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

Coastal landslide monitoring

P.R.N. Hobbs*, L.D. Jones, M.P. Kirkham, C.V.L. Pennington, D.J.R. Morgan, C. Dashwood
All authors: British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
Work carried out at: British Geological Survey, Keyworth, Nottingham NG12 5GG, UK
* Correspondence: **prnh@bgs.ac.uk**

Abstract

The paper describes results to date of an ongoing monitoring study of coastal 'soft cliff' recession at the British Geological Survey (BGS)'s 'Coastal Landslide Observatory' (CLO) on the east coast of England at Aldbrough, East Riding of Yorkshire, UK. 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: firstly terrestrial LiDAR surveying (TLS) and secondly 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 per year and a maximum rate of 3.4 m per year have been recorded for the site. The establishment of the CLO and its conceptual geological / geotechnical model are described in a related article (Hobbs *et al.* 2019a).

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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, UK; 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 recognised (Hobbs *et al*. 2002; Rosser *et al*. 2005; Poulton *et al*. 2006; Young & Ashford 2006; Quinn *et al*. 2010; Hobbs *et al*. 2013). The Holderness coast has been the subject of intensive study for many decades (Valentin 1971; Pringle 1985; Butcher 1991; Prandle *et al*. 1996; Pethick 1996; Lee & Clark 2002; Newsham *et al*. 2002; Lee 2008; Brown 2008; Quinn *et al*. 2009; Quinn *et al*. 2010; Lee 2011) and recently 'process-response' modellers have focused on this coastline (Walkden & Dickson 2008; Ashton *et al*. 2011; Walkden & Hall 2011; Castedo *et al*. 2012; Castedo *et al*. 2015). Holderness is reported to have the fastest receding coastline in Europe at 2 m per year overall (Bird 2008; Castedo *et al.* 2015). The 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 in (Hobbs *et al.* 2019a) 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 landslipped masses and on unslipped promontories, while 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

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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 (14th Feb 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 monthly intervals, though 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 to 2013) are given in Hobbs *et al.* (2013), drilling and instrumentation (to 2015) in Hobbs *et al.* (2015a) and geotechnical laboratory testing in Hobbs *et al.* (2015b).

Engineering geology

The lithostratigraphy at the site is summarised in Fig. 2; a fuller description provided in (Hobbs *et al.* 2019a). 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 Bell & Forster (1991), Bell (2002) and Powell & Butcher (2003). However, the laminated, silty, clayey (and glacitectonised) 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 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.

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Geotechnical laboratory testing, described in detail in (Hobbs *et al.* 2019a) 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 due to significant sand content*;
7. Geotechnical differences between tills are minor and are in general agreement with published values.

*The strength sensitivity of the tills is likely to be small (Reeves *et al.* 2006), though specimen size and preparation need to be taken into account.

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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 reducing vertical stress and increasing intact effective strength in that part of the cliff; at the same time stress relief reducing mass strength. Significant ground water 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 ground water 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. Whilst 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 ground water 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; Poulton *et al*. 2006; Miller *et al*. 2007; Buckley *et al*. 2008; Hobbs *et al*. 2013, 2015a); more recently augmented by UAV photogrammetry. The data from the TLS are used to construct Digital Elevation Models (DEM's), examples of which are shown in Fig. 3. These were compared and used to characterise landslide processes and to calculate volume changes between surveys. Up to November 2017 thirty-eight surveys had been carried out at Aldbrough, twenty-seven of which have been used in volume calculations. The data obtained from the monitoring surveys have enabled 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 (Walkden & Dickson 2008; Pethick 1996). 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.

The cumulative volume loss for the study period to date (1st September 2001 to 23rd November 2017 = 16.2 years) was 53 000 m^3 per 100 m along coast; giving an estimated gross weight of 111 300 tonnes. This translates to a total of approximately 27 m linear recession. Twelve-monthly volumetric losses from the cliff (Table 1) in the central embayment of the CLO range from 1.2 to 6.3 m^3 per metre (along coast); the average being 3.3 m^3. These figures equate to sediment yield, if sediment retained on the beach is included

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(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/yr. This agrees with historic average recession rates for Holderness as a whole, obtained from point data, of 0.80 to 2.0 m/yr determined by Pethick (1996) and Castedo *et al.* (2015), but greater than the 1.3 m/yr average of Quinn *et al* (2010).

Landslide processes

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

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, UK 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 (Figs. 6a & 6d) with near-vertical backscarps fully exposing the Hornsea Member. Pickwell (1878) emphasised 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's 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 (Figs. 6b & 6c), though toppling of Withernsea Member blocks (typical volume: 3 to 5 m^3) also occurs from the over-steepened promontories separating embayments. Toppling has also featured, but on a much larger scale, at Warden Point (Dixon & Bromhead, 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^o and a maximum of 66^o; though 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 due, 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 six to

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seven years; this being based on three events identified since September 2001, i.e. August 2004, March 2010 and February 2017 (Figs. 4 & 7). This compares with a cycle of around 30 to 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 to 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 Fig. 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. *NOTE: Pre-2012 rainfall data are averages taken from three East Riding of Yorkshire stations within a 23 km radius of the CLO*.

Oceanographic & 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 of the Humber (median duration >13 hours) with the likelihood of spanning High Water (Dhoop & Mason 2018); for example, an anticyclonic storm on 18th December 2009 lasted 19.5 hours at Hornsea. A storm surge, described by the EA as the most serious for 60 years, hit the east coast of England on 5th 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 hrs and 7.25 m at 18.53 hrs, 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 the 6th December with waves in excess of 6 m, accompanied by a maximum wind speed of 20.8 m/s (Force 8/9) recorded at the nearby BGS weather station. However, in terms of wave energy alone, higher peaks were recorded on 24th March and 10th October, 2013; a maximum wave height of 7.4 m having been recorded on 23rd March. Another notable 'storm' year (since June 2008) was in 2010. Wave direction was predominantly and consistently from the NNE and NE. 'Onshore' waves (defined here as derived from compass points N340^{o} to N140^{o}) 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^{o} to the current average coastline at Aldbrough (CCO 2017). Notable rainfall events included 12th – 15th and 24th – 25th June 2007; this month having over 4 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 Fig. 8. *NOTE: 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 yr 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.

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A plot of average wave-climate energy vs. incremental volume loss for 100 m of cliff (calculated from TLS) is shown in Fig. 9; the wave data for which was provided by the 'Hornsea' buoy (CCO 2017). The 'wave-climate' energy, P was calculated here as follows (Dexawave 2014):

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

Where: P is wave energy (kW/m)

H_S is significant wave height (m) (half-hourly data)

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.

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 near-shore zone (Wolf 1998). Pethick & Leggett (1993) indicated that high energy waves with long return periods (e.g. 8 to 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) is given in 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 14th February 2017 at the same embayment in-line with the boreholes and was 'captured' by the borehole instrumentation on 1st 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.

Instrumentation results

Inclinometers

Boreholes 1b, 2b and 3b (Figs. 10, 11 & 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 are described in Hobbs *et al.* (2015a).

