LOCAL COASTAL SLOPE MONITORING ANALYSIS

Interpretation Report 7: June 2016 to November 2016

Prepared for

Scarborough Borough Council

January 2017

Halcrow Group Limited, a CH2M HILL Company
62 Hagley Road Edgbaston
Birmingham, B16 8PE
GB
+44 121 456 2345
+44 121 456 1569

Contents

Appendix

Tables

Figures

Disclaimer

Halcrow Group Limited ('Halcrow') is a CH2M HILL company. Halcrow 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. Halcrow 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, Halcrow 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.

This report and associated data are available to download via the Cell 1 Regional Monitoring Programme's webpage: www.northeastcoastalobservatory.org.uk. The North East Coastal Observatory does not "license" the use of data or sign license agreements. The North East Coastal Observatory generally has no objection to the reproduction and use of these materials subject to the following conditions:

North East Coastal Observatory material may not be used to state or imply the endorsement by North East Coastal Observatory or by any North East Coastal Observatory employee of a commercial product, service, or activity, or used in any manner that might mislead.

North East Coastal Observatory should be acknowledged as the source of the material in any use of images and data accessed through this website, please state "Image/Data courtesy of North East Coastal Observatory". We recommend that the caption for any image and data published includes our website, so that others can locate or obtain copies when needed. We always appreciate notification of beneficial uses of images and data within your applications. This will help us continue to maintain these freely available services. Send email to robin.siddle@scarborough.gov.uk.

It is unlawful to falsely claim copyright or other rights in North East Coastal Observatory material.

North East Coastal Observatory shall in no way be liable for any costs, expenses, claims, or demands arising out of the use of North East Coastal Observatory material by a recipient or a recipient's distributees.

North East Coastal Observatory does not indemnify nor hold harmless users of North East Coastal Observatory material, nor release such users from copyright infringement, nor grant exclusive use rights with respect to North East Coastal Observatory material.

North East Coastal Observatory material is not protected by copyright unless noted (in associated metadata). If copyrighted, permission should be obtained from the copyright owner prior to use. If not copyrighted, North East Coastal Observatory material may be reproduced and distributed without further permission from North East Coastal Observatory.

Summary of findings

This report presents an interpretation of coastal slope monitoring data recorded between June and November 2016 along the Scarborough Borough Council frontage. It is the seventh in a series of 6-monthly updates on the cliff instability risk of the frontage that began in 2014. The weather over the summer and autumn 2016 period covered by this report was generally drier than average, with August being the only wet month, albeit no wetter than average for the region. Boreholes show that water levels have remained at previous low levels or fallen slightly during the monitoring period, except for Scalby Ness (Sn2b), Oasis Café (BH4p), Scarborough Spa (H5, BH1 Prom, BH104b, BH108b), and Filey Town (CPBH02a and CPBH09a) that remain at atypically high levels. In situ monitoring using inclinometers does not indicate any slope movement, indicating that localised elevated groundwater levels have not triggered ground movement. Experimental in situ monitoring using Acoustic Emissions devices installed by Loughborough University at Scarborough Spa and Flat Cliffs also show negligible slope movement.

Specific sites of concern and issues needing attention are as follows:

- At Robin Hood's Bay, BH1a shows groundwater levels have fallen considerably to historical levels that were seen prior to the installations being inadvertently covered with tarmac. It is likely that this borehole had been affected by surface water ingress, but now appears to be functioning correctly. Piezometers BH3a and BH3b need to be checked on the next site visit due to a data logger saving error during this monitoring period.
- At Scalby Ness, piezometers P1a, P1b and P3 experienced a problem downloading data and should be investigated and remedied by the monitoring contractor at the next download. Groundwater level has risen in borehole Sn2b to an historical high. No movement was detected at the nearby inclinometer, but this site should be visually monitored, particularly if rainfall is high during the winter and spring. Piezometers P4a and P4b record changes in groundwater with the same pattern but at slightly different levels, which suggests piezometers are not monitoring discrete horizons and the seal between the two piezometers is damaged.
- At Oasis Café attention should be given to piezometer BH4p where elevated groundwater during drier than average months suggest an ingress of surface water from above the cliff or a local source of groundwater not associated with rainfall recharge, such as leaking services.
- At Scarborough North Bay (The Holms), there was a problem downloading data at borehole BH9a. The issue should be investigated and remedied by the monitoring contractor next time.
- At Scarborough Spa Chalet, no data has been recorded beyond the previous monitoring period. This site requires attention, to fix or replace the piezometer and damaged cable.
- At Scarborough Spa, BH108b and BH104b show that while water-levels are falling, they still remain at an atypically high level. No movement was detected at inclinometers nearby, but these sites should be visually monitored, particularly following sustained wet weather. Several boreholes were dry (BH106a, BH106b and 5 spa), suggesting the piezometer installations are damaged. These locations should continue to be monitored. New telemetry loggers installed at H5 and BH1 Prom show a step-change in groundwater levels, which is now at a more elevated position relative to earlier recordings. These groundwater levels have fallen slightly towards the end of the current monitoring period, but remain close to the historical maximum. These locations should be reviewed in the next report to establish whether the trend in elevated groundwater levels continues. No movements were recorded in adjacent inclinometers BH107 and BH109, but visual inspection of the site is recommended if sustained wet weather occurs.
- At the Clock Café, borehole BH15 remains dry, and the integrity of the piezometer should be checked.

- At South Cliff Gardens, piezometers BH18a and BH18b show rapid and short lived peaks, which suggest surface water ingress. The contractor should ensure that plastic caps are in place and that water cannot collect at the top of the boreholes. At borehole D2a, D2b, BH3a and BH3b there was a problem downloading data. The issue should be investigated and remedied by the monitoring contractor next time. No movement has been indicated by the inclinometers in this location.
- At Holbeck Gardens there was a problem downloading data at borehole BH4a. The issue should be investigated and remedied by the monitoring contractor next time. The new data logger in BH4b recorded atypically high groundwater levels and the calibration and integrity of the piezometer should be checked.
- At Filey Town, in boreholes CPBH02a and CPBH09a water levels have risen slightly, nearing historical highs. This location should be visually checked and reviewed in the next monitoring period, particularly if wet weather occurs. At CPBH01a groundwater levels have returned to lower levels following the previous monitoring period when levels had risen to a new historical high. It is likely the borehole was flooded by surface water flows. There is a consistent offset between manually dipped water-levels and diver data at CPBH09b, suggesting the diver needs checking and re-calibrating. Boreholes CPBH08b and CPBH10b are dry suggesting the piezometer installation may be damaged, however, the location should continue to be monitored. There was a problem downloading data from CPBH01a, CPBH04 and CPBH06b. This issue should be investigated and remedied by the monitoring contractor during the next visit.
- At Filey Flat Cliffs there was a problem downloading data at borehole C4a. The issue should be investigated and remedied by the monitoring contractor next time. The acoustic inclinometer monitored by the University of Loughborough has experienced vandalism, which has affected the results.

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 particular 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 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 SBC and a four-year contract for regular data collection and monitoring reports was awarded. The 7th and final of these reports covered the period up to spring 2012, and was issued in August 2012 (Mouchel 2012).

On completion of this contract, SBC commissioned Haskoning UK Ltd to undertake a thorough review of the condition of boreholes and associated monitoring instruments (Haskoning, 2013). This report highlighted a number of instruments were damaged, due to shearing of the borehole, wear and tear, and vandalism. The work allowed SBC to develop a revised list of instruments and prepare tender documents for re-tendering of data collection and analysis work.

SBC invited tenders 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 (a CH2M company), for data collection and data analysis respectively. JBA undertook the first data collection exercise in November 2013. Data analysis is reported in separate CH2M reports (CH2M 2014a & b, 2015a & b, 2016a). A two year extension to the project was awarded to the incumbent team in March 2016.

This report provides the seventh set of data analysis and is presented as a stand-alone document.

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		6	
Scarborough South Bay	17*	1	38*	
Filey Town	4		24	
Filey, Flat Cliffs	4	1	4	1
TOTAL	40	2	93	1

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

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.

Table 1.2. Programme of data collection and reporting

JBA Monitoring Period	CH2M (Halcrow) 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: October 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 2016b)
Data set 7: June 2016 to November 2016	Report 7: January 2017 (this report)
Data set 8: December 2016 to May 2017	Report 8: August 2017
Data set 9: June 2017 to November 2017	Report 9: February 2018
Data set 10: December 2017 to May 2018	Report 10: August 2018

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 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.
- Inclinometer 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.
- Inclinometer 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 particular 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.

The scope of CH2M's 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.
- 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 for several months in 2015 and therefore supplemental data has been purchased from the MetOffice for Filey, around 3km to the north-northwest. Since 11 January 2016 meteorological data from Scarborough Spa has been used because the reliability of the Flat Cliffs weather station remains poor.
- 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 with regard to 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 with regard to 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 or not 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

A meteorological station that records wind speed and direction, air temperature, humidity, air pressure, rainfall and rainfall intensity every 15 minutes has been in place at Flat Cliffs, central Filey Bay, since 29 September 2011. 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 therefore data from that site has been used from 11 January 2016 onwards.

Data from all three weather stations are summarised in Table 2.1 and Figure 2.1. The records for the last six months show that August 2016 was close to the long-term mean (upper range) when compared to past records, whereas other months were relatively dry.

Table 2.1. Monthly rainfall recorded at Flat Cliffs met station

		Rainfall (mm)					
Month	**Long-term mean (upper range)**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**
January	80	No Data	31	41	113 (84.2)	No Data (13.4)	84* [part month]
February	60	No Data	8	38	96 (71.2)	No Data (44.8)	20.7*
March	60	No Data	27	32	29 (40.4)	No Data (22.2)	53.9* [part month]
April	60	No Data	96	4	26 (33)	No Data (15.8)	43.4*
May	60	No Data	34	37 [part month]	59 (50.8)	No Data (81.4)	15*
June	80	No Data	104	No Data	34 (61)	No Data (41.2)	23*
July	60	No Data	70	No Data	70 (93.2)	20	14.9*
August	80	No Data	45	38 [part month]	No data (108.2)	17	69.7*
September	80	0.14 (Part month)	69	15	No data (17)	46	13.8*
October	80	35	53	52	No Data (58)	29	15.4*
November	80	15	78	25	No Data (70)	63 [part month]	50.9*
December	80	72	132	6	No Data (27.2)	76.9	

Note: Data in brackets are from Filey No 2 station. Data marked * are from Scarborough Spa

Daily rainfall totals recorded by the Scarborough Spa weather station are presented in Figure 2.2, which shows peaks on 4 and 25 August. 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 December 2012 with 132mm, and that the wettest month during 2016 was January, with 84mm.

Seasonal totals are shown in Figure 2.3, which shows that the wettest seasons tend to be winter and summer and that the spring is the driest. The wettest season on record was winter of 2013/14 (i.e. December 2013, January and February 2014) that received a total of 244mm rainfall. The summers of 2012 and 2014 were also very wet, receiving 219mm and 211mm respectively. The winter of 2015/16 received around double the rainfall of 2014/5, but the spring was marginally drier.

Wind speed and air temperature records from Flat Cliffs are presented in Figures 2.4 and 2.5. The data shows November 2016 as the windiest month in the monitoring period and relatively gentle conditions persisted during late summer-early autumn 2016. Recorded temperatures during 2016 are average, except for the relatively warmer summer of 2016.

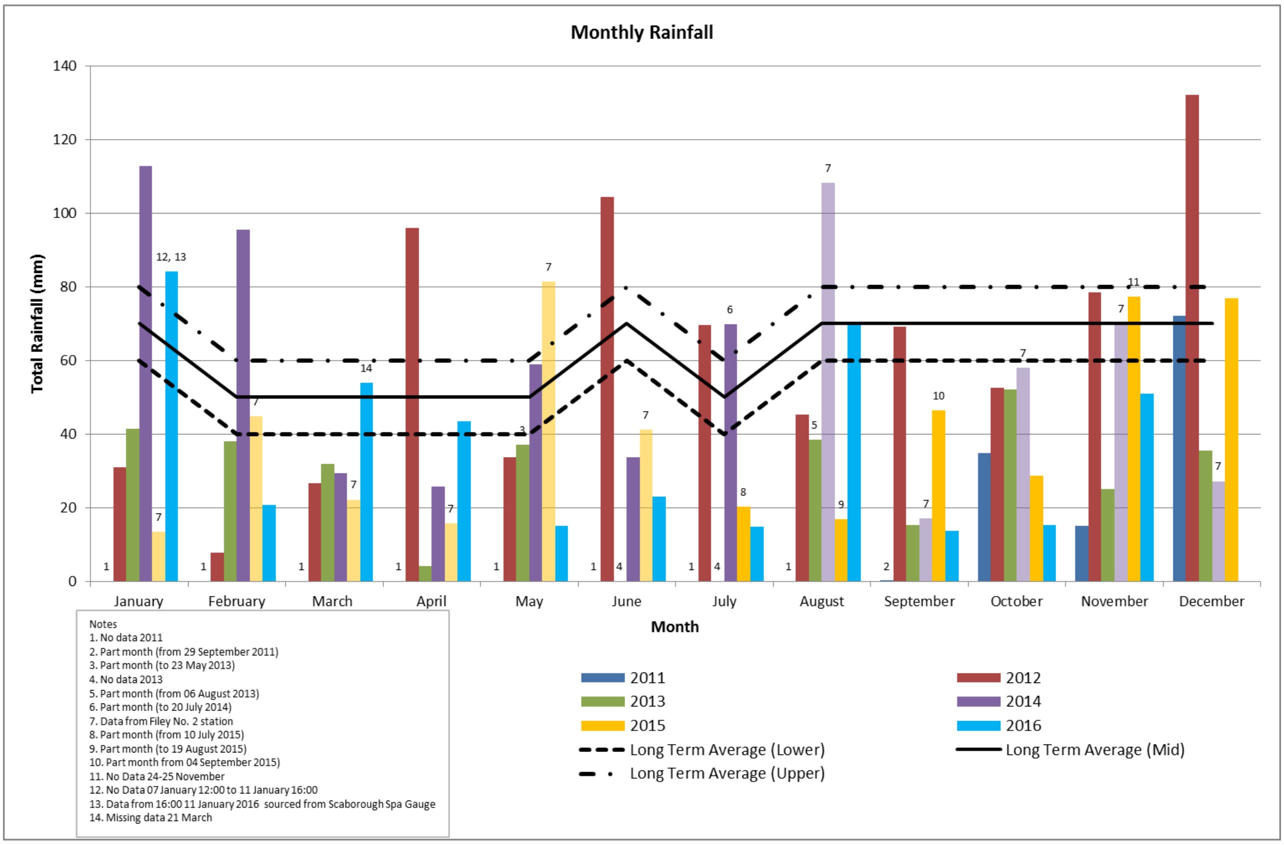


Figure 2.1 Comparison of monthly rainfall records (2011 to 2016).

