

Interpretation Report 13: June 2019 to November 2019

Prepared for
Scarborough
Borough Council

February 2020



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Document Information

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Document History and Status

Revision	Date	Description	By	Review	Approved
0	3 Feb 2020	SBC Geotechnical Monitoring Report 13 (draft, excluding AE data from Loughborough University)	Claire Czarnomski	Paul Fish	Roger Moore
1	3 Feb 2020	Final. As above since no AE data were available.			Paul Fish

Disclaimer

Jacobs Engineering Group UK Ltd (previously CH2M) has prepared this report in accordance with the instructions of our client Scarborough Borough Council (SBC) for the client's sole and specific use. Any other persons who use any information contained herein do so at their own risk. This report is a review of coastal slope monitoring data collected by JBA Consulting Ltd on behalf of SBC. The objective of this report is to analyse and interpret the slope monitoring data from specific locations in order to highlight any change in cliff instability risk. Jacobs has used reasonable skill, care and diligence in the interpretation of data provided to them and accepts no responsibility for the content, quality or accuracy of the monitoring data, third party reports, or further information provided either to them by SBC or, via SBC from a third-party source, for analysis under this term contract.

The interpretation of the level of cliff instability risk presented in this document is based solely on the data provided by JBA. While every effort will be made to ensure the data are correct, Jacobs cannot be held responsible for the quality of monitoring data. This data analysis report comments on the monitoring data collected over the preceding 6-month period at specific locations. It will not make projections of future cliff instability activity or discuss cliff instability risk at areas that are not monitored. It is Scarborough Borough Council's responsibility to determine an appropriate response to the guidance on cliff instability risk provided in this report.

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Summary of findings

This report presents an interpretation of coastal slope monitoring data recorded between June 2019 and November 2019 along the Scarborough Borough Council frontage. It is the thirteenth in a series of six-monthly updates on the cliff instability risk of the frontage that began in 2014. The weather during summer 2019 was marginally wetter compared to previous years. The autumn was exceptionally wetter than average, with rainfall totals for the months September to November all exceeding records since 2011.

Boreholes show that water levels have remained relatively steady around average levels during the monitoring period, except for Robin Hood's Bay (BH3b), Scalby Ness (WS6), Spa (1 spa), Filey Town (CPBH01a) and Filey Flat Cliffs (B1) that are at atypically high levels. In situ monitoring using inclinometers does not indicate any significant slope movements, although on-going except for displacement at Scarborough Spa in BH101 is seen at the base of the coastal slope. This area should be visually inspected.

The risk of slope instability is elevated following the very wet autumn period. Risk will increase if the winter of 2019/20 is also wet. Specific sites of concern and issues needing attention from Scarborough Borough Council and its monitoring contractor are as follows:

- At Runswick Bay, Inclinometer readings at the base of borehole A001 appear to be erroneous. This inclinometer monitors the performance of piles, and equipment should be checked to ensure there is no blockage.
- At Robin Hood's Bay, BH1a groundwater levels are at a low level. Piezometer BH1b, installed deeper in the same borehole, was dry and its integrity should be checked. This site would benefit from installation of automated piezometers to provide a continuous record of groundwater fluctuations.
- At Scalby Ness, groundwater levels are steady at low levels in most of the boreholes. However, piezometer WS6 located mid-slope shows groundwater levels have remained elevated close to the historical high. Auto-piezometers on the cliff top in boreholes P1b, P2b and P3 show groundwater levels have risen since replacement of the data loggers, which appears to be a systematic error. These piezometers should be checked to ensure caps are secure, there is no ingress of water from artificial recharge and calibration is correct. Piezometers P2a or P4b had data logger communication errors and should be repaired. Piezometers in borehole B6 and Sn2a were dry. These locations should continue to be monitored.
- At Oasis Café, no data are available for BH3p for this monitoring period due to temporary logger problems. The data should be downloaded and reviewed for the next monitoring period.
- At the Holms, there was a problem downloading data from piezometer BH9a. This issue should be investigated and remedied by the monitoring contractor. Inclinometer readings from BH10A appear to be erroneous and the equipment should be checked.
- At Scarborough Spa Chalet, no data has been recorded since May 2016 at piezometer BH12. This site requires attention to fix or replace the piezometer and damaged cable. Piezometer BH12a had data logger communication errors and should be repaired.
- At Scarborough Spa, the inclinometer in borehole BH101 indicates ongoing movement at 13 m depth below ground level within clay-rich glacial sediment. This may be related to disturbance of the slope and the site should be checked visually for signs of movement at the surface. Nearby piezometers show slight increases and/or peaks in groundwater levels which are expected to rise following the extreme rainfall received during October and November. The Spa area should

continue to be monitored visually, especially following sustained heavy rainfall, and the trend will be reviewed in the next monitoring period.

Groundwater levels at the Spa have remained steady at most piezometers where data has been retrieved. Piezometer 1 spa shows groundwater levels have risen by several metres over the monitoring period. This site should be inspected and monitored for evidence of ground movement, particularly following heavy rainfall events. Groundwater levels are elevated in BH108a, BH108b and BH104b, however this equipment is not functioning correctly, and results may be caused by surface ingress of water into the boreholes. The equipment should be repaired, and data collected on the next site visit. Shallow surface creep was evident at inclinometer BH14, however nearby piezometers are dry. The ground movement and groundwater trends will be reviewed in the next monitoring report. The inclinometer also shows potentially erroneous readings and should be checked, and data reviewed for the next monitoring period. No data were available for piezometers BH1 Prom, G3 and 5 spa, and inclinometer BH13. The loggers should be checked/repared, and data collected for the next monitoring period. Access to piezometers 2 spa and 3 spa and inclinometer BH105 was not possible during this monitoring period and the data should be downloaded and reviewed for the next monitoring period. Several boreholes were dry (BH106a, BH106b). These locations require attention and should continue to be monitored.

- At the Clock Café, borehole BH15 remains dry. The integrity of the piezometer should be checked. No ground movement data was available at the Clock Café (AA10, AA11), and data should be collected during the next monitoring period.
- At South Cliff Gardens, no data were available for borehole piezometers BH18a, D2b, BH3a and E2a. The issue should be investigated and remedied by the monitoring contractor.
- At Holbeck Gardens there was a problem downloading groundwater data at borehole BH4a and BH4b. The issue should be investigated and remedied ahead of the monitoring contractor. No evidence of movement is shown in the current inclinometer data (AA07), and erroneous readings appear at the base of the borehole.
- At Filey Town, in borehole CPBH02a groundwater level remains near the historical high. The piezometer lid was not secured, and it is possible that water ingress has resulted in continued elevated water level readings at this location. Groundwater levels are also elevated in CPBH01a. Borehole CPBH10b is dry. This location should continue to be monitored. There was a problem downloading data from piezometers CPBH01b, CPBH02b, CPBH04b, CPBH06b and CPBH08b. This issue should be investigated and remedied by the monitoring contractor. Access to inclinometer CPBH03 was not possible at the time of data collection. The data logger for borehole CPBH09b and CPBH10a should be checked and recalibrated as dip meter readings and diver readings have continued to be discordant since 2013.
- At Filey Flat Cliffs there was a problem downloading data at boreholes C4a, A3 and D1. The issue should be investigated and remedied by the monitoring contractor. Groundwater data show levels have increased significantly in borehole B1 and water appears to have risen well above the cover level of the piezometer. This trend should be monitored in the next report.

Introduction

1.1 Background to study

The Scarborough Borough Council coastline is affected by widespread cliff instability, largely due to its geology and climate. Since the Holbeck Hall landslide in June 1993, understanding the risk posed by landslides has been a high priority for the Council. Numerous ground investigations and associated studies at locations of concern have been undertaken in the last 20 years meaning the Council now has a widespread network of ground monitoring instrumentation installed, much of which is automated using data-loggers. The Council has also supported the installation of experimental acoustic inclinometers by Loughborough University along its frontage. These experimental devices, which are installed adjacent to conventional inclinometers, have the potential to provide cost-effective and accurate real time information on ground movement. The dataset allows the Council to better understand cliff instability risk and support decisions on risk management.

A comprehensive programme of data collection and analysis was commenced by the Council in October 2008, when SBC awarded Mouchel Ltd a contract to design a monitoring strategy for the coastline. Mouchel's recommendations were adopted by the Council and a contract for regular data collection and monitoring reports was awarded that operated to spring 2012 (Mouchel 2012). SBC then commissioned Haskoning UK Ltd to undertake a review of the condition of boreholes and associated monitoring instruments (Haskoning, 2013), which highlighted locations of damaged or worn equipment that needed repair. In addition to routine repairs and maintenance of equipment the Council has upgraded piezometers with automatic dataloggers to ensure the best possible data are collected.

SBC invited tenders for a new phase of slope monitoring on 24 July 2013, with separate contracts for data collection and data analysis being let. Contracts covering an initial three-year programme were awarded on 3 September 2013 to JBA Consulting Ltd and Halcrow Group Ltd (now Jacobs), for data collection and data analysis respectively. JBA undertook the first data collection exercise in November 2013. A two-year extension to the project was awarded to the incumbent team in March 2016. A second extension was awarded in February 2018 that provides for an additional five reports extending the work to the monitoring period June to November 2020. CH2M was purchased by Jacobs in August 2017.

This report provides the thirteenth set of data analysis and is presented as a stand-alone document to previous reports.

1.2 Aims and objectives of monitoring

The main objective of the monitoring programme is to provide property- and land-owners with information on instability hazard and risk in vulnerable areas.

The sites and monitoring devices covered by this work are summarised in Table 1.1. Note that some boreholes may have multiple piezometers installed in order to monitor multiple water tables, inclinometers and piezometers are never located in the same boreholes and water-levels are not recorded in boreholes instrumented with inclinometers.

To meet this objective, the specific aims of the study are as follows:

- To place the preceding 6 months' monitoring data in the context of the historical record
- To highlight the implications of the data to coastal instability risk management

In addition, the ultimate aim of the study is:

- To collect sufficient monitoring data to enable site-specific relationships between rainfall, groundwater levels and ground movement to be understood. With sufficient data, it is hoped that threshold rainfall and groundwater levels, above which instability is likely to be triggered, can be identified. This understanding will eventually allow early warning of potential ground movement to be provided.

Table 1.1. Monitoring locations and devices.

Location	Inclinometers	Acoustic Inclinometer	Piezometers	Weather station
Runswick Bay	4			
Whitby West Cliff	1			
Robin Hood's Bay	2		4	
Scalby Ness	4		14	
Scarborough North Bay – Oasis Café	2		3	
Scarborough North Bay – The Holmes	2		5**	
Scarborough South Bay	17*	1	38*	1^
Filey Town	4		16†	
Filey, Flat Cliffs	4	1	4	1^^
TOTAL	40	2	93	2

*a single inclinometer and a diver piezometer with barometric diver were added at St Nicholas Cliff in 2014 between collection of the 1st and 2nd set of monitoring data.

** a single automated piezometer has been removed since this monitoring period

† Eight of these boreholes are inland of the coast and have a focus on flood risk. They are no longer included in the coastal instability monitoring programme.

^The Scarborough South Bay (Spa) weather station was upgraded in July 2019 and provides monitoring data for this period. During the upgrade, a temporary rain gauge was in place to provide continuous rainfall data.

^^the Filey, Flat Cliffs met station has not functioned reliably since 2016 and has recently been replaced with a permanent rain gauge. Rainfall data only partially covers this monitoring period.

1.3 Programme of work

The planned programme of future analysis and reporting is shown in Table 1.2, which assumes the final interpretative report will be provided three months following receipt of the preceding 6 months' monitoring data.

1.4 Scope of data analysis work

JBA have sole responsibility for collection and checking of all inclinometer and piezometer data at 6-month intervals. JBA provide Jacobs (previously CH2M) with the inclinometer and ground water data presented as graphs, ready for interpretation. The following graphs are provided in Appendices to this report:

- Inclinometer incremental displacement – total displacement at 0.5m intervals down the length of borehole since the baseline reading along two axes (A0 being downslope, A180 being at right angles to the slope). This plot is free from errors associated with past readings as only the most recent and original readings are compared. This plot highlights the depths where most significant movement has occurred.

- Inclinator cumulative displacement – sum of all incremental displacements down the length of the borehole showing total deformation since the baseline reading along the two axes. If a user error has occurred, it is carried through all cumulative plots, potentially giving misleading results. Errors can usually be identified by comparison to incremental displacement plots.
- Inclinator absolute position – this plots the absolute position of the inclinometer casing when viewed vertically. While it does not give information on the rate of movement, it highlights the direction of any deformation and can be used to assess error in the data.
- Groundwater data from piezometer divers or data loggers – these data are plotted as a continuous line showing groundwater level fluctuation relative to Ordnance Datum (OD).
- Groundwater data from monitoring wells – these data are plotted as single points, showing groundwater level relative to OD at a point in time. They provide an independent check of piezometer data or water level information from boreholes that do not have automatic data logging capability.

Table 1.2. Programme of data collection and reporting

JBA Monitoring Period	Analysis Report
Data set 1: June 2012 to November 2013	Report 1: March 2014 (CH2M 2014a)
Data set 2: December 2013 to May 2014 (data received 1 Aug 2014)	Report 2: November 2014 (CH2M 2014b)
Data set 3: June 2014 to November 2014	Report 3: March 2015 (CH2M 2015a)
Data set 4: December 2014 to May 2015	Report 4: August 2015 (CH2M 2015b)
Data set 5: June 2015 to November 2015	Report 5: February 2016 (CH2M 2016a)
Data set 6: December 2015 to May 2016	Report 6: August 2016 (CH2M 2016c)
Data set 7: June 2016 to November 2016	Report 7: January 2017 (CH2M 2017a)
Data set 8: December 2016 to May 2017	Report 8: October 2017 (CH2M 2017b)
Data set 9: June 2017 to November 2017	Report 9: February 2018 (CH2M 2018a)
Data set 10: December 2017 to May 2018	Report 10: August 2018 (CH2M 2018b)
Data set 11: June 2018 to November 2018	Report 11: February 2019 (Jacobs 2019a)
Data set 12: December 2018 to May 2019	Report 12: August 2019 (Jacobs 2019b)
Data set 13: June 2019 to November 2019	Report 13: February 2020 (this report)
Data set 14: December 2019 to May 2020	Report 14: August 2020
Data set 15: June 2020 to November 2020	Report 15: February 2021

The scope of data analysis work involves the following tasks:

- Checks of inclinometer and piezometer monitoring data provided by JBA to ensure the correct information is provided, and identification of any obvious errors in the data. Inclinometer readings from Balfour Beatty have been acquired by JBA at Scarborough Spa for several boreholes where access is not currently possible. These will be used with caution as a different inclinometer probe has been used to obtain the readings.
- Downloading and analysis of meteorological data from the weather station installed at Filey Flat Cliffs and Scarborough Spa. The weather station at Filey Flat Cliffs was non-functional from 2016, and it has since been replaced with a permanent rain gauge collecting data since October 2018. Meteorological data from Scarborough Spa has been used from 2016 and is currently being

upgraded. A temporary rain gauge was in place from January 2018. A permanent rain gauge was installed at Filey Flat Cliffs and has been collecting data since October 2018.

- Acquisition of experimental acoustic inclinometer data from Loughborough University.
- Analysis and interpretation of the data, including commentary on short and long-term patterns of change and observed relationships between rainfall, groundwater levels and ground movement.
- Comment on the implications of the observed data regarding cliff instability hazard and risk management, allowing SBC to take any appropriate action.

The following sections provide a site-by-site discussion of the history of cliff instability and the monitoring regime, and interpretation of the new monitoring data. Comment is made on the relationships between rainfall, groundwater and ground movement, and the implications of the new data regarding cliff instability hazard and risk management.

1.5 Cliff instability hazard assessment

Cliff instability hazard at each monitoring location is presented using a simple colour-coding system that summarises the significance of the result (Table 1.3). The assessment provides a simple record of activity that will be developed in subsequent reports to indicate changing levels of hazard.

Table 1.3. Instability hazard assessment guidance level

Hazard (low to high)	Definition
Green	Situation normal. No change in groundwater level from previous records, which are low or falling. Movement in inclinometers within margin of error (<5mm).
Orange	Site requires attention. Moderate or large increase in groundwater level from previous records or moderate movement in inclinometers. Failure of equipment, unreliable or no data requires attention.
Red	Immediate action required. Significant movement of inclinometer indicating high cliff instability hazard potential. Carry out site inspection, consider increasing the frequency of monitoring and managing public access to the area.

1.6 Checks of monitoring equipment integrity

Following completion of checking and interpretation of the first round of monitoring in early 2014, several inclinometer readings appeared to be erroneous, with some locations showing potential ground movement. A series of checks were undertaken during 2014 to determine whether the data were accurate, the source of any errors, and the implications to cliff instability risk management. In most cases, the errors were systematic and represent minor settlement of the borehole casing that gives rise to a sinuous pattern of deformation. However, where random errors were reported, it is likely that the borehole is partially blocked, leading to the probe coming away from the key ways. The 17 potentially blocked boreholes were therefore repaired by means of high-pressure water jetting that was undertaken in early 2015.

In all cases where systematic or random errors have been identified, it has been recommended that the current reading is taken as a new baseline against which future recordings are made. In this way, potentially misleading historical results leading to cumulative errors will be removed. However, in order to determine whether change has occurred in the preceding 6-month period, data are also compared to the original baseline.

Weather Summary

2.1 Introduction

The project has a near-complete record of meteorological data from 2011 to the present day, allowing the response of groundwater to rainfall to be determined. Equipment upgrades and periodic outages mean that the sources of data have varied over this time.

