

# Interpretation Report 9: June 2017 to November 2017

*Prepared for*  
Scarborough  
Borough Council

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



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# Document History

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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.

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## Summary of findings

This report presents an interpretation of coastal slope monitoring data recorded between June 2017 and November 2017 along the Scarborough Borough Council frontage. It is the ninth in a series of 6-monthly updates on the cliff instability risk of the frontage that began in 2014. The weather over summer 2017 was wetter than average, particularly in June and August, whilst autumn 2017 was drier than average.

Boreholes show that water levels have remained at previous low levels or increased slightly during the monitoring period, except for Oasis Café (BH4p), Scarborough Spa (H5, BH104b), South Cliff Gardens (BH18a) and Filey Town (CPBH01a, CPBH02a, CPBH06a and CPBH10a) that are 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 remain steady at lower 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 following uncovering of the tarmac, but now functions correctly. Borehole BH1b was dry, and the integrity of the piezometer should be checked.
- At Scalby Ness, the groundwater level in borehole Sn2b remains steady at lower levels following the historical high recorded in the monitoring period between summer and autumn 2016. The earlier rise in groundwater suggested a discharge from cliff top developments, as groundwater levels remained relatively steady following above average rainfall in June and August 2017. This site should continue to be visually monitored, particularly following sustained periods of heavy rainfall. At borehole B9 overgrown vegetation, which currently blocks the access path, should be removed. Borehole B9 recorded rising groundwater levels in the previous monitoring period and this trend should be reviewed in the next report. Automated piezometers in boreholes P1a, P1b, P2a, P2b, P3, P4a and P4b all experienced problems downloading data and should be investigated and remedied by the monitoring contractor at the next site visit. Borehole Sn2a was dry, suggesting the piezometer is damaged. This location should continue to be monitored.
- 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), problems downloading data have re-occurred at piezometer BH09a following a temporary resumption of readings in the previous monitoring period. The issue should be investigated and remedied by the monitoring contractor next time. Piezometer BH9b is no longer functional and has been removed.
- At Scarborough Spa Chalet, no data has been recorded since May 2016 at piezometer BH12. This site requires attention to fix or replace the piezometer and damaged cable.
- At Scarborough Spa, groundwater levels have remained steady or have fluctuated slightly, except at BH104b where water level is close to a historical high and at H5 where levels remain elevated. No movement was detected at inclinometers nearby, but these sites should be visually monitored, particularly following sustained wet weather. Several boreholes were dry (1 Spa, 5 Spa, G1a, G1b, BH106a, BH106b and BH108b), suggesting the piezometer installations may be damaged. These locations require attention and should continue to be monitored. The borehole

containing piezometers BH102a and BH102b has been filled with tarmac and monitoring is no longer possible. This location should be reinstated if possible. Ground movements recorded in inclinometer in BH13 appear erroneous. The borehole may be blocked and require clearing.

- At the Clock Café, borehole BH15 remains dry, and the integrity of the piezometer should be checked.
- At South Cliff Gardens, shallow piezometer BH18a shows a rapid increase in groundwater levels relative to deeper piezometer BH18b which shows a more gradual increase. Groundwater also spikes significantly within boreholes BH19a and BH19b. This suggests surface water ingress may be occurring, and the contractor should ensure that plastic caps are in place and that water cannot collect at the top of the boreholes. No movement has been indicated by the inclinometers in these locations. At borehole D2b and BH3a there was a problem downloading data. The issue should be investigated and remedied by the monitoring contractor next time.
- At Holbeck Gardens there was a problem downloading data at borehole BH4a and BH4b. The issue should be investigated and remedied by the monitoring contractor next time.
- At Filey Town, in boreholes CPBH01a and CPBH02a groundwater levels remain near historical highs. At CPBH06a and CPBH010a groundwater levels have continued to rise toward historical highs, which may reflect the wetter than average summer conditions. These locations should be visually checked and reviewed in the next monitoring period, particularly if sustained wet weather occurs. Boreholes BH4, CPBH02, 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 piezometers CPBH01b, CPBH04b, CPBH06b, CPBH08b and CPBH09b. This issue should be investigated and remedied by the monitoring contractor during the next visit. Borehole CPBH03 was obstructed during the site visit and data should be collected for the next monitoring report.
- 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.

