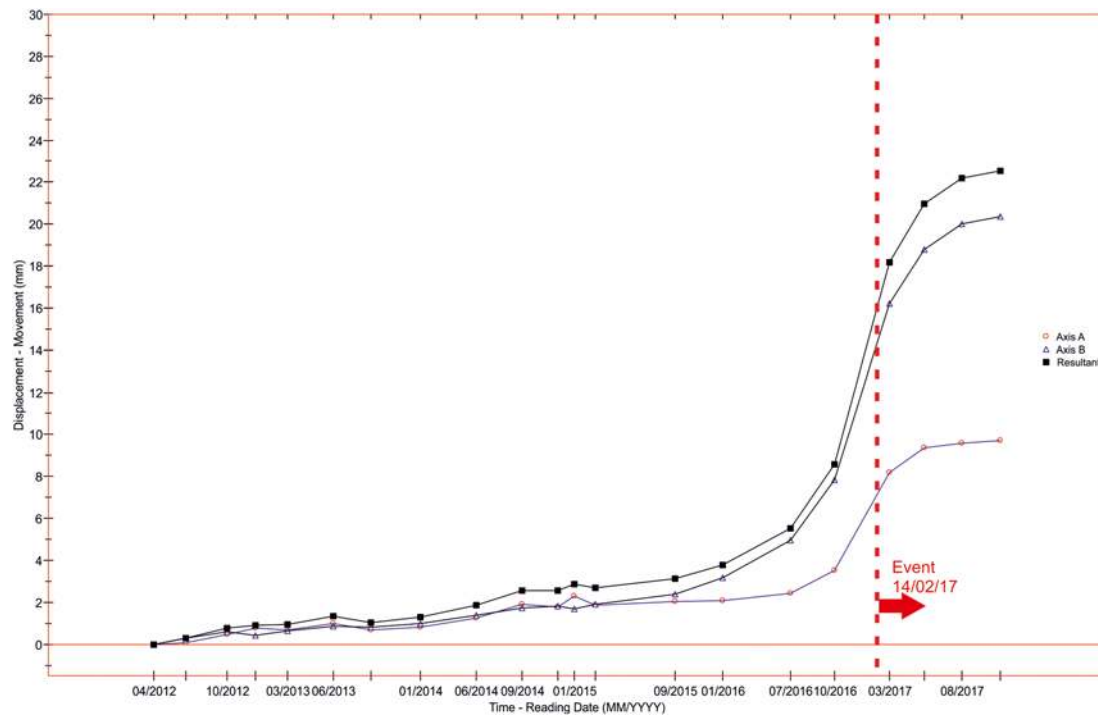
Fig. 13. Example plot of time v. displacement (cumulative) for BH1b inclinometer, 3.5 m depth (BGS©UKRI). Axis A is north; Axis B is east. April 2012 baseline. Dashed red line is landslide event.

increasing distance from the cliff (i.e. from BH1b to BH3b). There are no precursory rainfall or storm events suggestive of a link to this specific event.

Stress relief

In passive stress relief laboratory tests on London Clay, dilation was measured by Fourie & Potts (1991) as a consequence of a reduction in mean effective stress, and was found to be due to both swelling of clay minerals and passive shearing. Fourie & Potts concluded that this process, rather than being linear, accelerated with increased

stress relief. It is likely that the cliffs at the CLO are subject to the same processes as described above, although the time scales involved in clay swelling and the role of pre-existing discontinuities in the field are difficult to 'scale up' from laboratory tests. The presence of pre-existing shear surfaces within the tills is a consideration (Winter *et al.* 2017) and has been observed within unslipped cliff sections, although not in Phase 2 borehole core.

When lateral restraint is removed from a soil body a condition of 'active earth pressure' prevails, and K_a is used to represent the applicable 'coefficient of active earth pressure'. Typical pre-failure displacements are quoted for 'stiff clays' as $0.01H$, where H is soil
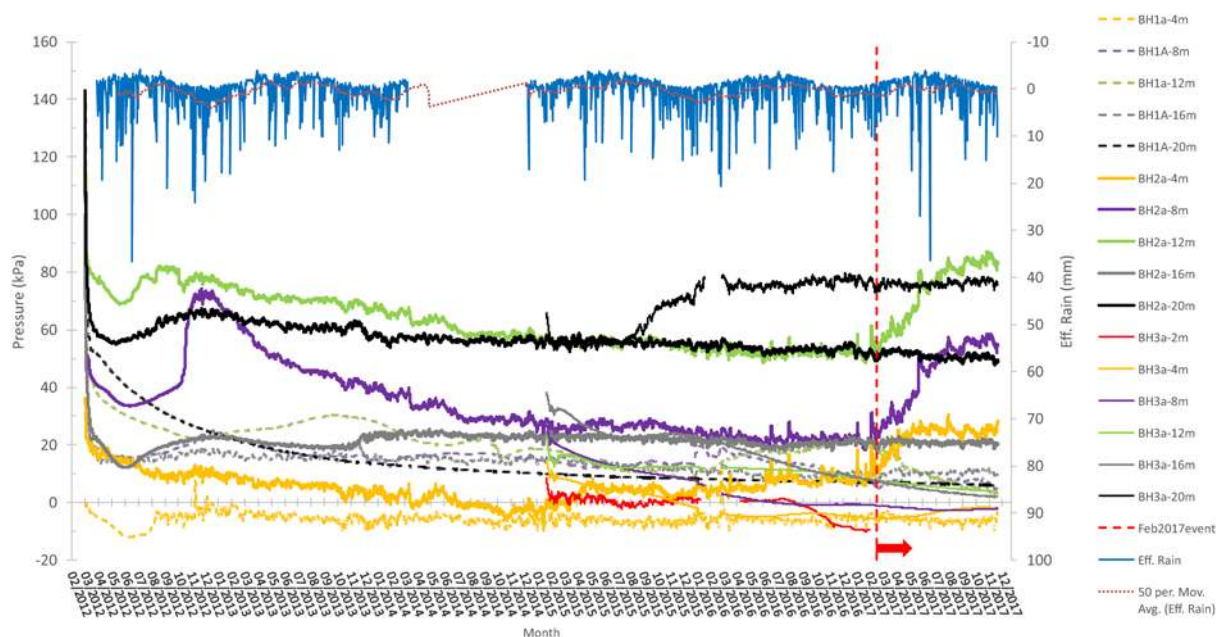