A meteorological station that records wind speed and direction, air temperature, humidity, air pressure, rainfall and rainfall intensity every 15 minutes were present at Flat Cliffs, central Filey Bay, between 29 September 2011 and March 2016. The device was inoperative from September 2014 to July 2015 and therefore supplemental MetOffice rainfall data were acquired from recording station Filey No 2 (54.20395, -0.30127), c. 3km north-northwest of Flat Cliffs. The Flat Cliffs weather station again failed in the period March to May 2016, however at this time a new weather station at Scarborough Spa had become operational and data from that site have been used from 11 January 2016 to until early 2018. The Scarborough Spa weather station became non-functional during January 2018, and rainfall data were acquired by the Met Office weather station at Scarborough to fill the gap. The weather station at Scarborough Spa was upgraded and a temporary rain gauge was in put in place from January 2018, collecting data until November 2018. A permanent rain gauge was installed at Filey Flat Cliffs and has been collecting data since October 2018. Filey Flat Cliffs rain gauge temporarily ceased recording data in early May 2019. Data from the Eastfield rain gauge, inland of Filey, was used to complete the record for May 2019. Data from Filey Flat Cliffs rain gauge was used for the period June to early July 2019, until Scarborough Spa weather station came online on 9 July 2019, providing rainfall, temperature and windspeed data between July and November 2019.

2.2 New data

Data from all sources are summarised in Table 2.1 and Figure 2.1. The records for the last six months show that summer 2019 was marginally wetter when compared to past records, but that autumn 2019 was exceptionally wet. Rainfall totals for the months September to November all exceed records since 2011, with October rainfall totals reaching 154 mm. This is the wettest month recorded since 2011.

Daily rainfall totals recorded by the Scarborough Spa weather station are presented in Figure 2.2, which shows eleven peaks in daily rainfall over 10 mm, mainly occurring in late September to mid-October. Rainfall peaked between 20 to 25 mm on 28 and 30 September, 14 October, and 14 and 27 November. The highest daily rainfall total over this monitoring period was 38.4 mm on 25 October.

The combined dataset has been used for comparison with all coastal slope monitoring data in order to identify relationships. The data are taken to be representative of the whole Scarborough Borough Council frontage, but it is accepted that micro-climate effects may lead to local variations.

The Filey No 2 MetOffice data were provided as weekly totals and therefore the calculated totals do not precisely correspond to calendar months. The data show that the wettest month on record was October 2019 with 154mm. This reflects the impact of the heavy rainfall event on 25 October.

Seasonal totals are shown in Figure 2.3, which shows that the wettest season tends to be autumn, and that the spring is the driest. The wettest season on record was autumn of 2019 (i.e. September, October and November) that received a total of 371mm rainfall, which is exceptional when compared to previous years. The next wettest season was the winter of 2013/14, with 244mm of rainfall. The winter of 2016/17 and summer 2013 have been the driest on record.

Wind speed and air temperature records are presented in Figures 2.4 and 2.5. In both cases, the failure of the Scarborough Spa met station means there are no data for the previous monitoring periods.

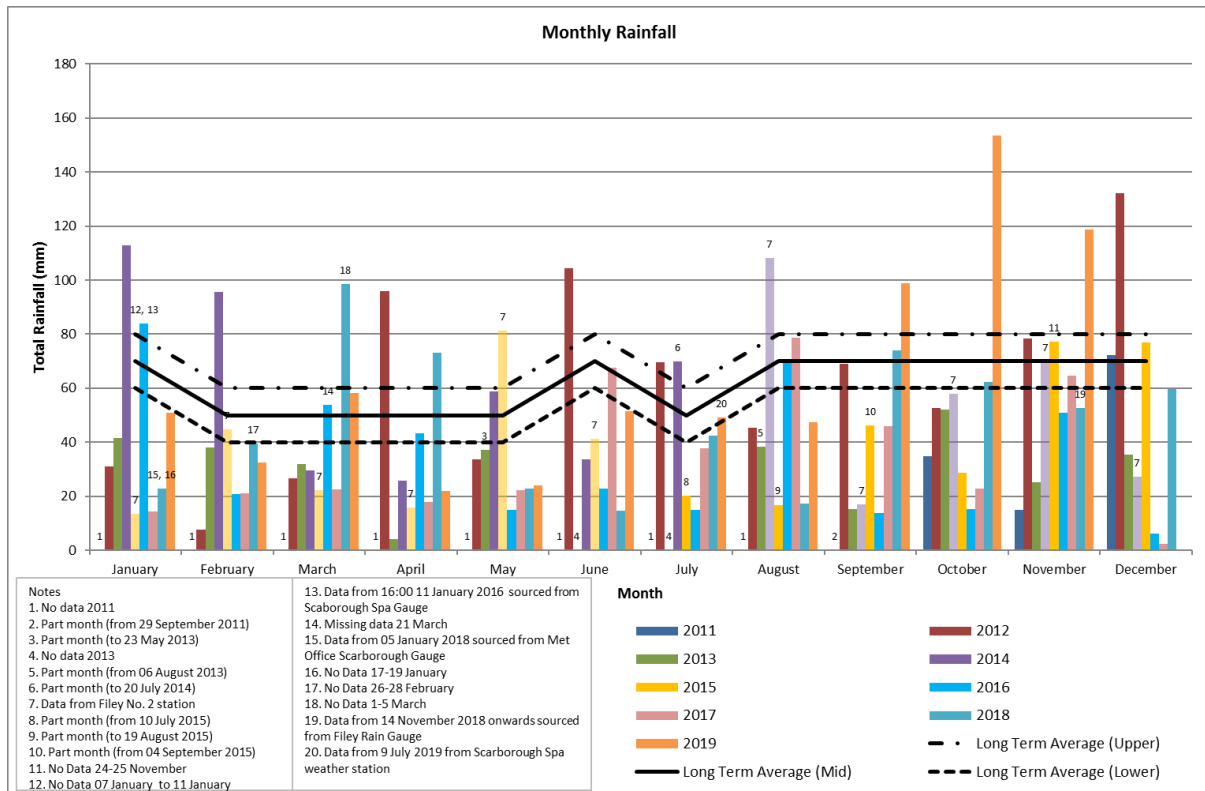


Figure 2.1 Comparison of monthly rainfall records (2011 to 2019).

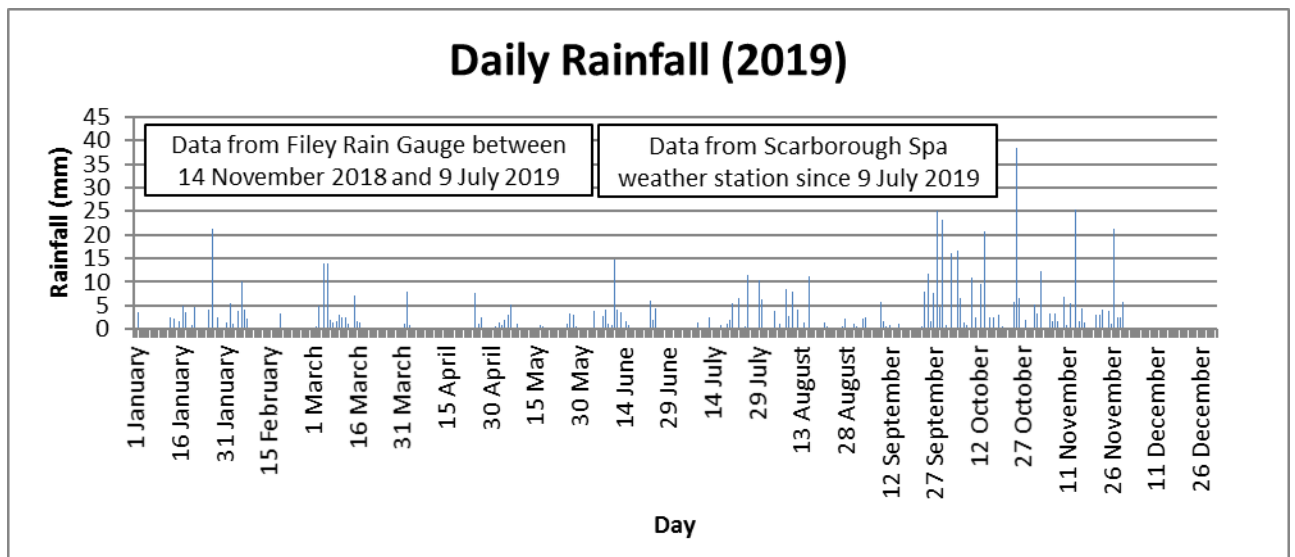


Figure 2.2 Daily rainfall recorded at Scarborough Spa during 2019.

SECTION 2

Table 2.1. Monthly rainfall (mm) recorded at Flat Cliffs or Scarborough Spa met station

Month	Long-term mean (upper range)	2011	2012	2013	2014	2015	2016	2017	2018	2019
January	80	No Data	31	41	113 (84.2)	No Data (13.4)	84 [part month]	14.5	22.8	50.8
February	60	No Data	8	38	96 (71.2)	No Data (44.8)	20.7	21.1	39.6	32.6
March	60	No Data	27	32	29 (40.4)	No Data (22.2)	53.9 [part month]	22.7	98.4	59.2
April	60	No Data	96	4	26 (33)	No Data (15.8)	43.4	17.8	73.2	22
May	60	No Data	34	37 [part month]	59 (50.8)	No Data (81.4)	15	22.4	23.6	24
June	80	No Data	104	No Data	34 (61)	No Data (41.2)	23	67.5	14.6	51.6
July	60	No Data	70	No Data	70 (93.2)	20	14.9	37.9	42.4	49.2
August	80	No Data	45	38 [part month]	No data (108.2)	17	69.7	78.7	17.2	47.4
September	80	0.14 (part month)	69	15	No data (17)	46	13.8	46.1	74	98.8
October	80	35	53	52	No Data (58)	29	15.4	22.9	62.4	153.6
November	80	15	78	25	No Data (70)	77.3	50.9	64.6	52.6	118.6
December	80	72	132	6	No Data (27.2)	76.9	6.4	2.5	59.8	

Note: Data in brackets are from Filey No 2 station. Data from January 2016 to January 2018 are from Scarborough Spa. Data between January 2018 to May 2018 were provided by the Met Office Scarborough rainfall gauge. Data from June 2018 to November 2018 are from the temporary rain gauge at Scarborough Spa. Data from November 2018 to 10 May 2019 are from Filey Rain Gauge. Data from Eastfield rain gauge have been used to complete the rainfall record for May 2019. Data from Filey Flat Cliffs rain gauge was used for the period June to early July 2019, until Scarborough Spa weather station came online on 9 July 2019.

SECTION 2

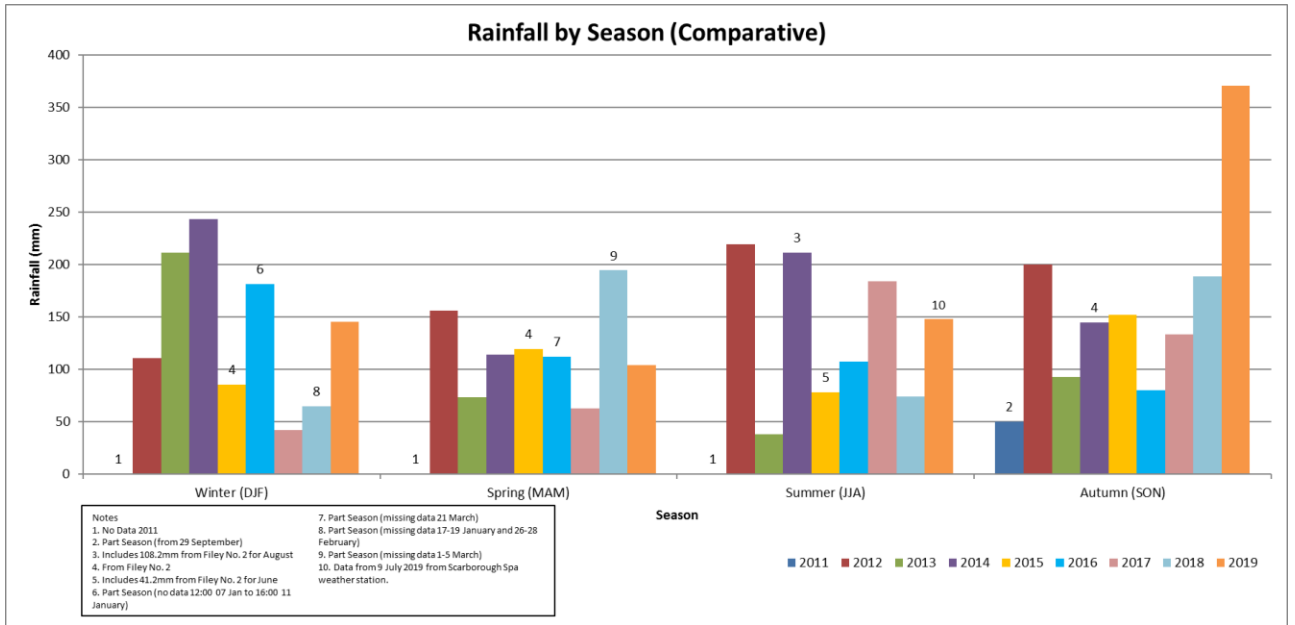


Figure 2.3 Seasonal rainfall comparison (2011-2019)

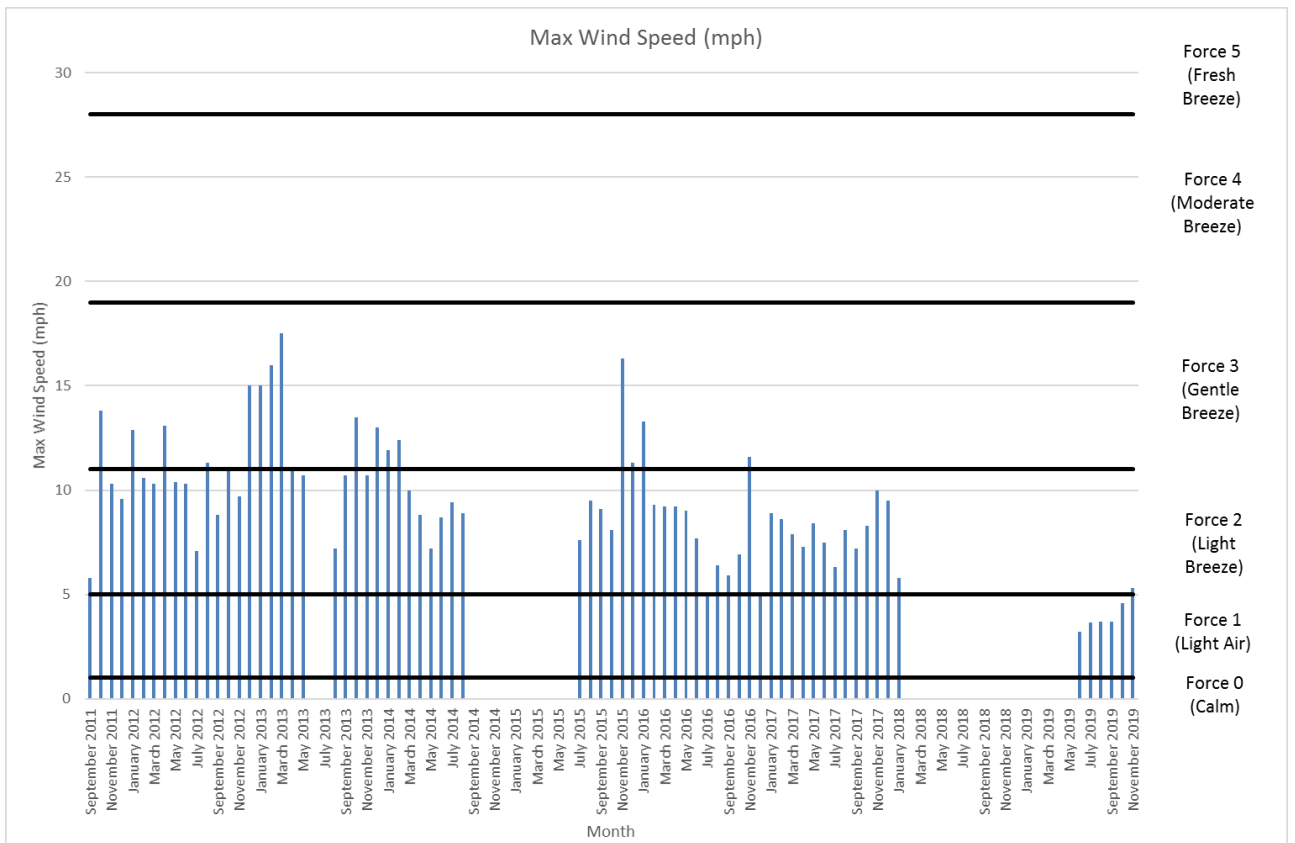


Figure 2.4 Maximum daily wind speed (2011 to 2019).