# 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 7<sup>th</sup> 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. A two-year extension to the project was awarded to the incumbent team in March 2016.

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

## 1.2 Aims and objectives of monitoring

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

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

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

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

In addition, the ultimate aim of the study is:

- To collect sufficient monitoring data to enable site-specific relationships between rainfall, groundwater levels and ground movement to be understood. With sufficient data, it is hoped

that threshold rainfall and groundwater levels, above which instability is likely to be triggered, can be identified. This understanding will eventually allow early warning of potential ground movement to be provided.

**Table 1.1. Monitoring locations and devices.**

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

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

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

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

## 1.3 Programme of work

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

## 1.4 Scope of data analysis work

JBA have sole responsibility for collection and checking of all inclinometer and piezometer data at 6 month intervals. JBA provide 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.

- Inclinator absolute position – this plots the absolute position of the inclinometer casing when viewed vertically. While it does not give information on the rate of movement, it highlights the direction of any deformation and can be used to assess error in the data.
- Groundwater data from piezometer divers or data loggers – these data are plotted as a continuous line showing groundwater level fluctuation relative to Ordnance Datum (OD).
- Groundwater data from monitoring wells – these data are plotted as single points, showing groundwater level relative to OD at a 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.

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: August 2015 (CH2M 2015b)
Data set 5: June 2015 to November 2015	Report 5: February 2016 (CH2M 2016a)
Data set 6: December 2015 to May 2016	Report 6: August 2016 (CH2M 2016c)
Data set 7: June 2016 to November 2016	Report 7: January 2017 (CH2M 2017a)
Data set 8: December 2016 to May 2017	Report 8: October 2017 (CH2M 2017b)
Data set 9: June 2017 to November 2017	Report 9: February 2018 (this report)
Data set 10: December 2017 to May 2018	Report 10: August 2018

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 overall summer 2017 was relatively wetter when compared to past records, with June and August close to the long-term mean (upper range). Comparatively, autumn 2017 was drier on average, with the exception of November which was close to the long-term mean (lower range).

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

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

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 28 June, 8 August, and 30 November.

On 23 August 2017, a daily peak rainfall total of 43mm was recorded, which represents the greatest daily rainfall total over the record period. This event was exceptional. Environment Agency analysis of their own rainfall records indicated a series of very intense but short-lived storms moved across the Yorkshire region on the day. In Scarborough 73% of the typical August rainfall fell in 1 hour between 10.45 and 11.45 on 23 August. The 1 hour peak rainfall intensity was 132mm/hour, which has a calculated return period of 1:96 years.

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 2017 was August, with 78.7mm. This reflects the impact of the storm event on 23 August.

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. The winter of 2016/17 and spring 2017 have been the driest on record. The summer of 2017 has been relatively wetter than previous years, receiving 183mm of rainfall, whereas slightly drier conditions occurred through autumn 2017.

Wind speed and air temperature records from Flat Cliffs are presented in Figures 2.4 and 2.5. The data shows November 2017 as the windiest month in the monitoring period. Relatively gentle conditions persisted during over summer and early autumn 2017. Recorded temperatures during 2017 are average.