The inclinometer results from Borehole 1b (up to August 2017) are shown in Fig. 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 (+ve) is 0 to 30 mm (displacement) and on the y-axes is 0 to 20 m (depth). The plots show positive lateral displacements from a depth of 17.5 m upward within the Bridlington Member, though significant displacements only occur 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 14th 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

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northerly displacement is 18 mm.

Prior to the event of February 2017 there has been a pre-cursory (+ve) 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. *NOTE: this dataset has a July 2012 baseline.*

Equivalent data for Borehole 2b (up to August 2017) are shown in Fig. 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. *NOTE: this dataset has an April 2012 baseline.*

Equivalent data, but over a shorter period, for Borehole 3b (up to August 2017) are shown in Fig. 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. *NOTE: this dataset has a March 2015 baseline.*

An example of a ‘time’ plot (BH1a, 4 m depth) is shown in Fig. 13. This sigmoidal curve clearly shows detection of the precursory build-up in displacement towards the cliff leading to the landslide event of 14th 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 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 that this was due to both swelling of clay minerals and passive shearing. They 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 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, though 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 body height (Azizi 2000); this giving a pre-failure displacement of around 170 mm at the CLO.

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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 latter promoting 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 whilst 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 6-hourly pore pressure readings 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 possibly influenced by temperature variation at the shallowest sensors. The piezometer installation and a detailed analysis of results are described in Hobbs *et al.* (2015a).

Whilst 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 though loss of contact between sensors and formation is suspected; possibly due 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 sensor at 4 m. However, apart from the anomalies described above, the results overall agree with those for nearby Cowden, described in 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 Fig. 15. These emphasise the markedly sub-hydrostatic nature for BH's 1a and 3a but less-markedly sub-hydrostatic in 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 BH's 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 (1978) 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, due 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 earlier.

The pore pressures at 20 m depth within the boreholes diminish toward the cliff from 75 kPa to 10 kPa and readings are relatively constant when compared with the shallower sensors.

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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 m, 4 m 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 whilst 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 pore water 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 due 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 & 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; (Hobbs *et al.* 2019a).

In order 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 (Fig. 17 and Fig. 18), the last before the 14th 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; WP/WLI 1993); though 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 are given in 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 FoS's for Galena and FLACslope using 'peak' strength data were 1.26 and 0.92, respectively (i.e. at or close to a stable condition). Drainage

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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. Whilst 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 resulting 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 in Butcher (1991), Dixon & Bromhead (2002) and Parkes (2015). While a fully undrained condition is unlikely (Quinn *et al* 2010), major till members tend to sub-divide 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 due 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 to 17 m high cliff, in glacial deposits typical of the Holderness coast, deep-seated rotational landslides are the dominant agent of cliff recession, though possibly with modification towards a composite mode near the toe. A potential cyclicity of 6 to 7 years has been shown covering three major rotational landslide events at the study site, occupying virtually the full width of the same embayment; the most recent dated 14th 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 which are here attributed to stress relief. Pre-cursory, 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 (*though it is recognised that the terminations of the boreholes would ideally have been deeper than 20 m*). This therefore provides an early warning methodology 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/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 & 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 due to a combination of stress relief and clay shrinkage, is suspected though 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 key as it provides a weak, saturated and (in part) permeable horizon which has been subjected to shear deformation, both during formation and

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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 ground water to the cliff slope and the landslide masses on it.

Whilst the TLS monitoring programme has suffered 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 recognised that it has not been able to monitor minor landslide activity, for example rock falls/topples/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. Whilst 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 particular 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/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 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 to 2 m above platform level (15 to 16 m below cliff-top);
4. Major rotational landslides utilise the undulose Dimlington Bed as the seaward/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 which 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

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develop in proximity to the cliff; thought to be as 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/yr.

Drilling, instrumentation & 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 due 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 draining to the cliff;
6. Piezometric pressures have continued to reduce after expected equilibration times following installation, presumably due to the reducing distance to the cliff with time;
7. Piezometric pressures increased in BH2a at 4 m, 8 m and 12 m in response to the February 2017 landslide event. No responses were recorded in BH1a and BH3a.
8. Small suctions (-ve pore pressures) exist in 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 individual tills were found to be small; older tills tending 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 sub-surface behaviour. Whilst this study has concentrated on the cliffs at the CLO, data from the beach/platform will also be analysed and reported in due course.

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Notation & abbreviations

c’	Effective cohesion
ϕ’	Effective friction angle
c_u	Total cohesion
ϕ_u	Total friction angle
c_r	Residual cohesion
ϕ_r	Residual friction angle
w_L	Liquid limit
w_p	Plastic limit
w_s	Shrinkage limit
I_P	Plasticity index
LS	Linear shrinkage
LI	Liquidity index
ρ_d	Particle density

WM	Withernsea Member
STM	Skipsea Till Member
DB	Dimlington Bed
BM	Bridlington Member
F.	Formation
M.	Member

BH	Borehole
CLO	Coastal Landslide Observatory
DEM	Digital Elevation Model
ERT	Electrical Resistivity Tomography
FoS	Factor of Safety
LiDAR	Light Detection & Ranging
PRIME	Proactive Infrastructure Monitoring and Evaluation
TLS	Terrestrial LiDAR Surveying
UAV	Unmanned Aerial Vehicle (drone)