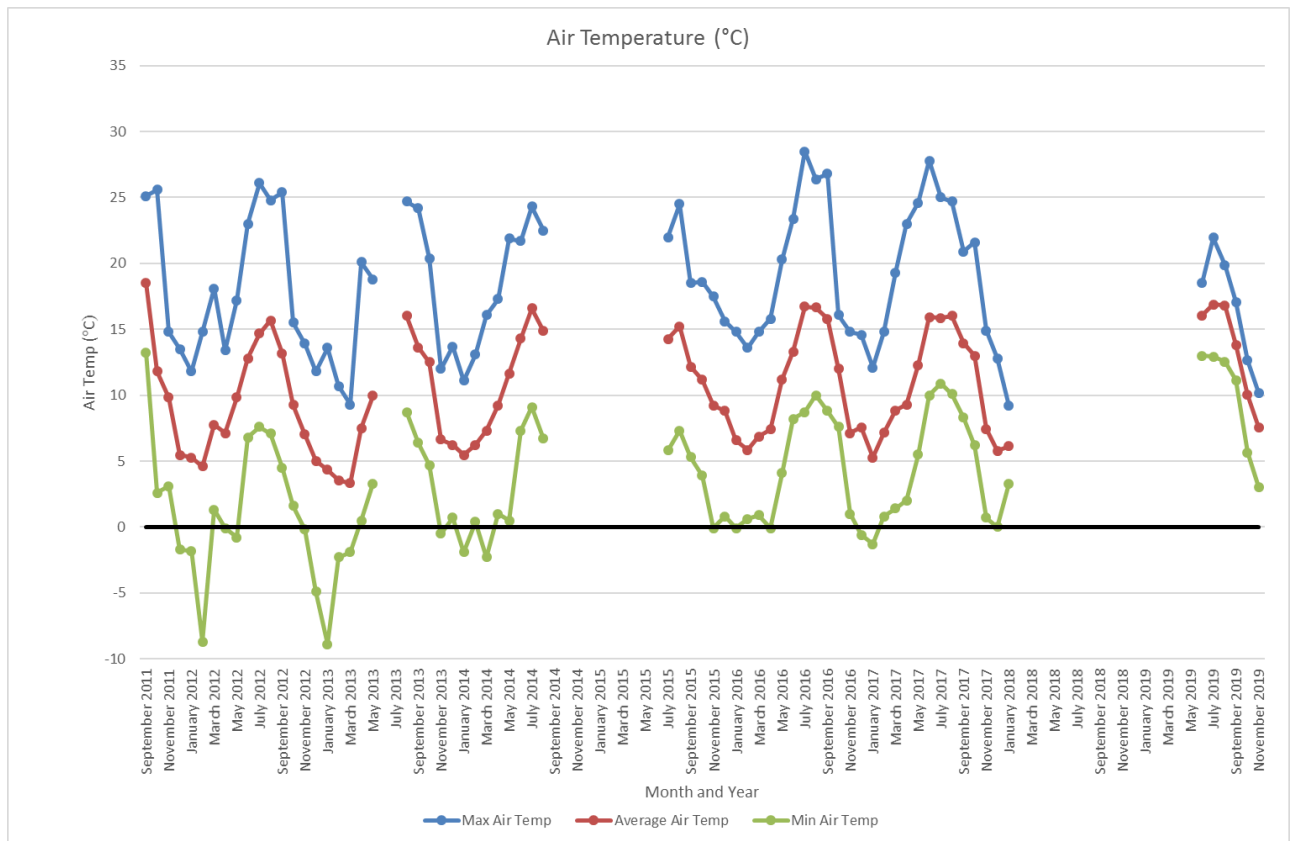


Figure 2.5 Air temperature variation (2011 to 2019).

2.2.1 Rainfall and landslides

The relationship between rainfall and the occurrence of landslides is complex and site-specific. It is often the case that a single intense rainfall event has little effect on a slope formed of relatively impermeable clay strata and soils, and instead cliff instability is only triggered after a period of sustained rainfall that allows groundwater levels to rise above a threshold level. This cumulative effect of sustained wet weather is known as antecedent rainfall. The time period over which antecedent rainfall exceeds a threshold for instability will vary from site to site, based principally on the local hydrogeology. It may vary from a period of days or weeks for sites formed of relatively higher permeability soils and rocks where groundwater responds rapidly to rainfall, to a period of months at locations of lower permeability soils and rocks.

The weather records for the SBC frontage spans a relatively short time period but does include the particularly wet year of 2012. ‘Significant’ ground movements at this time were recorded in BH7 at Scalby Ness, which occurred during December 2012. Monthly rainfall totals are provided in Table 2.1 and antecedent totals are presented in Figure 2.6. Assuming that rainfall was the sole trigger of this ground movement, it suggests a three-month antecedent rainfall threshold of 263mm is required to trigger movement. Similarly, at Filey Flat Cliffs accelerated slope movement occurred following high antecedent rainfall levels in winter 2012/13. The inclinometer monitoring interval 17 January 2013 to 22 March 2013 showed c. 13 mm of resultant incremental shear surface deformation. Acoustic emission monitoring collected since 2011 was used to increase the temporal resolution of the inclinometer deformation information through conversion of measured acoustic emission rates to cumulative displacement (Smith et al., 2017). It showed a period of increased AE rates at the end of January 2013 which was interpreted to as the initiation of landslide movement. Periodic surges of accelerated slope movement were also identified at the end of February and middle of March 2013. Antecedent rainfall over the weeks and months prior caused the build-up of porewater pressures,

which triggered the movement. The absence of movements elsewhere on the coast at that time suggests that the antecedent rainfall threshold levels are above this at other locations.

Antecedent rainfall over the current June-November 2019 monitoring period show peaks that are higher than that seen in December 2012. Antecedent rainfall conditions during this monitoring period increase rapidly from September 2019 and continues to rise through the autumn.

Antecedent rainfall totals significantly surpass those seen in December 2012 and it is concluded there is a high likelihood of rainfall-induced landslides occurring during the period Autumn-Winter 2019/2020.

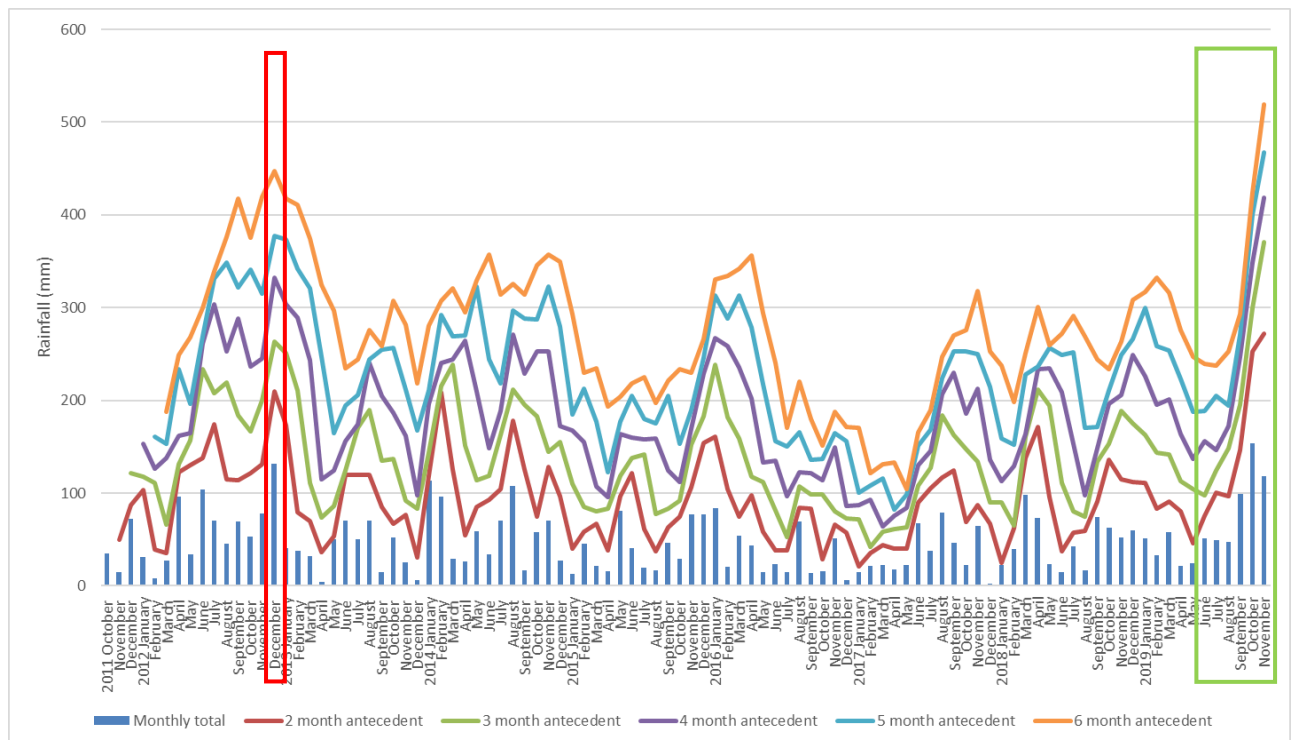


Figure 2.6. Monthly rainfall and two to six-month antecedent totals (2011 to 2019). Ground movements were recorded at Scalby Mills during December 2012 (red box). Current monitoring period shown by green box.

2.3 Summary

The weather data collected over the monitoring period was exceptionally wet. Rainfall totals for the months September to November all exceed records since 2011, with October rainfall totals reaching 154 mm, which is double the long-term average. Antecedent rainfall has rapidly increased over the autumn, well above conditions in December 2012 when ground movement occurred at Scalby Ness and there is an elevated risk of ground movement. The risk will increase further if the winter of 2019/2020 is wet.

The weather data collected to date highlights the following:

- 2012 was exceptionally wet, particularly in the months of April, June, July, November and December. This resulted in ground movement at Scalby Mills.
- 2013 was dry. After an unusually stormy spring period the temperatures remained high throughout the summer and rainfall in all months was below average.
- January and February 2014 were much wetter than average, and the period March to July 2014 was comparatively dry.

- While no data were recorded from early September 2014 to February 2015, a review of Met Office records shows the Autumn 2014 period was characterised by dryer than average conditions.
- MetOffice data purchased from Filey shows that the period Dec 2014 to April 2015 was generally much drier than average. Only May 2015 shows wetter than average conditions
- Data from Flat Cliffs collected in late 2015 shows September was wetter than average, and December was wet, although not exceptionally so. Rainfall peaks occurred on 14 September and 21 November and a sustained period of wet weather occurred from 25 to 30 December.
- Scarborough Spa weather station data collected over 2016 has shown that January, March and April have been slightly wetter than average. Rainfall peaked on 3 January and 28 March. Overall, data has shown Dec 2015 to May 2016 to have been typically wet, with mild weather conditions.
- Between June and November 2016, rainfall has been lower than average apart from August where significant rainfall occurred on 4 and 25 August. Conditions over the 6-month period have been relatively dry and mild. Overall, data shows the 6-month period to have been relatively dry, with mild weather conditions suggesting a low likelihood of rainfall-induced landslides occurring.
- Summer 2017 has been wetter than the previous two summers, with rainfall above average during June. High daily rainfall totals were experienced 23 August, when an exceptional storm occurred. Overall, autumn 2017 experienced average conditions, whereby in November antecedent rainfall peaked.
- Winter 2017/18 has been drier than average, however spring experienced above average rainfall particularly during March and April where several heavy rainfall events occurred. Antecedent rainfall has risen early in spring compared to previous years.
- Summer 2018 has been drier than average, and antecedent rainfall declined rapidly in response. However, Autumn has been wetter than average, particularly during September. Exceptionally high daily rainfall totals were experience on 20 September when Storm Bronagh passed over the region. Antecedent rainfall increased to typical levels in Autumn.
- Winter 2018/19 has been slightly wetter than the previous two winters, and antecedent rainfall increased in response to several heavy rainfall events in December and January. Spring 2019 has been drier on average, except for March which had above average rainfall. Antecedent rainfall remains elevated in response to these conditions.

Runswick Bay

3.1 Site description

Runswick Bay is the northern-most instrumented site on the Scarborough Borough Council coastline and is located 16 km north west of Whitby. The bay is formed in weak glacial sediments between the more resistant Jurassic-age bedrock headlands of Caldron Cliff to the north and Kettleless to the south. The village of Runswick Bay is developed on a coastal slope formed in glacial sediments and weathered shale bedrock and is bordered by incised valleys of the Runswick Beck and Nettledale Beck. The village and all existing monitoring devices are located in cliff behaviour unit MU7/1 (Figure 3.1).

The village has a long history of coastal instability, with records dating back to 1682 when the whole village was destroyed by landslides. It benefits from a coast protection and slope stabilisation scheme that was constructed in 2001-02 that comprises sections of seawall and rock armour together with drainage, piling and earthworks. The village has been subject to a strategy study review to improve the standard of protection of the coast protection measures and remedy minor issues with the 2001-02 scheme (Halcrow, 2016b). A scheme to implement the recommendations of the strategy study was completed in summer 2018.

3.2 Ground model and monitoring regime

The ground model for Runswick Bay was developed by High Point Rendel in the 1990s as part of the original strategy study for the area (High Point Rendel 1998). Their work included drilling a series of instrumented boreholes, geomorphological mapping and stability analysis. This work highlighted three landslide complexes that threaten properties and infrastructure:

- Topman End (MU7/1) steep till slopes (30° to 40°) between Nettledale Beck and continuing north to Runswick Beck. The village is sited on this landslide complex. The slopes are characterised by an extensive pattern of small scarps and tension cracks behind small shallow failures. Mid-way down the slope the profile shallows to between 5° and 10° over a distance of 10-15m. Where the slope angle exceeds 35° there are numerous shallow failures that tend to be caused by excessive water entrainment and generally leave behind triangular scars bounded by steep sides and disrupted vegetation. The mechanism is uncertain, but High Point Rendel (1998) suggests a model of superimposed mudslide lobes.
- Upgath Hill (MU 7/1) is the area north of Runswick Beck, beyond the village. The cliffs are formed in weathered Upper Lias shales capped by sandstone beds of the Saltwick Formation and thin veneer of till. Cliffs are fronted by steep talus slopes (20 to 30°) that are protected by a reinforced concrete sea wall. The toe of the southern facing slopes is continually undercut by stream flow in Runswick Beck. Over the years Runswick Beck has cut down through the weathered shale forming an incised valley with sides that are characteristically over-steep. The failure mechanism is believed to be rockfalls with shallow mudslides developed in the talus slope.
- Ings End (MU 7/2 and 7/3) comprises a series of sub-vertical head scarps, up to 2.5m in height, below the cliff top between incised valleys of Nettledale Beck and Limekiln Beck, south of the village. Movement here would adversely impact the village car parks and could trigger movement in Topman End. The headscarps front undulating, low angle slopes formed in till, characterised by springs, streams and water ponding. Shear surfaces are believed to be curved, suggesting the landslide is an ancient degraded multiple-rotational complex with superimposed shallow mudslides that are active during periods of prolonged heavy rainfall.

The monitoring regime at Runswick Bay comprises four inclinometers that are installed within piles

of a portal frame shear-key system designed to stabilise the slope within the Topman End landslide (Figure 3.1). The inclinometers were originally intended to monitor the response of the piles to loading, but due to uncertainty over methods to achieve this, the data has been used to simply monitor ground movement and performance of the piles.

3.3 Historical ground behaviour

A summary of historical data adapted from Mouchel (2012) is summarised in Table 3.1. Overall, the data show no ground movement since 2009 and only subtle variation in groundwater levels, and therefore no relationship between groundwater level and ground movement has been identified.

Table 3.1. Summary of historical ground behaviour at Runswick Bay.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Slopes indicated as stable. Groundwater levels variable across site in inclinometers, with no change since previous reading, except for A002 that showed a marked drop in water level since Dec 2011.	5mm movement indicated in A001 between 22.0 and 20.0 metres depth and in A004 from 10.0m depth increasing to 15mm at 2.0m depth. Groundwater is relatively static in each borehole, although A002, A003 and A004 experienced lowering of levels in summer 2011, with recovery to previous levels by Dec 2011.

3.4 New data

All monitoring data at Runswick Bay is at the Topman End landslide and is solely intended to monitor the effectiveness of the piles installed in the late 1990s to stabilise the slope. Water-levels within inclinometer tubes installed in the piles were recorded under the previous Mouchel contract. This has not been continued in the current phase of work as it was recognised that the data were of limited value to slope stability assessments and could be misleading. Inclinometer data are summarised in Table 3.2. These data indicate no movement in the piles.

3.5 Causal response relationships

No ground movements have been recorded at Runswick Bay over the monitoring period. Groundwater levels were previously monitored within the inclinometer tubes installed in piles, however, these data are unreliable, and no ground water monitoring is planned at this location. This means determining a relationship between rainfall, groundwater response and ground movement at Runswick Bay is not possible with the current monitoring set-up.

3.6 Implications and recommendations

Monitoring of the inclinometers should be continued to check the integrity and stability of the piles. In early 2019, residents reported to the local authority of apparent movement at the sailing club below borehole A001, where the ground has recently been resurfaced and levelled due to deformation of the old surface. The cause of this apparent movement is uncertain, and inclinometer trends during this monitoring period indicate no evidence for significant movement.

Inclinometer readings at the base of borehole A001 appear to be erroneous and the equipment should be checked.

Table 3.2. Summary of inclinometer data at Runswick Bay

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
A001	Data collected from within 22m deep concrete pile near the top of the slope. The data indicates no significant movement has been recorded in the pile													Incremental movements less than 1mm during the monitoring period, which is insignificant. No evidence of surface movement related to observed surface deformation.	Incremental movements less than 1mm during the monitoring period, which is insignificant. Minor downslope displacement of 2 mm is recorded at 21 m BGL. Displacement of 5mm in B axes at 21 m BGL represent possible blockage near the base of the borehole. The inclinometer should be checked.
A002	Data collected from within 17m deep concrete pile near the top of the slope. The data indicates no significant movement in the pile.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.
A003	Data collected from within 10.5m deep concrete pile near the bottom of the slope. The data indicates no significant movement in the pile.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.
A004	Data collected from within 10.5m deep concrete pile near the bottom of the slope. The data indicates no significant movement in the pile up to Dec 2011.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.

Whitby West Cliff

4.1 Site description

Whitby West Cliff extends from the West Pier of Whitby harbour to Upgang Beach and Sandsend (Figure 4.1). A short (c. 500m long) section at the eastern-most extent fronting the Whitby Spa Complex comprises Jurassic-age limestone, sandstone and mudstone of the Scalby Group overlain by glacial sediments (CBUs 11/3 and 11/4), but the greater part of the cliff line is cut entirely in glacial sediments (CBUs 11/1 and 11/2). The cliffs cut in glacial sediments have a long history of instability and numerous relict landslide scars associated with shallow failures and seepage lines are visible. West Cliff benefits from coastal defences and slope stabilisation measures comprising a seawall, slope drainage and slope re-profiling that were installed in phases between the 1930s and 1970s. These measures have significantly reduced the risk of cliff instability, but they are near the end of their design life and distress in the slope has been observed.