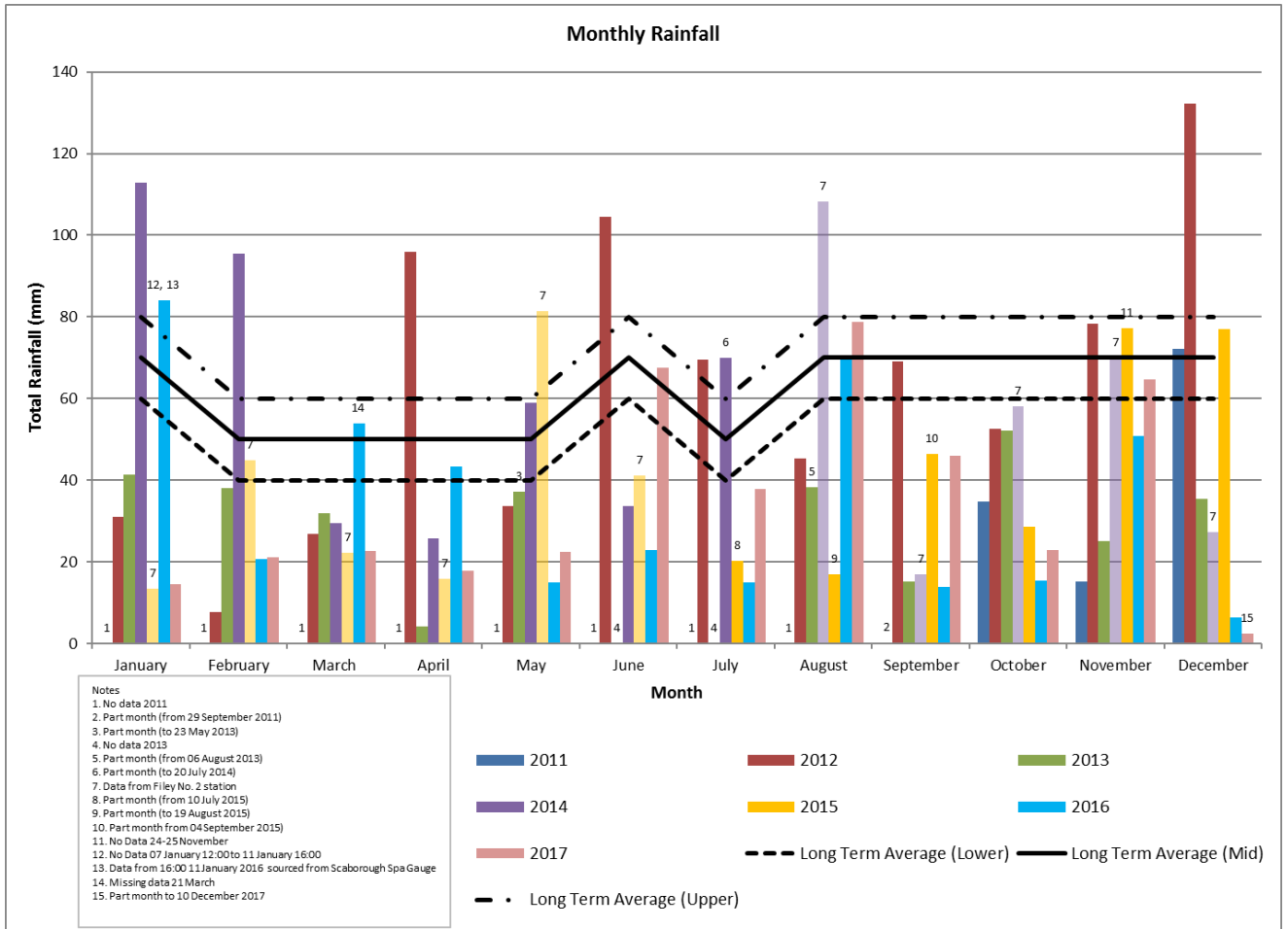


Figure 2.1 Comparison of monthly rainfall records (2011 to 2017).