Fig. 14. 'Time' plot of month v. piezometric pressure and total effective daily rainfall (BHs 1a, 2a and 3a), April 2012 to November 2017 (BGS©UKRI). Landslide event (14 February 2017) is marked by red dashed line and arrow. Borehole 3a record starts February 2015.
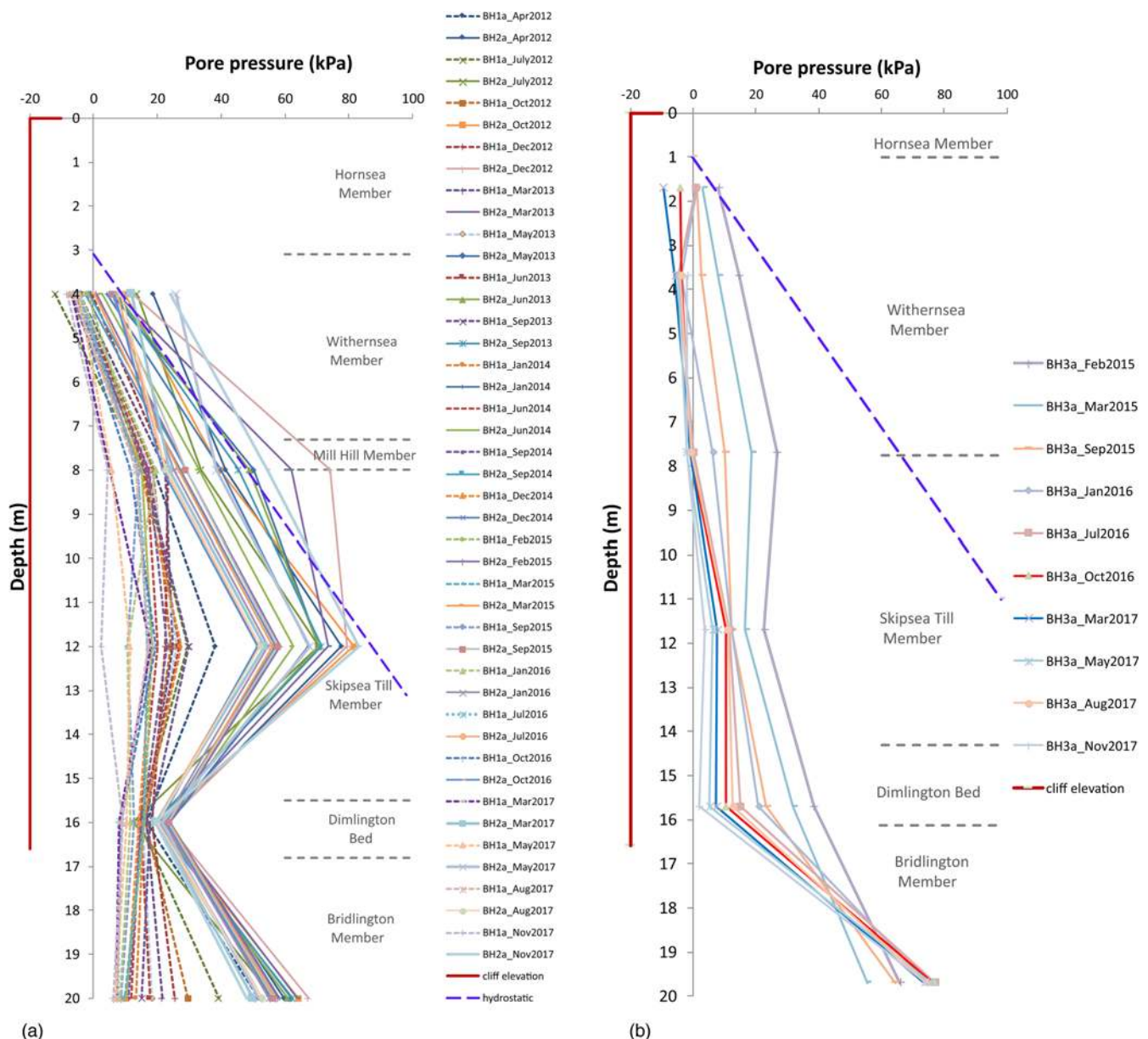
Fig. 15. Piezometer 'profile' plots: (**a**) BHs 1a and 2a; (**b**) BH3a (BGS©UKRI). No sensors were present in BHs 1a and 2a at 2 m depth. Purple dashed lines represent idealized hydrostatic profiles.

body height (Azizi 2000); this gives a pre-failure displacement of around 170 mm at the CLO. Coastal landslides in London Clay at Warden Point, Isle of Sheppey, were analysed by Dixon & Bromhead (2002). In a modelling study of cuttings in stiff, weathered London Clay, Ellis & O'Brien (2007) noted that slope stability in cuttings was reduced by the initial earth pressure coefficient and the pre-yield stiffness and rate of post-peak strain-softening; an increase in the last promoted progressive failure. They also described a 'fine balance' between horizontal stress decrease and a tendency for pore pressure increase (in cuttings). Tensile stress release was explored by Hampton (2002), who noted that although tensile stresses were small they peaked in near-vertical, saturated Californian cliffs of weakly lithified sediment, resulting in small, shallow but frequent block failures.