4.2 Ground model and monitoring regime

The cliff instability features of West Cliff comprise shallow mudslides that are periodically active, but there is a concern that deep-seated failures may develop. The defended stretches show evidence of historical failures and despite toe protection the slopes are susceptible to periodic phases of movement associated with sustained rainfall. The unprotected cliff sections at Upgang beach has active mudslides. Historically, the monitoring regime at Whitby West Cliffs has comprised a series of survey pins that follow the line of the slope, which were intended to record deformation associated with cliff instability, and a single inclinometer (BH2) located near the base of the slope to the west of the Whitby Spa complex within CBU 11/2 (Figure 4.1). The inclinometer was read at 6 monthly intervals and dipped to record water level. Survey pin data revealed no significant change during the period of monitoring by Mouchel. As water-level data derived from inclinometers is not recommended and liable to error, these readings are no longer taken, and the current monitoring regime comprises six-monthly inclinometer readings only.

4.3 Historical ground behaviour

A summary of historical data adapted from Mouchel (2012) is summarised in Table 4.1. Overall, the data show no deep ground movement since 2009 and only subtle creep of the upper metre of the slope, which is typical of glacial sediments. Groundwater data collected by dipping the inclinometer tube appeared to show a relationship with tide level and not groundwater. Groundwater data collected in this way are known to be very unreliable and therefore no relationship between groundwater level and ground movement can be identified.

The single monitoring location means the data from BH2 may not be representative of all West Cliff. Caution should therefore be taken before extrapolating results across the site and monitoring should be supplemented with regular site inspection.

Table 4.1. Summary of historical ground behaviour at Whitby West Cliff

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Survey pins show a total of 3mm movement at ground surface. Inclinometer indicates local slopes are stable, with surface creep in the top metre of ground.	Survey pins show -7mm movement in the top metre of ground. Inclinometer indicates local slopes are stable.

4.4 New data

Current data from the single inclinometer installed at Whitby West cliff is documented in Table 4.2 below.

Table 4.2. Summary of inclinometer data from Whitby West Cliff

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
BH02	Inclinometer installed in a 20m deep borehole that passes through glacial sediment. Ground level is 13.78m OD and the base of the borehole is at -6.22m OD.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.

4.5 Causal-response relationships

No relationships have been detected at this location.

4.6 Implications and recommendations

Monitoring at Whitby West Cliff is limited to a single inclinometer located near the base of the cliff to the west of the Whitby Spa complex. The device has not highlighted any cliff instability within the glacial sediments, although shallow failures have been observed on the cliff face during regular walk-over inspections by SBC. The absence of any water level data at Whitby means it is not possible to determine the relationship between rainfall and ground movement, therefore, opportunities for installation of automated piezometer(s) should be considered.

Robin Hood's Bay

5.1 Site description

Robin Hood's Bay village is located on the coastal slopes and cliff top area of the northern-most part of Robin Hood's Bay. The cliff top part of the village is known as Mount Pleasant. The old village, situated on the coastal slope, has a long history of landsliding and currently benefits from a coast protection and slope stabilisation scheme that was installed in 2001.

The area being monitored in this study is the Mount Pleasant area, between Victoria Hotel and the cliffs to the north, where cliff instability is a concern. Cliff behaviour units in this area are composite cliffs formed of near-vertical sea-cliffs cut in Lower Jurassic clays overlain by glacial sediments. CBU 16/1 fronts Mount Pleasant and CBU 16/2 fronts the Victoria Hotel and the slope down to the old village (Figure 5.1). This section of coastline is not defended and has no slope stabilisation measures. Despite the bedrock cliff eroding at a slow rate, the overlying glacial sediments are prone to instability, and landslides occur episodically in response to sea cliff erosion and/or prolonged wet weather.

5.2 Monitoring regime

In response to the risk from landslides affecting the village, four instrumented boreholes have been installed in CBUs 16/1 and 16/2. These comprise two inclinometers and two double piezometers installed in bedrock and glacial sediments (Figure 5.1).

5.3 Historical ground behaviour

Robin Hood's Bay was not included in the original programme of monitoring and the first readings were taken in March 2010. The readings documented by Mouchel (2012) are summarised in Table 5.1.

Table 5.1. Summary of historical ground behaviour at Robin Hood's Bay

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Inclinometer BH2 shows movement at 22m depth. BH4 shows movement at 25m depth. Groundwater levels reduced.	n/a. First investigated in Dec 2011. Total change is as recorded between Dec 2011 and June 2012.

5.4 New data

The inclinometer and piezometer data recorded up to November 2019 is summarised in Tables 5.2 and 5.3.

Inclinometer data shows no significant movements recorded at boreholes BH2 and BH4.

The piezometer data show groundwater levels have remained relatively steady over the monitoring period. Borehole Bh1a groundwater levels have fallen slightly yet remain near the historical low after mistakenly being covered with tarmac during an earlier monitoring period (CH2M, 2016c).

Meanwhile, deeper piezometer BH1b was dry during this monitoring period and should be checked as equipment may be damaged and requires attention to determine whether it can be repaired.

Readings for piezometer BH3a shows groundwater levels have increased slightly but remain near the historical low. Bh3b, which is a deep piezometer, shows groundwater levels are elevated, but below the historical high.

Table 5.2. Summary of inclinometer data from Robin Hood’s Bay

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
BH2	The borehole is 41m deep, but inclinometer records are only provided for the upper 22m. Ground level is c. 55.1m OD.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.
BH4	The borehole is 40m deep and passes through 12m of glacial sediment and 28m of siltstone bedrock. Ground level is c. 74.2m OD and the base of the hole is at 34.2m OD.													Incremental movements less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.

5.5 Causal-response relationships

A subtle relationship between rainfall and groundwater levels, particularly in the shallower piezometer BH1a, was observed for the wet December of 2011 and the wet summer of 2012, and wet winter of 2015/2016. However, the dry conditions of 2013 were not reflected in the groundwater data, suggesting surcharge of groundwater from local sources may be occurring. Water levels in BH3a had fallen significantly in 2017 to their lowest since 2012, which may reflect the exceptionally dry conditions during winter 2016/17 and spring. There is also the possibility that the low resolution of monitoring at this location, particularly in shallow piezometers, may simply be picking-up short duration responses to brief but intense rainfall events. There is no clear response in the groundwater levels to wetter than average conditions between spring and winter 2018, and during autumn 2019.

Table 5.3. Summary of groundwater data from Robin Hood's Bay

Borehole	Summary of past data	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11			
BH1a	Ground level is 51.6m OD, the piezometer tip is targeting a shallower horizon. Water-levels have remained reasonably constant at c. 30m OD since installation.	22.7m OD 39.7m OD 17m													Groundwater level has risen slightly to 29.3 m OD.	Groundwater levels have fallen slightly to 29.2 m OD.
BH1b	Ground level is 51.6m OD, the piezometer tip is targeting a deeper horizon. Water levels in this elevation have been less variable, having remained at around 37.6m OD.	37.6m OD 39.9m OD 2.3m													Groundwater levels are steady at 38.8 m OD.	Borehole dry. Check piezometer integrity.

BH3a	Ground level is 60.4m OD. Piezometer targeting a shallower horizon. Water level between 44.3m and 44.8m OD between March 2010 and May 2012.	44.5m OD 56.1m OD 11.6m											Groundwater levels have fallen to 46.6 m OD.	Groundwater levels have increased slightly to 47.4 m OD.
BH3b	Ground level is 60.4m OD. Piezometer targeting a deeper horizon. Water levels fluctuated by < 2m about a mean of c. 56m OD. Low levels occurred in May 2010 and highs in July 2010 and Nov 2011.	47.5m OD 56.7m OD 1.4m											Borehole dry. Check piezometer integrity.	Groundwater levels are at 56.3 m OD, which is elevated but below the historical high.

5.6 Implications and recommendations

The groundwater data indicates a continuation of past patterns at Robin Hood’s Bay. BH1a shows groundwater level has remained relatively steady at levels observed before the borehole was mistakenly covered with tarmac in 2016. However, deeper piezometer BH1b was dry and its integrity should be checked. BH3a indicates groundwater levels are low and have increased slightly. BH3b levels are elevated but they remain below the historical high. These locations should be checked, and the next monitoring data reviewed, whether this trend continues.

Results from inclinometers are hard to interpret, meaning there is uncertainty over the nature of any recent ground movement. These data should be carefully reviewed in future monitoring reports and erroneous data removed from record. To improve understanding of the relationship between groundwater and rainfall, this site would benefit from installation of automated piezometers to provide a continuous record of groundwater fluctuations.

Scalby Ness

6.1 Site description

Scalby Ness is the promontory that forms the northern boundary of Scarborough's North Bay. The headland is incised by Scalby Beck which flows through a steep-sided valley cut in glacial sediments and the underlying Jurassic sandstone/siltstone bedrock. Scalby Beck acts as a flood relief channel for the River Derwent via the 'Sea Cut', a man-made channel connecting the Derwent with the headwaters of Scalby Beck. The south side of the beck has housing that is threatened by ground instability in the over-steepened slopes cut in glacial sediments.

6.2 Ground model and monitoring regime

This site includes the cliff behaviour units MU19/11 and MU20/1 (Figure 6.1). The strategy study into the instability problems (Halcrow, 2005) characterised the area into three distinct landslide systems:

- CBU1 (northwest slopes) – periodically active translational landslides in glacial sediment that lead to gradual headscarp recession. Instability is partly caused by toe erosion by Scalby Beck, but rising ground water levels following prolonged or intense rainfall are the principal trigger.
- CBU2 (northern part of the northeast slopes) – large, ancient, deep-seated, periodically active landslide. Back-tilted blocks indicate a rotational failure, but translational mechanisms are also possible. Instability is partly caused by toe erosion by Scalby Beck but rising ground water levels following prolonged or intense rainfall are the principal trigger.
- CBU3 (southern part of the northeast slopes) – stable slopes that have been reprofiled when the Sealife Centre access road was constructed.

Both CBUs 1 and 2 are at risk of failure, particularly if groundwater levels rise significantly. CBU3 is not considered to be at risk.

The monitoring regime at Scalby Ness is summarised in Figure 6.1. The slope is instrumented with three inclinometers and fourteen piezometers, seven of which are automated. Two inclinometers and nine piezometers are on the slope itself and the remaining installations are positioned on the cliff top.

6.3 Historical ground behaviour

Ground movement and groundwater levels were monitored by Mouchel from July 2009 to June 2012 and limited additional records of groundwater data back to June 2004. Mouchel's observations showed significant movement in BH7 between June and December 2010. No relationship between groundwater level and ground movement was reported by Mouchel, although relationships between rainfall and ground water levels in piezometers with shallow tips are identified. The readings documented by Mouchel (2012) are summarised in Table 6.1.

Table 6.1. Summary of historical ground behaviour at Scalby Ness.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Mouchel's piezometer graphs show notable increases in groundwater level in some piezometers (WS4 and WS6) to May 2012.	<p>Ground movement reported at 12.0m BGL in BH7 at contact between gravelly sand and sandstone between June and December 2010, indicative of a developing shear plane although this movement has not yet manifested itself as recession of the headscarp. A failure was observed near the base of CBU1 between March and April 2010.</p> <p>They report decreasing groundwater levels in CBU1, and peaks in groundwater levels in the shallower piezometers linked to intense rainfall events. Deeper piezometers remained at approximately the same level and were therefore less susceptible to variations in rainfall.</p>

6.4 New data

Tables 6.2 and 6.3 summarise the monitoring data from the inclinometers and piezometers at Scalby Ness.

Table 6.2 Summary of inclinometer data from Scalby Ness

Borehole	Summary of past data	Report status										Change December 2018 to May 2019	Change June 2019 to November 2019		
		1	2	3	4	5	6	7	8	9	10			11	
L1(C003)	Borehole is c.32m deep and situated on the cliff top above CBU1. Ground level is 35.47m OD and the borehole extends to c. 2.5m OD. It passes through 29m of glacial sediment and 3m of sandstone/mudstone bedrock. No displacements of the inclinometer tube greater than 2mm.													Displacements up to 2 mm recorded at 28 m to 30 m BGL in positive and negative directions on both A and B axes at contact between till and mudstone represent error and possible blockage near the base of the borehole.	Incremental movements less than 1 mm during the monitoring period, which is insignificant.
L2(C002)	Borehole is c. 35m deep and situated on the cliff top above CBU2. Surface elevation is 34.1m OD and borehole extends to c.- 1.0m OD penetrating c. 31m of glacial sediment and 4m of mudstone bedrock. No displacements of the inclinometer.													Incremental movements less than 1 mm during the monitoring period, which is insignificant. Minor downslope displacement of 2 mm is recorded at 21 m BGL.	Incremental movements less than 1 mm during the monitoring period, which is insignificant.
L3(C004)	Borehole is ca. 17m deep, surface is 13.4m OD and borehole extends to c. - 3.6m OD through 8.5m of glacial sediment and 8.5m													Incremental movements less than 1 mm during the monitoring period, which is insignificant.	Incremental movements less than 1 mm during the monitoring period, which is insignificant.

	<p>of mudstone and sandstone that is weathered in the upper 3m. Cumulative plot is almost vertical with the exception of a large apparent displacement between June 2011 and December 2011 and minor (<5mm total displacement) near the surface, possibly due to surface creep.</p>														
<p>BH07</p>	<p>Borehole is c.20.5m deep and situated in the mid-slope of CBU2. Surface elevation is c. 16.7m OD and the borehole extends to c.-3.8m OD through 13m of glacial sediment and 7.5m of sandstone /mudstone bedrock. The cumulative plot shows around 20mm displacement between Feb 2011 and June 2011, above the contact between sandstone bedrock and gravelly sand at c.4.7m OD. Subsequent readings show positive and negative displacements on B axis that may be error.</p>													<p>Negligible movement in the downslope direction which is likely associated with shallow creep in sandy and gravelly clay at 1.5 m BGL.</p> <p>The trend will be reviewed in the next monitoring period.</p>	<p>Incremental movements less than 1 mm during the monitoring period, which is insignificant.</p>

*Surface elevations and borehole depths calculated from digital elevation model

Table 6.3. Summary of groundwater data at Scalby Ness.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11			
P1a	Automated piezometer. Tip at approx.25.65m OD*. Surface elevation at c. 35.6m OD* (cliff top above CBU 1, co-located with P1b). Fluctuates between 27.5 and 28.5m OD, with rapidly rising and falling peaks linked to higher rainfall and subsequent dry periods.	26.4m OD 28.9m OD 2.5m													Logger repaired. Groundwater level has fallen to 26.8 m OD, which is near to the historical low.	Groundwater levels have fallen to 26.4 m OD, a new historical low.
P1b	Automated piezometer. Tip at c. 18.1m OD*. Surface elevation at c. 35.6m OD (co-located with P1a). Relatively steady ground water level at ca.18.5m OD although fluctuations up to ca. 19.0m OD occur.	18.4m OD 25.5m OD 7.1m												Logger repaired. Groundwater level recording new historical high at 25.5 m OD. Groundwater level is static. Logger should be checked to ensure that readings are correct.	Groundwater level remains elevated recording historical high at 25.5 m OD. Groundwater level is static. Logger should be checked to ensure that readings are correct.	
P2a	Automated piezometer. Tip at c. 25.6m OD*. Surface elevation at c. 34.7m OD* (co-located with P2b). Fluctuates between 27.5 and 28.5m OD with peaks overlying a general trend of increasing water. Peaks and general trend correspond to the Filey rainfall record.	27.3m OD 28.7m OD 1.4m												No data available. Data logger communication error. SBC to arrange for repair of equipment.	No data available. Data logger communication error. SBC to arrange for repair of equipment.	

P2b	Automated piezometer. Tip at c. - 0.6m OD*. Surface elevation at c. 34.7m OD* (co-located with P2a). Prior to Oct 2009, ground water levels appear generally steady at c. 1.2m OD, except for fluctuations up to 2.5m OD in late 2007/early 2008. Records are absent between Oct 2009 and Mar 2010, after which levels are steady at around 2.5m OD.	0.9m OD 3.5m OD 2.6m																		Logger repaired. Groundwater level recording new historical high at 25.0 m OD, which appears to be systematic error. Groundwater level is static. Logger should be checked to ensure that readings are correct	Groundwater level recording new historical high at 25.0 m OD, which appears to be systematic error. Groundwater level is static. Logger should be checked to ensure that readings are correct
P3	Automated piezometer. Tip at c. 10.5m OD*. Surface elevation at c. 30.7m OD. Steady at around 14.6-14.7m OD until Oct 200. Apparent recalibration between Oct 2009 and Mar 2010 after which groundwater levels are again steady at ca.17.2-17.3m OD	14.2m OD 17.5m OD 3.3m																		Logger repaired. Groundwater level recording new historical high at 22.0 m OD, which appears to be systematic error. Logger should be checked and repaired on the next site visit.	Groundwater level remains elevated at 22.0 m OD, which appears to be systematic error. Logger should be checked and repaired on the next site visit.
P4a	Automated piezometer. Tip at c. 8.3m OD*. Surface elevation at 18.6m OD (co-located with P4b). Fluctuating pattern occur between June 2004 and Feb 2009 varying around 12m to 13.6m OD. Peaks show steep rise and gentler fall, which is a characteristic response to heavy rainfall.	11.6m OD 15.1m OD 3.5m																		Logger repaired. Groundwater level has fallen to a new historical low at 11.6 m OD.	Groundwater levels peaked in September at 11.9 m OD and declined to 11.5 m OD.