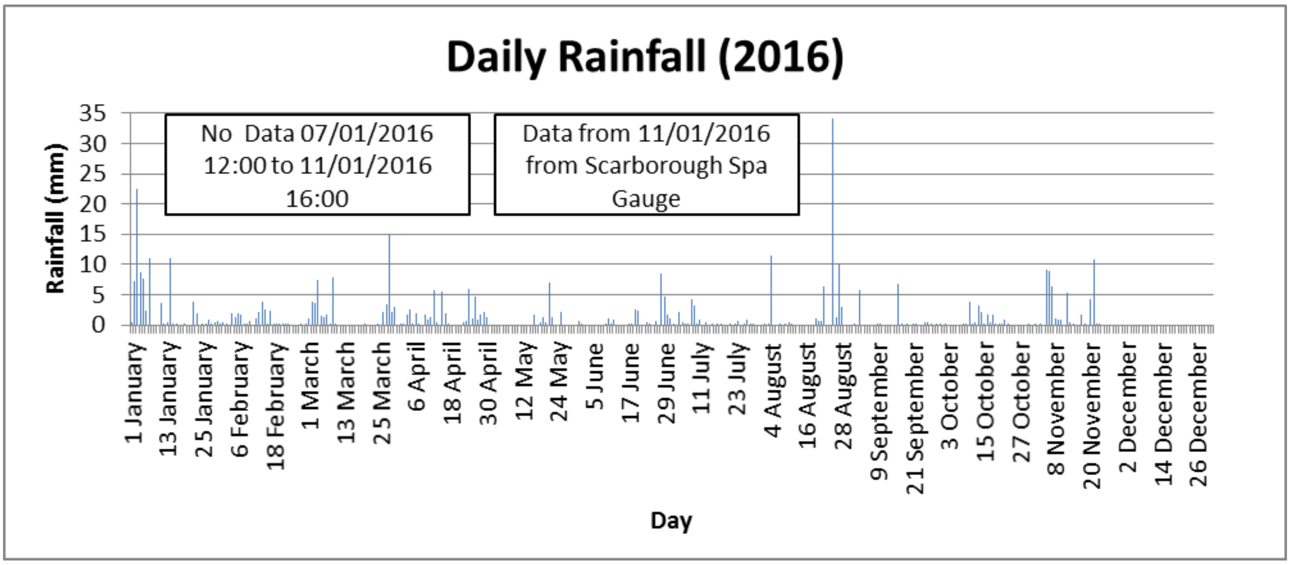


Figure 2.2 Daily rainfall recorded at Flat Cliffs during 2016

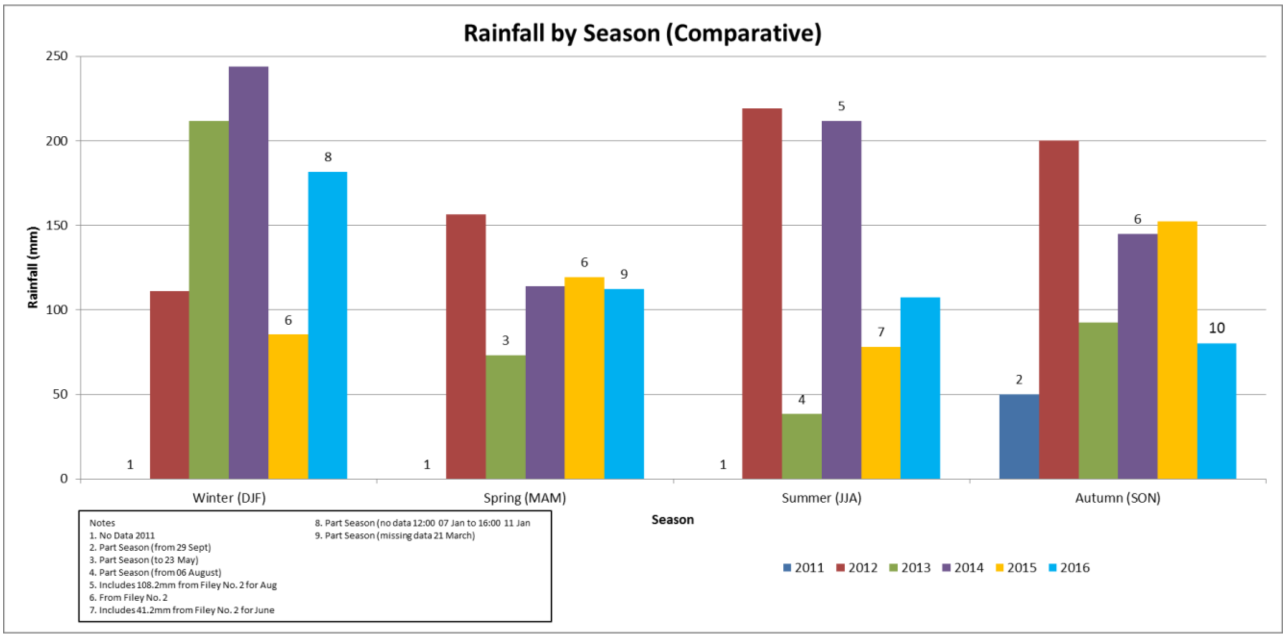


Figure 2.3 Seasonal rainfall comparison (2011-2016)

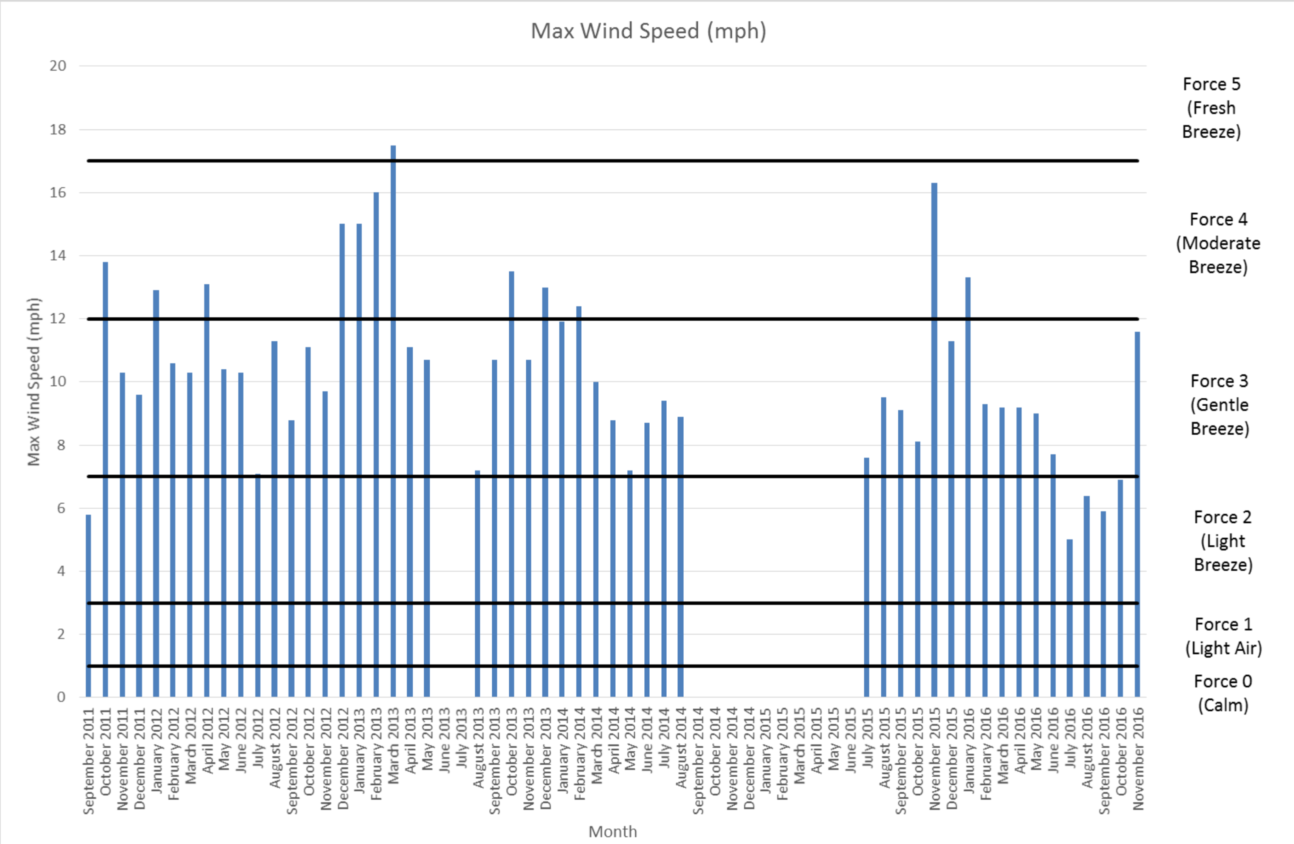


Figure 2.4 Maximum daily wind speed (2011 to 2016)

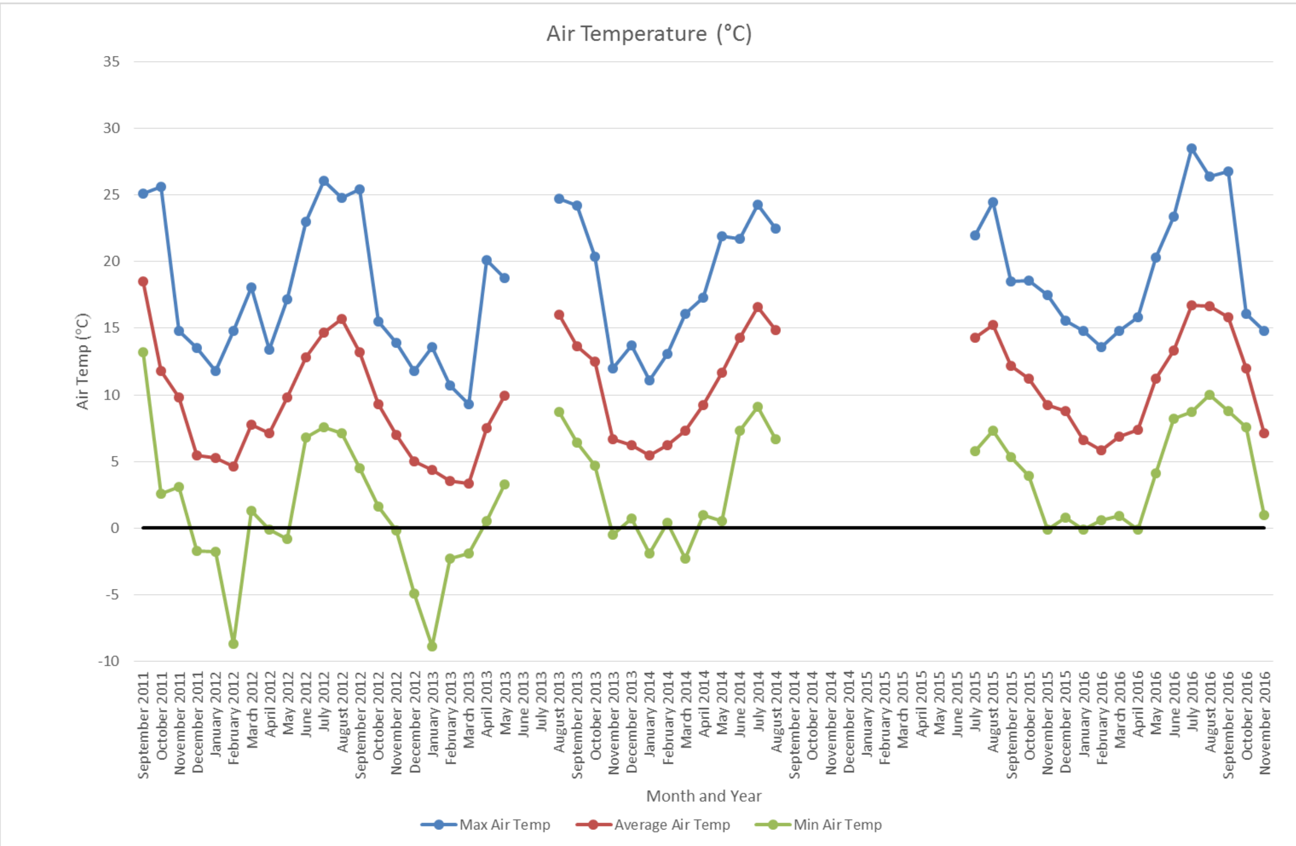


Figure 2.5 Air temperature variation (2011 to 2016)

2.1.1 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. The only '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. The absence of movements elsewhere on the coast at this time suggests that the antecedent rainfall threshold levels are above this at other locations.

Antecedent rainfall over the current June-November monitoring period show peaks that are lower than December 2012 and with a similar pattern to the previous June to November period.

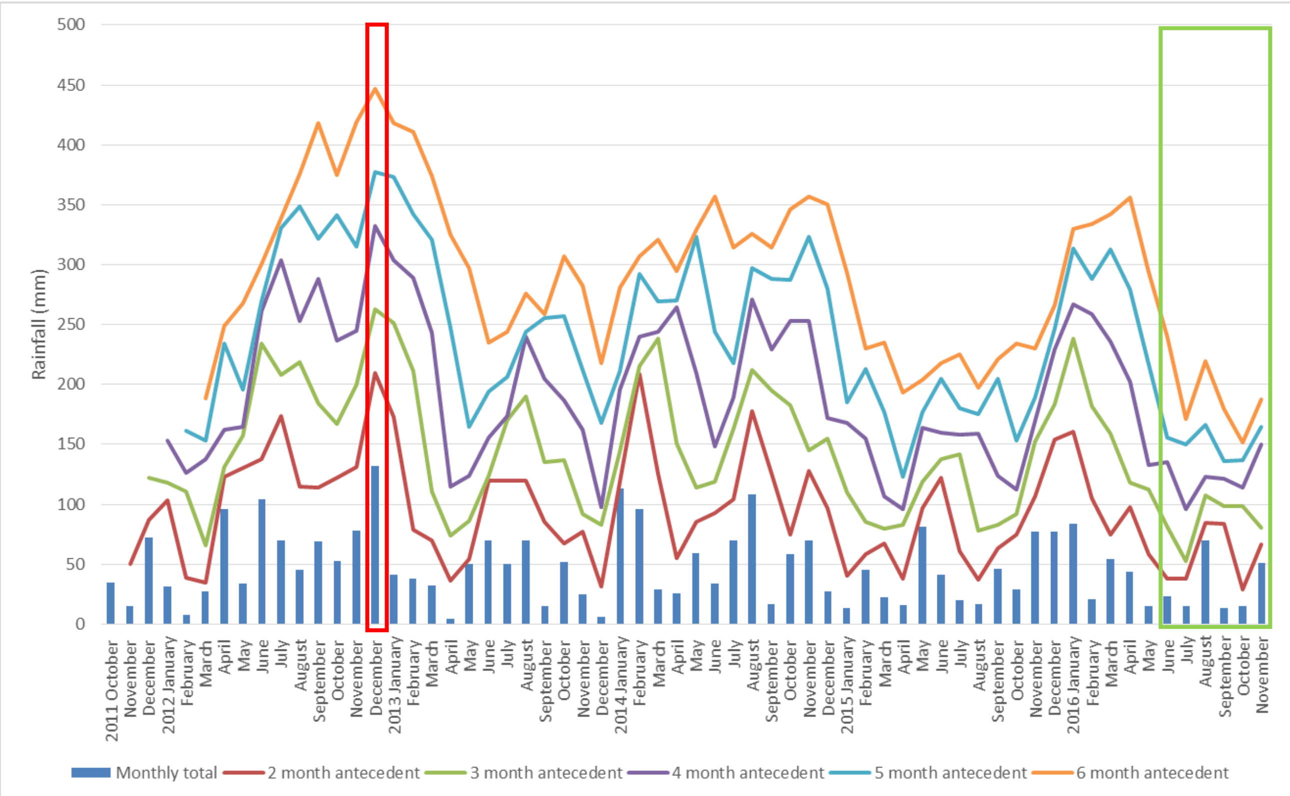


Figure 2.6. Monthly rainfall and two to six month antecedent totals (2011 to 2016). Ground movements were recorded at Scalby Mills during December 2012 (red box). Current monitoring period shown by green box.

2.2 Summary

The weather data collected to date highlights the following:

- 2012 was exceptionally wet, particularly in the months of April, June, July, November and December.
- 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 with the exception of August where significant rainfall occurred on 4 and 25 August. Conditions over the 6 month period have been relatively dry and mild.

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 Kettleness 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 Design and Build contractor for the scheme has been appointed and site works are due to begin in September 2017, with completion by May 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 a 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

There are no implications or recommendations arising for this site. Monitoring of the inclinometers should be continued to check the integrity and stability of the piles.

Table 3.2. Summary of inclinometer data at Runswick Bay

Borehole	Summary of past data	Report status						Change June - Nov 2016
		1	2	3	4	5	6	
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.	Incremental movements less than 1mm during the monitoring period, which is insignificant.
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 have 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 also 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 been identified.

The single monitoring location means the data from BH2 may not be representative of all of 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 June to Nov 2016
		1	2	3	4	5	6	
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. 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 2016 is summarised in Tables 5.2 and 5.3.

Inclinometer data shows no significant movements recorded at any of the boreholes.

The piezometer data show groundwater levels have remained relatively steady over the monitoring period in BH1b. BH1a, which is a shallower piezometer, shows groundwater levels have returned to previous levels observed following removal of tarmac that had been mistakenly laid over the boreholes. Given the close proximity of these boreholes, it is likely that the shallower borehole has been affected by surface water ingress from cliff top developments. Readings for piezometers BH3a and BH3b require re-taking.

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

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
BH2	The borehole is 41m deep but inclinometer records are only provided for the upper 22m. Ground level is c. 55.1m OD. The recorded pattern of movement is hard to explain and is likely to represent accumulated error.						Incremental movements are less than 1mm since the last reading.	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. Cumulative movement plots suggest error in the data.						Incremental movements are less than 1mm since the last reading. At 30m depth 2mm minor displacement.	Incremental movements are less than 1mm since the last reading. From 30m depth 2mm minor displacement.

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 June to Nov 2016
			1	2	3	4	5	6	
BH1a	Ground level is 51.63m 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						Increase in groundwater level by 9.14m since last reading in November 2014 to historical high at 39.65m OD. It is unclear if the tarmac covering affected this result.	Decrease in groundwater level to 29.37m OD, returning to previous levels observed before the tarmac covering which likely affected previous readings.
BH1b	Ground level is 51.63m 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						Readings remain steady at 37.8m OD.	Readings increase by 1m to 38.8m OD, well within historical range.