Piezometers

Five fully grouted vibrating-wire piezometer sensors were installed in boreholes 1a and 2a and six in borehole 3a. The results are shown in the form of a 'time' plot (Fig. 14) of pore pressure readings at intervals of 6 h from shortly after the Phase 1 installations, and the equivalent 'profile' plots (Fig. 15). The results show extended periods of pore pressure equilibration for most sensors plus wide variation in the long-term stability of individual sensors, the latter being possibly influenced by temperature variation at the shallowest sensors. The piezometer installation and a detailed analysis of results have been described by Hobbs *et al.* (2015*a*).

Although pore pressure values tend to be low overall, the landslide event of February 2017 triggered distinct increases at the 4 m, 8 m and 12 m sensors in BH2a (Fig. 14). Somewhat unexpectedly, there was no response to this event in BH1a, which is closest to the cliff. This is currently unexplained, although loss of contact between sensors and formation is suspected, possibly owing to clay shrinkage and/or stress relief. There was also no response in BH3a, which is furthest from the cliff. With respect to effective rainfall (Fig. 14) there is no discernible correlation with pore pressure at any depth in the boreholes. Overall, there is a trend of either steady decreases of pore pressures with time or maintenance of constant values, with the exceptions of the February 2017 landslide event in BH2a, the BH3a sensor at 20 m and the BH2a
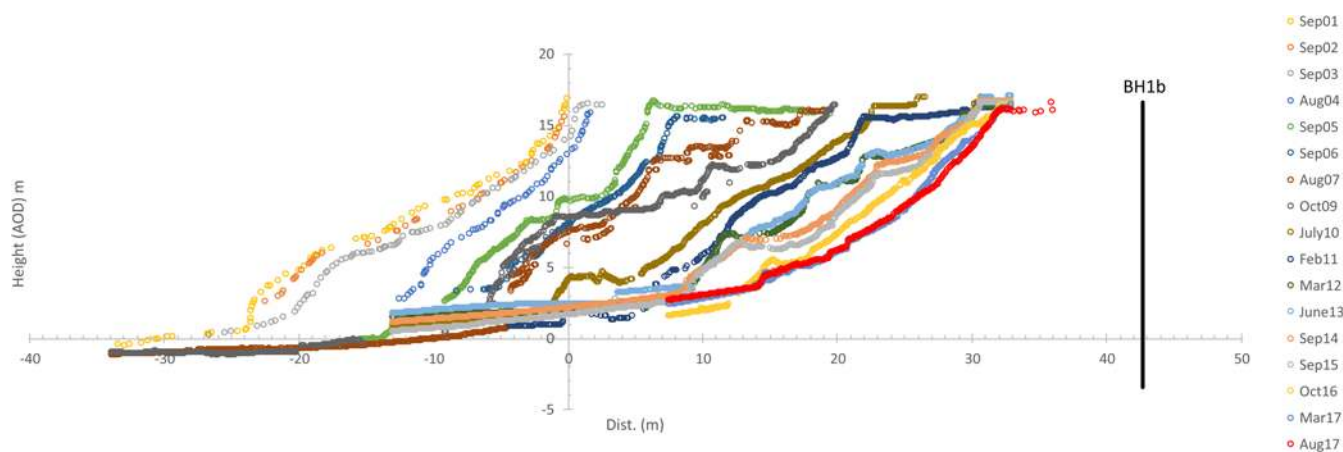
Fig. 16. Selected cross-sections aligned with 'b' boreholes, derived from TLS (September 2001 to August 2017: left to right) (BGS©UKRI). Location of BH1b (installed March 2012). March and August 2017 profiles do not illustrate 14 February 2017 landslide event owing to concentration of displacement in southern part of the embayment at this time. Cliff-top displacement between February 2011 and March 2012 profiles was due to subsidence and destruction of concrete roadway.

sensor at 4 m. However, apart from the anomalies described above, the results overall agree with those for nearby Cowden, described by Powell & Butcher (2003), where observed pore pressure values did not exceed 60 kPa to 20 m depth.

Plots of piezometer borehole profiles for each site visit are shown in Figure 15. These emphasize the markedly sub-hydrostatic nature for Boreholes (BHs) 1a and 3a but less markedly sub-hydrostatic for BH2a down to 12 m. Similar 'depressed' pore pressures were described for the London Clay Formation cliffs at Warden Point (Dixon & Bromhead 2002). The Dimlington Bed, at least in BHs 1a and 2a, acts as a minor source of water to the lower cliff, whereas the Skipsea Till Member in BH2a does not. The Dimlington Bed also saturates the upper parts of the underlying Bridlington Member. Observations of the cliff slope indicate that the Mill Hill Bed is a major source of water to the mid- and lower cliff and, hence, to landslide deposits on the cliff. Pickwell (1878) described 'land springs' as the chief cause of the landslides at Aldbrough. Any mechanism whereby drainage from the Mill Hill and Dimlington Beds is blocked by landslide deposits on the cliff slope is likely to be transient and difficult to observe and quantify. The data indicate that hydraulic continuity with the cliff and between boreholes is in an enhanced state compared with the situation further inland, owing mainly to the presence of persistent joints within the till members and their 'opening out' with time as a result of progressive stress relief as discussed above.

The pore pressures at 20 m depth within the boreholes diminish toward the cliff from 75 to 10 kPa and readings are relatively constant when compared with the shallower sensors. This is probably because at this depth the formation is at constant temperature and beyond the direct influence of stress relief and joint opening caused by cliff recession. Negative (suction) pressures have been recorded at 4 m depth in BH1a and at 2, 4 and 8 m depth in BH3a, a maximum suction of −12 kPa having been recorded (to November 2017) in BH1a at 4 m depth. These suctions do not appear to respond to seasonal influences. It is possible that infiltration from the surface is simply inadequate to influence the sensors at 4 m depth and below. It was noted by Powell & Butcher (2003) that, at Cowden to the north of Aldbrough, suctions of −20 kPa were required for slope stability analyses to emulate observed landslide behaviour.