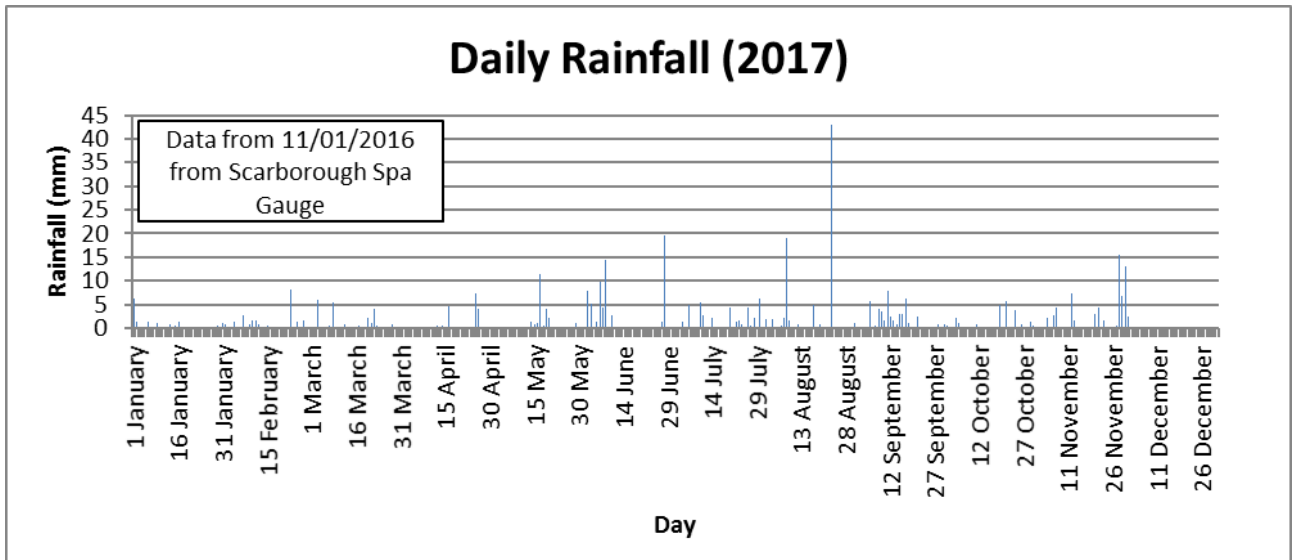


Figure 2.2 Daily rainfall recorded at Scarborough Spa during 2017. Note the exceptional rainfall on 23 August, which was recorded across the Yorkshire region on this day.

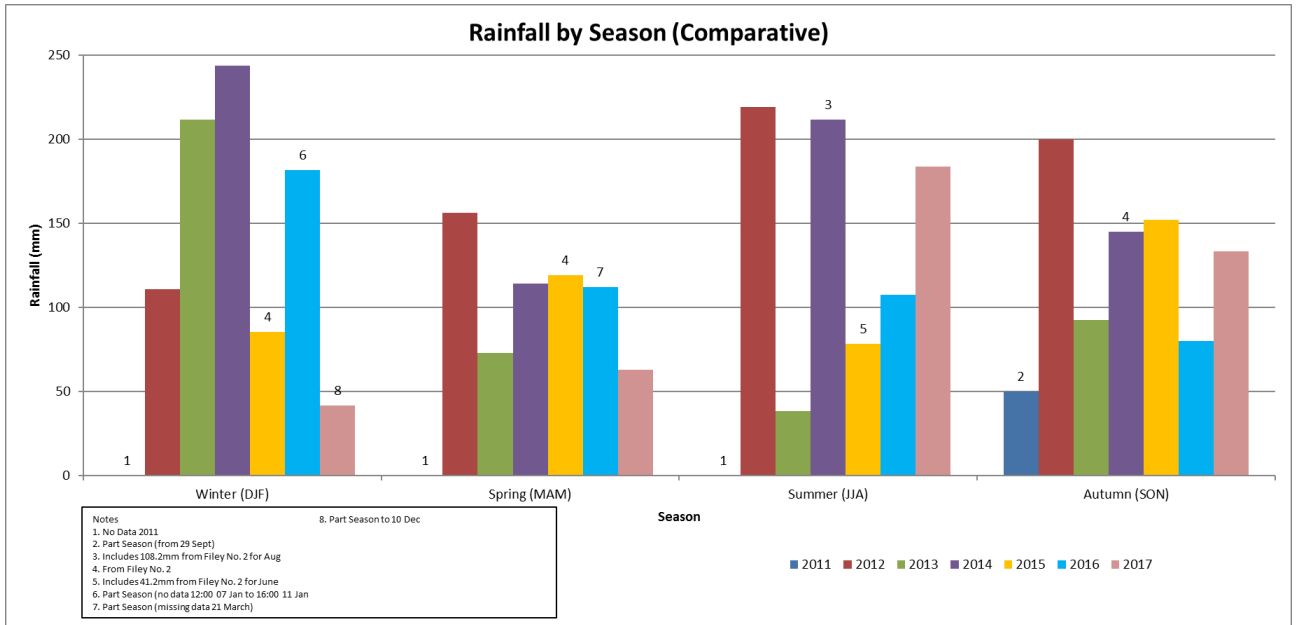


Figure 2.3 Seasonal rainfall comparison (2011-2017)