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Fig. 1. Map showing location of Aldbrough Coastal Landslide Observatory, CLO (box) (BGS©UKRI**)**
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Fig. 2. Schematic stratigraphy with photo of central (100 m) embayment (not to scale) (BGS©UKRI**)**
Fig. 3. Selected bi-annual Digital Elevation Models (DEM's) for CLO cliff (central embayment) (BGS©UKRI**).** NOTE 1: Intermediate DEM's omitted for clarity. NOTE 2: Width of DEM is 100 m.
Fig. 4 Plot of Date vs. Cumulative volume loss from cliff (per 100 m) at CLO (September 2001 datum) (BGS©UKRI**)**
NOTE: Dates of major fresh landslide events in central embayment shown as dashed red lines with arrows.
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. NOTE: All cliff access was carried out with a full risk assessment (BGS©UKRI)
Fig. 7. Plot of Date vs. Total rainfall & Incremental volume loss (per 100 m) from cliff. Includes Met Office data (2001 to 2011) (BGS©UKRI**)**
NOTE 1: "Total rainfall" refers to total rainfall since last survey.
NOTE 2: Dates of major fresh landslide events in central embayment shown by dotted red lines with arrows; notable storms shown by dotted blue lines.
Fig. 8. Plot of Date vs. Incremental volume loss from cliff (per 100 m) & Number of storms since last survey (Hornsea buoy) ERYRCMP (1995). Includes data from CCO. (BGS©UKRI**)**
Fig. 9. Plot of Date vs. Incremental volume loss from cliff (per 100 m) & Average wave-climate energy (Hornsea buoy) ERYRCMP (1995). Includes data from CCO. (BGS©UKRI**)**
Fig. 10. Cumulative displacements for BH1b up to November 2017. (BGS©UKRI**)**
NOTE 1: Axis A is North, Axis B is East; NOTE 2: July 2012 baseline; NOTE 3: Blue arrows indicate pre-event displacements of winter 2016/17.
Fig. 11. Cumulative displacements for BH2b up to November 2017. (BGS©UKRI**)**
NOTE 1: Axis A is North, Axis B is East; NOTE 2: April 2012 baseline.
Fig. 12. Cumulative displacements for BH3b up to August 2017. (BGS©UKRI**)**
NOTE 1: Axis A is North, Axis B is East; NOTE 2: March 2015 baseline.
Fig. 13. Example plot of Time vs. Displacement (cumulative) for BH1a inclinometer, 4.0 m depth. (BGS©UKRI**)**
NOTE 1: Axis A is North, Axis B is East. NOTE 2: April 2012 baseline. NOTE 3: Dashed red line is landslide event
Fig. 14. 'Time' plot of Month vs. Piezometric pressure & Total effective daily rainfall (BH's 1a, 2a & 3a), April 2012 to November 2017 (BGS©UKRI**).** NOTE 1: Landslide event (14th February 2017) marked by red dashed line & arrow. NOTE 2: Borehole 3a record starts February 2015
Fig. 15. Piezometer 'profile' plots (a) BH's 1a & 2a (b) BH3a (BGS©UKRI**)**
NOTE 1: No sensors present in BH's 1a & 2a at 2 m depth; NOTE 2: Purple dashed lines represent idealised hydrostatic profiles.
Fig. 16 Selected cross-sections aligned with 'b' boreholes, derived from TLS (September 2001 to August 2017: left to right) (BGS©UKRI**).**
NOTE 1: Location of BH1b (installed March 2012); NOTE 2: March and August 2017 profiles do not illustrate 14th February 2017 landslide event due to concentration of displacement in southern part of the embayment at this time; NOTE 3: Cliff-top displacement between February 2011 and March 2012 profiles due to subsidence & destruction of concrete roadway
Fig. 17. Example of Galena output: Profile aligned with 'b' boreholes, October 2016 using residual strength data (BGS©UKRI**).** NOTE 1: Dashed horizontal lines are piezometric levels, solid red line is slip surface (estimated)
Fig. 18. Example of FLACslope output: Profile aligned with 'b' boreholes, October 2016 using residual strength data. FoS is 0.44. (BGS©UKRI**).** NOTE: Shear strain rate contours (colours) and displacement vectors (arrows).

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Table 1 *Table of cliff recession derived from selected Terrestrial LiDAR Surveys (TLS), September 2001 to November 2017. (BGS©UKRI). NOTE: TLS data unavailable for 2008*

			Increm.	Cumul.	Increm.	Cumul.	Cumul.	Increm.	Cumul.	Cumul.	12 mnth	Mean
			time	time	loss	loss	loss/m	loss	loss	loss/m	incr. loss	recess.
	Period				/100 m	/100 m		/100 m	/100 m		/100 m	rate
Date	start	end	(days)	(days)	(m^3)	(m^3)	(m^3)	(tonnes)	(tonnes)	(tonnes)	(m^3)	(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**		

NOTE: Mean recession rate is here calculated from incremental volumetric loss for each monitoring period by normalising 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.

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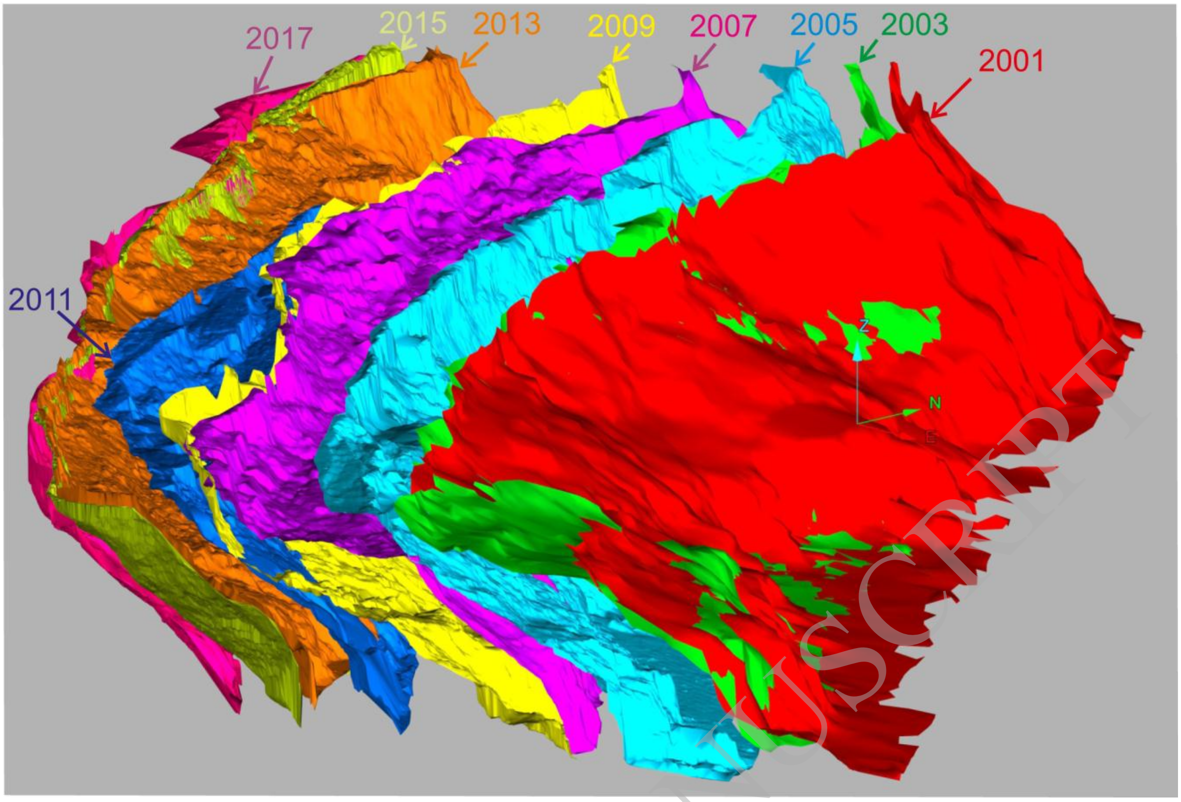