The effect of cliff slope and formation saturation on tensile stress release was explored by Hampton (2002), who noted that although tensile stresses are small they peak in near-vertical, saturated cliffs. Dixon & Bromhead (2002) noted that 'a zone of depressed pore pressures was carried inland' as the (largely unweathered) London Clay cliff at Warden Point retreated. Unlike the porewater regime at

the CLO, the cliffs at Warden Point exhibited sub-hydrostatic or hydrostatic behaviour. However, like Warden Point, the rate of stress relief at the CLO does not allow a steady-state seepage regime to develop. Dixon & Bromhead (2002) concluded that 'lateral stress reduction has an important role in modifying pore pressures in heavily over-consolidated cohesive soils'. This probably applies at the CLO but to a lesser extent owing to the greater permeability of some lithostratigraphic units.

Slope stability analysis

Cross-sections have been constructed from TLS surveys (Fig. 16) so as to be aligned with the 'b' boreholes. These were then used to create the ground surface profiles for 2D slope stability analyses. The inputs to slope stability analysis also included stratigraphic layers, strength and density data, and hydrological data obtained from the conceptual model (Fig. 5), the last of these probably being the most problematic. Geotechnical data were taken from the testing programme (Hobbs *et al.* 2015b, 2019).

To investigate the engineering stability of the cliff sections, derived from TLS surveys, landslides were modelled in 'Galena' (limit equilibrium) software (v.7.10) supported by 'FLACslope' (finite-element) software (v. 7.0). This approach has the advantage that these two independent methods may be combined to refine each model. A key difference in their use is that the Galena model allows the input of a slip surface whereas the FLACslope model is capable of 'suggesting' one. Examples are taken from the October 2016 TLS survey (Figs 17 and 18), the last before the 14 January 2017 landslide event. The FLACslope model suggests a flattening (no toe uplift) of the slip plane close to the cliff within or close to the level of the Dimlington Bed, thus providing more of a 'composite' style of landslide (Varnes 1978; UNESCO Working Party on World Landslide Inventory 1993), although field evidence suggests this may be exaggerated and reflect the simplified nature of the CLO model in terms of 3D bedding morphology. The Galena example uses multiple piezometric levels for the major lithostratigraphic units and the FLACslope example a single phreatic surface. Details of slope stability methods and results have been given by Hobbs *et al.* (2013) and Parkes (2015).

It will be noted that the examples do not agree regarding Factor of Safety (FoS) but both are significantly less than unity (i.e. unstable). The latter is due, in part, to enhanced suctions close to the cliff face and depressed pore pressures overall but mainly to the use (in this case) of residual strength data. The equivalent FoSs for Galena and FLACslope using 'peak' strength data were 1.26 and 0.92,
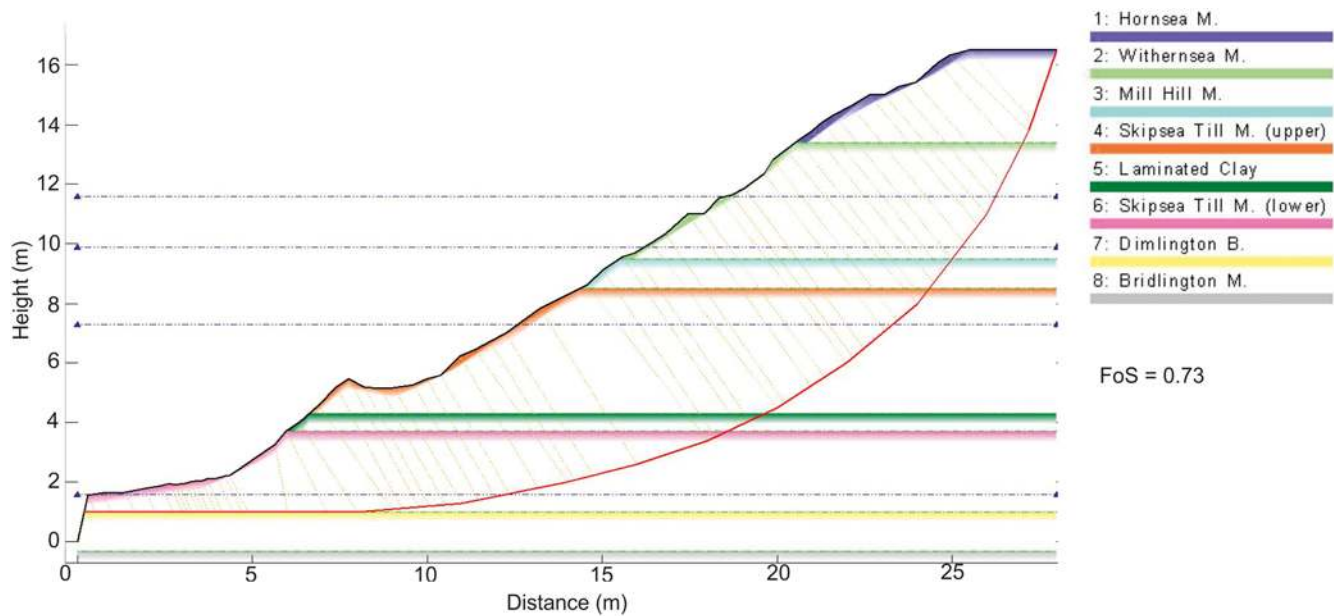
Fig. 17. Example of Galena output: Profile aligned with 'b' boreholes, October 2016 using residual strength data (BGS©UKRI). Dashed horizontal lines are piezometric levels; continuous red line is slip surface (estimated).

respectively (i.e. at or close to a stable condition). Drainage and under-drainage pathways are complex and time-dependent, as they are prone to disruption by landslide activity on the cliff. The slip surface input to 'Galena' (Fig. 17) is based on observation, TLS data and the FLACslope model, and is considered representative of the subsequent major fresh event (February 2017), which daylighted at the cliff within the Dimlington Bed and with a cliff-top recession of 3 m on the 'b' borehole alignment. Although the FLACslope example shown (Fig. 18) reflects the observed landslide profile of February 2017, the model is very sensitive to the position of the phreatic surface; small changes result in wide differences in the pattern of displacement and hence 'suggested' landslides with very different scales and mechanisms.