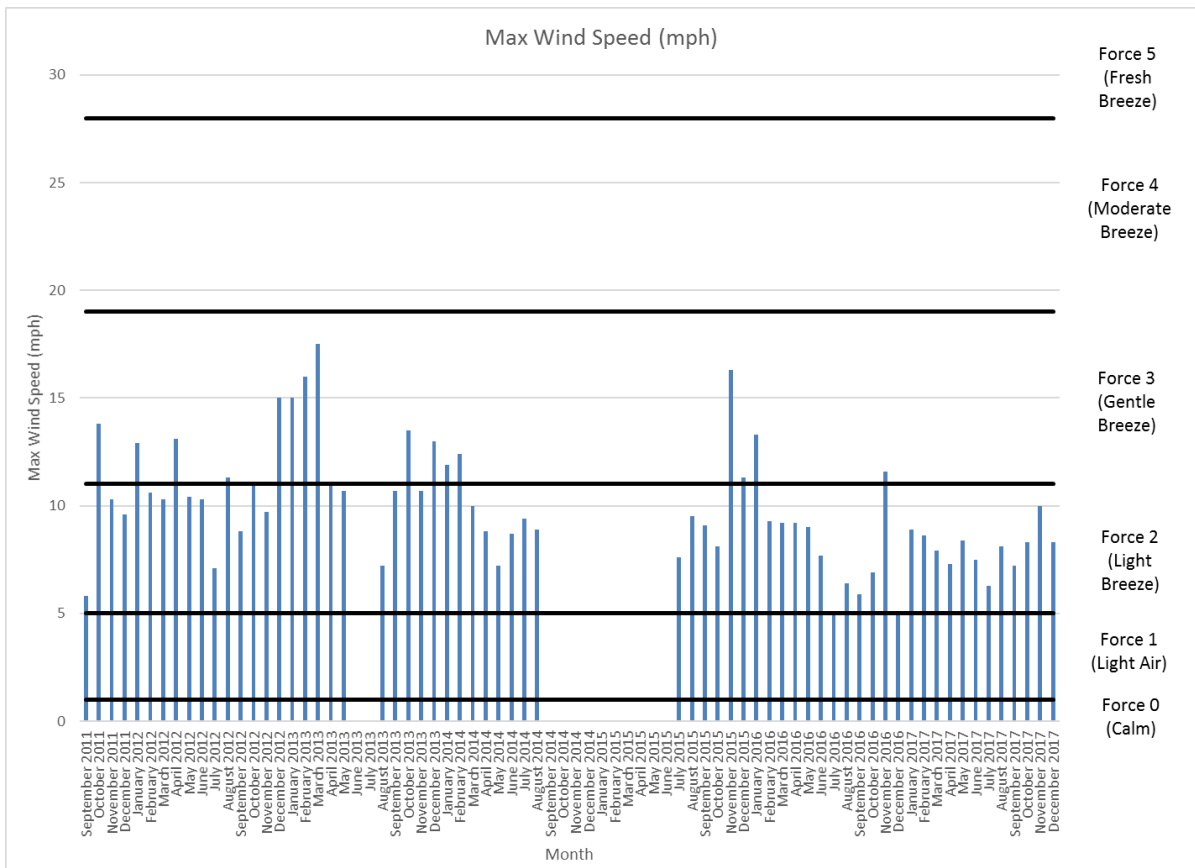


Figure 2.4 Maximum daily wind speed (2011 to 2017)