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
BH3a	Ground level is 60.35m OD, the piezometer tip is targeting a shallower horizon. Water level has remained between 44.3m and 44.8m OD between installation in March 2010 and May 2012.	44.5m OD 56.1m OD 11.6m						Site readings lost due to saving error. Readings should be re-taken on next visit.	Site readings lost due to data logger saving error. Readings should be re-taken on next visit.
BH3b	Ground level is 60.35m OD, the piezometer tip is targeting a deeper horizon. Water levels have fluctuated by no more 2m about a mean of c. 56m OD. Low groundwater levels occurred in May 2010 and highs occurred in July 2010 and Nov 2011.	55.3m OD 56.7m OD 1.4m						Site readings lost due to saving error. Readings should be re-taken on next visit.	Site readings lost due to data logger saving error. Readings should be re-taken on next visit.

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 remain high to the autumn of 2015, however later records are unavailable. 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.

5.6 Implications and recommendations

The groundwater data indicates a continuation of past patterns at Robin Hood's Bay. BH1a shows groundwater level has significantly fallen to previous levels observed before the tarmac covering. This location should be checked and the next monitoring data reviewed, whether this trend continues. Boreholes BH3a and BH3b require readings to be re-taken on the next site visit.

Previous work by Mouchel has noted that piezometer tubes have progressively become shallower, suggesting ingress of sediment. It is therefore recommended that the piezometer tubes be flushed out. 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.	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. 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.

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 *Surface elevations and borehole depths calculated from digital elevation model

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
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.						Incremental movements are less than 1 mm during the monitoring period, which is insignificant.	Incremental movements are 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 are less than 1 mm during the monitoring period, which is insignificant.	Incremental movements are less than 1 mm during the monitoring period, which is insignificant.
L3(C004)	Borehole is ca. 17m deep, surface is 13.4m OD and						No significant movement since last reading, except for minor displacement, likely relatively	No significant movement since last reading, except for minor displacement, likely

	borehole extends to c. -3.6m OD through 8.5m of glacial sediment and 8.5m 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.						shallow surface creep that extends to ca. 2m BGL in clay.	relatively shallow surface creep that extends to ca. 2m BGL in clay.
BH7	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.						Incremental movements are insignificant at less than 1mm. There has been no additional movement along the shear surface at c. 11 to 12m depth.	Incremental movements are insignificant at less than 1mm. There has been no additional movement along the shear surface at c. 11 to 12m depth. The minor displacement extending to c. 2m depth is relatively shallow surface creep.

Table 6.3. Summary of groundwater data at Scalby Ness. *Indicates approx. tip and surface elevations calculated from elevation from digital elevation model and known tip depth, rather than topographic survey

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
P1a	Automated piezometer. Tip at appox.25.65m OD*. Surface elevation at c. 35.6m OD* (cliff top above CBU 1, co-located with P1b). Fluctuates	27.1m OD 28.9m OD 1.8m						Data not downloaded correctly. Collect on next visit.	Data not downloaded since October 2015. Collect on next site visit.

	between 27.5 and 28.5m OD, with rapidly rising and falling peaks linked to higher rainfall and subsequent dry periods.								
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 19.2m OD 1.8m						Data not downloaded correctly, to collect on next visit.	Data not downloaded since October 2015, to collect on next site visit.
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.	27.2m OD 28.7m OD 2.6m						Groundwater levels rapidly increased in December 2015 to 28.3m OD, close to the historical high. It has since remained high at 27.8 m OD.	Groundwater levels falling gradually to 27.5m OD.
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 1.7m						Readings remained steady at 2.4m OD, with the exception of a short-lived spike in February reaching a historical high of 3.5m OD.	Readings remain steady at 2.4m OD.
P3	Automated piezometer. Tip at c. 10.5m OD*. Surface elevation at c. 30.7m OD. Steady at around 14.6-14.7m	14.2m OD 17.5m OD 3.3m						Continuation of past pattern, with levels constant at c. 17.2m OD.	Data not downloaded since May 2016. Collect on next site visit.

	OD until Oct 2009. Apparent recalibration between Oct 2009 and Mar 2010 after which groundwater levels are again steady at ca.17.2-17.3m OD								
P4a	Automated piezometer. Tip at c. 8.3m OD*. Surface elevation at 18.6m OD (co-located with P4b). Fluctuating pattern occurs 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.	12.7m OD 15.1m OD 1.4m						Rapid increase in groundwater levels in late December 2015 and January 2016 to 14.6m OD. Levels remain elevated.	Groundwater levels steadily fall to 13.4m OD in saw-tooth pattern following previous readings.
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						Same pattern as P4a, but offset by c. -0.3m since early 2010.	Same pattern as P4a, but offset by c. -0.3m since early 2010. Piezometer may need recalibration.
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						Increase in groundwater level by 3.1m since last reading to historical high at 15.4m OD. Ponding of water noted on slope during data collection.	Decrease in groundwater level by 1.6m to 13.8m 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	6.5m OD 9.7m OD 3.2m						Borehole no longer functioning.	Borehole no longer functioning.

	OD between September 2010 and June 2011 (low in summer/early autumn, high in winter).								
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 steady at 13.3m OD.	Groundwater levels remain steady at 13.3m 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, with the exception of major low in August 2008 when installation may have been almost dry (groundwater level ca. 10m OD).	10m OD 13.8m OD 3.8m						Groundwater levels increase slightly from historical low to 10.6m OD.	Groundwater levels fall to 10.4m OD.
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 increase by 1.4m to 15.5m OD following a general falling trend in groundwater level.	Groundwater levels fall by 1m OD to 14.5m OD.
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	12.5m OD 13.3m OD 0.8m						Groundwater levels increase by 0.8m to 13.3m OD, reaching a new historical high.	Ground water levels fall to 12.8m OD.

	incorrect;groundwater elevations not possible for tip depth stated.								
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 11.9m OD 1.6m						Groundwater levels increased by 1.6m from historical low to a historical high of 11.9m OD.	Groundwater levels continue to increase to new historical high of 12.8m OD.

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- Groundwater levels have fallen in almost all boreholes with the exception of borehole Sn2b.
- Groundwater levels have risen in Snb2 to a historical high, however no significant movements over the monitoring period were indicated at adjacent inclinometers.
- Water levels recorded in boreholes P4a and P4b follow the same pattern but at slightly differing levels, and it is recommended the piezometer calibration be checked.
- Piezometers in boreholes P1a, P1b and P3 require checking and downloading of data on next visit.

6.5 Causal-response relationships

Since the summer of 2012, much of the rainfall in the study area has been atypical. Following a dry start to 2012, the spring and summer were exceptionally wet and the latter half of 2012 was also wet. Overall, 2013, 2014 and 2015 were drier than average. The majority of shallow piezometers at Scalby Ness closely reflect that pattern of rainfall. Those installed with data loggers show peaks in April/May 2012, July 2012 and December 2012, and falling groundwater levels until December 2013, after which groundwater levels rise and peak in mid-late February 2014, before falling and stabilising at lower levels by late 2014. Groundwater levels are typically lower than average during the first and second half of 2015, except for May where levels peak following higher than average rainfall. The above average rainfall in December 2015 and January 2016 is reflected in rising groundwater levels at many of the piezometers, however these levels have been maintained during drier months that follow and have fallen since May 2016.

Deeper piezometers have a longer lag between rainfall and groundwater response. Those with data loggers show a much more muted response and those without data loggers tend to show peaks in May 2012, or in earlier winter periods. The exception to this rule is WS5 which appears to show a rising groundwater level towards 2013 but was dry in July and November 2014.

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 (nearby piezometers P4a and P4b show elevated groundwater peaking in mid-February 2014 at 13.5 and 13.8m respectively). Neither inclinometer recorded movement between June and November 2014, associated with low groundwater levels. The precise relationship between groundwater level and ground movement is unclear. While movement in the winters of 2010/11 and 2013/14 can be associated with elevated groundwater, similarly high groundwater levels in the winter of 2012/13 and 2015/2016 are not associated with ground movement, possibly due to slow borehole equilibration with the surrounding ground.

6.6 Implications and recommendations

The groundwater data indicates levels have fallen overall in the area. Rising water levels in Sn2b experienced from early to mid-2016 suggest discharge from cliff top developments or a natural response to the localised movement at the slope toe. While localised reactivation at the slope toe is apparent in past reports, no movements were indicated at adjacent inclinometer BH7 or other inclinometers at the location. The location will be reviewed in the next report. In addition, piezometers P1a, P1b and P3 require readings to be re-taken on the next site visit.

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 shows a continuation of past patterns at a lowered position.
- The summer and autumn have been drier than average and water levels have decreased, with the exception of high rainfall recorded in August which resulted in a short lagged response in BH3p.
- Elevated and fluctuating water levels in BH4p over drier months may suggest an influence from cliff top developments.

Table 7.2. Summary of inclinometer data at Oasis Café

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
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 winter 2013 to summer 2014 monitoring period was characterised by higher rainfall compared to the previous 6 months. The latter half of 2014 and 2015 were slightly drier than average and water levels tend to show very slight falls with superimposed monthly fluctuations. 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. The patterns seen in the past are still visible, with BH2p having an unclear response to rainfall and/or tides. Shallow piezometer BH3p continues to show 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), while 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.

7.6 Implications and recommendations

All the piezometers appear to read correctly and provide reliable data. The inclinometers also appear to be functioning correctly. No movements have been recorded at Oasis Café, and there are no specific recommendations at this location beyond on-going collection and analysis of data.

Future reports should pay particular attention to the midslope piezometer (BH3p) which shows rapid response to rainfall conditions, but no associated ground movements to date. In addition, attention should be given to piezometer BH4p where rising groundwater over drier than average months may suggest an ingress of water from cliff top developments.

Table 7.3. Summary of groundwater data at Oasis Café

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
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 8.6m OD 0.7m						Continuation of past pattern. In March groundwater level rapidly rises and falls near to historical low at 8m OD, and gradually rises to higher levels at 8.5m OD. Average groundwater level c. 8.3m OD.	Continuation of past pattern. In October groundwater levels rapidly rise to historical high of 8.6m OD and fall to an average of c. 8.4m OD.
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 level follows a two-week cyclical pattern, with rapid rises and gradual falls. Levels are elevated initially during this period at an average of c. 15.5m OD, however this falls significantly in May to 14m OD.	Groundwater levels at an average of 14.5m OD. On 27th August levels rapidly increased to 15.7m OD, coinciding with heavy rainfall on the 25th. Groundwater levels rapidly returned to steady levels c. 14.2m OD.
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 of past cyclical pattern with sub-weekly variation, averaging 18.9m OD. Groundwater peaks in March near historical high at 19.2m OD but rapidly falls on 28 March when rainfall peaks. Groundwater level remains at an elevated position.	Continuation of past cyclical pattern with sub-weekly variation, averaging 18.7m OD. Range of change small between 18.7 and 19m OD. Peaks in early October 2016. Groundwater level has decreased somewhat, but still remains at an elevated position.

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 glacial sediments overlie 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 landside 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 2016.

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- Groundwater data shows a continuation of past patterns.
- Water levels remained steady or decreased slightly, with generally dry conditions over the monitoring period with the exception of August 2016.
- Data collection resumed in BH9a until May 2016. This site requires attention, to fix or replace the piezometer.

Table 8.2. Summary of inclinometer data at The Holms

Borehole	Summary of past data	Report Status						Change June to Nov 2016
		1	2	3	4	5	6	
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.						Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.
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 13m depth.	No change detected in sinusoidal pattern of deformation between 9 and 13m depth.

8.5 Causal-response relationships

Rainfall has been lower than average since mid-2015, with the exception of above average rainfall in winter 2015/2016. The piezometers at The Holms show a lagged response to these conditions with only BH8a showing a rapid response to May 2015 and March 2016 rainfall. 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.

8.6 Implications and recommendations

No data was recorded since May 2016 in BH9a. This site requires attention, to fix or replace the piezometer.

Table 8.3. Summary of groundwater data at The Holms

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
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. 0.6m in March 2016. The monitoring period represents a decrease in average groundwater levels from 1m OD to 0.6m OD. Readings are comparably very low to past records, reaching a historical low of 0.5m OD in March.	Continuation of past cyclical patterns, with 2 to 3 week variations of up to c. 0.3m in August 2016. The monitoring period represents an increase in average groundwater levels from 0.6m OD to 0.9m OD, which is very low compared to past records.
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.	3.7m OD 4.7m OD 1.0m						Continuation of 2 to 3 week cyclical pattern. Average groundwater level has increased slightly at 4.4m OD, with a rapid increase to historical high and fall in March by 0.7m.	Continuation of 2 to 3 week cyclical pattern. Average groundwater level has fallen slightly at 4.2m OD. Groundwater level rapidly peaks and falls in early October 2016 to highs of 4.4m OD. Antecedent rainfall was low and therefore it is unclear what triggered this groundwater response, which may relate to ingress of water from cliff top developments.
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 as a result of exceptional rainfall.	9.7m OD 10.7m OD 1.0m						Groundwater levels gradually rise over the period, averaging 10.3m OD, comparably still low to past records. A rapid rise and fall in groundwater by 0.6m occurs in March 2016, in a similar pattern to other boreholes located in the vicinity.	Groundwater levels remain steady during the monitoring period, averaging 10.3m OD. A rapid rise and fall of 0.4m OD occurs in early October 2016, similar to other boreholes in the vicinity. Antecedent rainfall was low and therefore it is unclear what triggered this groundwater response, which may relate to ingress of water from cliff top developments.
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	9.4m OD 14.5m OD 5.1m						Groundwater levels have increased gradually over the period to 12.1m OD, well below the historical high.	Groundwater levels continue to rise until August where they rapidly drop from 12.6m OD to 10m OD and continue to remain steady.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
	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.								
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.	13.6m OD 26.2m OD 10.9m						No data recorded since November 2014. This site requires attention, to fix or replace the piezometer and damaged cable.	No data recorded for monitoring period. Last data record for May 2016 at 19m OD. This site requires attention to fix or replace the piezometer and damaged cable.
BH9b	Tip depth at 0.49m OD, surface at 33.49m OD co-located with BH9a. Shows sharp increase in ground water levels from c. 10m OD after installation in Sept 2010 to c. 25m OD in Feb 2011. Continues to gradually rise to c. 26m OD in June 2011 before gradually falling to 23.2m OD by May 2012. This pattern is similar to that recorded in BH9a, but contrary to that in BH8a and BH8b.	9.7m OD 30m OD 18.5m						No data. Communication error.	Data retrieved for previous and current monitoring period shows gradual fall from peak historical high groundwater levels in January 2016 of 40m OD to October at 14.2m OD.

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 at 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 a three locations.

These areas include both pre-existing landslides and also intact cliffs and headscarps where instability is considered to be 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 June to Nov 2016
		1	2	3	4	5	6	
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.	n/a					B-Axis incremental readings show error at base of borehole leading to systematic offset of c. 2mm. No genuine movements are apparent.	Readings show less than 1mm movement and 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 June to Nov 2016
			1	2	3	4	5	6	
FR02	FR02 has been monitored since 21 May 2014. Tip is at 18.0m depth (c.-6.5m OD). Pattern shows variation consistent with short and medium term tidal cycles.	7.4m OD 8.4m OD 9m	n/a					Continuation of past cyclical pattern. Groundwater levels fell in December 2015 and have remained steady, reaching a historical low of 7.4m OD by May 2016.	Continuation of past cyclical pattern, with groundwater levels averaging at 7.6m OD.

No ground movement is recorded at this site and water levels are stable.

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 June to Nov 2016
		1	2	3	4	5	6	
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. Cumulative readings show a pattern of subtle movement that is interpreted as error.						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 June to Nov 2016
			1	2	3	4	5		
BH12	Tip at -8.4 OD. Cyclical pattern with c. two-week frequency between peaks. Maximum levels are between 1.25 and 1.5m above OD and minimum levels are between 0.3 and 0.5m above OD. Given the tip is below mean sea-level it is possible the cyclical pattern is related to tides.	0.0m OD 2.3m OD 2.3m						Range of fluctuations within past limits and linked to tidal cycles. Fluctuations range from 0.2 to 1.5m OD, averaging c. 0.9m OD.	No data recorded for monitoring period. Last data recorded in May 2016. This site requires attention, to fix or replace the piezometer and damaged cable.
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 AOD and minimum levels are c. 3.3m AOD.	3.2m OD 3.9m OD 0.7m						Range of fluctuations within past limits and linked to tidal cycles. Fluctuations range from 3.3 to 3.9m OD, averaging c. 3.6m OD. There is a rapid rise and fall in groundwater level over March 2016.	Range of fluctuations within past limits and linked to tidal cycles. Fluctuations range from 3.4 to 3.9m OD, averaging c. 3.6m OD. Groundwater rapidly peaks and falls in early October to 3.9m OD.