P4b	Automated Piezometer. Tip at c. 6.35m OD*. Surface elevation at c. 18.6m OD (co-located with P4a). Fluctuating pattern between June 2004 and Feb 2009 with lows at around 12m OD and peaks to 13.6m OD. Peaks show steep rise and gentler fall characteristic of response to heavy rainfall	12.4m OD 14.8m OD 1.4m											Logger repaired. Groundwater level is within historical range at 13.9 m OD.	No data available. Data logger communication error. SBC to arrange for repair of equipment.
WS4	Tip at 9.9m OD. Surface elevation at 16.3m OD (midslope, CBU 2). Fluctuations from c. 10m OD to c.15m OD in response to long-term/seasonal rainfall patterns. Limited response to short-lived rainfall peaks.	10.0m OD 15.4m OD 5.4m											Groundwater levels have fallen to 11.1 m OD.	Groundwater levels have fallen to 11.0 m OD.
WS5	Tip at 6.5m OD. Surface elevation at 11.3m OD (lower slope, CBU 2). Fluctuates between 6.5m OD and 7.5m OD between September 2010 and June 2011 (low in summer/early autumn, high in winter).	6.5m OD 9.7m OD 3.2m											Borehole no longer functioning.	Borehole no longer functioning.
WS6	Tip at 9.72m OD. Surface elevation at 16.2m OD (midslope, CBU2). After an initial sharp rise post installation from ca. 10m OD to 12.5m OD, measurements from this piezometer show a gradual and uninterrupted increase to a high of 14.3m OD in May 2012.	10.0m OD 14.3m OD 4.3m											Groundwater levels remain elevated at 13.8 m OD.	Groundwater levels remain elevated at 13.8 m OD.

B6	Tip at 10.0m OD. Surface elevation at 18.55m OD (midslope, northern edge of CBU2). Pattern of substantial fluctuation, usually between 14m OD and 17m OD, except for major low in August 2008 when installation may have been almost dry (groundwater level ca. 10m OD).	9.9m OD 13.8m OD 3.8m											Borehole dry. Check piezometer integrity.	Borehole dry. Check piezometer integrity.
B9	Tip at 9.25m OD. Surface elevation at 17.8m OD (upper slope, CBU2). Fluctuation between ca. 10.0m OD and 12m OD except for substantial peaks in January 2008 (13.8m OD) and May 2008 (13.4m OD).	9.8m OD 16.7m OD 6.9m											Groundwater levels have fallen to 14.9 m OD but remain above the average elevation.	Groundwater levels remain steady at 14.9 m OD and remain above the average elevation.
Sn2a	Tip depth at c. 13.9m OD*. Surface elevation at 16.35m OD* (co-located with SN2b). Likely that past results for 2a and 2b confused or tip depth for Sn2a incorrect; groundwater elevations not possible for tip depth stated.	12.5m OD 13.7m OD 0.8m											Groundwater levels increase slightly to 12.6 m OD.	Borehole dry. Check piezometer integrity.
Sn2b	Tip depth at c. 8.35m OD*. Surface elevation at 16.35m OD* (co-located with SN2a). Likely that past results for 2a and 2b confused or tip depth for Sn2a incorrect. Sn2b shows groundwater levels between 1.6m OD and 11m BGL during 2011 and 2012.	10.3m OD 12.8m OD 2.5m											Groundwater levels increase slightly to 11.3 m OD, remaining below the historical high.	Groundwater levels have fallen to 10.5 m OD.

*Indicates approx. tip and surface elevations calculated from elevation from digital elevation model and known tip depth, rather than topographic survey

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- No data are available for P2a and P4b for this monitoring period due to temporary logger problems. The data should be downloaded and reviewed for the next monitoring period.
- Piezometer data from P1b, P2b and P3 show groundwater levels have increased to historical highs and remain static since the replacement of the loggers. The integrity of the piezometers should be checked on the next site visit.
- Groundwater levels have fallen or remained relatively steady in all other boreholes, except for midslope piezometer WS6 in which groundwater levels have remained elevated.
- Groundwater levels rapidly peaked briefly in shallow piezometer P4a in September, which may indicate water ingress into the borehole from the surface at this time.
- Piezometer in boreholes B6 and Sn2a was dry and its integrity requires checking on next site visit.

6.5 Causal-response relationships

Most shallow piezometers at Scalby Ness closely reflect the pattern of rainfall. During this monitoring period, groundwater levels have remained relatively steady or fallen across most functioning boreholes following a wetter summer and autumn.

Deeper piezometers have a longer lag between rainfall and groundwater response. Those with data loggers show a much more muted response.

The inclinometers in BH7 and L2 show significant periodic sub-surface movement. BH7 is the most pronounced and indicates movement on an existing shear surface in glacial sediments above sandstone bedrock. Movement occurred between November 2013 and March 2014, associated with a period of high groundwater levels. Rainfall over the monitoring period was exceptionally high and ground water levels are very high at some locations or low at others. No ground movement has been recorded. This area is at high risk of ground movement, particularly if the winter of 2019/2020 is wet.

6.6 Implications and recommendations

The groundwater data indicates levels have decreased or remained steadily high in the area. The piezometer located mid-slope at WS6 show groundwater levels had remained elevated, and levels peaked briefly at P4a before falling to average levels. It is recommended this trend in groundwater levels is monitored and reviewed in the next monitoring report, together with inclinometer readings. In addition, auto-piezometers on the cliff top in boreholes P1b, P2b and P3, show groundwater levels have risen since replacement of the data loggers, which appears to be erroneous. These piezometers should be checked to ensure the cap is secure and there is no ingress of water from artificial recharge. Piezometers P2a or P4b had data logger communication errors and should be repaired. Piezometers in borehole B6 and Sn2a were dry. These locations should continue to be monitored.

Observations during the previous monitoring period suggested ground movement had occurred at the cliff toe at the lower end of the valley. An eye-witness account reported to JBA indicated that during high rainfall events the discharge of the stream increases and causes bank erosion at the end of the valley. It is suggested this site is visually inspected for the next monitoring period.

Scarborough North Bay – Oasis Café

7.1 Site description

Oasis Café cliffs are situated in the southern part of Scarborough's North Bay and occupy part of Clarence Gardens, which are landscaped coastal slopes open to the public (Figure 7.1). The cliffs rise to c. 30m OD and have a typical angle of 25-30°, although the main headscarp reaches 50°. The upper c. 15m of cliff is cut in glacial sediments and Jurassic sandstones and mudstones form the basal part of the cliff. The Holbeck to Scalby Mills strategy study (High-Point Rendel, 1999) classified the cliffs as multiple rotational landslides formed predominantly in the Jurassic bedrock. The landslides are fronted by the Marine Parade road and coast protection scheme and have not experienced toe erosion for over 100 years. Despite the toe protection, cliff instability risk in response to extreme rainfall remains a concern.

7.2 Ground model and monitoring regime

This frontage is covered by a single cliff behaviour unit, MU20/4a. Geomorphological mapping undertaken as part of the strategy study recognises a series of discrete landslides within this CBU, but all are classified as multiple rotational landslides formed predominantly in bedrock. It is assumed the basal shear surface is near Ordnance Datum and has formed in weak layers within the interbedded sandstones and mudstones. The monitoring regime comprises inclinometers and co-located automated piezometers at the cliff top, mid-slope and cliff toe positions aligned along a southwest to northeast bearing (Figure 7.1).

7.3 Historical ground behaviour

Table 7.1 summarises the observations in Mouchel (2012) from the monitoring undertaken at the Oasis Café.

Table 7.1. Summary of historical ground behaviour at Oasis Café

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Static groundwater at around 8.05m at BH2p and increase in water levels at BH3p and a decrease at BH4p. Slopes here appear to be stable from inclinometer readings although shallow ground movements were observed.	Apparent movements reported but these are attributed to operator error or temperature fluctuation rather than actual ground movements.

7.4 New data

Tables 7.2 and 7.3 summarise the monitoring data from inclinometer and piezometer installations at the Oasis Café.

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- Groundwater data show a decrease in level.
- No data are available for BH3p for this monitoring period due to temporary logger problems. The data should be downloaded and reviewed for the next monitoring period.

Table 7.2. Summary of inclinometer data at Oasis Café

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
BH3	BH3 is situated in the midslope and extends to c. 5.5m BGL. Surface elevation is 17.8m OD and the base of the hole is at c. 12.3m OD. The borehole extends through c. 3 m of glacial sediment before encountering 2.5m of mudstone, the uppermost metre of which is weathered. Past readings show no significant ground movement.													Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH4	BH4 is situated on the cliff top and extends to ca.13.5m BGL. Ground level is 31.1m OD and the borehole extends to c 17.6m OD, penetrating 14m of glacial sediment and 3.5m of sandstone bedrock. Past readings show no significant ground movement.													Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

7.5 Causal-response relationships

The higher than average rainfall in early winter 2015/2016 is reflected by elevated groundwater levels which fall in response to drier than average conditions which follow into 2017. On 23 August 2017 extremely heavy rainfall occurred, coinciding with a spike in groundwater levels at borehole BH2p, however this occurs only once in the record during high rainfall events. For example, the response of groundwater level in this borehole to the extreme rainfall on 20 September 2018 was indistinguishable. Borehole BH2p has an unclear response to rainfall and/or tides. Shallow piezometer BH3p shows a very rapid response to rainfall events (which probably explains the spikes on 10 Aug and 8 Oct 2014, and 9 May and 12 Dec 2015, 3 Jan and 27 August 2016, 12 March, 2 April, 27 July and 20 September 2018). Although a peak in groundwater in response to the 23 August 2017 rainfall event is evident, it is muted when compared to other high rainfall events. This piezometer showed a very clear response to the rainfall on 15 December, 27 January, and 5 to 6 March 2019. Only marginally deeper piezometer BH4p shows a lag response to prolonged periods of high rainfall. Groundwater levels in all boreholes remain below their peaks of winter 2012/13 and the inclinometers do not indicate movement. The extreme rainfall during autumn 2019 is not reflected by the changes in groundwater levels.

Table 7.3. Summary of groundwater data at Oasis Café

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status													Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11					
BH2p	Tip depth at 8.05m OD. Situated in the lower cliff. Manual dip readings from Sept 2009 to May 2012 show fluctuation between 8.0 and 8.5mOD from Sept to Dec 2009 followed by no change to December 2011. Groundwater level then rises to 8.5m OD by May 2012.	7.9m OD 8.7m OD 0.8m															Continuation of past pattern fluctuating weekly around an average of 8.3 m OD, increasing to a new historical high of 8.7 m OD by December and falling again to 8.1 m OD by March. Groundwater levels averaged at 8.3 m OD by May.	Continuation of past pattern fluctuating weekly around an average of 8.3 m OD, increasing to 8.6 m OD mid-September and falling to a low of 8.1 m. Groundwater levels averaged 8.3 m OD at the end of the monitoring period.
BH3p	Tip depth at 12.4m OD. Situated in the midslope. Manual dip readings from Sept 2009 to Dec 2011 show fluctuation between ca. 13.8m OD (June 2010) and 14.7m OD (Dec 2010). Final manual reading May 2012 shows substantial rise to 17.6m OD, reflecting high rainfall during spring 2012.	13.5m OD 16.7m OD 3.2m															Groundwater levels have risen slightly overall during the monitoring period. Levels peak at approx. 15.5 m OD during mid-December, late-January and early March. Peaks in groundwater levels during these months coincide with heavy rainfall events.	No data available. Data logger communication error. SBC to arrange for repair of equipment.
BH4p	Tip Depth at 17.0m OD. Situated at the cliff top. Manual dip readings from September 2009 to May 2012 show groundwater levels fluctuating between 18.0m to 19.3m OD with peaks in April 2010, December 2010 and May 2012.	17.2m OD 19.4m OD 2.2m															Continuation past cyclical pattern with sub-weekly variation. Groundwater levels increased from early December to 19.0 m OD where it remains relatively steady, close to the historical high.	Continuation past cyclical pattern with sub-weekly variation. Groundwater levels have gradually fallen over the monitoring period to 18.5 m OD.

7.6 Implications and recommendations

No data are available for BH3p for this monitoring period due to temporary logger problems. The data should be downloaded and reviewed for the next monitoring period. Future reports should pay attention to the midslope piezometer (BH3p) which has shown rapid response to rainfall conditions, but no associated ground movements to date. No significant ground movements have been recorded at Oasis Café, and there are no other specific recommendations at this location beyond on-going collection and analysis of data.

Scarborough North Bay – The Holms

8.1 Site description

The Holms is situated towards the southern end of North Bay, adjacent to Castle Headland. It is an area of sloping, hummocky, open parkland with a deeply-indented, arcuate headscarp between the castle at the cliff top and Marine Drive along the coast.

The slopes rise from Marine Drive at angles of c. 25-30° to a midslope bench at 35m OD and upper cliff at c. 55m OD, where a near-vertical cliff face rises to the cliff top at c 85m OD. A variable thickness of glacial sediments overlies interbedded sandstones and mudstones of Jurassic age. Two faults cross the site, one of which delineates the boundary of younger more resistant geological strata that form Castle Headland from the succession underlying much of the rest of North Bay.

The Holbeck to Scalby Mills strategy study (High-Point Rendel, 1999) classified the cliffs as multiple rotational landslides formed predominantly in the Jurassic bedrock. The landslides are fronted by the Marine Parade road and coast protection scheme and have not experienced toe erosion for over 100 years. Previous instability problems include a 200mm displacement of the sea wall, likely a result of reactivation of the pre-existing landslides. Movements of the main landslide body are estimated to be in the order of 10s of centimetres. Therefore, despite the toe protection, cliff instability risk in response to extreme rainfall remains a concern.

8.2 Ground model and monitoring regime

This site includes the Cell 1 cliff units MU21/1, which is the main landslide embayment, and MU20/4b which covers the cliffs to the west towards Oasis Café.

Mouchel (2012) state 'The Holms landslide system comprises 10 to 17m of landslide debris which overlies the intact Scalby Formation'. Two units within the landslide have been identified from ground investigations undertaken in 2000:

- An eastern unit, comprising a deep-seated landslide which daylights close to the foreshore
- A western unit, composed of a shallower landslide which daylights approximately 1.5m above Marine Drive (c. 8.5m OD)

The monitoring regime at The Holms comprises:

- Lower slope – two co-located piezometers. Each piezometer measures groundwater level at a different depth.
- Midslope – two sets of two co-located piezometers, one set on the more north-easterly midslope bench and one set on the more westerly slopes. Each multiple piezometer location measures groundwater levels at different depths.
- Upper slope – inclinometer in the central part, c. 50m NE and downslope of the bridge on the entrance road to the castle.
- Cliff top – one inclinometer on the cliff top at the northern end of Mulgrave Place c. 50m to the west of the western end of the arcuate headscarp of The Holms.

8.3 Historical ground behaviour

The Holms was monitored by Mouchel between summer 2009 and summer 2012. A summary of their results is provided at Table 8.1. The pattern of groundwater variation at L1 appears to be affected by tidal influences and all other piezometers are affected by accuracy issues which prevent meaningful conclusions being reached about the groundwater regime at The Holms.

Table 8.1. Summary of historical ground behaviour at The Holms.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Mouchel (2012) comments that no ground movement has been indicated at BH10A. They mention continued ground movements of around 14mm between 13 and 10m depth (ca. 46-43m OD) in BH11. They report erratic groundwater readings from BH8 and BH9 a & b, and recommended flushing them as they believed they were blocked. As such, they report it was not possible to provide definitive information about the groundwater regime at The Holms.	Displacements of around 18mm at 10-13m depth (46-43m OD) in BH11, 4mm of which occurred between December 2010 and June 2011 and a further 14mm between June 2011 and June 2012. Groundwater at L1 shows fluctuations of between 40mm and 120mm which is attributed by Mouchel (2012) to tidal level fluctuations.

8.4 New data

Tables 8.2 and 8.3 summarise the readings from the inclinometers and piezometers at The Holms up to May 2019.

The new data indicate:

- No significant ground movements recorded in any of the inclinometers. However, inclinometer BH10a appears to be providing erroneous readings.
- Groundwater data shows a continuation of past patterns. Water levels increased slightly in all boreholes, remaining well below historical high levels. Groundwater tended to peak in September. This may be a short-lagged response to rainfall in July and August.
- Auto-piezometer in borehole BH9a had a data logger communication error. No data was available during this monitoring period.
- Piezometer BH9b is no longer monitored.

8.5 Causal-response relationships

The piezometers at The Holms show a lagged response to above average rainfall conditions, with only BH8a showing a rapid response. Groundwater levels in BH8a responded rapidly to higher than average rainfall in May 2015, March and November 2016. Levels fell during winter 2016/2017 following months of dry conditions then stabilised following a wet summer in 2017. Levels increased again over the drier than average winter 2017/18 and have stabilised at average levels following this. Other boreholes show a continuation of past fluctuating or steady levels of groundwater, suggesting they respond to several months' antecedent rainfall. Over the whole record, BH8b shows a different pattern of gradual highs followed by sharp falls, however movements are not shown in the inclinometer upslope at BH10A. There is no clear response in any of the boreholes to the extreme rainfall events experienced on 23 August 2017, 20 September 2018 or during autumn 2019. During this monitoring period, most piezometers show groundwater levels peaking in September 2019, which reflects up to two months' antecedent rainfall.

8.6 Implications and recommendations

Auto-piezometer in borehole BH09a had a data logger communication error which should be checked and repaired. Inclinometer readings from BH10A appear to be erroneous and the equipment should be checked.