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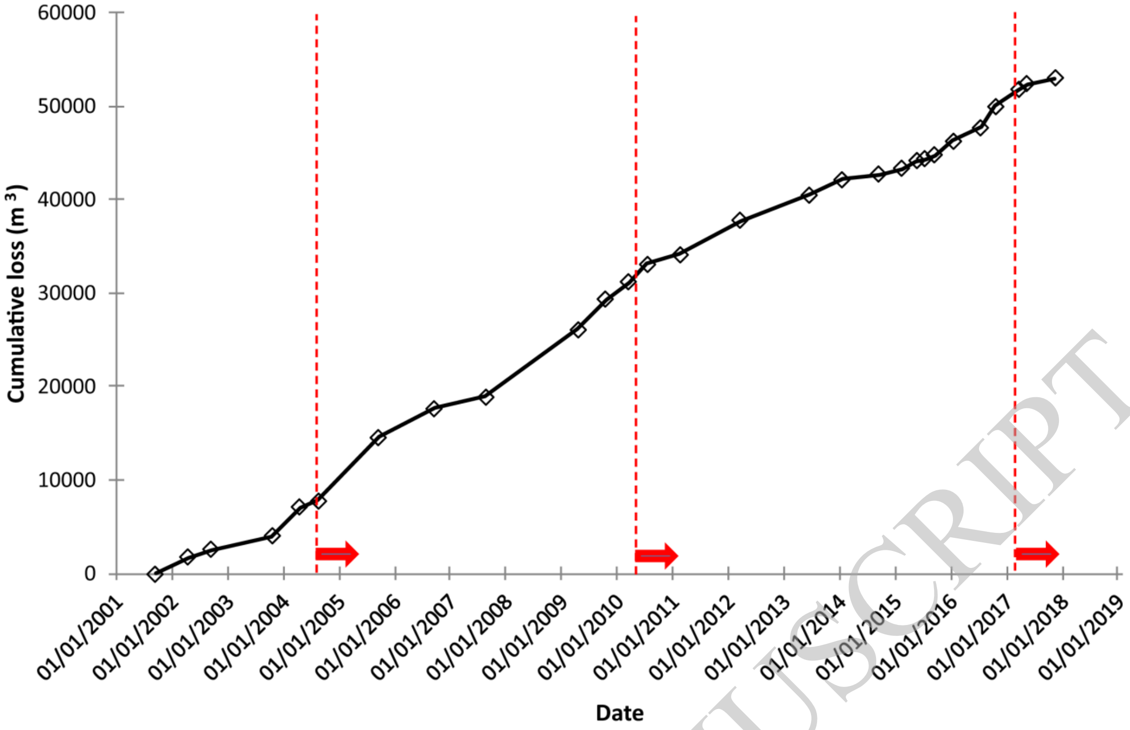

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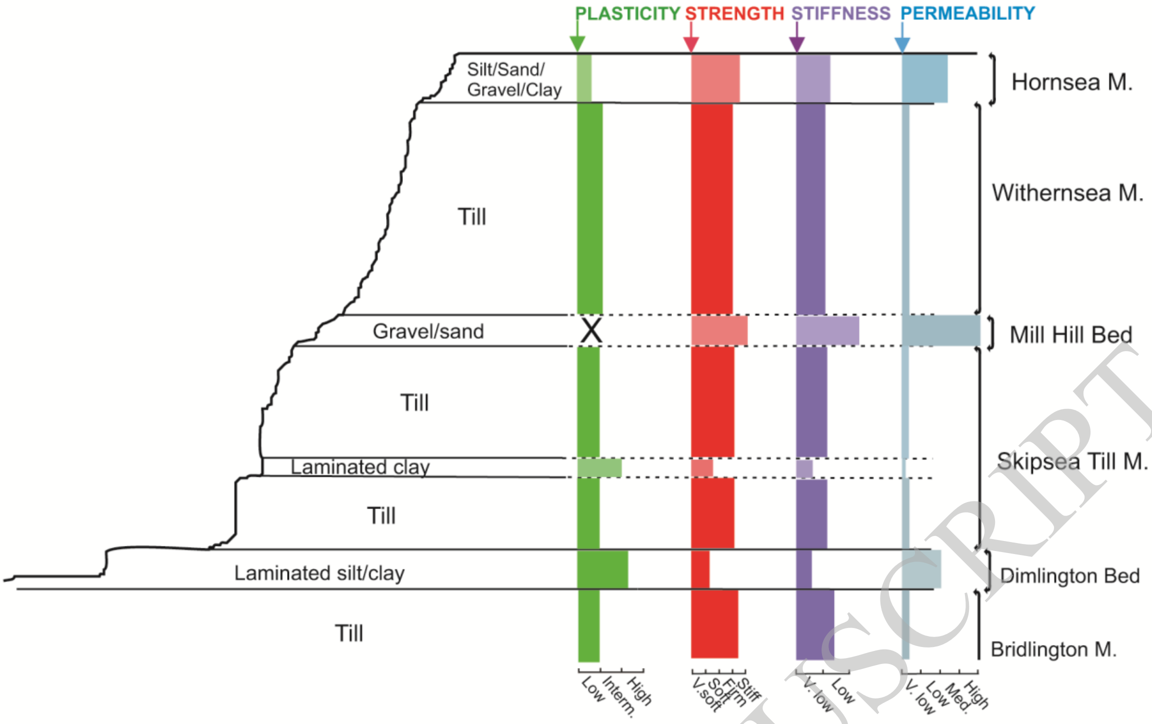

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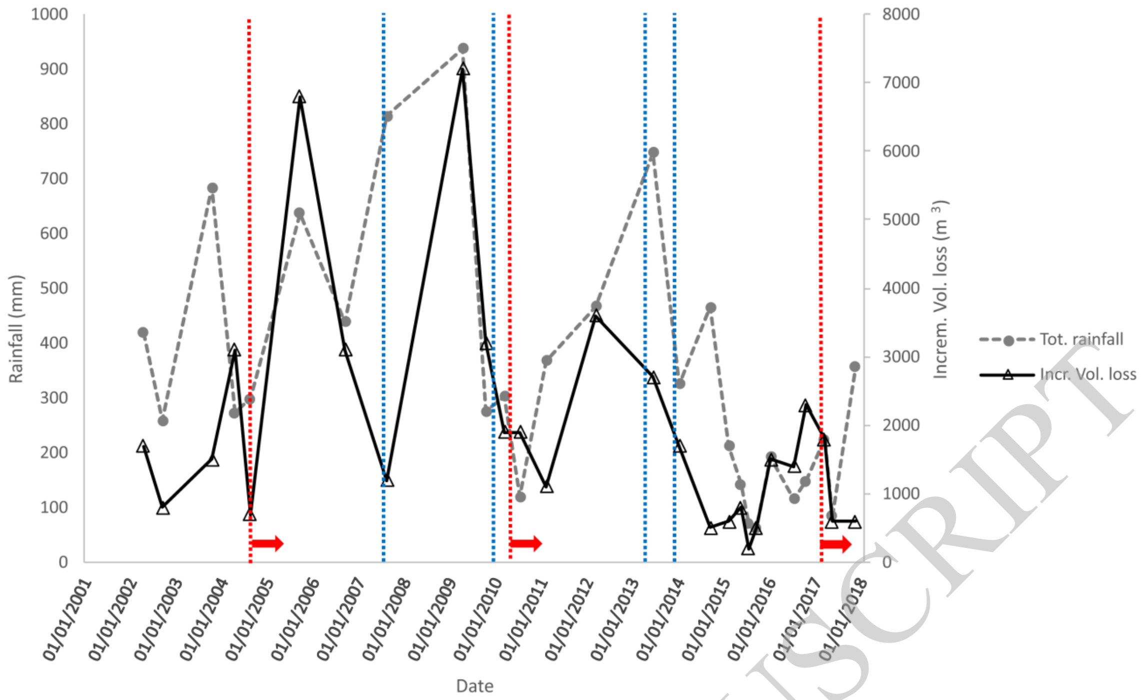