It is unclear to what extent the presence of suctions near-surface enhances slope stability by increasing effective strength in those strata affected as described by Butcher (1991), Dixon & Bromhead (2002) and Parkes (2015). Although a fully undrained condition is

unlikely (Quinn *et al* 2010), major till members tend to subdivide into blocks separated by pre-existing joints and stress-relief induced fissures (close to the cliff), within which transient undrained unloading conditions can occur at depth. Such conditions may not have been detected owing to the 'off-slip' location of the piezometer installations at the CLO, and are probably therefore not well modelled by the slope stability analysis software employed here.

Discussion

The monitoring study at Aldbrough, reported between September 2001 and November 2017, has demonstrated that, at a specific site with a 16–17 m high cliff, in glacial deposits typical of the Holderness coast, deep-seated rotational landslides are the dominant agent of cliff recession, although possibly with modification towards a composite mode near the toe. A potential cyclicity of 6–7 years has been shown covering three major rotational landslide
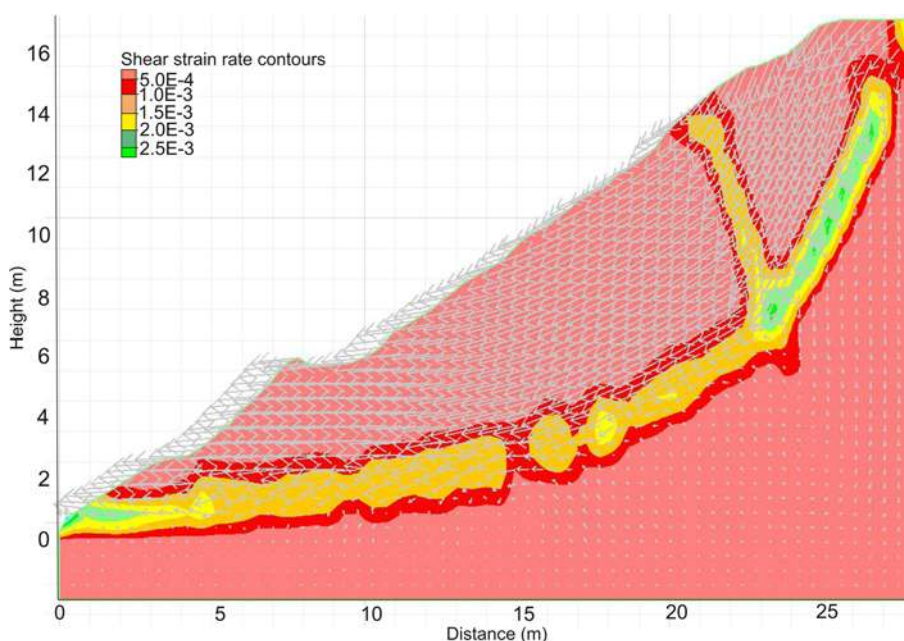

Fig. 18. Example of FLACslope output: profile aligned with 'b' boreholes, October 2016 using residual strength data. FoS is 0.44 (BGS©UKRI). Colours indicate shear strain rate contours; arrows indicate displacement vectors.

events at the study site, occupying virtually the full width of the same embayment; the most recent dated 14 February 2017. Relationships between cliff recession and landsliding and environmental factors such as rainfall, storms and wave height are complex but matching trends over several years have been demonstrated. However, causal relationships have been tentative, partial or not demonstrated.

The establishment of an array of six boreholes landward of the cliff and the use of a digital inclinometer probe, in particular, has been very successful in resolving small displacements that are here attributed to stress relief. Precursory, enhanced cliffward displacements have been demonstrated many months prior to the February 2017 landslide event. These displacements have also been shown to be consistent and proportional to depth and distance from the cliff (although it is recognized that the terminations of the boreholes would ideally have been deeper than 20 m). This therefore provides an early warning method for the types of geological materials found at Holderness. The hydrological factors such as drainage to the cliff from the Mill Hill and Dimlington Beds, and an established partial saturation or suction regime within the near-surface Withernsea Till close to the cliff, have been shown to affect slope stability. The piezometer array in BH2a has responded directly (at 4, 8 and 12 m) to the February 2017 event, whereas the closest array to the cliff (BH1a) has not. Loss of contact between the sensors and the formation, possibly owing to a combination of stress relief and clay shrinkage, is suspected, although this cannot be confirmed at present.

The mechanism for deep-seated rotational landsliding at the CLO has been established. The role of the Dimlington Bed here is critical, as it provides a weak, saturated and (in part) permeable horizon that has been subjected to shear deformation, both during formation and as a result of landsliding. The bed is assumed to provide the basal shear medium for the landslides and, as the elevation is undulating, this affects the precise landslide morphology locally. There is also evidence at its outcrop on the cliff that the bed may have been subject to extrusion, possibly in response to liquefaction. Natural as-formed or post-deformational variations in thickness are unknown at this scale. In addition, the Mill Hill Bed has been shown to act as an aquifer supplying significant amounts of groundwater to the cliff slope and the landslide masses on it.