No ground movement has been recorded and fluctuations in groundwater levels are within the ranges previously observed. The piezometer in borehole BH12 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 June to Nov 2016
		1	2	3	4	5	6	
AA04 (G2)	40.5m deep borehole penetrating 34.5m of glacial sediments and 6m of sandstone/siltstone bedrock. Ground level is 47.62m OD, base of hole is 7.12m OD.						Readings are less than 1mm and therefore not significant.	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 movements recorded since the last readings.	No significant movements recorded since the last readings.
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.						No significant movements recorded since the last readings.	No significant movements recorded since the last readings.
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.						No significant movement.	No significant movement.
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.	No significant movement.
BH107	18m deep borehole that passes through 13m of glacial sediments and 5m of sandstone/mudstone bedrock. Ground level is 20.39m OD, base of hole at 2.39m 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 movements since last reading, except between ground level and 10.5m depth (BGL) with minor displacement <2mm.	Movements of less than 1mm in the borehole are not significant.
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.						Movements of less than 1mm in the borehole are not significant.	Movements of less than 1mm in the borehole are not significant.

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.						No significant movements since last reading.	No significant movements since last reading.
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 measurements between February 2016 and August 2016 do not show significant slope movements. Periods of elevated AE activity are likely to be a response to rainfall events generating seepage in the gravel beds.	AE measurements between February 2016 and December 2016 do not show significant slope movements. As seen previously, periods of elevated AE activity are thought to be a response to rainfall events generating seepage in the gravel beds.

Table 9.7. Summary of groundwater data at the Spa

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
H2a	Located near the headscarp of the Spa landslide. Tip at 17.3m AOD. 3 to 5 day frequency fluctuation around mean of c. 17.25m OD with amplitude of c. 0.5m. No clear long term trend or temporal pattern. Max water level 17.6m OD on 4 June 2013, min of 16.9m OD on 15 March 2013.	16.7m OD 17.6m OD 0.9m						No change in past pattern. Levels range from 16.8 to 17.5m OD, and average c. 17.2m OD. Rapid rise and fall in groundwater level by 0.5m in March 2016.	No change in past pattern. Levels range from 17 to 17.5m OD. Groundwater levels peak in June and October 2016, suggesting a complex relationship to rainfall.
H2b	Located near the headscarp of the Spa landslide. Tip at 11.1m AOD. 3 to 7 day frequency fluctuation around mean of c. 12.7m OD with amplitude of c. 0.3m. No clear long term trend or temporal pattern. Maximum water level 12.9m OD	12.0m OD 13.0m OD 1.0m						No change in pattern, groundwater levels steadily fluctuate around an average of 12.7m OD. Levels range from 12.4m OD to 12.9m OD. A rapid rise and fall in groundwater level in March 2016 is apparent.	No change in pattern, groundwater levels steadily fluctuate around an average of 12.6m OD. During June 2016, groundwater levels do not fluctuate. Levels range between 12.5m OD to 12.7m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
	on 3 June 2013 and 7 July 2013, minimum of 12.3m OD on 14 December 2012.								
H5	Located near the base of the cliff behind the Spa building. Tip at 15.5m OD. Marked drop in water level from 22m OD in late 2012 to 17.5m OD in late 2013. Slight but short-lived recoveries on 5 Nov 2012 and 15 Aug 2013 when water-levels rose by almost 1m in a day.	17.0m OD 23.01m OD 6.01m						New telemetry logger installed 24/03/15. Conversion of piezometer readings to m AOD undertaken by logger software. Groundwater levels increase from 20m OD to 22.3m OD in March, and gradually fall to 20.5m OD by 19 June	Water levels rise to 22.2m OD between 19 and 29 June, then fluctuate between 21.5 and 22.4m OD for remainder of period. While water levels have remained high during this period, they have not reached historical highs of 23.1mOD. Note the new telemetry logger records water levels are 15 minute intervals, whereas the former system records hourly. Despite this higher resolution, the data recorded by the telemetry system show a smoother pattern, which suggests variations in earlier data are 'noise'.
1 spa	Located near the base of the cliff. Tip at 6.3m OD. Water levels fluctuate between c. 7m OD and c. 12m OD. High levels over 11m AOD occurred in May 2008, Dec 2009 to Apr 2009 with historical low of c.7m OD between Aug 2008 and Aug 2009.	6.7m OD 11.9m OD 5.2m						Groundwater levels rise to 9.2m OD by May 2016, well within the range of historical records.	Groundwater levels fall to 7.8m OD in October 2016.
2 spa	Located near the base of the cliff. Tip at 6.4m OD. Water levels fluctuated between c. 10m OD and c. 12m OD between Jan 2003 and Aug 2009. Thereafter, variation increases with low levels recorded down to c. 8m OD. Low levels recorded	7.2m OD 12.1m OD 4.9m						Groundwater levels rise slightly to 10.3m OD, well within range of historical records.	Groundwater levels fall slightly to 10m OD in October 2016.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
	during the winters of 2010 and 2011.								
3 spa	Located near the base of the cliff. Tip at 7.2m OD. As in '2 spa' water levels fluctuated between c. 12m OD and c. 13m OD between Jan until Aug 2009 and thereafter, variation increases with low levels recorded down to c. 7m OD.	7.1m OD 13.0m OD 5.9m						Groundwater levels rise slightly to 12.3m OD, well within range of historical records.	Groundwater levels fall slightly to 11.9m OD in October 2016.
4 spa	Located near the base of the cliff. Tip at 10.9m OD. Very similar pattern to '3 spa'. Water levels fluctuated between c. 10m OD and c. 13m OD between Jan until Aug 2009 and thereafter, variation increases with low levels recorded down to c. 6m OD	6.1m OD 12.6m OD 6.5m						Groundwater levels rise slightly to 12.2m OD.	Groundwater levels fall to 11.6m OD in October 2016.
G3	Located near the base of the cliff. Tip at 13.6m OD. Complex pattern comprising c. 7 month period cycle of rising water level with superimposed sub-weekly fluctuations. 7 month cycle shows rise in water levels of c 1m from 13.3m OD in Oct 2012 to high of 14.4m OD in Feb 2013, falling to low of	13.2m OD 14.4m OD 1.2m						New telemetry logger installed 24/03/15. Between April and May 2016, groundwater level falls by 0.3m to 13.6m OD.	Groundwater level continues to fall at 13.2m OD in August 2016, before rising and gradually falling to 13.3m OD by October 2016.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
	13.5m OD in June 2013.								
5 spa	Located near the base of the cliff. Tip at 9.4m OD. No correlation with the upper tip in this well. Data only recorded between Sep 2006 and May 2012, after which the hole is dry. Limited fluctuation between c. 8.5m and c.9.5m OD.	8.5m OD 9.6m OD 1.1m						No data.	Borehole dry. **Check piezometer integrity**
BH1a spa	Located at the toe of the Spa landslide. Tip at 2m OD. Sub-weekly fluctuation about mean around 4.4m. Water levels were at their highest during Jan and Feb 2012 when they were c. 0.5m higher than average. Sub-weekly fluctuations are c. 0.4m in the period Oct 2012 to Mar 2013.	3.9m OD 5.0m OD 1.1m						Continuing cyclical pattern overlain onto steady groundwater levels during the monitoring period. Fluctuations within range of previous records. Groundwater rapidly peaks and falls in January and March 2016. Average groundwater level c. 4.6m OD.	Continuing cyclical pattern overlain onto steady groundwater levels during the monitoring period. Fluctuations within range of previous records. Average groundwater level c. 4.5m OD.
BH1b spa	Located at the toe of the Spa landslide. Tip at 10.1m OD. Similar pattern to BH1a. Sub-weekly fluctuation in water level about mean of c. 12.4m OD. Water levels highest in late Feb 2012 when they reached 12.7m OD. Sub-weekly fluctuations were up to 0.5m in the	12.0m OD 12.7m OD 0.7m						Continuing cyclical pattern overlain onto minor rise in groundwater levels during the monitoring period. Levels rapidly peak at historical high of 12.7m OD in March and fall to an average of 12.5m OD.	Continuing cyclical pattern in groundwater levels. Average groundwater level c. 12.5m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
	period Oct 2012 to Mar 2013.								
BH1 Prom	Located inland of the cliff top. Tip at 41.4m OD. 5 month period where water-level rose c. 1m from 41.5m OD in Oct 2012 to 42.6m OD in late Feb 2013, followed by period of gradual fall to 41.8 in late 2013. Superimposed on this trend are sub-weekly fluctuations of c. 0.3m.	41.2m OD 43.7m OD 1.4m						New telemetry logger installed 24/03/15. Groundwater levels rise to historical maximum of 43.7m OD following installation of logger and remain steady at 43.6m OD.	Groundwater levels fall rapidly to 42.9m OD in August 2016 and continue to gradually fall in October to 42.7m OD. Groundwater levels remain elevated.
G1a	Located inland of the cliff top. Dipped piezometer that shows consistent water levels of c. 53.5m OD since late 1997.	53.4m OD 53.9m OD 0.3m						Borehole dry.	Groundwater level at historical low of 53.4m OD in October 2016.
G1b	Located inland of the cliff top. Dipped piezometer that shows significant variability from late 1997 to early 2003 when water levels dropped from c 50m OD to c. 20m OD with significant fluctuations, and subsequent period of consistent level at c. 19m OD. There was a short lived rise to c. 21m during Dec 2012.	19.2m OD 51.1m OD 31.9m						Consistent water level since previous recording at 19.2m OD.	Consistent water level since previous recording at 19.2m OD.
BH108a	Deep piezometer tip located mid-slope. Solinst data logger. Record begins on 18 Dec 2012 and	9.3m OD 31.4m OD 22.1m						New telemetry logger installed 24/03/15. Groundwater levels gradually fall to 24.5m OD, which is well below previous readings.	Groundwater levels continue to fall over monitoring period to 23.7m OD by October 2016.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
	shows several sharp fluctuations that may be a response to rainfall events or ingress of surface water.								
BH108b	Shallow piezometer tip co-located with deeper BH108a. Dry between Sept 2012 and Jan 2013.	25.6m OD 31.6m OD 5.8m						Water level rises to historical high at 31.6m OD.	Water level falls to 29.2m OD, remaining close to historical high.
BH106a	Located at the cliff top. Solinst data logger. Borehole 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. Borehole dry between Oct 2012 and Jan 2013.	n/a (dry)						Borehole dry. **Check piezometer integrity**	Borehole dry. **Check piezometer integrity**
BH104a	Located near the base of the slope. Solinst data logger.	5.0m OD 20.0m OD 15.0m						New telemetry logger installed 24/03/15. Water levels fall from 5.9m OD to 4.3m OD, with a peak in April 2016.	Groundwater levels remain steady at 4.3m OD. No fluctuation.
BH104b	Located near the base of the slope. Manual piezometer tube. Borehole dry between Sept 2012 and Jan 2013.	4.3m OD 11.0m OD 6.6m OD						Groundwater level rises to 11.0m OD, equal to historical high.	Groundwater level falls to 10.3m OD. Remains close to historical high.
BH102a	Located at the base of the slope behind the seawall. Solinst data logger. Reading will be reported in next report.	0m OD 2.6m OD 2.6m						Increase in magnitude to cyclical change to 1.8m. Average groundwater remains steady at 1.6m OD over monitoring period.	Decrease in magnitude of cyclical change to 0.9m. Average groundwater levels steady at 1.4m OD over monitoring period.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
BH102b	Located at the base of the slope behind the seawall. Manual piezometer.	1.1m OD 2.1m OD 1.0m						Slight fall in groundwater level at 1.5m OD.	Slight increase in groundwater to 1.9m OD.

These data indicate:

- Inclinometers show no significant movement in the monitoring period.
- Most locations show continuation of past patterns or slight decreases in water level over the monitoring period.
- Piezometers 5 Spa, BH106a and b should be checked because they remain dry. This equipment may be damaged and required attention to determine whether they can be repaired.
- New telemetry loggers installed at H5 and BH1 Prom show a step-change in groundwater levels at an elevated position relative to earlier recordings. These groundwater levels have fallen at the end of this monitoring period, however remain elevated close to the historical maximum. These locations should be reviewed in the next report to establish whether the trend in elevated groundwater levels continues. No movements were recorded in adjacent inclinometers BH107 and BH109.
- Piezometer data from BH108a shows that the earlier trend in rising groundwater level has changed following installation of the new telemetry logger. This shows groundwater is falling well below earlier levels. Piezometer BH108b is adjacent, and shows levels are also falling. These trends should be reviewed in the next report.
- Acoustic emissions (AE) detected are negligible and do not suggest slope movement. Fluctuations in the data represent the specific hydrogeological conditions at this site (i.e. time dependent seepage conditions following rainfall events). This is supported by the inclinometer measurements at BH105, which show negligible movement. (Figure 9.2 and 9.3)

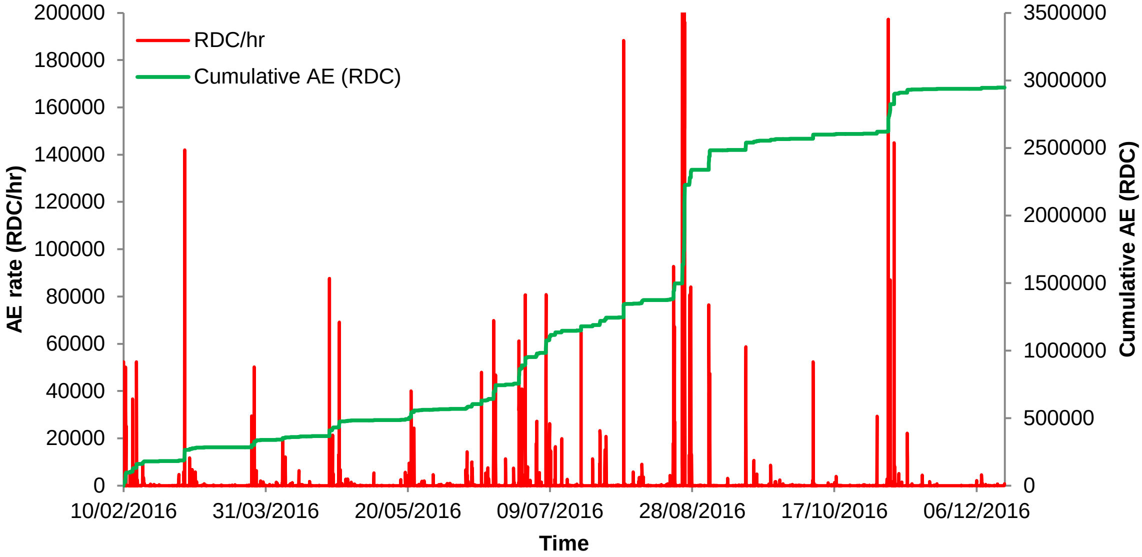


Figure 9.2. Cumulative AE (RDC) and AE rate (RDC/hr) time series at Scarborough Spa for the period February 2016 to December 2016.

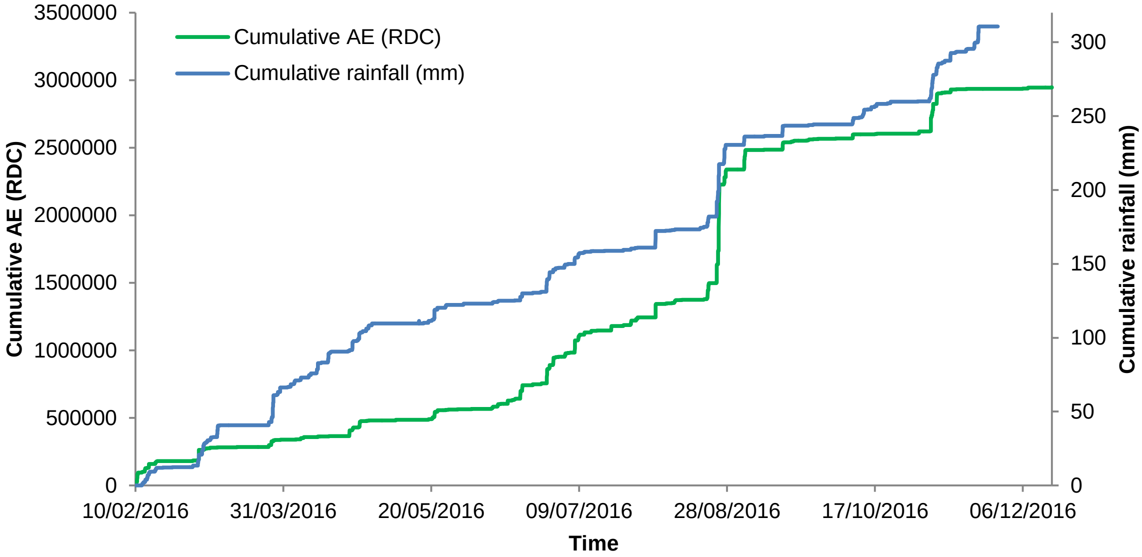


Figure 9.3. Cumulative AE (RDC) and cumulative rainfall time series at Scarborough Spa for the period February 2016 to December 2016.