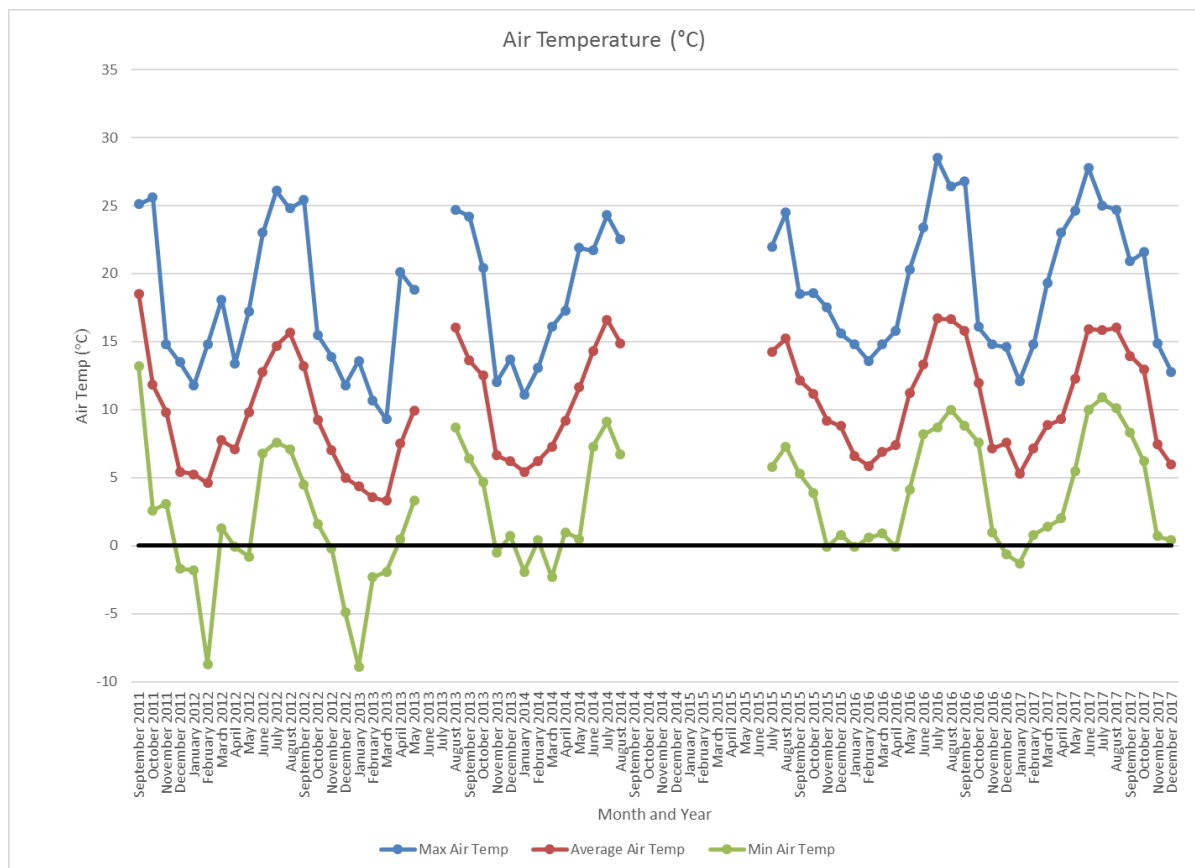


Figure 2.5 Air temperature variation (2011 to 2017)

### 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 that 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 that seen in December 2012, despite the exceptional event of 23 August, however a rapidly increasing trend in antecedent rainfall over the monitoring period is evident, unlike the pattern to the previous June to November monitoring period which saw a falling trend. Antecedent rainfall totals do not reach those seen in December 2012 and it is therefore concluded there is a low likelihood of rainfall-induced landslides occurring in the monitoring period. However, the antecedent

rainfall at the end of this monitoring period is relatively high, meaning if the winter of 2017/8 is wet, there would be an increased likelihood of ground movement in the next monitoring period.