Table 8.2. Summary of inclinometer data at The Holms

Borehole	Summary of past data	Report Status										Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10			11
BH10A	BH10A c. 42m deep. Surface of borehole is 46.75m OD, base at 4.75m OD. Borehole passes 2m of made ground, 1m of clay and c.8m of clayey sand before encountering sandstone bedrock. Progressive movements in the positive A axis direction (upslope) are recorded between the surface and 5m BGL (a. 42m OD). The total maximum displacement that occurred by May 2012 was around 10mm.												Repeated minor displacements in sandstone bedrock at 16 m depth are error. Cumulative readings show no net direction to movement, suggesting inclinometer probe meets a small obstruction at this depth.	Changes in inclinometer readings across entire length of borehole. Readings do not reflect type of movement expected in this system, as the borehole is located on multiple rotation landslide. Likely a result of erroneous readings or the inclinometer becoming loose in keying. The inclinometer should be checked.
BH11	BH11 is c.22m deep. Surface elevation is 55.86m OD, base at c.34m OD. Borehole passes through 5m of till before encountering weathered sandstone at c. 51m OD and intact sandstone at 41m OD. The inclinometer readings show a series of progressively larger deformations of around 20mm in the both axes within the weathered sandstone.												No change detected in sinusoidal pattern of deformation between 9 and 13 m depth.	Readings are less than 1mm and therefore not significant.

Table 8.3. Summary of groundwater data at The Holms

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status													Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11					
L1a	Tip depth at -8.03m OD, co-located with L1b. Manual dip readings from June 2009 to May 2012 show limited groundwater with variation between 5.9m OD (June 2010) to 4.6m OD (March 10). Piezometer tip is deeper than BH1Lb, but shows a higher piezometric level that may indicate a confined aquifer under artesian pressure	0.5m OD 2.5m OD 2m															Continuation of past cyclical patterns, with 2 to 3-week variations of up to c. 0.6 m from December to May. Groundwater levels have fallen on average from 1.1 m OD to 0.7 m OD. Groundwater peaks on 3 January at 1.3 m OD, which may reflect two months antecedent rainfall.	Continuation of past cyclical patterns, with 2 to 3-week variations of up to c. 0.2 m. Groundwater levels have increased during the monitoring period to 1.1 m OD. Groundwater peaks on 13 September.
L1b	Tip depth at -2.97m OD co-located with L1a. Manual dip readings between June 2009 and May 2012 show steady groundwater level around 1.9m OD.	3.6m OD 4.7m OD 1.1m															Continuation of 2 to 3-week cyclical pattern, with variations up to 0.5 m over monitoring period. Groundwater levels had peaked on 2 January at 4.3 m OD and fell on average until the end of the monitoring period to 3.8 m OD.	Continuation of 2 to 3-week cyclical pattern, with variations up to 0.4 m over monitoring period. Groundwater levels peaked on 13 September at 3.9 m OD but is steady around an average of 3.7 m OD.
BH8a	Tip depth at 10.16m OD. Borehole top at 31.16m OD Co-located with BH8b. Monitoring from Sept 2010 shows an initial fall in level to a low of 10.43m OD in June 2011 then a gradual rise to Dec 2011, reflecting wetter weather, before a sharp rise to 23.6m OD by May 2012 following exceptional rainfall.	9.7m OD 10.7m OD 1.0m															Groundwater levels remained relatively steady over the monitoring period, around and average of 10.1 m OD. Groundwater level peaked on 2 January, possibly in response to two months antecedent rainfall. Variations of up to 1 m occurred during early March where levels fell to 9.7 m.	Groundwater levels have increased slightly from an average of 10.1 m OD to 10.4 m OD. Groundwater levels peaked at 10.6 m OD on 13 September. Variations of up to 1 m occurred during September.

BH8b	Tip depth at 3.16m OD. BH top at 31.16m OD, co-located with BH8a. Groundwater levels dropped from an initial high of 17.3m OD at installation in Sept 2010 to a low of 9.55m OD in Feb 2011. Levels then gradually rise through 2011 to c. 10.6m OD in Dec 2012 before a sharp rise to 22.2m OD by May 2012. This shows a similar rainfall-influenced pattern to BH8a.	9.4m OD 14.5m OD 5.1m													Groundwater levels continue a saw-tooth pattern, rising in December to 10.7 m OD and rapidly falling in mid-December to 9.4 m OD. Groundwater levels remain steady over the remainder of the monitoring period around 9.3 m OD.	Groundwater levels continue a saw-tooth pattern, rising during the monitoring period to a peak of 10 m OD on 13 September. Groundwater levels remain well below the historical high.
BH9a	Tip depth at 9.49m OD. Surface at 33.49m OD co-located with BH9b. Shows sharp increase after installation from c. 11.5m OD to a high of 26.6m OD by Feb 2011 before falling to 24.3m OD in June 2011. Between June and Dec 2011 ground water levels rise again to around 27.0m OD before falling to 26.3m OD.	12.1m OD 26.2m OD 14.1m												No data available. Data logger communication error. Logger removed and sent for repair.	No data available. Data logger communication error. Logger removed and sent for repair.	
BH9b	Tip depth at 0.49m OD, surface at 33.49m OD co-located with BH9a. Historical data showed similar pattern to BH9a, but contrary to that in BH8a and BH8b.	9.7m OD 30m OD 18.5m												Logger removed as piezometer no longer functioning.	Logger removed as piezometer no longer functioning.	

Scarborough South Bay

9.1 Site description

South Bay is formed from cliffs cut in Jurassic sandstones and siltstones that are overlain by a thick sequence of glacial sediments. A series of deep-seated landslides have developed in the glacial sediments and underlying weathered bedrock in post-glacial times. Since Victorian times, the cliffs have been extensively landscaped into public areas that include the Spa conference centre complex. The coastline has marginal stability, but first-time failures do occur: the Holbeck Hall Hotel landslide occurred in June 1993 and there are records of similar cliff failures occurring elsewhere along the frontage over the last several hundred years. The whole frontage benefits from coastal defences, but ground movements in pre-existing landslides and over-steep cliff sections continue to occur, particularly in response to periods of elevated ground water levels, and there remains concern of first-time failures and reactivation failures in the cliffs. Instability risk is therefore a concern along the whole of South Bay.

The majority of South Cliff (from St Nicholas Cliff to Holbeck Gardens) was mapped in 2011 as part of the Scarborough Spa Coast Protection scheme. This mapping underpins the ground model for this site. Cliff behaviour units (CBUs) have been defined and their activity status classified under the Cell 1 Regional Monitoring Programme.

9.2 Ground model and monitoring regime

Pre-existing landslides have developed in the thick sequence of glacial sediments that form the upper coastal slope. Their geomorphology generally comprises arcuate landslide embayments with mid-slope benches that are fronted by elongate mudslide tracks and vertical *in situ* bedrock cliffs. The basal shear surface typically appears at the contact between the glacial sediment and underlying Jurassic bedrock, but it is likely that the significant local variation in the glacial sediments allows secondary shear surfaces to form along clay layers.

The monitoring regime at South Bay is summarised in Appendix A and Figure 9.1. It comprises an extensive suite of inclinometers and piezometers, most of which are automated, and an experimental acoustic inclinometer installed near the Spa Centre.

The areas being monitored comprise, from north to south:

- St Nicholas Cliff – till cliff fronting the Grand Hotel and cliff lift with a co-located single inclinometer and diver piezometer with barometric diver that were installed in 2014 (MU22/0)
- Spa Chalet Gardens – till cliff with groundwater monitoring at its toe and an inclinometer inland of the cliff top (MU22/1).
- Spa Centre and gardens – rotational landslide (MU 22/2) and very steep till cliff (MU22/3) in the vicinity of the Spa buildings. Extensive monitoring of groundwater levels and ground movements at locations inland of the cliff top, on the slope and at the cliff toe.
- Clock Café – rotational landslide (MU 22/3) that is monitored with transect of devices comprising two inclinometers on the slope and a piezometer inland of the headscarp.
- South Cliff Gardens – till cliff with a mudslide embayment north of the Rose Garden (CBU 22/5), a small rotational landslide at the Rose Garden and a much larger rotational landslide at the Italian Garden, known as the South Bay Pool landslide (CBU 22/6). The area is monitored by three transects of devices that cover each of the landslides.
- Holbeck Gardens (CBU 22/7) – till cliff monitored at three locations.

These areas include both pre-existing landslides and intact cliffs and headscarps where instability is a risk. The Spa Centre is the focus of monitoring and is also the subject of an on-going coast defence scheme to improve the seawall and stabilise the slope.

At each location, a suite of instruments are installed on the promenade, on the coastal slope and at the cliff toe allowing ground models to be developed and stability modelling to be undertaken.

9.3 Historical ground behaviour

South Bay was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 9.1, which shows slight movement in a number of inclinometers and variable groundwater levels. No relationship between groundwater level and ground movement was reported by Mouchel.

Table 9.1. Summary of historical ground behaviour at Scarborough South Bay.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
AA10 (Clock Cafe) and AA08 (south Cliff Gardens) showed slight movement at shallow depths. Movement at greater depth was indicated in BHs 12, 13, 14 (at the Spa) and 16A (South Cliff Gardens). No movements indicated by other inclinometers. Groundwater levels are generally variable across the sites, except in the south of the Spa, where levels were reduced.	In addition to observations between Dec 2011 and June 2012, slight movement was recorded at AA04 in the upper 7m of ground, at AA10 in the upper 3.5m and at AA11 in the upper 3m. All net movements have been less than 10mm.

9.4 New data

For clarity, new data for South Bay are presented for each of the monitoring areas separately.

9.4.1 St Nicholas Cliff (MU 22A)

The cliff here is around 30m high and heavily landscaped with terraces and footpaths and formed in fine-grained glacial sediments (Figure 9.1A). Average slope angle is 20 to 30° but is locally steeper with sections supported by retaining walls. The cliff is crossed by a cliff lift and the cliff top is occupied by the Grand Hotel. There is no history of instability in recent years and this CBU was not reported on by Mouchel.

Table 9.2 Summary of inclinometer data at St Nicholas Cliff

Borehole	Summary of past data	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
FR01	FR01 is situated above Foreshore Road in front of the Grand Hotel at 11.43m OD. The borehole is c.20m deep with its base at c.-8.5m OD and passes through c.10.5m of made ground and 9.5m of fine-grained glacial sediments. FR01 has been monitored since 16 June 2014.													Readings show less than 1mm movement and are not significant, except for at 3 m BGL there is upslope movement of 4 mm, which likely represents error.	Readings are less than 1mm and therefore not significant.

Table 9.3 Summary of groundwater data at St Nicholas Cliff

Borehole	Summary of past data	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
			1	2	3	4	5	6	7	8	9	10	11				
FR02	FR02 has been monitored since 21 May 2014. Tip is at 18.0m depth (c.-6.5m OD). Variation may reflect tidal cycles.	6.6m OD 8.4m OD 9m														Continuation of past cyclical pattern, with groundwater levels are relatively steady averaging 7 m OD. Groundwater levels rise slightly from December to March, where groundwater peaks on 6 March coinciding with two days of heavy rainfall	Continuation of past cyclical pattern, with groundwater levels are relatively steady averaging 7 m OD. Groundwater levels peak at the end of September at 7.9 m OD.

No significant ground movement is recorded at this site and water levels remain near the historical low.

9.4.2 Spa Chalet (MU 22/1)

This cliff is very steep and formed in glacial sediment that does not appear to have been affected by landsliding. The cliff has been previously stabilised with soil nails and netting. Monitoring comprises a single inclinometer on the promenade and a pair of closely located piezometers at the cliff toe. Inclinometer data are summarised in Table 9.4 and piezometer data in Table 9.5.

Table 9.4 Summary of inclinometer data at Spa Chalet

Borehole	Summary of past data	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019		
		1	2	3	4	5	6	7	8	9	10	11				
BH12	BH12 is 65m deep (ground level at 48.05m OD, base at -16.95m OD) and extends through 60m of glacial sediment and 5m of sandstone/mudstone bedrock.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 9.5. Summary of groundwater data at Spa Chalet.

Borehole	Summary of past data	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
			1	2	3	4	5	6	7	8	9	10	11				
BH12	Tip at -8.4 OD. Cyclical pattern with c. two-week frequency between peaks. Max. levels are between 1.25 and 1.5m above OD and min. between 0.3 and 0.5m above OD. May be influenced by tides.	0.0m OD 2.3m OD 2.3m														No data recorded for monitoring period, unable to connect to data logger. Last data recorded in May 2016. This site requires attention.	No data recorded for monitoring period, unable to connect to data logger. Last data recorded in May 2016. This site requires attention.
BH12a	Tip at 3.6m AOD. High degree of variability, with rapid fluctuation about a mean water level of c. 3.6m above OD. Peak water levels are c. 3.9m OD and min levels are c. 3.3m OD.	3.2m OD 3.9m OD 0.7m														Range of fluctuations within past limits and linked to tidal cycles. Groundwater levels remain steady. Fluctuation ranges from 3.3 to 3.9 m OD, averaging 3.6 m OD. Large cyclical variations occur during March when conditions are wetter.	No data recorded for monitoring period, unable to connect to data logger.

The piezometer in borehole BH12 and BH12A requires attention to fix or replace faulty equipment.

9.4.3 Spa (MU 22/2 and 22/3)

The Spa is the focus of monitoring in South Bay, with eight inclinometers and 21 piezometers installed in the area (Figure 9.1B). The cliffs are generally steep and formed in glacial sediment. Shallower cliff sections are associated with a deep-seated landslide seen immediately north of the Spa Centre and localised shallow landslides. The monitoring results are described in Tables 9.6 and 9.7.

Table 9.6. Summary of inclinometer data at the Spa

Borehole	Summary of past data	Report Status										Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10			11
AA04 (G2)	40.5m deep borehole penetrating 34.5m of glacial sediments and 6m of sandstone/siltstone bedrock. Ground level is 47.6m OD, base of hole is 7.1m OD.												Downslope movement of up to 22 mm, in upper 13m of borehole within till. Pattern of movement shows negative and positive deflection, which suggests error. Inspect site and take careful readings next time.	Readings are less than 1mm and therefore not significant.
BH13	61m deep borehole inland of the headscarp that penetrates 52m of glacial sediment and 9m of sandstone bedrock. Ground level is 53.93m OD, base of hole at -7.07 OD. Deflection of up to 80mm in the upper 35m (i.e. above 19m OD) of the borehole associated with creep.												No significant movement. Upslope movement of 18 mm at 62 m BGL likely represents error.	Readings are missing for this monitoring period. Data should be downloaded for the next monitoring period.
BH14	55m deep borehole penetrating c. 50m of glacial sediments and 5m of sandstone bedrock. Ground level at 55.73m OD, base of hole at 0.73m OD. Uniform cumulative displacement of c. 5mm in the upper 35m of the borehole, with peaks of up to 10mm displacement from 35 to 55m depth. Readings are not progressive in time, suggesting shrink-swell behaviour.												Up to 33 mm downslope movement in upper 3 m BGL. This may represent shallow surface creep. This trend should be reviewed in the next monitoring report. Up to 8 mm positive and negative displacement on both A and B axes in the upper 20m of the borehole reflects blockages in the upper borehole and/or careless reading.	Continued minor displacement downslope in upper 3 m BGL of 3mm. This may represent shallow surface creep. Other minor displacements on both A and B axis in upper 20m of borehole reflects blockages in the upper borehole and/or erroneous readings. The inclinometer should be checked.
BH101	Borehole is located in the seawall, beyond the toe of the Spa landslide and is 26.5m deep, passing through 21m of glacial sediment and 5.5m of sandstone and mudstone bedrock. Ground level is 6.77m OD and the base is -19.7m OD. No significant movement has been detected in the past.												Minor displacement of 3 mm downslope at 12 m depth within clay.	Accelerated displacement of several mm is evident at 13 m BGL, which appears to reflect shearing in the clay. This may relate to disturbance of the slope and should be checked visually. This trend should be checked in the next monitoring period.

BH103	10m deep borehole that only penetrates glacial sediments. Ground level is 6.65m OD, base of hole at -3.35m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm.											No significant movement. Upslope movement of 4 mm recorded at 7 m BGL likely represents error.	Readings are less than 1mm and therefore not significant.
BH107	18m deep borehole that passes through 13m of glacial sediments and 5m of sandstone/mudstone bedrock. Ground level is 20.4m OD, base of hole at 2.4m OD. No displacements between installation in Oct 2012 and Dec 2012. Historical readings unavailable at current time therefore current reading cannot be compared to baseline.											No significant movement.	Minor downslope movement of 2mm recorded at 13 m BGL in clay.
BH109	15m deep borehole that passes through 9m of glacial sediment and 6m of sandstone/mudstone bedrock. Ground level is 31.6m OD, base of hole is 16.6m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm.											Minor downslope movement of 2 mm recorded at 9 m BGL and 1 m BGL.	Minor downslope movement of 2mm recorded at 9 m BGL in clay.
BH105	45m deep borehole passing through 44m of glacial sediments an 1m of sandstone bedrock. Ground level is 41.75m OD and base of hole is -3.25m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm.											Downslope movement of 5 mm in within upper 5 m BGL. This may represent shallow surface creep. This trend should be reviewed in the next monitoring report.	Borehole could not be accessed. Site requires rope access. Data should be collected during next monitoring period.