9.4.4 Clock Café (MU 22/4)

Monitoring at the Clock Café comprises a line of three boreholes from the promenade (BH15) to the midslope (AA10 F2) and lower slope (AA11 F4) (Table 9.8, Figure 9.1B).

Table 9.8. Summary of inclinometer data at the Clock Café

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
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 34.98m OD, base of hole is 4.98m OD. Very low creep indicated in the upper 5m, with incremental displacements of up to 5mm. 30 June 2012 reading is erroneous.						No significant change.	No significant change.
AA11 (F4)	20m deep borehole penetrating 8m of glacial sediment and 12m of siltstone/sandstone bedrock near the toe of the Clock Café landslide. Very low cumulative movement along whole length of borehole of up to 3mm is within tolerance of the device.						No significant change.	No significant change.

Table 9.9. Summary of groundwater data at the Clock Café

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
BH15	Located inland of the landslide headscarp. No historical data	n/a						Borehole dry. Check function of piezometer.	Borehole dry. Check function of piezometer.

The data show no ground movements at the Clock Café, which is a continuation of the past pattern of stability at this location. 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.

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 Bay Gardens

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	

AA08 (D3)	24m deep borehole that penetrates 12m of glacial sediment and 12m of interbedded bedrock. Ground level is 38.43m OD, base of hole is at 14.43m OD. Data indicate slight progressive creep along the whole length of the borehole,						No significant change.	No significant change.
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 57.46m OD, base of hole at 7.46m OD.						No significant change.	No significant change.
BH16A	54m deep borehole than penetrates of 33m of glacial sediment and 21m of siltstone/sandstone bedrock inland of the Rose Garden rotational landslide. Ground level is 62.88m OD, base of hole is 8.88m OD.						No significant change.	No significant change.
BH20	41m deep borehole that penetrates 27m of glacial sediments and 14m of sandstone bedrock within the body of a small landslide. Ground level is 58.98m OD, base of borehole is 17.98m OD.						No significant change.	No significant change.

Table 9.11. Summary of groundwater data at the South Bay Gardens

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
BH18a	Tip at 26.8m OD near the base of the cliff and Rose Garden landslide. Complex pattern, with sub-weekly peaks 4m to 5m higher than base readings associated with storms. From Nov 2012 to May 2013 base readings were 37m OD. Between May and Aug 2013 levels rose to 38m OD.	34.4m OD 42.5m OD 6.1m						Continuation of past pattern of short lived spikes. Base levels are high in December 2015 at c. 38m OD but this falls to c. 36m OD over the monitoring period. Base levels remain elevated compared to historical records.	Continuation of past pattern of short lived spikes. In August 2016 a spike ranged 3.7m. Base levels have gradually decreased over the monitoring period to 34.5m OD in October close to the historical low.
BH18b	Tip at 23.8m OD near the base of the cliff and Rose	34.3m OD 42.4m OD						Same pattern and water levels as BH18a. Spikes on same days, suggesting	Same pattern and water levels as BH18a. Spikes on same days,

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
	Garden landslide. Pattern very similar to BH18a installed higher in the borehole	6.1m						connectivity between both piezometer tips and possible ingress of surface water to the borehole. Base levels falling over monitoring period from c 36m OD to c. 34m OD. **Recommend integrity of installation is checked.**	suggesting connectivity between both piezometer tips and possible ingress of surface water to the borehole. Base levels falling over monitoring period to 34.3m OD. **Recommend integrity of installation is checked.**
BH19a	Tip at 53.8m OD inland of the headscarp of the South Bay Pool landslide. This piezometer has been dry since installation.	52.8m OD 53.3m OD 0.5m OD						Cyclical pattern with magnitude of variation ranging 0.5m averaging 53.1m OD.	Cyclical pattern with magnitude of variation ranging 0.4m averaging 53.1m OD. Peaks in groundwater levels in August and October 2016.
BH19b	Tip at 47.3m OD inland of the headscarp of the South Bay Pool landslide. Sub-metre variation about an average level of 47.8 OD. Periods of slightly higher water level from Dec 2012 to Mar 2013, late May 2013 and early Aug 2013.	47.1m OD 49.3m OD 2.2m						Continuation of sub-weekly fluctuation of c. 1.2m about monthly variation. Levels high in March at 48.1m OD, and fall to minimum of 47.4m OD during monitoring period.	Continuation of sub-weekly fluctuation of c. 1.m about monthly variation. Levels spike to historical high in late June at 49.3m OD and in August 2016. Overall decline in base levels, minimum at 47.2m OD.
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						Levels remain steady around 31.6m OD with sub-weekly fluctuations of up to c. 1m in December. Slight net rise in levels over monitoring period.	No data since May 2016, logger to be checked.
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							No data, logger to be checked.	No data, logger to be checked.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
	sub-metre variation about mean of c. 45.8m OD. Slight peak in water level occurred in late Nov to late Dec 2012. Gap in data between April and Aug 2013.								
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 sat in water. 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, however uniform level of 10.5m OD is interrupted by frequent short-duration (1 day) peaks that are up to 8m higher. Peaks particularly common during period Nov 2012 to Feb 2013 and May to June 2013.	10.3m OD 18.6m OD 8.3m						Continuation of past pattern with levels fluctuating by 0.5m about mean of 10.6m OD. Data spikes suggest ingress of surface water to the borehole. Levels peak at 10.8m OD in March falling to 10.3 m OD.	No data since May 2016, logger to be checked.
E2a	Tip at 31.4m OD below the headscarp of the mudslide embayment. Cyclical long-term pattern with sub-metre fluctuations superimposed. Water levels rise from c. 44m AOD to 46.5m OD between Oct 2012 and late Feb 2013 thereafter they fall	43.3m OD 46.5m OD 3.2m						Groundwater level gradually rises to 44.7m OD throughout monitoring period.	Groundwater level gradually falls to 44m OD throughout monitoring period.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
	gradually to 44.7m OD in Oct 2013								
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 increase gradually from a low of 49.6m OD to 50.4m OD.	Groundwater levels remain steady averaging c. 50.4m OD.

These data indicate:

- No movement has been recorded in any boreholes at South Cliff Gardens.
- Water levels are generally stable or show gradual decreases. Short-lived peaks are recorded in BH18a and BH18b, which suggests ingress of water to the borehole.
- Borehole piezometers D2a, D2b, BH3a and BH3b should be checked and repaired.
- Gradually falling water levels occur in E2b. This may reflect the antecedent rainfall occurring during in the Spring/Summer 2016. The integrity of piezometer tip should be checked and the next monitoring data reviewed, whether this trend continues.

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 June to Nov 2016
		1	2	3	4	5	6	
AA07 (BH2)	60m deep borehole penetrating 31m of glacial sediments and 29m of siltstone/sandstone bedrock. Ground level is 56.33m OD, base of hole is -3.67m 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 also at c.14m depth, within the glacial sediments.						Incremental movements at same depths seen before are not significant.	No significant movement.

Table 9.13. Summary of groundwater data at Holbeck Gardens

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
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						Groundwater levels remain elevated reaching historical high of 59.9m OD in March 2016. Levels fell by 1m in May.	Groundwater levels fall to 57.7m OD in August 2016 before rising to 58.4m OD in September. Levels return to 57.7m OD at end of monitoring period. Levels remain elevated.

The data logger was at fault for Bh4a and data were not downloaded. The integrity of the piezometer should be checked. The data logger at BH4b has been replaced showing groundwater levels have generally reduced during the monitoring period however remain elevated. The integrity of the piezometer should be checked and the next monitoring data reviewed to determine whether this trend continues. No evidence of movement is shown in the current inclinometer data.

9.5 Causal-response relationships

For the most part, groundwater levels show a slight decrease or remain steady, reflecting the relatively warm and dry weather from April onwards, with the exception of heavy rainfall occurring on a number of days in August and October. There is little evidence of movement in the inclinometers and no critical groundwater level thresholds have been identified during this period.

9.6 Implications and recommendations

None of the inclinometers indicate ground movement.

The majority of piezometers show groundwater levels have either been maintained or decreased. Several piezometers have had data loggers removed for repair and so no data have been recorded during the current monitoring period. One of the replaced data loggers show step-changes in groundwater levels whereby levels have increased. The integrity of piezometer tips should be checked and the next monitoring data reviewed, whether these trends continue. Others show short-lived peaks in water level that suggests ingress of surface water during storms. Checks should be made at these locations to ensure water-proof caps are in place.

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 August 2014.

These data indicate:

- No movement has been recorded in any boreholes at Filey Town.
- Water levels are generally stable or decreasing slightly.
- Groundwater levels have risen in borehole CPBH09a and CPBH02a near to historical highs.
- CPBH01a groundwater levels have returned to lower levels following the previous monitoring period whereby levels had risen by 9.1m to a new historical high. It is likely the borehole was flooded by surface water flows.
- Dip meter reading at CPBH09b does not reflect water levels recorded by the diver, suggesting a systematic error. It is recommended that the diver be checked and recalibrated if necessary.
- Boreholes CPBH10b and CPBH08b are dry.
- CPBH01b (Diver), CPBH04 (Diver) and CPBH06b (Diver), were not downloaded for this monitoring period.

Note boreholes BHA, BHB, BHC, BHD, TP3, TP6 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. Note: *Surface elevation and borehole depth calculated from digital elevation model.

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
CPBH03	CPBH03 is 10m deep. Surface elevation is c. 6m OD* therefore the base of the borehole is at -4.0m OD* and extends through 4.4m of made ground and 5.6m of glacial sediment.						No significant movement.	No significant movement.
CPBH05	CPBH05 is 10m deep. Surface elevation is c.6.5m OD* therefore the borehole extends to ca. -3.5m OD* through glacial sediments.						No significant movement.	No significant movement.
RCBH07	CPBH07 is 20m deep. Surface elevation is at c. 5m OD* therefore the borehole extends to c. -15m OD through glacial sediments.						No significant movement.	No significant movement.
BH6	BH6 is 30m deep. Surface elevation is c.27.4m OD* therefore the base of the hole is c. -2.6m OD. The borehole extends through glacial sediment. Cumulative displacements of 10mm in a negative B axis between Sept and Dec 2009 likely to be error.						No significant movement. Large displacement (20mm) at base of borehole is likely to be associated with debris.	No significant movement.

Table 10.3. Summary of groundwater data at Filey Town

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
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						Levels increase slightly to 1.5m OD during monitoring period.	Levels increase slightly to 1.6m OD during monitoring period.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
BH4	Tip at 18.07m OD. Major fluctuations (>7m) in groundwater elevation between Dec 2009 and June 2011. Mouchel (2012) have previously reported groundwater readings from this piezometer as 'erratic'. Readings have been more settled 2011 albeit showing an increase to 20.2m OD in May 2012.	19.7m OD 27.1m OD 7.4m						Levels slightly increase to 21.4m OD, remaining well within historical range.	Levels slightly decrease to 21m OD.
CPBH01a	Readings sporadic BH often dry. Mean level is 17.17m OD, with variation between 16.89m OD (15/12/2011) and 17.48m OD (20/12/2012). This latter measurement is likely to reflect the cumulative impact of the wet spring, summer and winter of 2012.	16.9m OD 26.2m OD 8.3m						Water levels rise to highest on record at 26.2m OD.	Groundwater levels fall near to historical low of 17.1m OD.
CPBH01b (Diver)	Tip at 32.63m 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 35.0m OD 2.0m						No data. Readings to be re-taken.	No data. Readings to be re-taken. Manual dip readings at 33.4m OD, which suggests levels are near the historical low.
CPHB02a	Tip at 1.57m OD. Mean groundwater elevation at c. 5m OD with minor fluctuations. Short lived drop to 3.57m in Sept 2012. Maximum level 5.23m OD on 19/04/2012.	3.6m OD 5.2m OD 1.6m						Water levels increase slightly to 4.9m OD, within range of historical records.	Water levels increase slightly to 5m OD, close to historical high.
CPBH02b (Diver)	Tip at 8.17m 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						Water level steady at 8.6m OD.	Water level steady at 8.6m OD.
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						Water levels slightly increase to 7.2m OD.	Water levels remain steady at 7.2m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
CPBH04 (Diver)	Tip at 9.9m OD. Steady around 13.5m OD until Dec 2012 although dip in Dec2012 reads significantly higher (16.3m OD).	13.2m OD 13.6m OD 0.4m						Water level static at 13.5m OD.	No data. Readings to be re-taken. Manual dip readings at 13.3m OD, which indicates levels are static.
CPBH06a	Tip depth at 0.13m OD. Mean groundwater elevation at 19.86m OD. Range between 18.85m OD (27/02/2012) and 20.11 (20/12/2012). Notable increase in March/April 2012 followed the dry period of late autumn 2011 to winter of 2011/12. Rises to highest level in Dec 2012 after very wet year.	18.9m OD 20.0m OD 1.1m						Water level remains within historical range at 19.0m OD.	Water level falls slightly to 18.9m 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 20/03/2012 and 06/09/2012 and sudden drop on 19/04/2012 followed by a prolonged steady period at c. 15m OD before sudden recovery on 24/05/2012 to 18m OD.	9.2m OD 19.1m OD 9.9m						No data. Readings to be re-taken.	No data. Readings to be re-taken. Manual dip reading at 18.9m OD, which indicates continuation of historical water level.
CPBH08a	Mean groundwater elevation is 8.71m OD ranging between 8.48m OD (19/04/2012) and 9.46m OD (20/12/2012), suggesting a greater lag time or less responsiveness to antecedent rainfall conditions.	8.5m OD 11.4m OD 1.9m						Slight increase in water level to 9.3m OD.	Slight increase in water level to 9.6m OD.
CPBH08b (Diver)	Very steady with fluctuations over whole period only between 17.90m OD and 17.97m OD.	17.7m OD 19.3m OD 1.6m						Water levels static at 17.9m OD. Dip meter data suggest borehole is dry so diver may need resetting.	Water levels static at 17.9m.
CPBH09a	Tip depth at 0.64m OD. Mean groundwater elevation is 20.27m OD and ranges between 19.86m OD (01/08/2012) and 20.98m OD (06/09/2012).	19.9m OD 21.0m OD 1.1m						No change in water-level which is at 20.2m OD. Dip meter readings corroborate diver data.	No change in water-level which is at 20.2m OD. Dip meter readings corroborate diver data.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status						Change June to Nov 2016
			1	2	3	4	5	6	
CPBH09b (Diver)	Tip Depth at 17.74m OD. Between 01/01/2012 and 20/12/2012 levels fluctuate between 19.9m OD and 20.5m OD. There is a general trend of slight decline towards June 2012 followed by a rise towards peaks in late Oct and mid-Dec 2012.	18.8m OD 21.1m OD 2.3m						Groundwater levels remain steady at 3.0m OD. Dip meter readings do not reflect this drop in level, which suggests diver needs to be recalibrated.	Spreadsheet error detected and resolved. Water-levels static at c. 20.5m, which is corroborated by dip meter data.
CPBH10a (Diver)	Tip depth at 23.82m 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 comparatively 'flashy' response to rainfall, with lag times reducing towards the end of 2012 as atypically low groundwater levels recovered. Max peak is 30.8m OD in late Dec 2012.	24.6m OD 30.8m OD 6.2m						Continuation of saw-tooth pattern. Rises over 30m OD in January and falls to 29m OD. Levels are comparatively low.	Continuation of saw-tooth pattern, generally decreasing groundwater levels. Slight increase in August to 28.7m OD. Decreasing for remainder for monitoring period to 28.5m OD.
CPBH10b	Tip depth at 11.92m. 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 with the exception of shallow piezometers CPBH01a and CPBH10a which respond rapidly within a month to peaks in rainfall. Most of the piezometers show steady groundwater levels or slight decreases. There has not been movement in inclinometers and therefore no relationships between groundwater and ground movement have been identified.

10.6 Implications and recommendations

The diver installed in CPBH09b requires recalibration as readings differ markedly from data derived from dip meter data. Boreholes CPBH01b, CPBH04b and CPBH06b require readings to be re-taken on the next site visit. CPBH10b and CPBH08b are dry and require investigation and repair work where necessary.

Inclinometer at BH6 appears to have debris at its base, causing error at the lower part of the reading.

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 2016.