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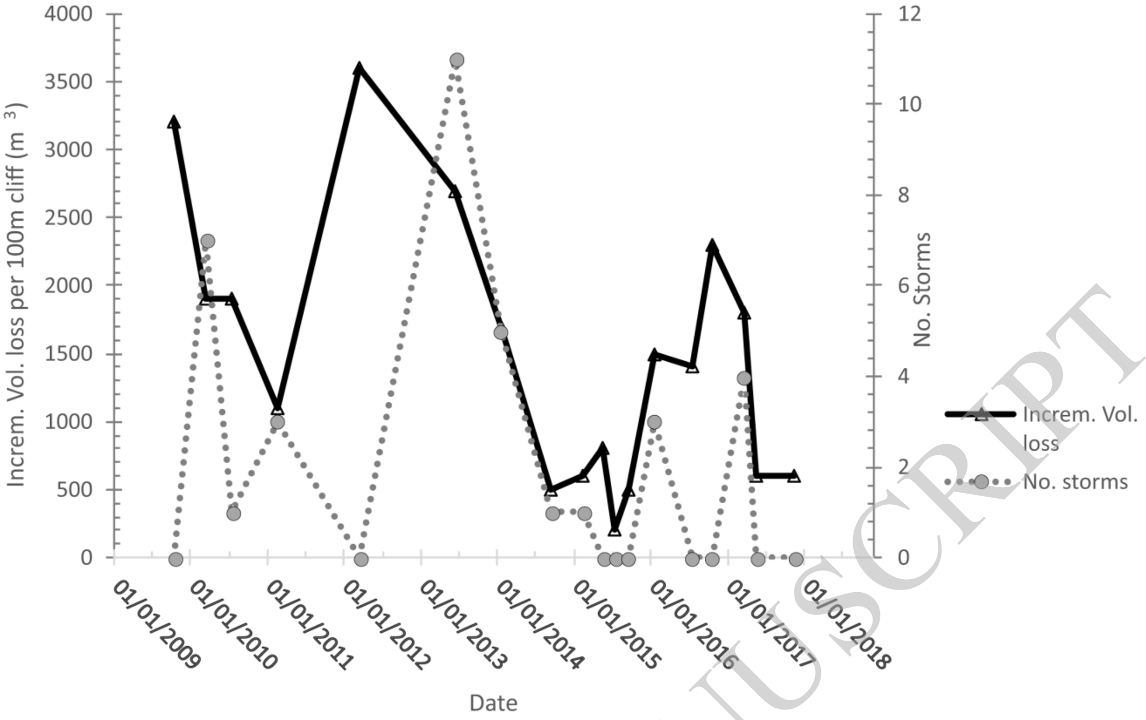

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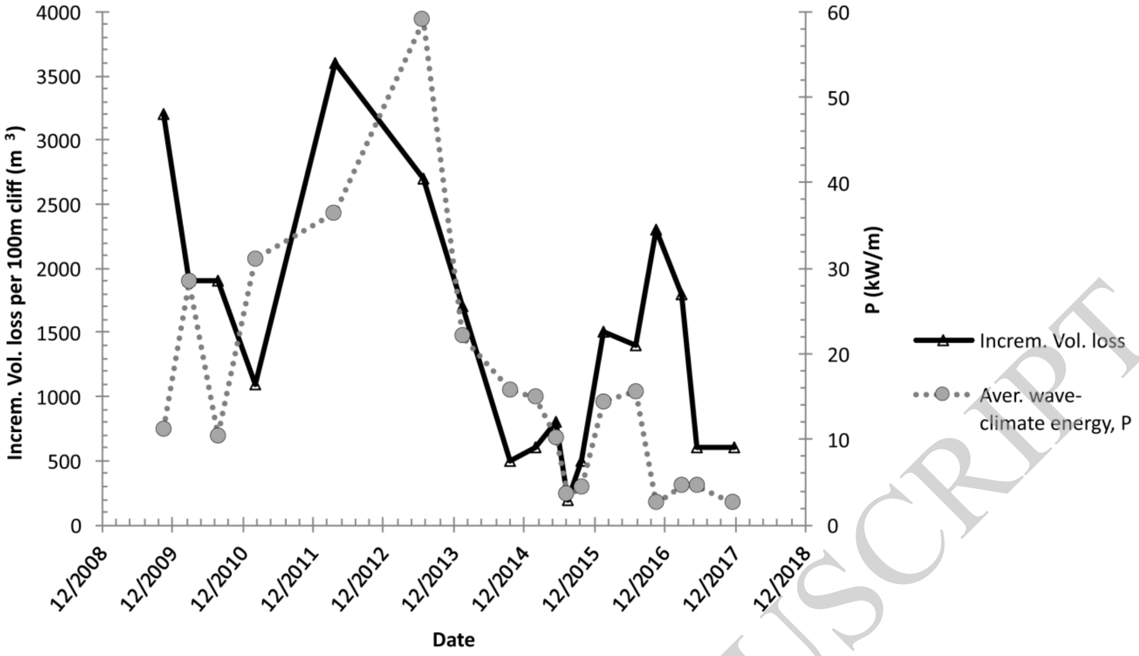

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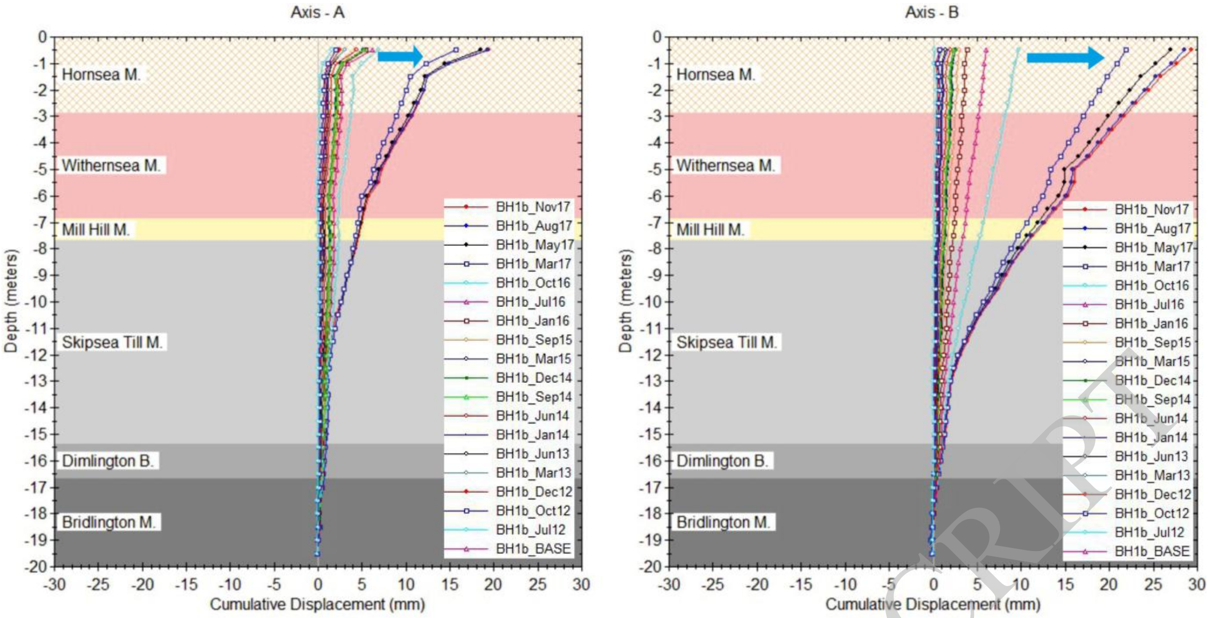