BH105a	Acoustic inclinometer installed to a depth of 40m since 14 Nov 2012 adjacent to BH105. Ground level is 42m OD, base of hole is 2m OD. Since installation in Feb 2013, the device has detected a relatively low level of activity in response to rainfall events. No significant ground deformations have been indicated by the acoustic monitoring.															AE data could not be collected during this monitoring period due to on-going construction works in the vicinity of the borehole.	
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Table 9.7. Summary of groundwater data at the Spa

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
H2a	Located near the headscarp of the Spa landslide. Tip at 17.3m OD. 3 to 5-day frequency fluctuation around mean of c. 17.3m OD with amplitude of c. 0.5m. No clear long-term trend or temporal pattern.	16.7m OD 17.6m OD 0.9m															Groundwater levels remained static between December and March at 17.4 m OD. Groundwater levels fall in mid-March to 16.9 m OD, and peak twice at 17.5 m OD in late March and mid-April. Levels average 17.3 m OD during the monitoring period.	Groundwater levels average 17.2 m OD, peaking only on 13 September at 17.4 m OD.
H2b	Located near the headscarp of the Spa landslide. Tip at 11.1m OD. 3 to 7-day frequency fluctuation around mean of c. 12.7m OD with amplitude of c. 0.3m. Highs and low reflect antecedent rainfall	12.0m OD 13.0m OD 1.0m															Groundwater level is static from December to March at 12 m OD. Levels fluctuate between March and May around an average of 19.8 m OD, peaking in late March.	Groundwater levels were steady during summer at an average of 11.7 m OD before increasing gradually to an average of 11.8 m OD in September.
H5	Located near the base of the cliff behind the Spa building. Tip at 15.5m OD.	17.0m OD 23.01m OD 6.01m															Groundwater levels continue to follow a saw-tooth pattern, with a sharp rise and fall, with more muted variation of 0.6m.	Groundwater levels continue to follow a saw-tooth pattern, with a sharp rise and fall, with more muted variation of 0.4m.

	fluctuations of uncertain cause.														extreme rainfall events on these days.	need recalibrating. Equipment to be repaired and data collected on next site visit.
BH108b	Shallow piezometer tip co-located with deeper BH108a. Dry between Sept 2012 and Jan 2013.	25.6m OD 31.6m OD 6m													No access to site. Data to be collected at the next site visit.	Piezometer damaged. Dip meter readings indicate water levels are elevated at 49.2 m OD. Equipment to be repaired and data collected on next site visit.
BH106a	Located at the cliff top. Solinst data logger. BH dry between Oct 2012 and Jan 2013.														Borehole dry. Check piezometer integrity	Borehole dry. Check piezometer integrity
BH106b	Located at the cliff top. Located at the cliff top. BH dry between Oct 2012 and Jan 2013.														Groundwater level recorded at 8.5 m OD.	Borehole dry. Check piezometer integrity
BH104a	Located near the base of the slope. Solinst data logger replaced by telemetry system in 2018.	4.30m OD 20.0m OD 15.7m													Groundwater is steady around 4.3 m OD.	Groundwater level peaks on 20 July at 9.5 m OD and returns to an average of 4.3 m OD.
BH104b	Located near the base of the slope. Manual piezometer tube. BH dry between Sept 2012 and Jan 2013.	4.3m OD 11.2m OD 6.8m													Groundwater level rises to 10.7 m OD.	Piezometer cover is damaged. Manual dip readings of 17.6 m OD suggest possible ingress of water from the surface. Equipment to be repaired and data collected on next site visit.
BH102a	Located at the base of the slope behind the seawall. Solinst data logger.	0m OD 3.7m OD 3.7m													Groundwater levels steady averaging 1.4 m OD. Levels peak to 3.7 m OD on 8 January, which does not coincide with rainfall events recorded at Filey.	Groundwater levels fluctuate around an average of 1.4 m OD. Levels peak at 1.6 m OD in early September and October.

BH102b	Located at the base of the slope behind the seawall. Manual piezometer.	1.0m OD 2.1m OD 1.1m																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																
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These data indicate:

- Functioning inclinometers show minor movement over the monitoring period, except for borehole BH101 which indicates accelerated movement at 13 m depth within the clay by several millimetres. This may be related to disturbance of the slope but should be checked visually for signs of movement at the surface. Nearby piezometers (BH1a spa, BH1b spa, BH102a and BH102b) show slight increases and peaks in groundwater levels which appear to reflect up to 2 months antecedent rainfall.
- Inclinometer BH14 shows evidence for shallow surface creep within the clay. Nearby piezometers are dry. These trends will be reviewed in the next monitoring report. The inclinometer also shows potentially erroneous readings and should be checked, and data reviewed

Table 9.8. Summary of inclinometer data at the Clock Café

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
AA10 (F2)	30m deep borehole through 3m of made ground, 21m of glacial sediment and 6m of siltstone/sandstone bedrock at the headscarp of the Clock Café landslide. Ground level is 35.0m OD, base of hole is 5.0m OD. Very low creep indicated in the upper 5m.													No significant movement.	Data not collected for monitoring period. Data should be downloaded for next monitoring period.
AA11 (F4)	20m deep borehole penetrating 8m of glacial sediment and 12m of siltstone/sandstone bedrock near the toe of the Clock Café landslide.													No significant movement.	Data not collected for monitoring period. Data should be downloaded for next monitoring period.

Table 9.9. Summary of groundwater data at the Clock Café

Borehole	Summary of past data	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
			1	2	3	4	5	6	7	8	9	10	11				
BH15	Located inland of the landslide headscarp. No historical data	n/a														Borehole dry. Check piezometer integrity	Borehole dry. Check piezometer integrity

No ground movement data was available at the Clock Café, and data should be collected during the next monitoring period. The one piezometer at this location continues to be dry. This equipment may be damaged and required attention to determine whether it can be repaired and/or should continue to be read.

In mid-March 2018, a retaining wall behind chalets south of the Clock Café failed, resulting in significant cracks forming on the footpath behind the chalets. There are no inclinometers or piezometers in the vicinity of the wall failure, however adjacent data do not indicate any movement nearby. A ground investigation concluded that bedrock was at shallow depth and the failure was the result of collapse of the retaining wall structure rather than ground movement. High antecedent groundwater levels due to heavy rainfall in early spring 2018 were probably a trigger of the failure.

9.4.5 South Cliff Gardens (MU 22/5 and 22/6)

The South Cliff Gardens area comprises landscaped public areas and the former South Bay Pool, which lies at the foot of a relict landslide complex (the South Bay Pool landslide). There are three transects of monitoring locations (Tables 9.10 and 9.11; Figure 9.1C).

Table 9.10. Summary of inclinometer data at South Cliff Gardens

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019			
		1	2	3	4	5	6	7	8	9	10	11					
AA08 (D3)	24m deep borehole that penetrates 12m of glacial sediment and 12m of interbedded bedrock. Ground level is 38.4m OD, base of hole is at 14.4m OD. Data indicate slight progressive creep along the whole length of the borehole,															Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH17	50m deep borehole than penetrates 34m of glacial sediment and 16m of siltstone bedrock at the top of a mudslide embayment. Ground level is 57.5m OD, base of hole at 7.5m OD.															Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
	Periods of slightly higher water level from Dec 2012 to Mar 2013, late May 2013 and early Aug 2013.																OD, which probably represents ingress of water into the borehole from the surface during heavy rainfall.	
D2a	Tip at 27.5m OD at the headscarp of the South Bay Pool landslide. Sub-metre variation about an average level of 40.5m OD. Periods where hole appears dry occurred regularly from late June to early July 2013, following which no data has been recorded.	31.1m OD 40.9m OD 9.8m															Groundwater levels were steady during the monitoring period, averaging 31.5 m OD. There was no clear response to heavy rainfall events.	Groundwater levels were steady during the monitoring period, averaging 31.5 m OD. There was no clear response to heavy rainfall events.
D2b	Tip at 41.5m OD at the headscarp of the South Bay Pool landslide. Pattern similar to that recorded by lower elevation tip, with sub-metre variation about mean of c. 45.8m OD.																No data, logger to be checked.	No data, logger to be checked.
Bh3a	Tip at 41.5m OD at a mid-slope position adjacent to the South Bay Pool landslide. Sub-metre variation about a mean value. Change occurs in Apr 2013, before which mean is 44.5m OD, after which it is drops to c. 44m AOD.	Original logger: 43.6 44.8 1.2 Replacement logger: 45.6m OD 50.0m OD 4.4m															No data, logger to be checked.	No data, logger to be checked.
Bh3b	Tip at 10.5m OD at a mid-slope position adjacent to the South Bay Pool landslide. Similar pattern to high elevation tip (Bh3a), but typical level of 10.5m OD is interrupted by frequent short-duration (1 day) peaks up to 8m higher.	10.3m OD 18.6m OD 8.3m															Levels steady around 10.6 m OD with sub-weekly fluctuations of up to 0.6 m. Groundwater level peaks in mid-December, coinciding with high daily rainfall totals. There is no clear response to the extreme rainfall event on 15 January.	Levels steady around 10.6 m OD with sub-weekly fluctuations of up to 0.4 m. Groundwater levels peak on 27 June and 13 September and this does not appear to coincide with high daily rainfall totals.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11			
E2a	Tip at 31.4m OD below the headscarp of the mudslide embayment. Cyclical long-term pattern with sub-metre fluctuations superimposed.	43.3m OD 46.5m OD 3.2m													Groundwater levels decline over the monitoring period to an average of 43.5 m OD until March, where levels rise slightly to 43.7 m OD.	No data, logger to be checked.
E2b	Tip at 43.6m OD below the headscarp of the mudslide embayment. Different pattern to shallower tip, with sub-metre variation about a mean of 51m OD.	49.6m OD 51.4m OD 1.7m												Groundwater levels fall slightly to 50.4 m OD, varying up to 0.7 m during January and March. Levels are greatest during January at 50.8 m OD.	Groundwater levels increase slightly to 50.5 m OD, varying up to 0.5 m during September.	

These data indicate:

- No movement has been recorded in any boreholes at South Cliff Gardens.
- Overall, groundwater levels have mostly remained steady during the monitoring period; however, slight increases in levels are apparent in BH19b and E2b, peaking in late September which is coincident with a period of sustained heavy rainfall.
- No data were available for borehole piezometers BH18a, D2b, BH3a and E2a. These piezometers should be checked and repaired.

9.4.6 Holbeck Gardens (MU 22/7)

This area comprises two monitoring locations (Figure 9.1C); water levels are monitored at two depths along the promenade and ground movements are recorded by an inclinometer on the upper slope (Tables 9.12 and 9.13).

Table 9.12. Summary of inclinometer data at Holbeck Gardens

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
		1	2	3	4	5	6	7	8	9	10	11			
AA07 (BH2)	60m deep borehole penetrating 31m of glacial sediments and 29m of siltstone/sandstone bedrock. Ground level is 56.3m OD, base of hole is -3.7m OD. Data show progressive displacement of the glacial sediments, with up to c. 15mm at the ground surface. There is a suggestion of a shear developing at the contact between the glacial sediments and underlying bedrock and at c. 14m depth, within the glacial sediments.													Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant. Erroneous readings at base of borehole by several mm. The inclinometer should be checked.

The data logger was at fault for Bh4a and Bh4b, and data were not downloaded. The integrity of the piezometers should be checked. No evidence of movement is shown in the current inclinometer data, and erroneous readings appear at the base of the borehole.

Table 9.13. Summary of groundwater data at Holbeck Gardens

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
			1	2	3	4	5	6	7	8	9	10	11				
Bh4a	Tip at 31.5m OD. Complex pattern with periods of stability interspersed by rapid rises or falls of up to 2m.	47.1m OD 58.8m OD 11.7m														Unable to download logger data. Check integrity of piezometer.	Unable to download logger data. Check integrity of piezometer.
Bh4b	Tip at 35m OD. Different pattern to records of shallower tip. Highly variable	31.8m OD 59.9m OD 26.7m														Unable to download logger data. Check integrity of piezometer.	Unable to download logger data. Check integrity of piezometer.

9.5 Causal-response relationships

Groundwater levels in South Cliff tend to show a decrease in groundwater levels or remain steady since reaching historical high levels during previous monitoring periods. Some piezometers with data loggers show a response to the peak rainfall events in December, January and March, however, the most common response is for steady or falling groundwater levels, which suggests a lagged response to the drier conditions over spring, and/or a relationship to the 5 or 6-month antecedent rainfall (Figure 2.6).

9.6 Implications and recommendations

Inclinometer in borehole BH101 indicates accelerated movement at 13 m depth within the clay by several millimetres. This may be related to disturbance of the slope but should be checked visually for signs of movement at the surface. Nearby piezometers show slight increases and peaks in groundwater levels which appear to reflect up to 2 months antecedent rainfall. Antecedent rainfall will increase due to the extreme rainfall during October, and it is expected that groundwater levels are likely rise during autumn and winter. This site should continue to be monitored visually, especially following sustained heavy rainfall, and the trend will be reviewed in the next monitoring period.

Boreholes BH14 (Spa) and AA07 (Holbeck Gardens) have readings that are interpreted as error due to blockages in the shallow borehole, erroneous readings or potentially ground movements-on the coastal slope at the Spa. It is possible that the probe was removed too quickly or there is material in the tube causing the probe to come away from its keyholes. The inclinometers and surrounding land should be checked, and data reviewed for the next monitoring period. No data was collected from inclinometers BH13 (Spa), AA10 and AA11 (Clock Café). Data should be collected during the next monitoring period. No data was collected from inclinometer BH105 (Spa) as it requires rope access.

Shallow surface creep is also evident in borehole BH14. The ground movement and groundwater trends will be reviewed in the next monitoring report.

Most piezometers show groundwater levels have either remained steady or slightly increased or decreased. Several show short-lived peaks in water level that suggests ingress of surface water during heavy rainfall. Checks should be made at these locations to ensure water-proof caps are in place.

No data were collected at a number of piezometers including BH12 and BH12a (Spa Chalet), 5 spa, BH108b, BH104b, BH1 Prom and G3 (Spa), BH18a, D2b, BH3a and E2a (South Cliff Gardens), and BH4a and BH4b (Holbeck Gardens) due to data logger communication errors or damage to the equipment. No access was possible at piezometers 2 spa and 3 spa, and the data should be downloaded and reviewed for the next monitoring period. Boreholes BH106a and BH106b (Spa) and BH15 (Clock Café) are recorded as dry. The integrity of piezometer tips should be checked, and the next monitoring data reviewed, whether these trends continue.

Filey Town

10.1 Site description

The cliffs at Filey are formed in thick (c. 50m) glacial sediments that overlie the Upper Jurassic Kimmeridge Clay Formation across the town frontage and Upper Calcareous Grit north of the town towards Filey Brigg. The cliffs are protected by a sea wall at Filey and unprotected to the north and south of the town. Outflanking of the seawall and cliff instability of both the protected and unprotected cliffs at Filey is a concern. The cliffs across the town frontage have been landscaped and are criss-crossed with public footpaths. The glacial sediments have been deeply incised to form Church Ravine to the north of the town and Martin's Ravine to the south.

In July 2007, an intense rainstorm resulted in severe and widespread flooding throughout Filey; the storm water run-off caused many slope failures and extensive scour damage to paths and bridge abutments within Martin's Ravine. Existing drainage was overwhelmed and extensively damaged due to the excessive storm water run-off around Glen Gardens and this also caused drainage to collapse leading to slope instability behind Royal Parade chalets and Crescent Hill (Mouchel, 2012). The unprotected cliffs to the north and the south of the town are susceptible to toe erosion by the sea and are actively retreating. Cliff behaviour units (CBUs) have been defined and their activity status classified under the Cell 1 Regional Monitoring Programme.

10.2 Ground model and monitoring regime

Cliff behaviour units, reflecting individual mudslides and areas of relict cliff protected by the seawall, have been mapped for the frontage (Figure 10.1):

- MU29/AA and /AB are cliffs and mudslides south of the town
- MU 28/Z is a till cliff protected by rock armour immediately south of the sea wall
- MU27/X and MU28/Y are dormant cliffs protected by the seawall
- MU27/T /U, /V and /W are cliffs and mudslides north of the town

Halcrow (2012a) provides an overview of the ground models throughout the Filey Town frontage. The whole cliff line is comprised of weak glacial sediments that tend to fail through simple landslides triggered by both toe erosion and elevated groundwater levels.

The cliffs at Filey town, which are protected by a seawall, display evidence of historical instability. Shallow failures last occurred in this area in response to the intense storm event of July 2007.

Within the ravines, the steep till slopes are susceptible to shallow failure resulting from toe undercutting and excess groundwater levels due to intense and prolonged rainfall events.

The monitoring regime at Filey Town comprises the following:

- Filey Park – Till cliff with ground water monitoring at the cliff top.
- Golf Course – Ground water monitoring at the cliff top.
- Church Ravine/Coble Landing – Ground water monitoring at the cliff top and an inclinometer at the cliff toe.
- The Crescent/Rutland St – Groundwater monitoring at the cliff top and an inclinometer at the cliff toe.
- Glen Gardens/Martin's Ravine – Ground water monitoring on the cliff top and toe. Inclinometers at the cliff top and toe.

- Muston Sands – Ground water monitoring at the cliff top.
- Inland North – Groundwater monitoring near Church Cliff Farm, Pinewood Avenue and Parish Wood.
- Inland South – Groundwater monitoring near Filey Fields Farm, Long Plantation (west of Rivelin Way and Fewston Close) and Filey School.

10.3 Historical ground behaviour

Filey town was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 10.1, which shows minor movement in one borehole during the autumn of 2009 but without subsequent movement and limited fluctuation in ground water level which Mouchel attribute to tidal variation in some boreholes and variations in stream flow in others. No relationship between groundwater level and ground movement was reported by Mouchel. Additional monitoring covering the period April 2011 to Dec 2012, associated with the recent seawall outflanking study, are provided in Halcrow (2013a).

Table 10.1 Summary of historical ground behaviour at Filey Town.

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total Change observed between July 2009 and June 2012
Groundwater levels in BH5B (toe of Glen Gardens/Martin's Ravine) and BH6 (midslope Glen Gardens/Martin's Ravine) rose by 49mm and 560mm respectively. BH1 (cliff top Glen Gardens/Martin's Ravine, now inactive) rose 152mm which appeared to reflect prevailing water level in Martin's Ravine. BH04 (midslope Glen Gardens) was noted to be recording erratically. The inclinometer in BH3 was not readable during this time and no new movement was reported at BH6.	Mouchel report that ground water levels have increased since December 2011, the maximum rise having been identified as 560mm at BH4, Mouchel also describe erratic readings from this borehole. Mouchel describe an increase of 49mm at BH5b and attribute this to tidal fluctuations. Ground water readings from BH1 and BH2 appear to have remained relatively constant at about 15m OD. Only 'baseline' inclinometer readings have been determinable from BH3. Mouchel observe that ground water readings from BH1 seem to reflect water levels within the stream flowing in Martin's Ravine. Initially (between September and December 2009), displacements of <5mm were noted in BH6 but no further movements have been identified.