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 June to Nov 2016
		1	2	3	4	5	6	
A2	A2 is 27.5m deep (surface elevation at 17.93m OD) and extends through glacial sediment. Moderate movements (<5mm cumulative) between Dec 2009 and Dec 2010 increase by a further c. 10mm by June 2011 at shear at c. 6m to 7m OD						No significant movement.	No significant movement.
C1	C1 is c. 25m deep. Surface elevation is 25.7m OD* the base of the hole is c. 0.7m OD. Shows very minor (<2mm cumulative) displacements up to and including October 2012.						No significant movement.	No significant movement.
C2	C2 is c. 21m deep. Surface elevation is at 16.5m* and the borehole extends to -4.5m OD through glacial sediments. Displacements to Oct 2012 within margin of instrument error						No significant movement.	No significant movement. Minor displacement extending to ca. 1.5m depth, likely relatively shallow surface creep in clay.
C5	C5 is c. 16m deep. Surface elevation is 12.0m OD* and the borehole extends to -4.0m OD passing through variable glacial sediments. No movement to Oct 2012 apart very minor displacement in the uppermost 1.5m						No significant movement.	No significant movement. Minor displacement extending to ca. 1m depth, likely relatively shallow surface creep in glacial till.

Borehole	Summary of past data	Report status						Change June to Nov 2016
		1	2	3	4	5	6	
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 February 2016 and August 2016 do not show significant slope movements. The period of elevated AE activity after June 2016 could be indicative of minor deformations. It is likely that this is a function of the deterioration of the cover lid generating spurious AE.	AE measurements between February 2016 and December 2016 do not show significant slope movements. The period of elevated AE activity after June 2016 could be indicative of minor deformations, but it is likely that this is a function of the deterioration of the cover lid generating spurious AE. The lid was replaced on 11 August 2016. The elevated bursts of activity recorded in November are thought to be caused by vandalism, with residents reporting youths kicking the equipment.

Table 11.3. Summary of groundwater data at Flat Cliffs

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
B1	Tip Depth at -7.64m OD. Monitored since July 2001. Fluctuates between c. 11.2 m OD and 15.6m OD with peaks in July 2003, April 2004 and Dec 2010. Groundwater at 12.9m OD in May 2012.	11.2m OD 15.6m OD 4.4m						Groundwater level falls to 13.9m OD in May 2015.	Groundwater level continues to fall to 12.9m OD in October 2016.
D1	Tip depth at 15.61m OD. Monitored with data loggers since late 2011. Levels show large fluctuations between 15.7 m OD (Sept 2008) and 38.4m OD (March 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						Groundwater levels increased significantly from late December to mid-January reaching an historical high of 29.9m OD. From late January levels gradually fell to 20.4m OD.	Groundwater levels fall to 18.6m OD in October 2016 and remain steady.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status						Change June to Nov 2016
			1	2	3	4	5	6	
A3	Tip depth at 6.37m OD. Monitored since March 2001. Dipped readings show static ground water level at c. 18.75m OD with for peaks in July 2001 (19.8m OD) and Dec 2010 (21.4m OD) and a low in July 2008 of 11.63m OD. Vibrating wire piezometer installed in Sept 2011 shows static groundwater level of c. 18.0m OD with minor fluctuation.	17.7m OD 18.2m OD 5.0m						No significant change with continuation of 4 to 6 week fluctuations. Gradual increase in groundwater level from 17.8m OD to 18.1m OD. Highest levels occur in March 2016.	No significant change with continuation of 4 to 6 week fluctuations. Groundwater levels remain steady around c. 18m OD.
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 significant change. Continued fluctuation of +/- 0.3m around an average of 8.0m OD.	No data collected since May 2016. Readings to be re-taken.

The new data indicate:

- No evidence for ground movements is shown by inclinometers.
- AE measurements between February 2016 and August 2016 do not show significant slope movements. The period of elevated AE activity after June 2016 could be indicative of minor deformations of a very slow rate and magnitude. It is likely that this is a function of the deterioration of the cover lid generating spurious AE. The cover lid has been replaced. Bursts of high activity in November are thought to be a result of interference with the equipment by the public.
- Groundwater data show no significant change except for Borehole D1 near the top of the slope adjacent to the main access road. Here, water levels have decreased significantly since Winter 2015/16.
- No data collected at piezometer in borehole C4a, and requires readings to be retaken.

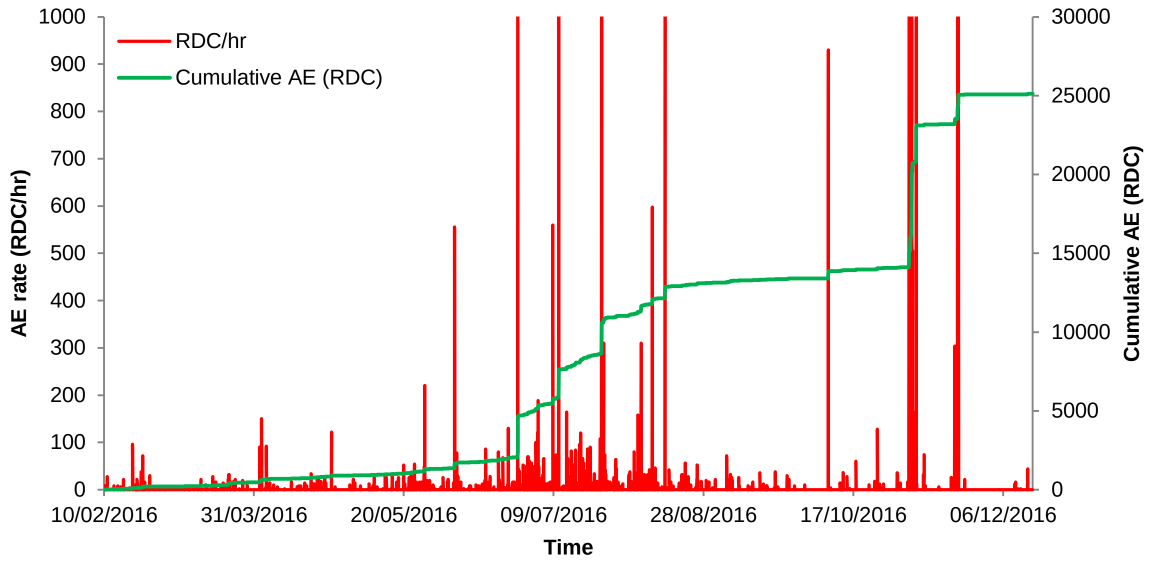


Figure 11.2 *Cumulative AE (RDC) and AE rate (RDC/hr) time series at Flat Cliffs, Filey for the period February 2016 to December 2016.*

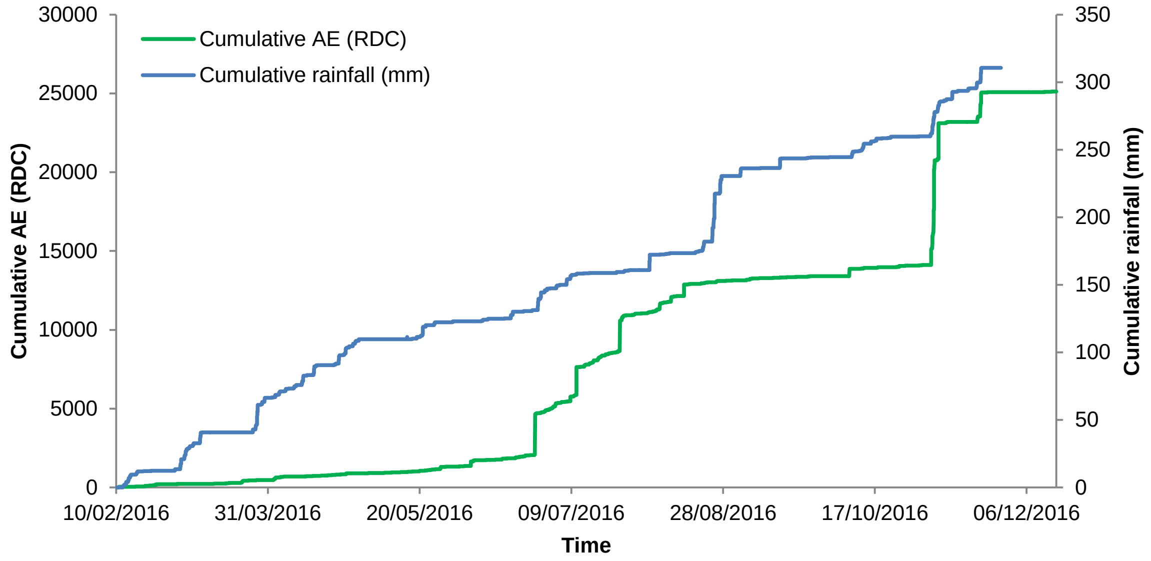


Figure 11.3 *Cumulative AE (RDC) and cumulative rainfall time series at Flat Cliffs, Filey for the period February 2016 to December 2016.*

11.5 Causal-response relationships

No relationship is identifiable between ground movements and rainfall as no substantial ground movements have occurred. However, 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. Much of the current monitoring period experienced lower than average rainfall. The data from borehole D1 do not record a peak associated with August rainfall, however B1 gradual decrease in groundwater level follows a month antecedent rainfall.

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.

The publically accessible location of the acoustic inclinometer means it has become a target for vandalism, with youths seen by residents kicking the equipment. This has resulted in spurious data being recorded. It is recommended that any future acoustic installations are placed well-away from public accessible land to mitigate the risk of vandalism.

References

CH2M HILL (Halcrow) 2014a. Local Coastal Slope Monitoring Analysis Interpretation Report 1, June 2012 to November 2013. Report for Scarborough Borough Council, March 2014.

CH2M HILL (Halcrow) 2014b. Local Coastal Slope Monitoring Analysis Interpretation Report 2, December 2013 to May 2014. Report for Scarborough Borough Council, November 2014.

CH2M HILL (Halcrow) 2015a. Local Coastal Slope Monitoring Analysis Interpretation Report 3, June 2014 to December 2014. Report for Scarborough Borough Council, March 2015.

CH2M HILL (Halcrow) 2015b. Local Coastal Slope Monitoring Analysis Interpretation Report 4, December to May 2014. Report for Scarborough Borough Council, September 2015.

CH2M HILL (Halcrow) 2016a. Local Coastal Slope Monitoring Analysis Interpretation Report 5, June to December 2015. Report for Scarborough Borough Council, February 2016.

CH2M HILL (Halcrow) 2016b. Project appraisal report for Runswick Bay Coastal Protection Scheme. Report for Scarborough Borough Council, January 2016.

Halcrow, 2005. Scalby Ness Coastal Strategy Study. Report for Scarborough Borough Council

Halcrow, 2012a. Filey Town Defences coastal Slope Stabilisation and outflanking Prevention: Cliff Stability Technical Report. Report for Scarborough Borough Council, September 2012.

Halcrow, 2012b. Flat Cliffs Stability assessment and Management Plan: Ground Investigation and Monitoring Report. Report for Scarborough Borough Council, 31 May 2012.

Halcrow, 2013a. Filey Town ground investigation. Analysis of cliff monitoring data. Report for Scarborough Borough Council, January 2013.

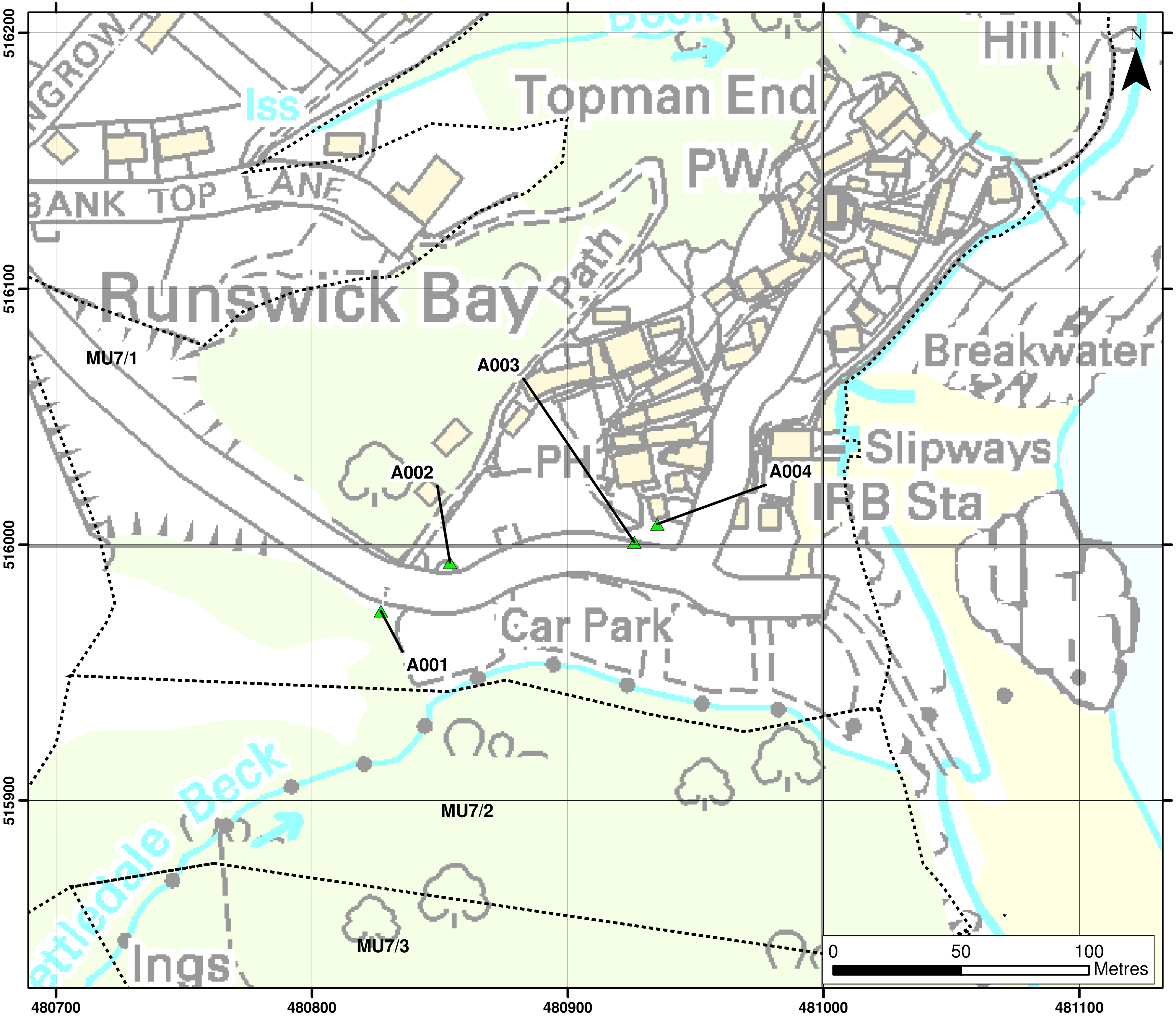
Halcrow, 2013b. Flat Cliffs ground investigation. Analysis of cliff monitoring data. Report for Scarborough Borough Council, January 2013.

Halcrow, 2013. Scarborough Spa Coastal Protection Scheme, 2013 Cliff Geotechnical Interpretive Report. Report for Birse Coastal to Scarborough Borough Council, February 2013.

Mouchel, 2012. Ongoing Analysis and Interpretation of Coastal Monitoring Data: Seventh Review of full Suite Monitoring: geotechnical Interpretive Report. Report for Scarborough Borough Council, August 2012.

Royal Haskoning DHV, 2013. Borehole location and condition survey. Report for Scarborough Borough Council, May 2013.