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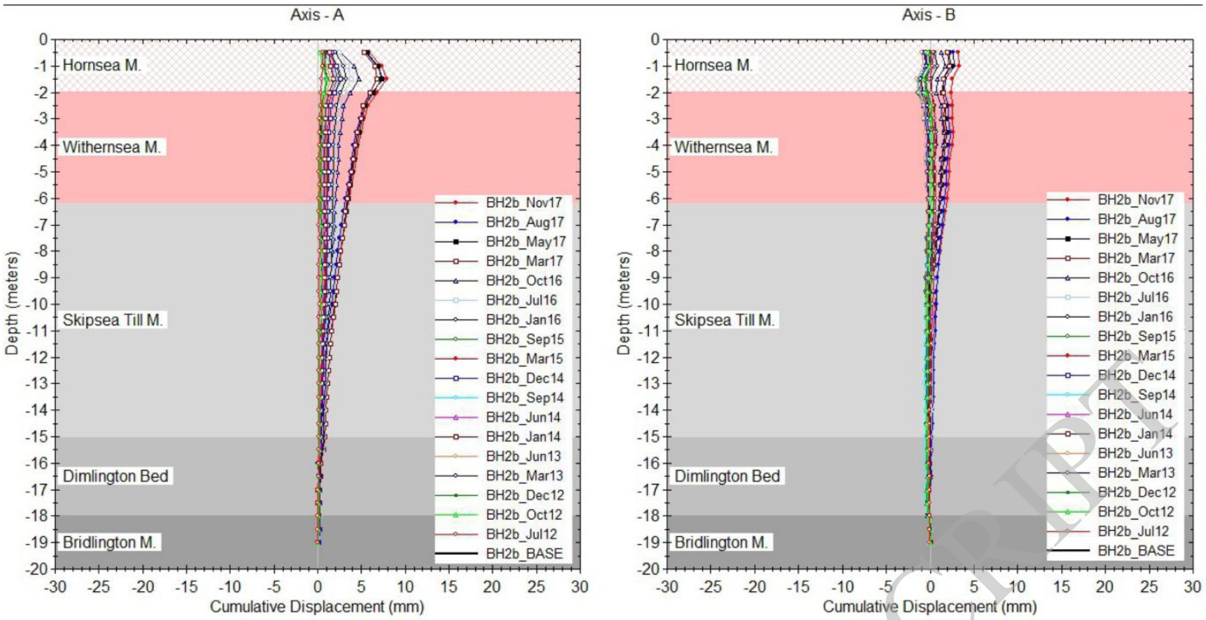

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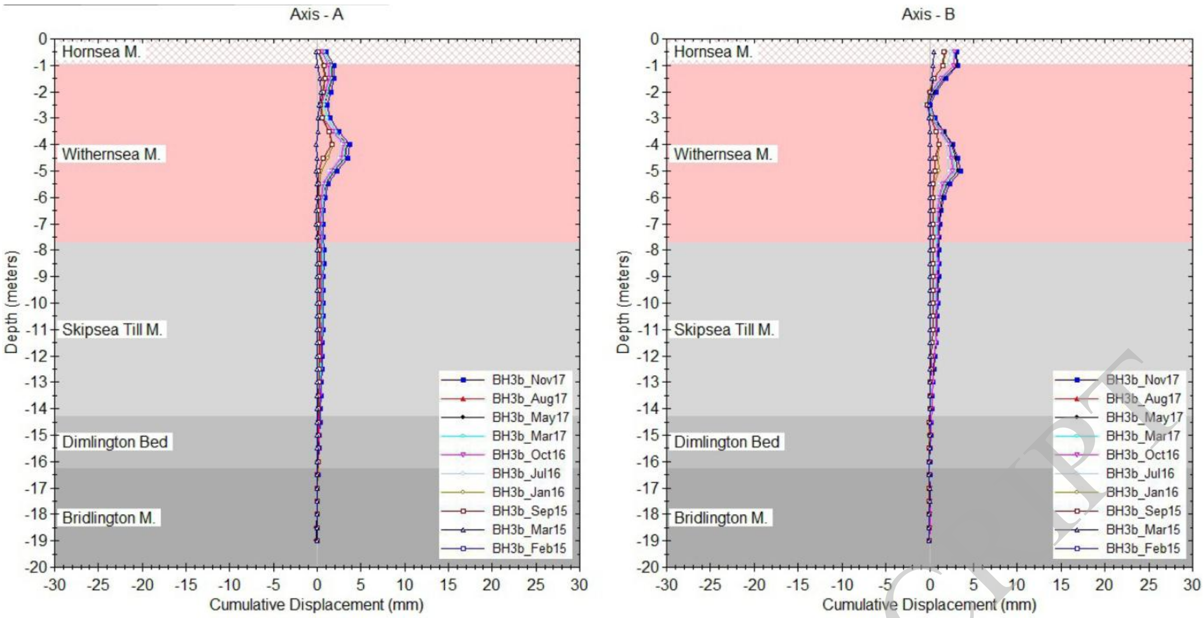