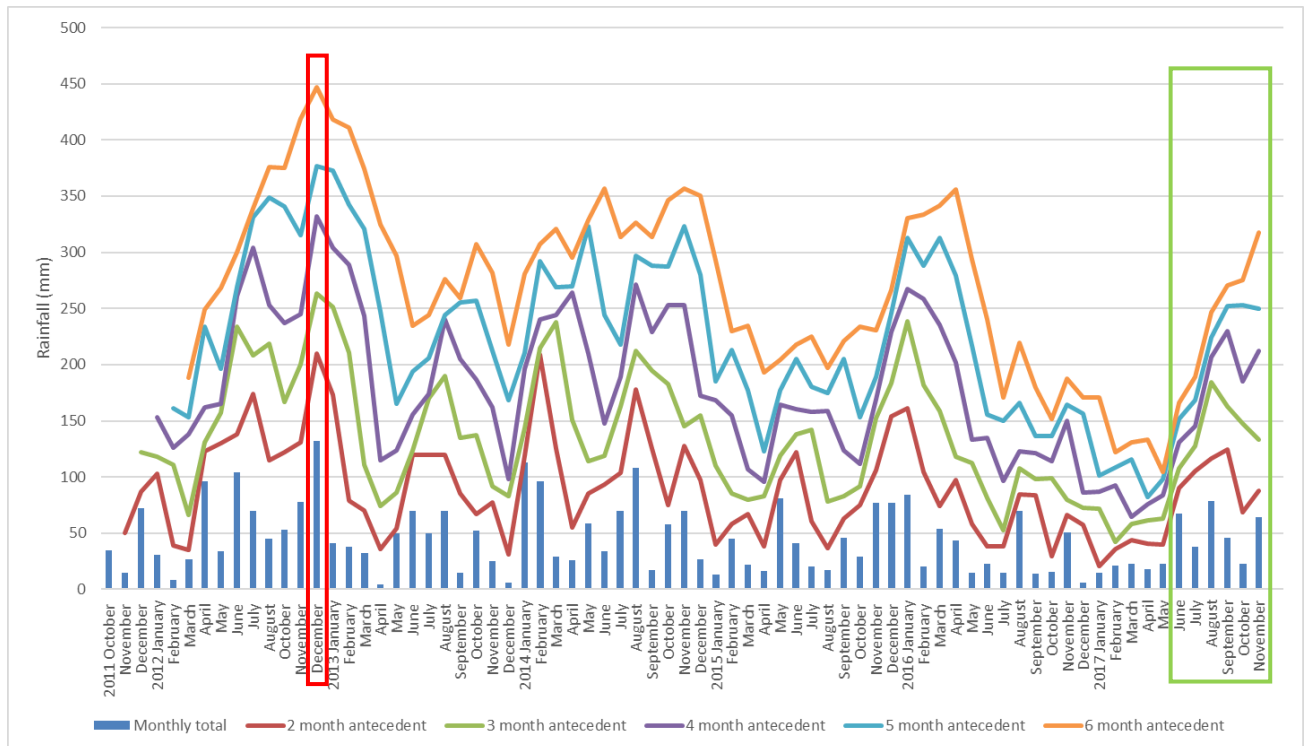


Figure 2.6. Monthly rainfall and two to six month antecedent totals (2011 to 2017). Ground movements were recorded at Scalby Mills during December 2012 (red box). Current monitoring period shown by green box.

## 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. This resulted in ground movement at Scalby Mills.
- 2013 was dry. After an unusually stormy spring period the temperatures remained high throughout the summer and rainfall in all months was below average.
- January and February 2014 were much wetter than average, and the period March to July 2014 was comparatively dry.
- While no data were recorded from early September 2014 to February 2015, a review of Met Office records shows the Autumn 2014 period was characterised by dryer than average conditions.
- MetOffice data purchased from Filey shows that the period Dec 2014 to April 2015 was generally much drier than average. Only May 2015 shows wetter than average conditions
- Data from Flat Cliffs collected in late 2015 shows September was wetter than average, and December was wet, although not exceptionally so. Rainfall peaks occurred on 14 September and 21 November and a sustained period of wet weather occurred from 25 to 30 December.
- Scarborough Spa weather station data collected over 2016 has shown that January, March and April have been slightly wetter than average. Rainfall peaked on 3 January and 28 March.

Overall, data has shown Dec 2015 to May 2016 to have been typically wet, with mild weather conditions.

- Between June and November 2016, rainfall has been lower than average apart from August where significant rainfall occurred on 4 and 25 August. Conditions over the 6-month period have been relatively dry and mild. Overall, data shows the 6-month period to have been relatively dry, with mild weather conditions suggesting a low likelihood of rainfall-induced landslides occurring.
- Summer 2017 has been significantly wetter than the previous two summers, and rainfall is above average during June and August where high daily rainfall totals were experienced during 28 June, 8 and on 23 August, when an exceptional storm occurred. Overall, autumn 2017 was drier than average, with average conditions occurring in November.