Appendix A
Digital data



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 3.1 Location of slope monitoring at Runswick Bay

CH2MHILL®
Halcrow

Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com

Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

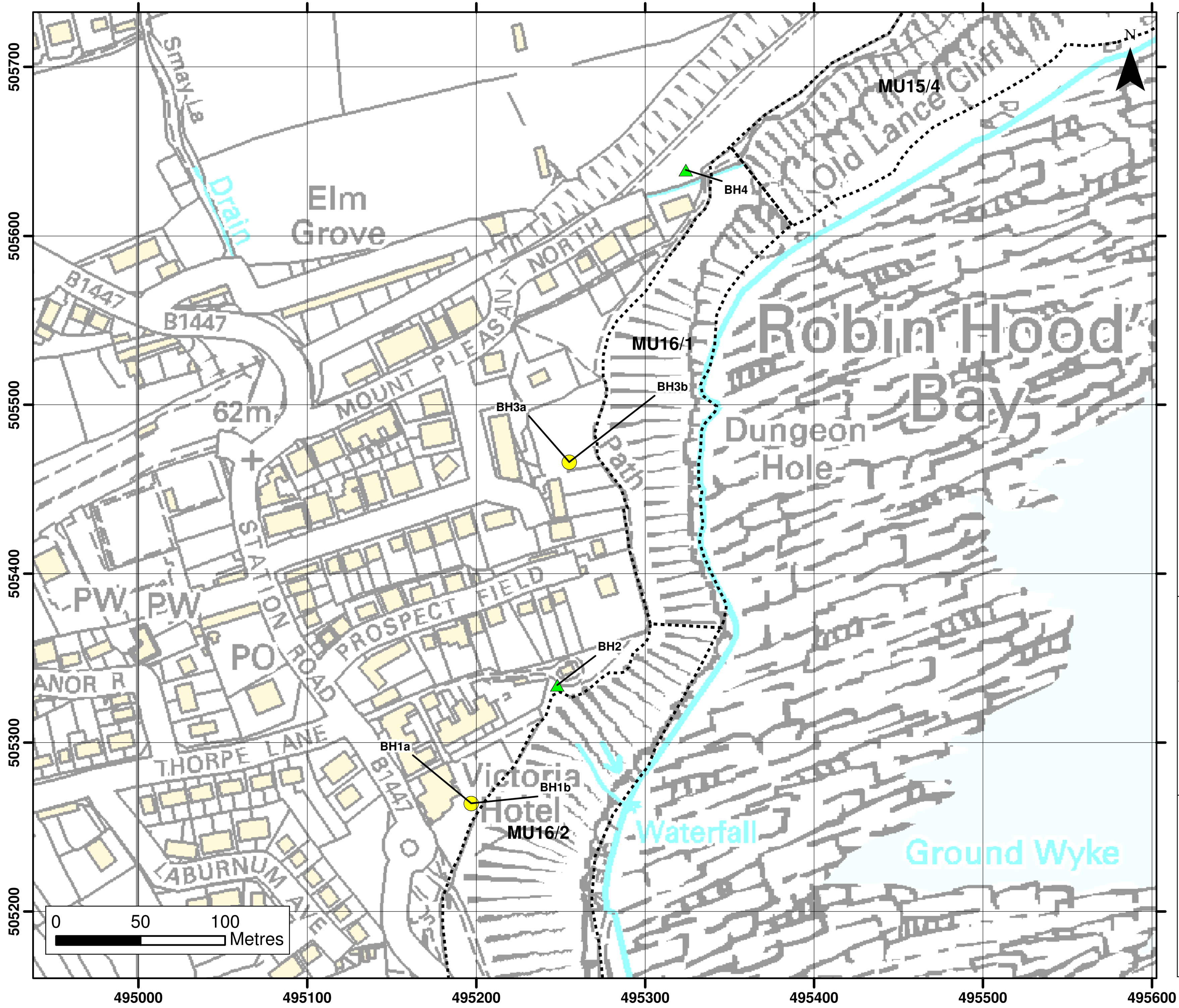
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 4.1 Location of slope monitoring at Whitby West Cliff

CH2MHILL®
Halcrow

Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

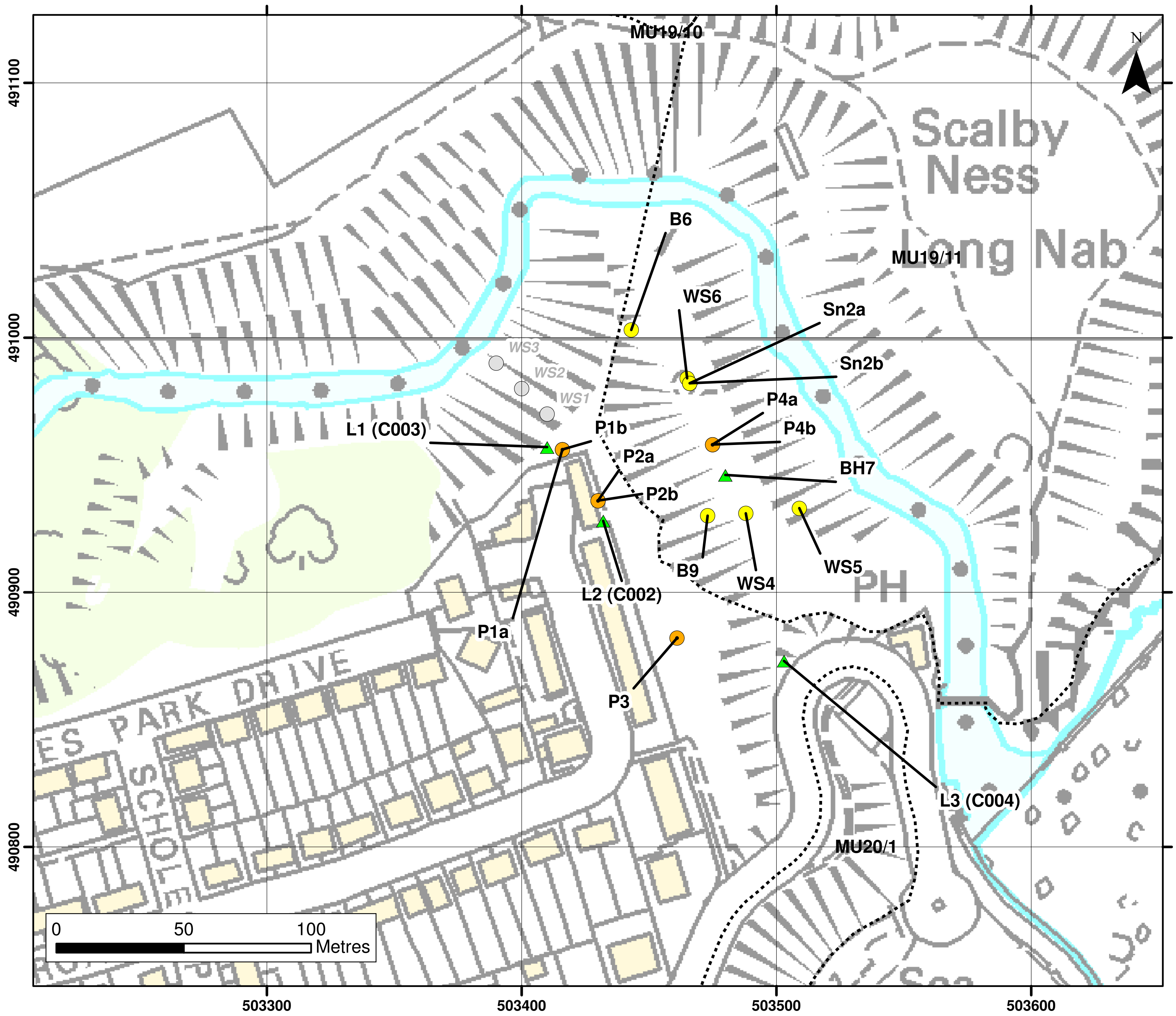
Project: Scarborough Borough Council Geotechnical Monitoring

Figure 5.1 Location of slope monitoring at Robin Hood's Bay

CH2MHILL®
Halcrow

Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

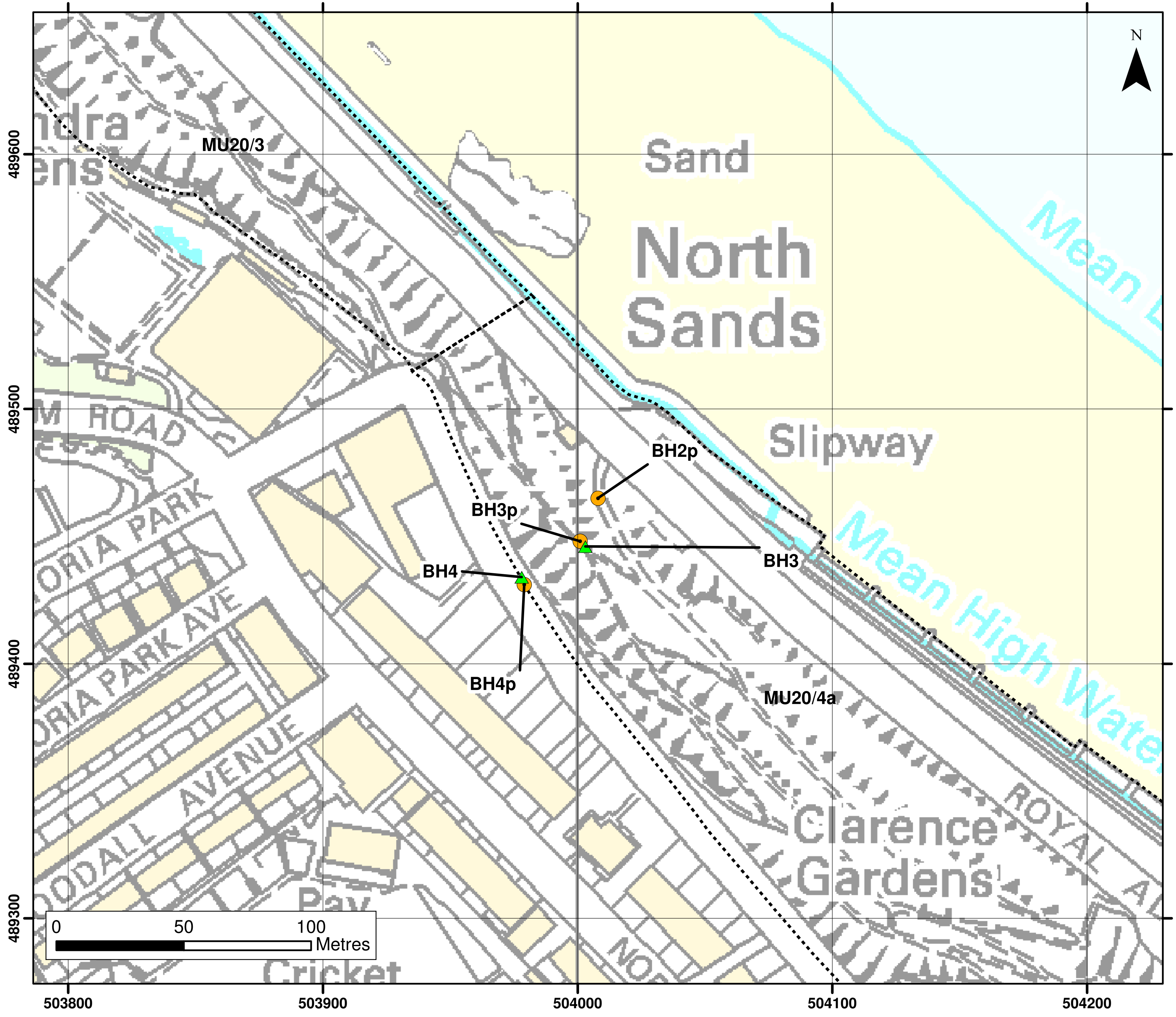
- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 6.1 Location of slope monitoring at Scalby Ness

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

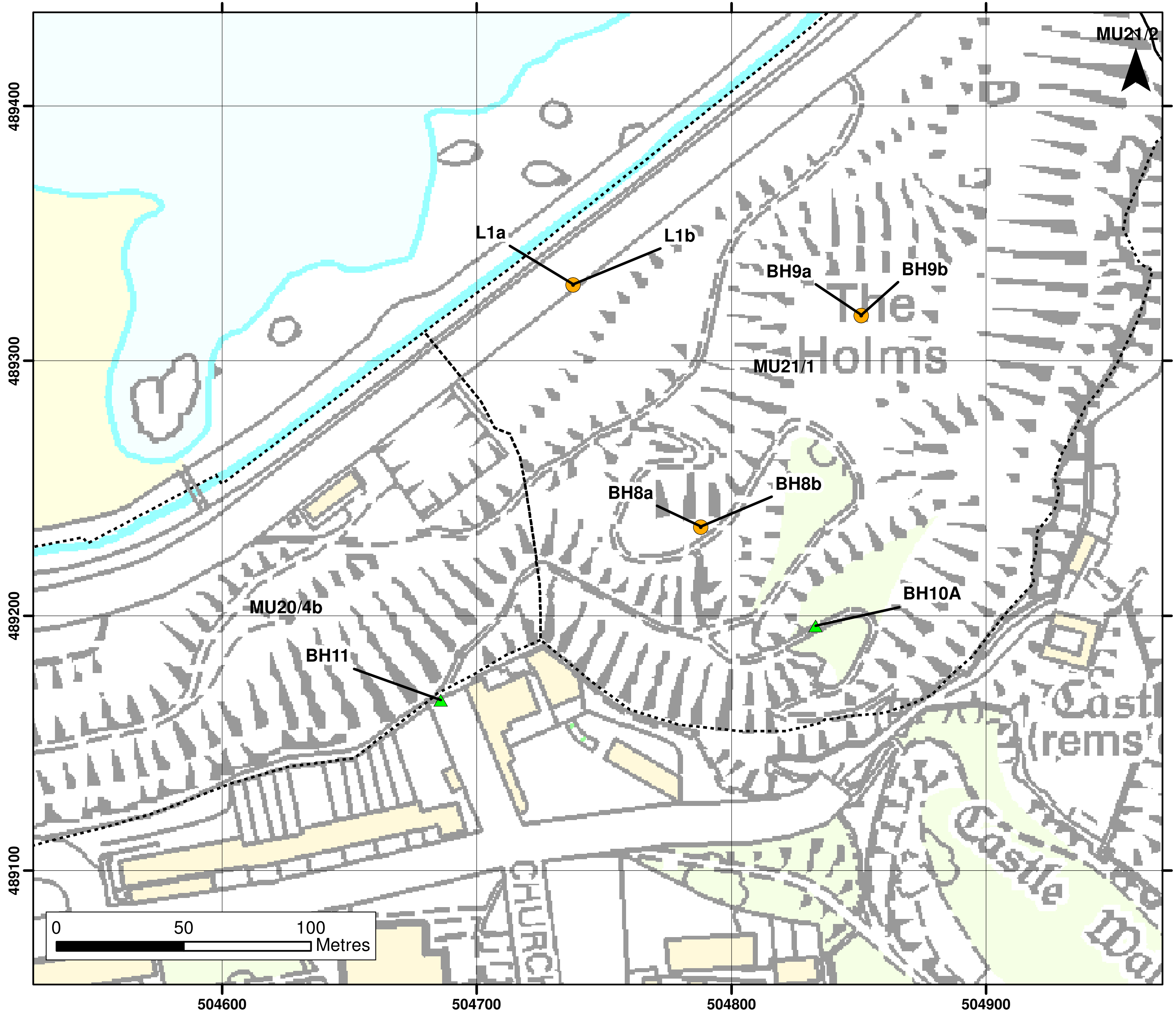
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 7.1 Location of slope monitoring at Scarborough North Bay –Oasis Cafe

CH2MHILL
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

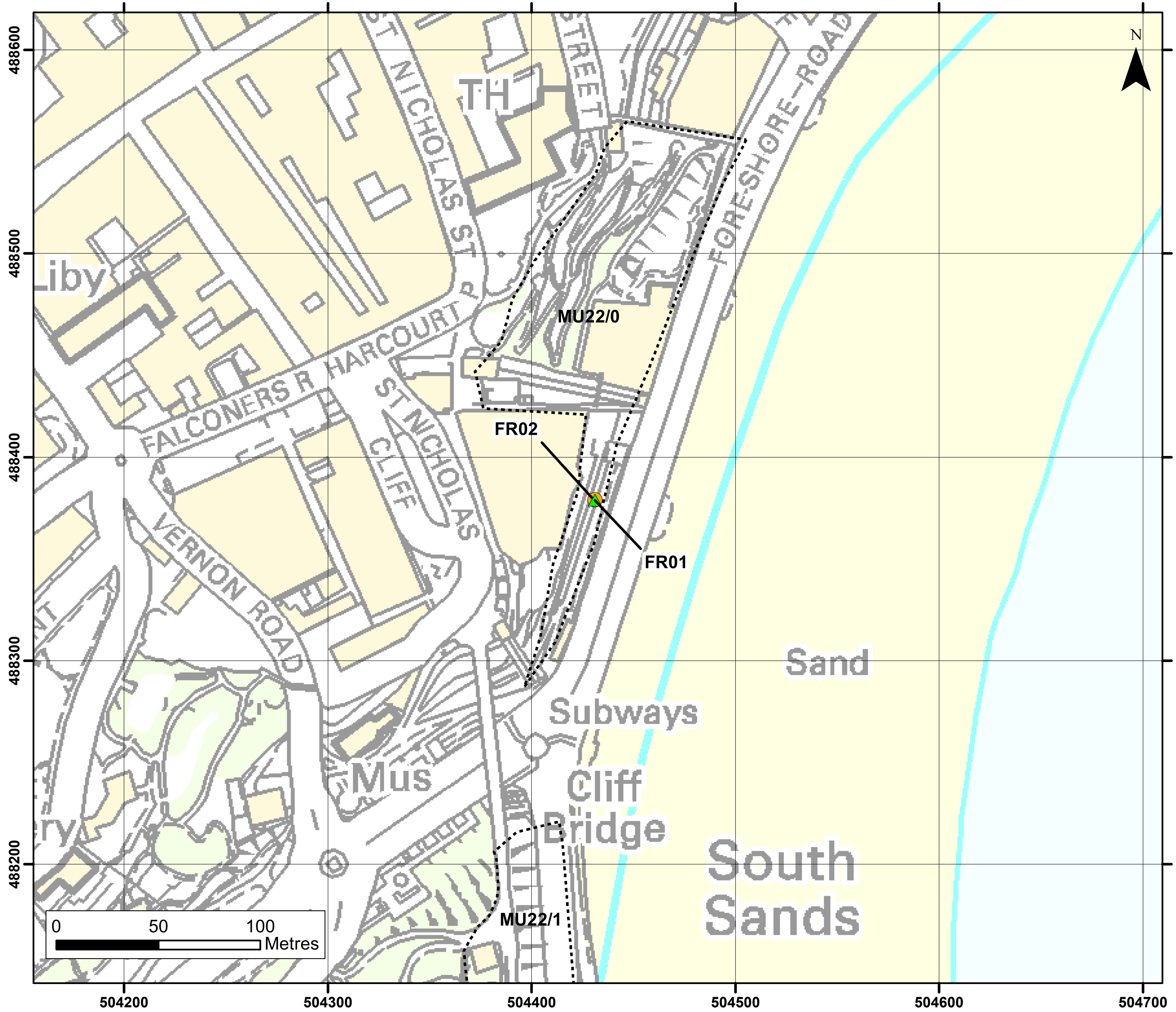
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 8.1 Location of slope monitoring at Scarborough North Bay (The Holms)