10.4 New data

Tables 10.2 and 10.3 summarise the inclinometer and piezometer data from Filey Town to May 2019.

These data indicate:

- No movement has been recorded in any boreholes at Filey Town
- Inclinometer in borehole CPBH03 was not accessible at the time of data collection.
- Water levels are generally stable or falling in most boreholes.
- Groundwater level remains elevated in CPBH02a. The piezometer lid was not secured, and it is likely that water ingress has resulted in continued elevated water level readings at this location. Groundwater levels are also elevated in CPBH01a.
- Borehole CPBH10b was dry.
- Data logger communication errors occurred at boreholes CPBH01b (vandalism), CPBH02b, CPBH04b, CPBH06b and CPBH08b, and data was not downloaded for this monitoring period.
- The data logger for borehole CPBH09b and CPBH10a should be checked and recalibrated as dip meter readings and diver readings are discordant.

Note boreholes BHA, BHB, BHC, BHD, TP3, TP6, TP8 and TP9, which are inland of the coast and have a focus on flood risk, are no longer included in the coastal instability monitoring programme.

Table 10.2. Summary of inclinometer data at Filey Town.

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
		1	2	3	4	5	6	7	8	9	10	11				
CPBH03	CPBH03 is 10m deep. Surface elevation is c. 6m OD and the base of the borehole is at -4.0m OD*, extending through 4.4m of made ground and 5.6m of glacial sediment.														No access to site. Readings to be taken on next site visit.	No access to site. Readings to be taken on next site visit.
CPBH05	CPBH05 is 10m deep. Surface elevation is c.6.5m OD and the borehole extends to c. -3.5m OD* through glacial sediments.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
CPBH07	CPBH07 is 20m deep. Surface elevation is at c. 5m OD* and the borehole extends to c. -15m OD through glacial sediments.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
BH6	BH6 is 30m deep. Surface elevation is c.27.4m OD* and the base of the hole is c. -2.6m OD. The borehole extends through glacial sediment.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Note: *Surface elevation and borehole depth calculated from digital elevation model.

Table 10.3. Summary of groundwater data at Filey Town

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019		
			1	2	3	4	5	6	7	8	9	10	11				
BH5b	Tip depth at 1.09m OD. Levels constant with limited fluctuation between 1.1m OD (Aug 2008) and 1.7m (Dec 2009).	1.1m OD 7.5m OD 6.4m														Groundwater levels fall to 1.4 m OD.	Groundwater levels have increased slightly to 1.7 m OD.
BH4	Tip at 18.1m OD. Major fluctuations (>7m) in groundwater elevation between Dec 2009 and June 2011. reported as 'erratic' (Mouchel 2012). Levels more settled 2011 albeit showing an increase to 20.2m OD in May 2012.	19.7m OD 27.1m OD 7.4m														Groundwater levels are steady at 20.8 m OD.	Groundwater levels have decreased to 20.5 m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
CPBH01a	Readings sporadic and hole often dry. Mean level is 17.2m	16.9m OD 26.2m OD 8.3m															Groundwater level falls to 17.1 m OD, below historical high.	Groundwater levels increase to 26.0 m, back to an elevated level.
CPBH01b (Diver)	Tip at 32.6m OD. Fluctuating but steadily rising water level from 33m OD in late 2011 to 34m OD in summer 2012. Slight drop in autumn 2012 before sudden rise to maximum of 35.0m OD on 14 Dec 2012.	33.0m OD 36.0m OD 3.0m															No data available. Dip meter to be repaired following vandalism.	No data available. Dip meter to be repaired following vandalism.
CPBH02a	Tip at 1.6m OD. Mean groundwater elevation at c. 5m OD with minor fluctuations. Short lived drop to 3.6m in Sept 2012. Max level 5.3m OD on 19/04/2012.	3.6m OD 5.2m OD 1.6m															Groundwater levels remain at 4.9 m OD, at an elevated position. During data collection the lid was not secure. Replace/repair lid and review trend for next monitoring report.	Groundwater levels remain at 4.9 m OD, at an elevated position.
CPBH02b (Diver)	Tip at 8.2m OD. Generally steady at c. 8.7m OD except for spikes in on 6 July 2012 (to 15.6m OD) and 7 Dec 2012 (to 20.0m OD). Smaller spikes (to c. 9.7m OD in late Nov/early Dec 2012).	5.1m OD 20.0m OD 14.9m															Groundwater levels fall slightly to 8.5 m OD.	Data logger communication error. Repair/collect on next site visit.
CPBH04a	Tip at 2.90m OD. Mean ground water level at 7.2m OD, with range of fluctuation between 7.02m OD (06/09/2012) and 7.33m OD (19/04/2012).	7.1m OD 32.9m OD 25.8m															Groundwater levels remain steady at 7.2 m OD.	Groundwater levels remain steady at 7.2 m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
CPBH04b (Diver)	Tip at 9.9m OD. Steady around 13.5m OD until Dec 2012 although dip in Dec 2012 reads significantly higher (16.3m OD).	13.2m OD 13.7m OD 0.5m															Data logger communication error. Repair/collect on next site visit. Manual dip readings at 13.3 m OD suggest levels have fallen.	Data logger communication error. Repair/collect on next site visit. Manual dip readings at 13.3 m OD suggest levels are steady.
CPBH06a	Tip depth at 0.13m OD. Mean groundwater elevation at 19.9m OD. Range between 18.9m OD (27/02/12) and 20.1 (20/12/12). Rises to highest level in Dec 2012 after very wet year.	18.8m OD 20.0m OD 1.2m															Groundwater levels increased to 19.3 m OD.	Groundwater levels have decreased to 19.2 m OD.
CPBH06b (Diver)	Tip depth at 8.63m OD. Steady at c. 18m OD except for sudden drop to around 14.5m OD and immediate recovery on 20/03/12 and 06/09/12 and sudden drop on 19/04/12 followed by a prolonged steady period at c. 15m OD before sudden recovery on 24/05/12 to 18m OD.	9.2m OD 19.3m OD 10.1m															Data logger communication error. Repair/collect on next site visit. Manual dip readings at 19 m OD suggests levels have fallen.	Data logger communication error. Repair/collect on next site visit. Manual dip readings at 18.9 m OD suggests levels have fallen.
CPBH08a	Mean groundwater elevation is 8.7m OD ranging between 8.5m OD (19/04/2012) and 9.5m OD (20/12/2012), suggesting a greater lag time or less responsiveness to antecedent rainfall conditions.	8.5m OD 11.4m OD 1.9m															Groundwater levels are steady at 10.7 m OD, remaining well within the historical range.	Groundwater levels are steady at 10.7 m OD, remaining well within the historical range.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
CPBH08b (Diver)	Very steady with fluctuations over whole period only between 17.9m OD and 18.0m OD.	17.7m OD 19.3m OD 1.6m															Data logger communication error. Repair/collect on next site visit. Dip meter data indicates borehole is dry.	Data logger communication error. Repair/collect on next site visit. Dip meter data indicates borehole is dry.
CPBH09a	Tip depth at 0.6m OD. Mean groundwater elevation is 20.3m OD with variation of c. 1m.	19.9m OD 21.0m OD 1.1m															Groundwater levels fall to 20.4 m OD.	Groundwater levels fall slightly to 20.3 m OD.
CPBH09b (Diver)	Tip depth at 17.7m OD. .	18.8m OD 21.1m OD 2.3m															Data logger indicates water level is at 3.2 m OD, however manual dip readings are at 20.4 m OD, suggesting a data logger communication error. Repair/collect on next site visit.	Data logger indicates water level is at 3.0 m OD, however manual dip readings are at 20.2 m OD, suggesting a data logger communication error. Repair/collect on next site visit.
CPBH10a (Diver)	Tip depth at 23.8m OD. Shows pattern of sharp increases over a week, followed by gentle decreases over several weeks, to c. 28.5m OD. Comparison to rainfall records indicates borehole has a flashy response to rainfall	24.6m OD 37.7m OD 13.1m															Diver data indicates groundwater levels are steady at an elevated level of 37.6 m OD until April, where by the levels fall rapidly to 20.1 m OD. Dipped readings indicate groundwater levels are higher at 28.8 m OD. Check diver calibration.	Data logger communication error. Repair/collect on next site visit. Dip meter data indicates groundwater levels have increased slightly to 28.9 m OD. Check diver calibration.

Borehole	Long-term Pattern	Groundwater summary Min/Max/ Range	Report Status											Change December 2018 to May 2019	Change June 2019 to November 2019			
			1	2	3	4	5	6	7	8	9	10	11					
CPBH10b	Tip depth at 11.9m. No data prior to October 2013 due to blockage by slip rod.	n/a (dry)															Borehole dry. Recommend installation integrity is checked.	Borehole dry. Recommend installation integrity is checked.

10.5 Causal-response relationships

Most piezometers show a weak response to rainfall, except for shallow piezometers CPBH01a and CPBH10a that respond rapidly, within a month, to peaks in rainfall. Muted antecedent rainfall responses are also noted in CPBH06a and CPBH09a. There is no clear response in groundwater level following the extreme rainfall during autumn 2019 in any of the boreholes. Most of the piezometers show steady or falling groundwater levels, which may reflect the preceding conditions in summer. There has not been movement in inclinometers and therefore no relationships between groundwater and ground movement have been identified.

10.6 Implications and recommendations

No data are available for boreholes CPBH01b, CPBH02b, CPBH04b, CPBH06b and CPBH08b and require readings to be re-taken on the next site visit. Borehole CPBH10b was dry and its integrity should be checked. Data from manual readings in CPBH9b and CPBH10a show different results to the diver data and it is suggested the diver calibration is checked to ensure accuracy. Groundwater levels in CPBH02a remain elevated as a result of water ingress into the borehole through an insecure lid. The lid should be repaired or replaced. Groundwater levels are elevated again in CPBH01a and may reflect the heavy rainfall during the autumn. The trend should be monitored in the next report.

Filey Flat Cliffs

11.1 Site description

Flat Cliffs is a private residential settlement located on coastal slopes in central Filey Bay. The settlement includes private homes and a Yorkshire Water pumping station accessed via a private road down the cliffs that is particularly steep near the top of the cliffs (Halcrow, 2012b). The cliffs are formed in thick and variable glacial sediments that continue to at least 12.4m below OD and which are prone to cliff instability. There is concern that ongoing cliff instability threatens properties and the only access road to about 40 homes at Flat Cliffs (Halcrow, 2012b).

11.2 Ground model and monitoring regime

This site comprises three cliff behaviour units: MU29/AQ, which is an active mudslide complex north of the main settlement and MU29/AR and MU29/AS that form the main landslide undercliff upon which the settlement has been developed.

The undercliff ground model can be described as a complex landslide system that is backed by a steep headscarp and fronted by a sea-cliff (Halcrow, 2012b). The undercliff morphology comprises landslide scarps and benches, some of which are back-tilted although interpreted as failing on translational shear surfaces rather than rotational failure. A large mudslide complex in the north of the site is periodically active and threatens the access road and properties. Activity is generally associated with accelerated toe erosion and elevated groundwater levels.

The monitoring regime at Flat Cliffs includes the following (Figure 11.1):

- North of site – automated piezometer on the cliff top and inclinometer on the access road.
- Central site – Piezometers with data loggers on the cliff top and next to the access road in the lower slope. Two inclinometers either side of the main access road (Flat Cliffs Road and Lower Flat Cliffs) on the coastal slope (one of which is an experimental acoustic inclinometer installed by Loughborough University).
- South of site – Co-located automated piezometer and inclinometer on the Lower Flat Cliffs part of the coastal slope.

11.3 Historical ground behaviour

Filey Flat Cliffs was monitored by Mouchel Ltd for the period between summer 2009 and summer 2012. A summary of their results is provided in Table 11.1, which shows some movement in Borehole A2. No relationship between groundwater level and ground movement was reported by Mouchel. Additional monitoring covering the period April 2011 to Dec 2012, associated with a landslide investigation, are provided in Halcrow (2013b).

Table 11.1. Summary of historical ground behaviour at Flat Cliffs

Observations in Mouchel 2012 (covering 6-month period between Dec 2011 and June 2012)	Total Change observed between July 2009 and June 2012
Mouchel monitored inclinometer A2 during this period and reported no movement. Mouchel report a groundwater level reading from B1 in June 2012 as revealing a reduction of 520mm relative to December 2011. The report mentions that groundwater readings up to May 2012 are reported in Appendix E to that report, but no readings after June 2010 are identifiable from the graph.	Deviation of 15mm near the surface indicated in A2 between December 2010 and June 2011. This had increased by a further 5mm to 20mm by December 2011. No specific comment is made on ground water levels, but it appears from the chart in the appendix that ground water levels remain relatively constant at piezometers A2, A3 and D2, with minor fluctuations in B1 and major fluctuations in D1.

11.4 New data

Tables 11.2 and 11.3 summarise the monitoring results from inclinometers and piezometers at Flat Cliffs up to May 2019.

Table 11.2. Summary of inclinometer data at Flat Cliffs. *Surface elevations and borehole depths calculated from digital elevation model.

Borehole	Summary of past data	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019		
		1	2	3	4	5	6	7	8	9	10	11				
A2	A2 is 27.5m deep (surface elevation at 17.9m OD) and extends through glacial sediment. Moderate movements (<5mm cumulative) recorded between c. 6m - 7m OD														At 12 m BGL, there is displacement of up to 9 mm at the contact between mudstone and till in both the A and B axis. This likely related to a blockage in the inclinometer tracking. This trend should be reviewed in the next monitoring report.	Readings are less than 1mm and therefore not significant.
C1	25m deep. Surface elevation is 25.7m OD* the base of the hole is c. 0.7m OD.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C2	21m deep. Surface elevation is at 16.5m* and the borehole extends to -4.5m OD through glacial sediments.														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C5	16m deep. Surface elevation is 12.0m OD* and the borehole extends to -4.0m OD passing through variable glacial sediments. Very minor displacement in the uppermost 1.5m														Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
C1A	Acoustic inclinometer. The Acoustic Emissions (AE) monitoring has not detected any movement of the landslide to the end of 2012. Higher than average rainfall from April to Dec 2012 had no impact on ground movement. The AE monitoring and inclinometer measurements are consistent														AE measurements between December 2018 and May 2019 do not appear to show significant slope movements.	No data collected.

Table 11.3. Summary of groundwater data at Flat Cliffs

Borehole	Summary of past data	Groundwater summary Min/Max/ Range	Report status											Change December 2018 to May 2019	Change June 2019 to November 2019	
			1	2	3	4	5	6	7	8	9	10	11			
B1	Tip Depth at -7.6m OD. Monitored since July 2001. Fluctuates between c. 11.2 m OD and 15.6m OD.	11.2m OD 15.6m OD 4.4m													Groundwater level falls to 12.6 m OD.	Groundwater levels have increased to historical high of 15.6 m OD. Water appears to have risen well above the cover level of the piezometer.
D1	Tip depth at 15.61m OD. Monitored with data loggers since 2011. Levels show large fluctuations between 15.7 m OD (Sept 2008) and 38.4m OD (Mar 2010). Peaks of 28.2m OD in July 2012 and 24.5m OD in early Jan 2012. Mean base groundwater level is 18 to 18.5m OD.	18.1m OD 29.9m OD 11.8m OD													No data available. Data logger communication error. Repair/collect on next site visit.	No data available. Data logger communication error. Repair/collect on next site visit.
A3	Tip depth at 6.4m OD. Monitored since 2001. Dipped readings show static ground water level at c. 18.8m OD with for peaks up to c. 2m higher. Vibrating wire piezometer installed in Sept 2011 shows static groundwater level of c. 18.0m OD with minor fluctuations.	17.7m OD 18.2m OD 5.0m													No data available. Data logger communication error. Repair/collect on next site visit.	No data available. Data logger communication error. Repair/collect on next site visit.
C4a	Tip depth at -3.7m OD. Monitored since Sept 2011. Levels vary between 7.5m OD and 8.4m OD in response to short- and medium-term tidal cycles (ca. 6 hourly and 4-weekly).	7.5m OD 8.5m OD 1.0m													No data available. Data logger communication error. Repair/collect on next site visit.	Logger not accessible during visit.

The new data indicate:

- No evidence for ground movements is shown by inclinometers.
- Groundwater data show levels have increased significantly in borehole B1, and water appears to have risen well above the cover level of the piezometer. This trend should be monitored in the next report.
- No data collected at piezometer in borehole C4a, A3 and D1, requires readings to be retaken.

11.5 Causal-response relationships

No relationship is identifiable between ground movements and rainfall as no substantial ground movements have occurred. Acoustic emissions data indicates low rate and slow magnitude movement in borehole C1a at the end of November 2017 lasting for 5 days coincident with a period of high rainfall. However, there was no significant movement recorded during the extreme rainfall event on 23 August 2017. Borehole D1 appears to show a response to above average rainfall in January and February 2014 and borehole C4a clearly shows the effect of the 5 December 2013 storm surge on groundwater levels as the highest peak in the record. B1 gradual decrease in groundwater level follows a month antecedent rainfall. There is no clear response in groundwater levels to the extreme rainfall event on 23 August 2017, or heavy rainfall event on 12 March 2018. However, during this monitoring period, groundwater levels have significantly increased again in B1, which is coincident with heavy rainfall during autumn 2019.

11.6 Implications and recommendations

Previous reports have highlighted a possible relationship between groundwater levels in piezometer D1 and movements in inclinometer C1. Groundwater levels in piezometer D1 have previously shown a strong relationship with rainfall and this relationship should be specifically reviewed in future reports when data is available to refine understanding of that relationship. Piezometers in borehole A3, C1a and D1 require attention and should be repaired or cleared for access.

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Appendix A

Digital data