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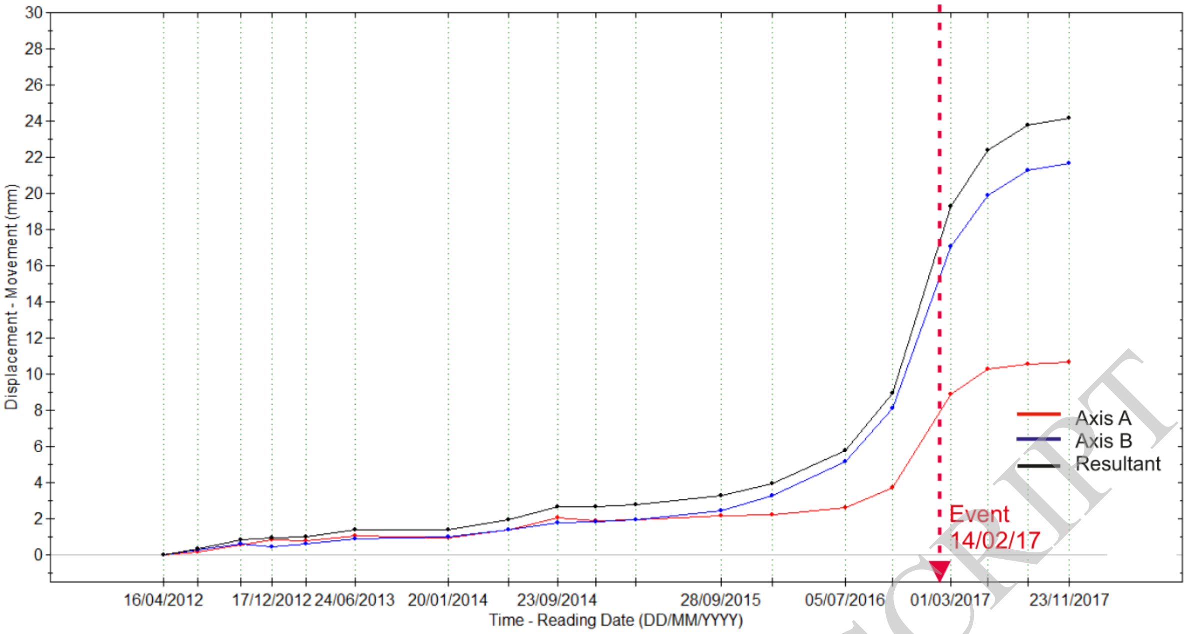

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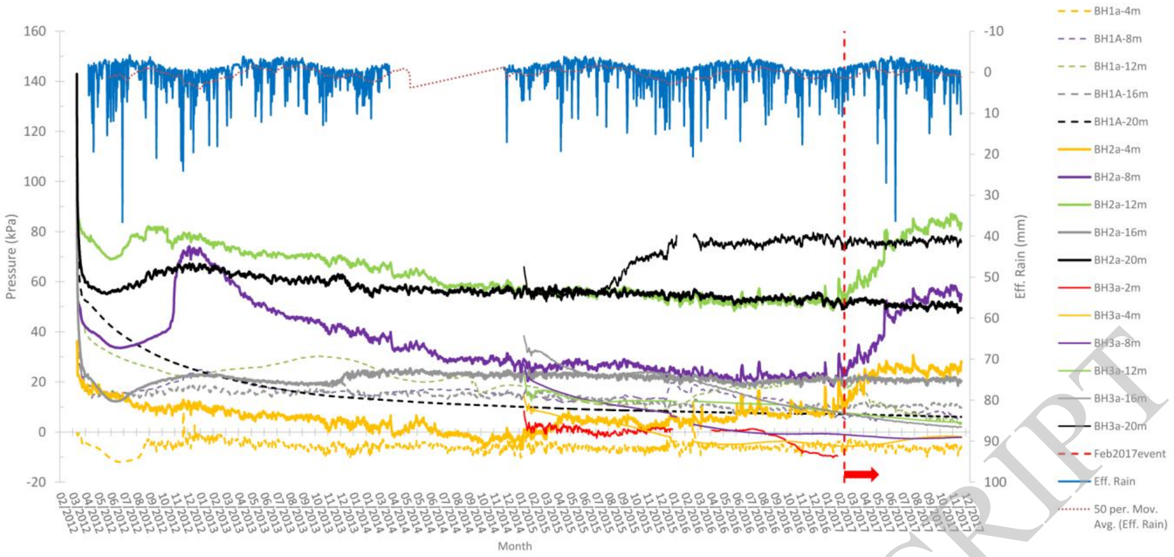

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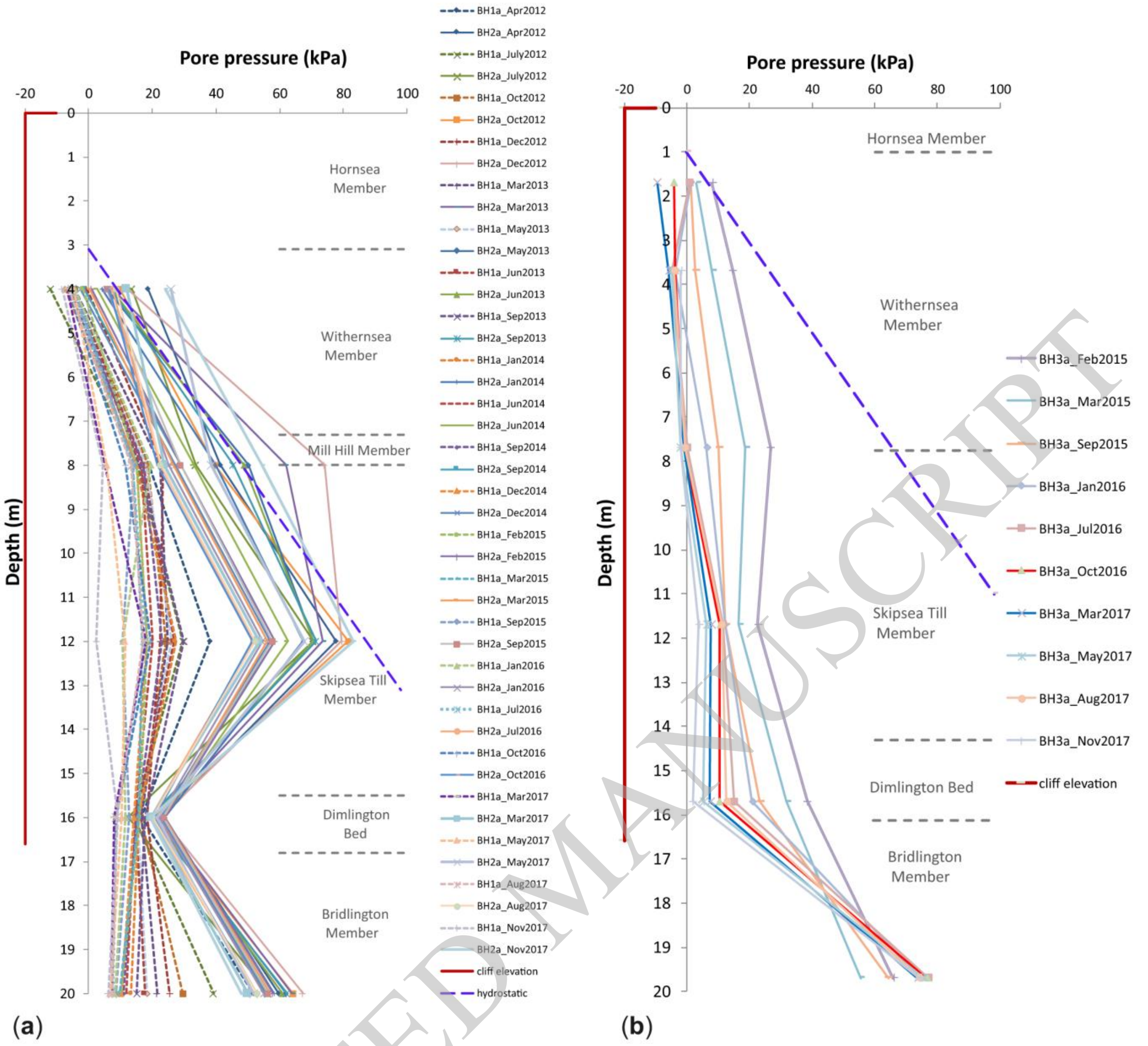