Although the TLS monitoring programme has been affected by some irregularities in the timing of surveys and technical problems since 2001, mainly associated with global positioning, it has demonstrated that the technique is capable of tracking gross morphological changes in the cliff slope more accurately than previously possible. At the same time it is recognized that it has not been able to monitor minor landslide activity (e.g. rock falls, topples or mudflows) occurring between major deep-seated events. Nevertheless, determination of cliff volumes lost to instability and erosion has been possible and these data should be valuable in calibrating coastal modelling, preparing coastal engineering assessments and comparing with Holderness-wide erosion calculations. Although observations have been made of the beach throughout the monitoring a quantitative assessment has yet to be made. The fact that the deep-seated landslides did not penetrate to beach or platform level at this site to some extent justified this. Clearly, erosion of the cliff by waves, and particularly by storms, provides the conditions for the dynamics of the geotechnical processes to persist.

For future work it is proposed to study in more detail the relationship between landsliding and the wave and storm regime (where available), to continue the observations of landslide cyclicity and ultimately the progressive interception of the cliff with the downhole instruments. Preliminary results of the recent Proactive Infrastructure Monitoring and Evaluation (Electrical Resistivity Tomography) (PRIME (ERT)) installations will also be reported.

Conclusions

Cliff recession monitoring (since 2001) has revealed the following at the BGS's Aldbrough Coastal Landslide Observatory (CLO).

(1) Landslide processes are the major factors in cliff recession.

(2) Primary landslide type is deep-seated rotational with secondary topples, rock fall and mudflows.

(3) Major rotational landslides daylight at 1–2 m above platform level (15–16 m below cliff-top).

(4) Major rotational landslides utilize the undulose Dimlington Bed as the seaward or basal part of the slip surface.

(5) The Dimlington Bed is subject to liquefaction and possibly extrusion at outcrop on the cliff. This may be a contributory factor to observed landsliding and cliff edge subsidence.

(6) Major co-located rotational landslide events follow a 6 or 7 year cycle.

(7) Landslide activity is related to antecedent rainfall and to storm frequency and wave-climate energy. The new PRIME (ERT) installations will be monitored and any relationships with rainfall examined.

(8) Landslide embayments are formed by individual landslides that subsequently degrade on the cliff slope.

(9) Established landslide embayments have consistently migrated westward.

(10) Till strata have pervasive but widely spaced joints. Widespread additional fissures develop in proximity to the cliff, and are thought to be a result of stress relief.

(11) Volumetric losses from the cliff range from 1200 to 6300 m^3 per 100 m per annum.

(12) Average equivalent cliff recession of the CLO, derived from TLS, is 1.8 m a^{-1}.

Drilling, instrumentation and testing have revealed the following at the CLO.

(1) Borehole displacements (derived from inclinometers) have increased progressively towards the cliff as the cliff 'approaches' the boreholes.

(2) Significant borehole displacements are founded at around 12 m below ground level (i.e. within the Skipsea Till Member) and increase uphole.

(3) Borehole displacements have undergone a period of significant acceleration owing to the landslide event of February 2017.

(4) Piezometric pressures are below hydrostatic throughout all boreholes.

(5) Piezometric pressures reduce (at the same level) towards the cliff; persistent permeable layers drain to the cliff.

(6) Piezometric pressures have continued to reduce after expected equilibration times following installation, presumably owing to the reducing distance to the cliff with time.

(7) Piezometric pressures increased in BH2a at 4, 8 and 12 m in response to the February 2017 landslide event. No responses were recorded in BH1a and BH3a.

(8) Small suctions (negative pore pressures) exist in the uppermost 4 m in BH1a closest to the cliff.

(9) The residual strength of the Dimlington Bed is 60% lower than the average for the tills.

(10) Applying residual rather than peak strength data to most slope stability models reduces the factor of safety against sliding to well below 1.0, indicating a condition of instability.

(11) Geotechnical properties of the tills agree with published data. Differences between tills were found to be small; older tills tended to be only slightly stronger and stiffer than younger tills.

(12) High-quality core recovery in weak and heterogeneous glacial deposits requires specialist drilling techniques.

The project has demonstrated the need for geological and geotechnical information in coastal landslide analysis and modelling. The project has also demonstrated the usefulness of rapidly eroding 'soft clay' cliffs in the study of landslide processes; in particular, their pre- and post-event behaviour in terms of geomorphology and subsurface behaviour. Although this study has concentrated on the cliffs at the CLO, data from the beach and platform will also be analysed and reported in due course.

Scientific editing by Joel Smethurst; Mark Lee

References

Ashton, A.D., Walkden, M. & Dickson, M. 2011. Equilibrium responses of cliffed coasts to changes in the rate of sea level rise. *Marine Geology*, **284**, 217–229, https://doi.org/10.1016/j.margeo.2011.01.007

Azizi, F. 2000. *Applied Analyses in Geotechnics*. Spon, London.

Bell, F.G. 2002. The geotechnical properties of some till deposits occurring along the coastal areas of Eastern England. *Engineering Geology*, **63**, 49–68, https://doi.org/10.1016/S0013-7952(01)00068-0

Bell, F.G. & Forster, A. 1991. Geotechnical characteristics of the till deposits of Holderness. *In*: Forster, A., Culshaw, M.G., Cripps, J.C., Little, J.A. & Moon, C.F. (eds) *Quaternary Engineering Geology: Proceedings of the 25th Annual Conference of the Engineering Group of the Geological Society, Heriot–Watt University, Edinburgh, 10–14 September 1989*. Geological Society, London, Engineering Geology Special Publications, **7**, 111–118, https://doi.org/10.1144/GSL.ENG.1991.007.01.07

Bird, E. 2008. *Coastal Geomorphology, an Introduction*, 2nd edn. Wiley, New York.