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

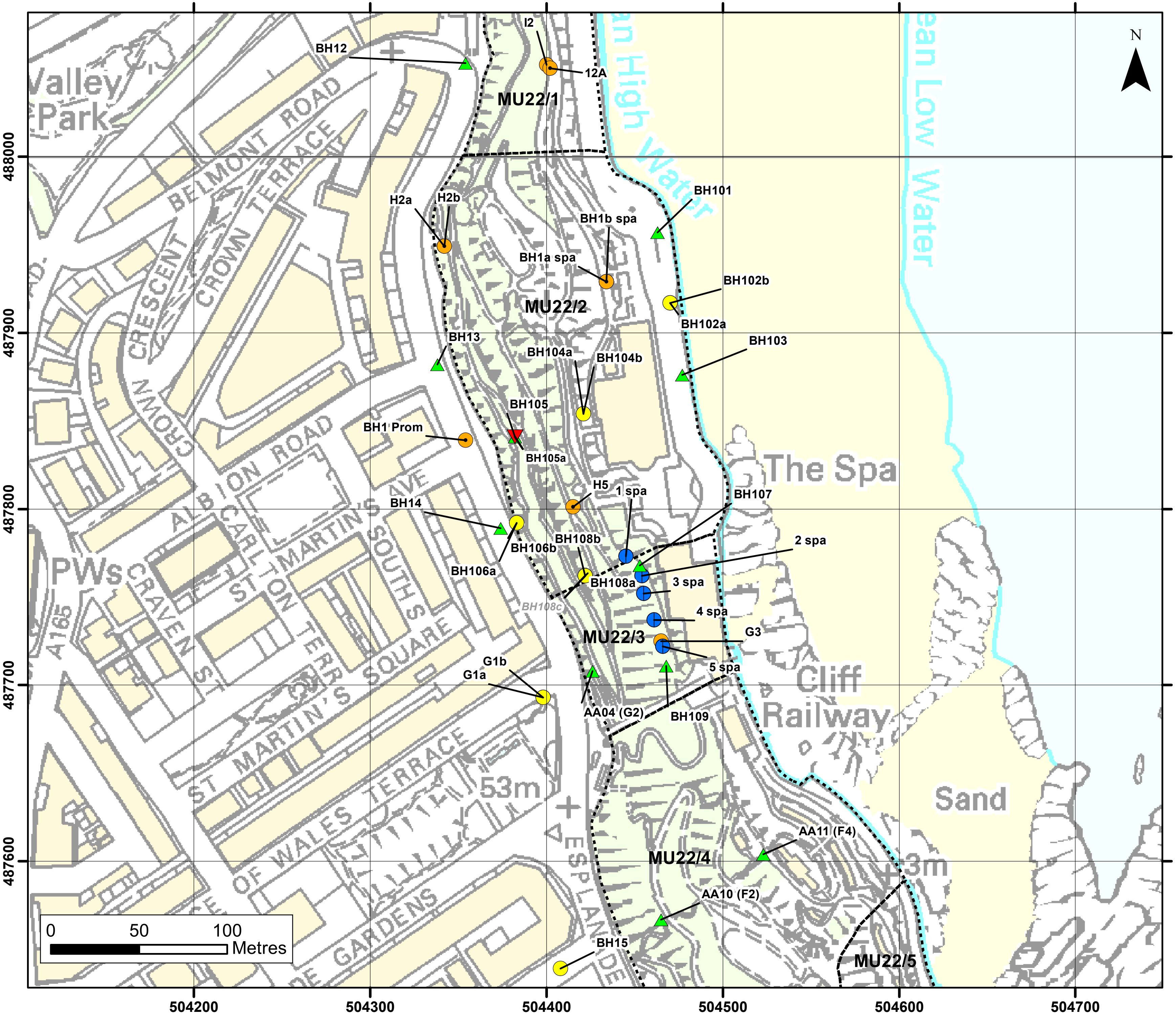
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1A Location of monitoring at Scarborough South Bay

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Acoustic inclinometer
- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

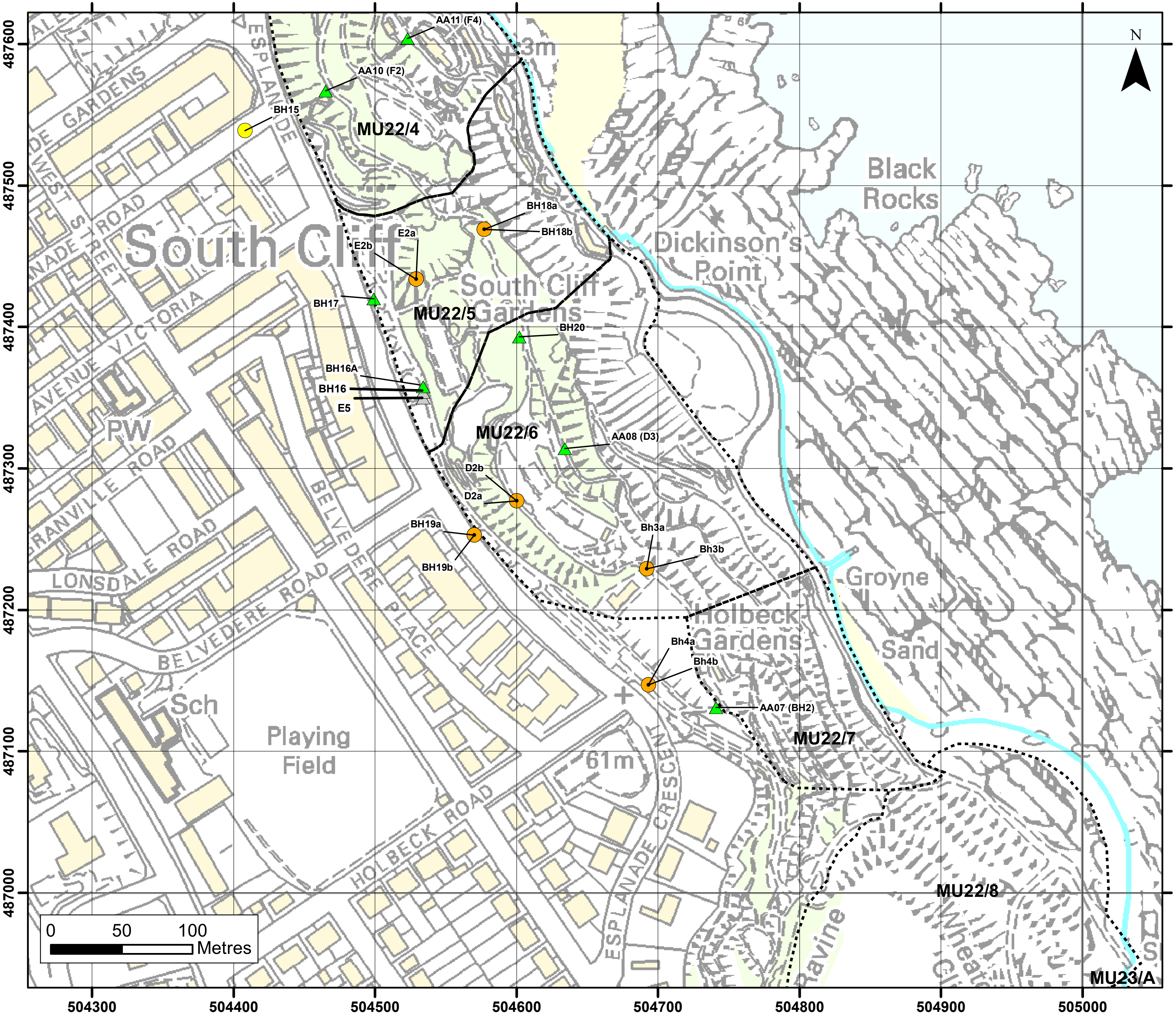
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1B Location of monitoring at Scarborough South Bay

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

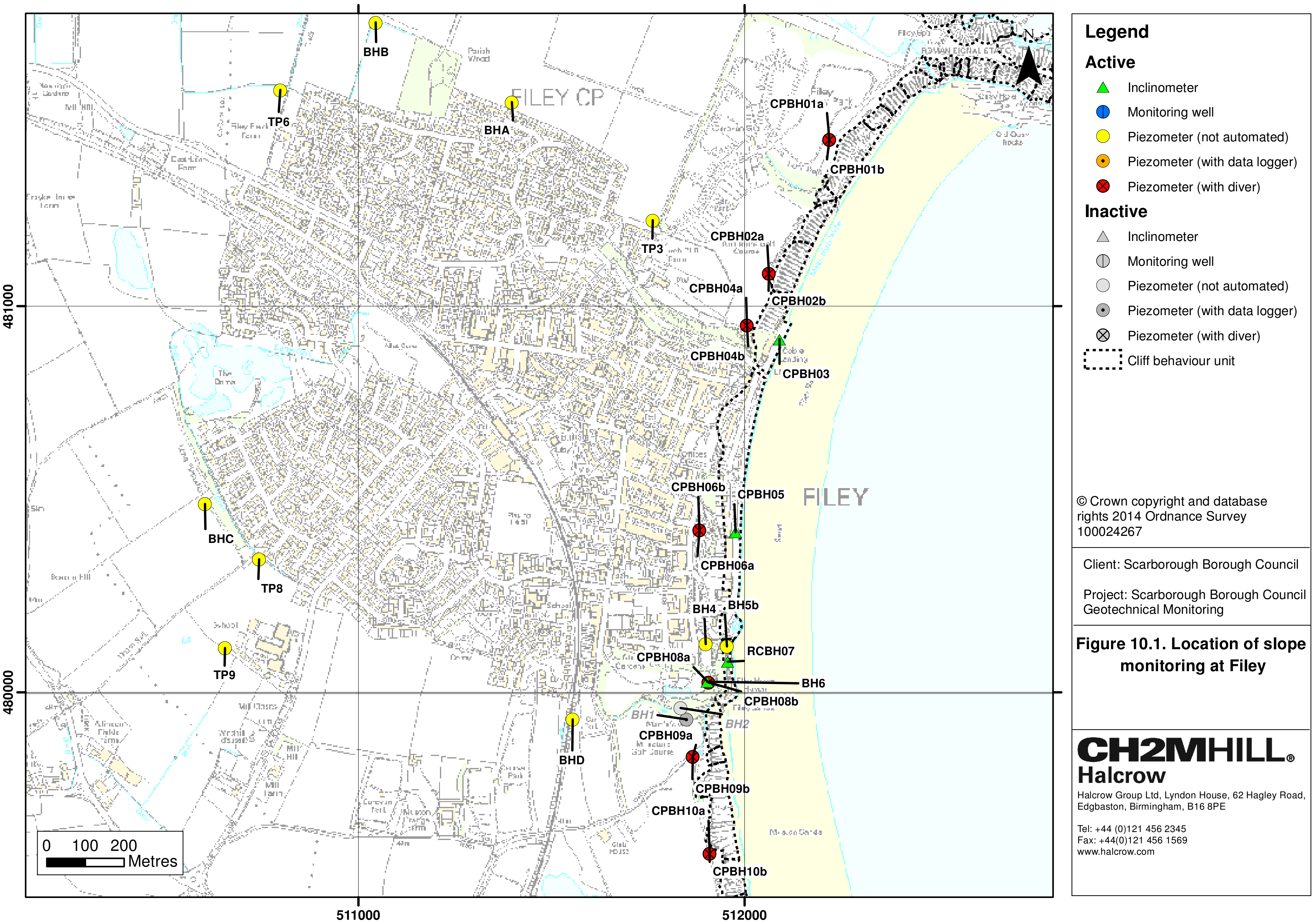
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 9.1C Location of monitoring at Scarborough South Bay

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



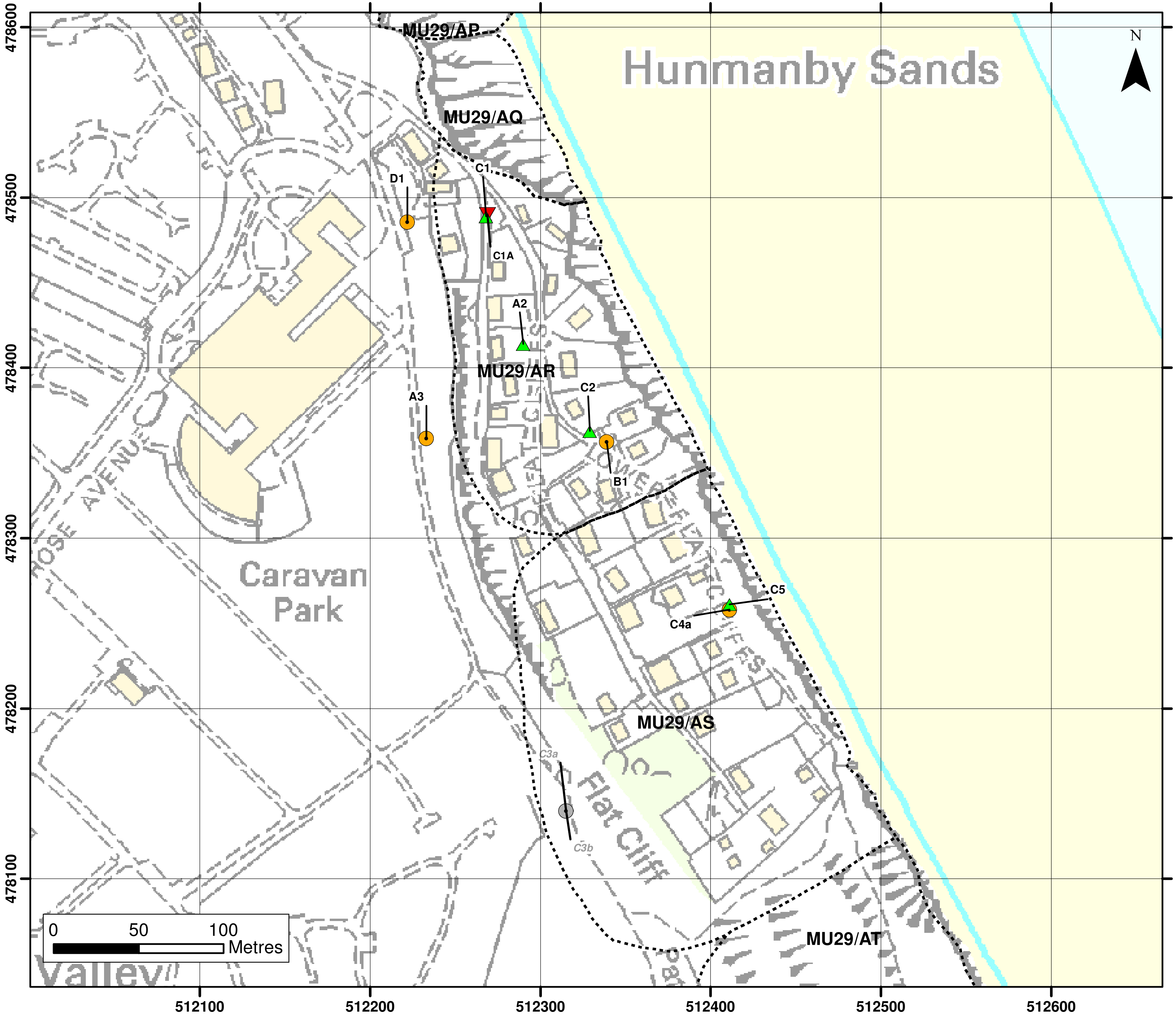
Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 10.1. Location of slope monitoring at Filey

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE

Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com



Legend

Active

- Acoustic inclinometer
- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 11.1 Location of slope monitoring at Filey Flat Cliffs

CH2MHILL®
Halcrow
Halcrow Group Ltd, Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 456 2345
Fax: +44(0)121 456 1569
www.halcrow.com