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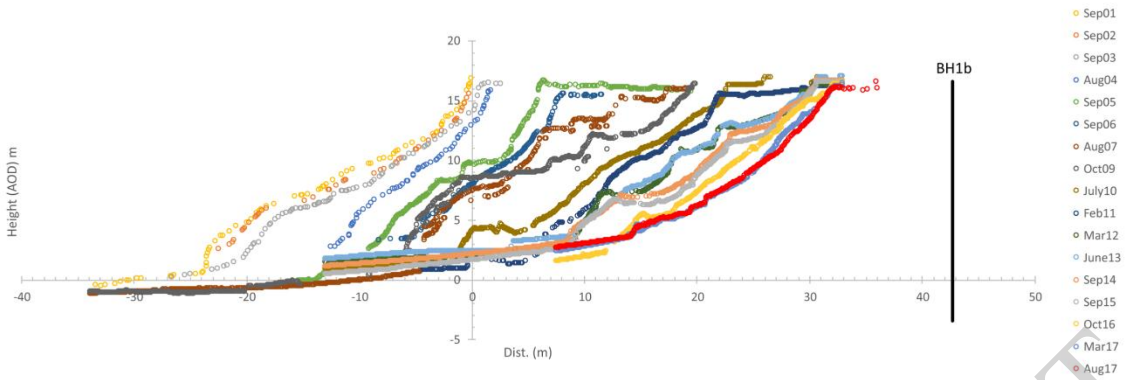

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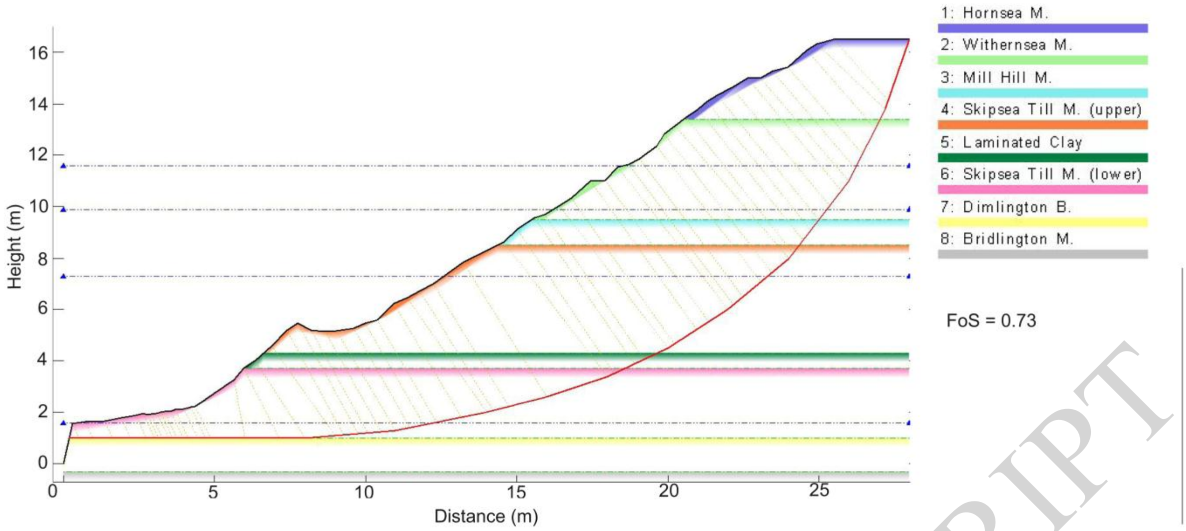

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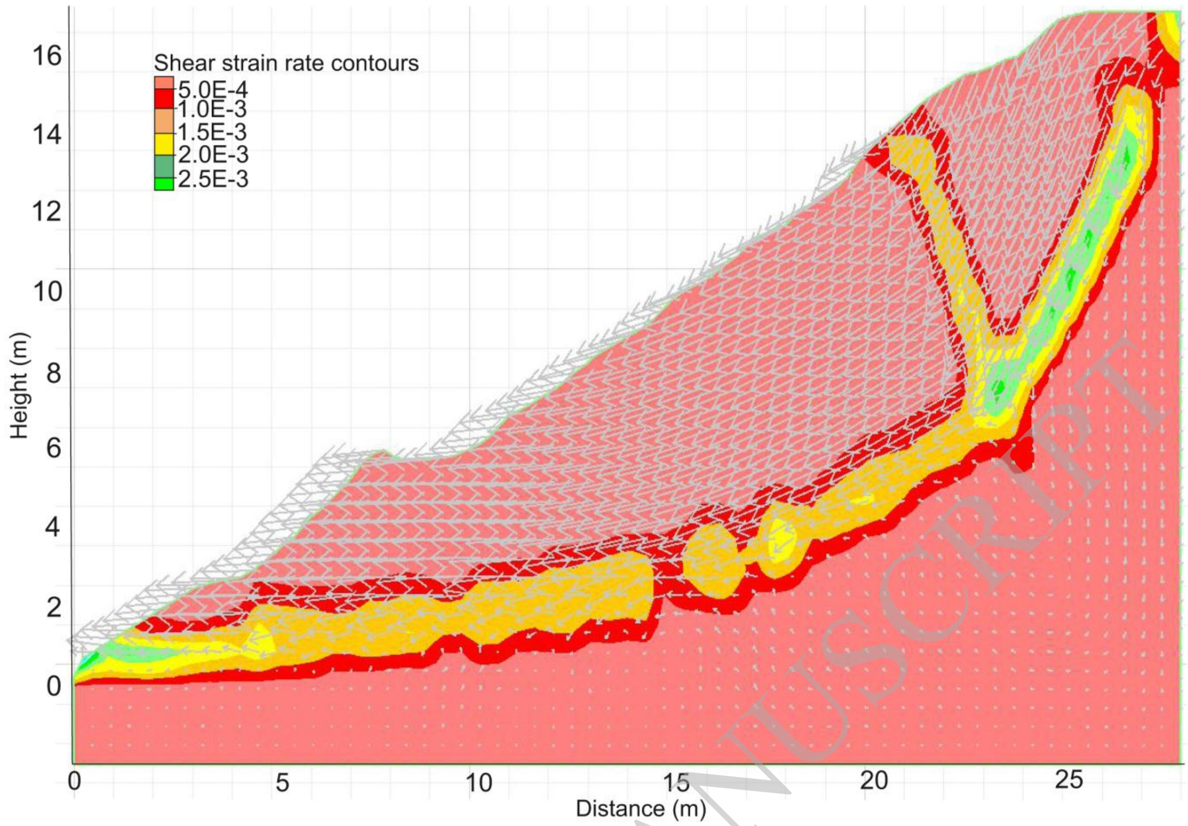

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