Brown, S. 2008. *Soft cliff retreat adjacent to coastal defences, with particular reference to Holderness and Christchurch Bay, UK*. Doctoral thesis, University of Southampton.

Buckley, S.J., Howell, J.A., Enge, H.D. & Kurz, T.H. 2008. Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. *Journal of the Geological Society, London*, **165**, 625–638, https://doi.org/10.1144/0016-76492007-100

Butcher, A.P. 1991. The observation and analysis of a failure in a cliff of glacial clay till at Cowden, Holderness. *In*: Chandler, R.J. (ed.) *Slope Stability Engineering*. Thomas Telford, London, 271–276.

Castedo, R., Paredes, C., Fernández, M. & de la Vega, R. 2012. Modelo proceso-respuesta de recesión de acantilados por variación del nivel del mar. Aplicación en la Costa de Holderness (Reino Unido). *Boletín Geológico y Minero*, **123**, 109–126.

Castedo, R., de la Vega-Panizo, R., Fernandez-Hernandez, M. & Paredes, C. 2015. Measurement of historical cliff-top changes and estimation of future trends using GIS data between Bridlington and Hornsea – Holderness Coast (UK). *Geomorphology*, **230**, 146–160, https://doi.org/10.1016/j.geomorph.2014.11.013

CCO 2017. Channel Coastal Observatory website: https://www.channelcoast.org/

Chandler, J.H. & Brunsden, D. 1995. Steady state behaviour of the Black Ven mudslide: The application of archival analytical photogrammetry to studies of landform change. *Earth Surface Processes and Landforms*, **20**, 255–275, https://doi.org/10.1002/esp.3290200307

Dhoop, T. & Mason, T. 2018. Spatial characteristics and duration of extreme wave events around the English coastline. *Journal of Marine Science and Engineering*, **6**, 14, https://doi.org/10.3390/jmse6010014

Dixon, N. & Bromhead, E.N. 2002. Landsliding in London Clay coastal cliffs. *Quarterly Journal of Engineering Geology and Hydrogeology*, **35**, 327–343, https://doi.org/10.1144/1470-9236/2000-53

ERYRCMP 1995. *East Riding of Yorkshire Regional Coastal Monitoring Programme*. East Riding of Yorkshire Council, Beverley.

Ellis, E.A. & O'Brien, A.S. 2007. Effect of height on delayed collapse of cuttings in stiff clay. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, **160**, 73–84, https://doi.org/10.1680/geng.2007.160.2.73

Evans, D.J.A. 2017. Conceptual glacial ground models: British and Irish case studies. *In*: Griffiths, J.S. & Martin, C.J. (eds) *Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains – Engineering Group Working Party Report*. Geological Society, London, Engineering Geology Special Publications, **28**, 369–500, https://doi.org/10.1144/EGSP28.4

Fourie, A.B. & Potts, D.M. 1991. A numerical and experimental study of London Clay subjected to passive stress relief. *Géotechnique*, **41**, 1–15, https://doi.org/10.1680/geot.1991.41.1.1

Hampton, M.A. 2002. Gravitational failure of sea cliffs in weakly lithified sediment. *Environmental and Engineering Geoscience*, **8**, 175–191, https://doi.org/10.2113/8.3.175

Hanna, E., Mayes, J., Beswick, M., Prior, J. & Wood, L. 2008. An analysis of the extreme rainfall in Yorkshire, June 2007, and its rarity. *Weather*, **53**, 253–260, https://doi.org/10.1002/wea.319

Hobbs, P.R.N., Humphreys, B. *et al.* 2002. Monitoring the role of landslides in 'soft cliff' coastal recession. *In*: McInnes, R.G. & Jakeways, J. (eds) *Proceedings of the International Conference on Instability, Planning and Management, May 2002, Ventnor, Isle of Wight*. Thomas Telford, London, 589–600.

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, **OR/08/018**.

Hobbs, P.R.N., Jones, L.D. *et al.* 2013. *Slope Dynamics Project Report: Holderness Coast – Aldbrough, Survey & Monitoring, 2001–2013*. British Geological Survey, Open Report, **OR/11/063**.

Hobbs, P.R.N., Jones, L.D. & Kirkham, M.P. 2015*a*. *Slope Dynamics Project Report: Holderness Coast – Aldbrough: Drilling & Instrumentation*. British Geological Survey, Internal Report, **IR/15/001**.

Hobbs, P.R.N., Kirkham, M.P. & Morgan, D.J.R. 2015*b*. *Geotechnical laboratory testing of glacial deposits from Aldbrough, Phase 2 boreholes*. British Geological Survey, Internal Report, **OR/15/056**.

Hobbs, P.R.N., Jones, L.D. *et al.* 2019. Establishment of a coastal landslide observatory at Aldbrough, East Riding of Yorkshire, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, https://doi.org/10.1144/qjegh2018-209

Lee, E.M. 2008. Coastal cliff behaviour: Observations on the relationship between beach levels and recession rates. *Geomorphology*, **101**, 558–571, https://doi.org/10.1016/j.geomorph.2008.02.010

Lee, E.M. 2011. Reflections on the decadal-scale response of coastal cliffs to sea-level rise. *Quarterly Journal of Engineering Geology and Hydrogeology*, **44**, 481–489, https://doi.org/10.1144/1470-9236/10-063

Lee, E.M. & Clark, A.R. 2002. *Investigation and Management of Soft Rock Cliffs*. Thomas Telford, London.

Marsland, A. & Powell, J.J.M. 1985. Field and Laboratory Investigations of the Clay Tills at the Building Research Establishment Test Site at Cowden, Holderness. *In*: Forde, M.C. (ed.) *Proceedings of the International Conference on Construction in Glacial Tills and Boulder Clays*. Edinburgh Technics Press, Edinburgh, 147–168.

Miller, P.E., Mills, J.P., Edwards, S.J., Bryan, P.G., Marsh, S.H., Hobbs, P. & Mitchell, H. 2007. A robust surface matching technique for integrated monitoring of coastal geohazards. *Marine Geology*, **30**, 109–123, https://doi.org/10.1080/01490410701296598

Newsham, R., Balson, P.S., Tragheim, D.G. & Denniss, A.M. 2002. Determination and prediction of sediment yields from recession of the Holderness Coast. *Journal of Coastal Conservation*, **8**, 49–54, https://doi.org/10.1652/1400-0350(2002)008[0049:DAPOSY]2.0.CO;2

Parkes, M.T. 2015. *Back analysis of slope instability at an active coastal site in Aldbrough, East Ridings of Yorkshire through limit equilibrium and finite difference software approaches to assess driving mechanisms and differences between approaches*. MSc thesis, University of Portsmouth.

Pethick, J. 1996. Coastal slope development: temporal and spatial periodicity in the Holderness cliff recession. *In*: Anderson, M.G. & Brooks, S.M. (eds) *Advances in Hillslope Processes*, **2**. Wiley, Chichester, 897–917.

Pethick, J. & Leggett, D. 1993. The morphology of the Anglian coast. *In*: Hillen, R. & Verhagen, H.J. (eds) *Coastlines of the Southern North Sea*. American Society of Civil Engineers, New York, 52–64.

Pickwell, R. 1878. The encroachments of the sea from Spurn Point to Flamborough Head, and the works executed to prevent the loss of land. *Minutes and Proceedings of the Institute of Civil Engineers*, **51**, 191–212, https://doi.org/10.1680/imotp.1878.22489

Poulton, C.V.L., Lee, J.R., Hobbs, P.R.N., Jones, L.D. & Hall, M. 2006. Preliminary investigation into monitoring coastal erosion using terrestrial laser scanning: case study at Happisburgh, Norfolk. *Bulletin of the Geological Society of Norfolk*, **56**, 45–64.

Powell, J.J.M. & Butcher, A.P. 2003. Characterisation of a glacial clay till at Cowden, Humberside. *In*: Tan, T.S., Phoon, K.K. *et al.* (ed.) *Characterisation and Engineering Properties of Natural Soils*. Swets & Zeitlinger, Lisse, 983–1020.

Prandle, D., Ballard, G. *et al.* 1996. *The Holderness Coastal Experiment, '93–'96*. Proudman Oceanographic Laboratory, Report, **44**.

Pringle, A.W. 1985. Holderness coastal erosion and the significance of ords. *Earth Surface Processes and Landforms*, **10**, 107–124, https://doi.org/10.1002/esp.3290100204

Quinn, J.D., Philip, L.K. & Murphy, W. 2009. Understanding the recession of the Holderness Coast, East Yorkshire, UK: a new presentation of temporal and

spatial patterns. *Quarterly Journal of Engineering Geology and Hydrogeology*, **42**, 165–178, https://doi.org/10.1144/1470-9236/08-032

Quinn, J.D., Rosser, N.J., Murphy, W. & Lawrence, J.A. 2010. Identifying the behavioural characteristics of clay cliffs using intensive monitoring and geotechnical numerical modelling. *Geomorphology*, **120**, 107–122, https://doi.org/10.1016/j.geomorph.2010.03.004

Reeves, G.M., Sims, I. & Cripps, J.C. (eds) 2006. *Clay Materials Used in Construction*. Geological Society, London, Engineering Geology Special Publications, **21**.

Rosser, N.J., Petley, D.N., Lim, M., Dunning, S.A. & Allison, R.J. 2005. Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Quarterly Journal of Engineering Geology and Hydrogeology*, **38**, 363–375, https://doi.org/10.1144/1470-9236/05-008

UNESCO Working Party on World Landslide Inventory. 1993. A suggested method for describing the activity of a landslide. *Bulletin of the International Association of Engineering Geology*, **47**, 53–57.

Valentin, H. 1971. Land loss at Holderness. *In*: Steers, J.A. (ed.) *Applied Coastal Geomorphology*. Macmillan, London, 116–137.

Varnes, D.J. 1978. Slope movement types and processes. *In*: Schuster, R.L. & Krizek, R.J. (eds) *Landslides, analysis and control*. Transportation Research Board, Special Report, **176**. National Academy of Sciences, Washington, DC, 11–33.

Walkden, M.J.A. & Dickson, M. 2008. Equilibrium erosion of soft rock shores with a shallow or absent beach under increased sea level rise. *Marine Geology*, **251**, 75–84, https://doi.org/10.1016/j.margeo.2008.02.003

Walkden, M.J.A. & Hall, J.W. 2011. A mesoscale predictive model of the evolution and management of a soft-rock coast. *Journal of Coastal Research*, **27**, 529–543, https://doi.org/10.2112/JCOASTRES-D-10-00099.1

Winter, M.G., Troughton, V., Bayliss, R., Golightly, C., Spasic-Gril, L., Hobbs, P.R.N. & Privett, K.D. 2017. Design and construction considerations. *In*: Griffiths, J.S. & Martin, C.J. (eds) *Engineering Geology and Geomorphology of Glaciated and Periglaciated Terrains*. Geological Society, London, Engineering Geology Special Publications, **28**, 831–890, https://doi.org/10.1144/EGSP28.8

Wolf, J. 1998. Waves at Holderness: Results from in-situ measurements. *In*: *Proceedings of Oceanology International 98, 'The Global Ocean'*, Society for Underwater Technology, Spearhead Exhibitions Ltd, Brighton, **3**, 387–398.

Young, A.P. & Ashford, S.A. 2006. Application of airborne LiDAR for seacliff volumetric change and beach-sediment budget contributions. *Journal of Coastal Research*, **22**, 307–318, https://doi.org/10.2112/05-0548.1