# 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 was appointed and all Stage 1 detailed design are complete with permissions to start work. Site works are due to start on the 12th of Feb, with completion aimed for the end of June 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 ( $30^{\circ}$  to  $40^{\circ}$ ) 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  $5^{\circ}$  and  $10^{\circ}$  over a distance of 10-15m. Where the slope angle exceeds  $35^{\circ}$  there are numerous shallow failures that tend to be caused by excessive water entrainment and generally leave behind triangular scars bounded by steep sides and disrupted vegetation. The mechanism is uncertain, but High Point Rendel (1998) suggests a model of superimposed mudslide lobes.
- Upgath Hill (MU 7/1) is the area north of Runswick Beck, beyond the village. The cliffs are formed in weathered Upper Lias shales capped by sandstone beds of the Saltwick Formation and thin veneer of till. Cliffs are fronted by steep talus slopes ( $20$  to  $30^{\circ}$ ) 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 – November 2017	
		1	2	3	4	5	6	7	8		
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 be 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 November 2017	
		1	2	3	4	5	6	7	8		
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 2017 is summarised in Tables 5.2 and 5.3.

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

The piezometer data show groundwater levels have remained relatively steady or increased slightly over the monitoring period. BH1a, which is a shallower piezometer, shows groundwater levels have returned to previous levels observed and remained steady following removal of tarmac that had been mistakenly laid over the borehole. The deeper borehole BH1b is dry and should be checked as equipment may be damaged and requires attention to determine whether they can be repaired. Readings for piezometer BH3a and BH3b shows groundwater levels have increased slightly from near historical lows during the monitoring period.

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

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
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.									No data available, borehole obstructed.	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 less than 1mm during the monitoring period, which is insignificant.	Incremental movements less than 1mm during the monitoring period, which is insignificant.

**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 November 2017	
			1	2	3	4	5	6	7	8		
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									Groundwater level at 29.4m OD, remaining stable around levels previous observed before the covering of tarmac, which may have affected previous readings.	Groundwater level remains steady at 29.3m OD.
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									Borehole dry. <b>Check piezometer integrity.</b>	Borehole dry. <b>Check piezometer integrity.</b>
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									Readings fall from 56.2m OD in October 2016, close to historical low at 47.5m OD in May 2016, the lowest groundwater level since 2012.	Groundwater levels increase slightly to 47.8m OD, close to the historical low.
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.	47.5m OD 56.7m OD 1.4m									Borehole dry. Readings from previous monitoring period indicate groundwater levels had fallen to historical low of 47.5m OD in October 2016. <b>Check piezometer integrity.</b>	Groundwater levels are at 56.2m OD, increasing from historical low in October 2016, however similar to previous readings that are below historical high.

## 5.5 Causal-response relationships

A subtle relationship between rainfall and groundwater levels, particularly in the shallower piezometer BH1a, was observed for the wet December of 2011 and the wet summer of 2012, and wet winter of 2015/2016. However, the dry conditions of 2013 were not reflected in the groundwater data, suggesting surcharge of groundwater from local sources may be occurring. Water levels in BH3a had fallen significantly in 2017 to their lowest since 2012, which may reflect the exceptionally dry conditions during winter 2016/17 and spring. There is also the possibility that the low resolution of monitoring at this location, particularly in shallow piezometers, may simply be picking-up short duration responses to brief but intense rainfall events.

## 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, and remained steady. BH3a and BH3b indicates groundwater levels are low and have increased slightly. These locations should be checked and the next monitoring data reviewed, whether this trend continues. Borehole BH1b was dry should be checked 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.	<p>Ground movement reported at 12.0m BGL in BH7 at contact between gravelly sand and sandstone between June and December 2010, indicative of a developing shear plane although this movement has not yet manifested itself as recession of the headscarp. A failure was observed near the base of CBU1 between March and April 2010.</p> <p>They report decreasing groundwater levels in CBU1, and peaks in groundwater levels in the shallower piezometers linked to intense rainfall events. Deeper piezometers remained at approximately the same level and were therefore less susceptible to variations in rainfall.</p>

## 6.4 New data

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

**Table 6.2 Summary of inclinometer data from Scalby Ness**

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
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 borehole extends to									No significant movement since last reading, Minor displacement that extends to ca. 2m BGL in clay is	No significant movement since last reading, Minor displacement that extends to ca. 2m BGL in



	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.									likely to be relatively shallow surface creep	clay is likely to be relatively shallow surface creep
BH07	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 less than 1 mm during the monitoring period, which is insignificant. No further movement along shear surface at c. 11 to 12m depth. Very minor displacement up to c. 2m depth within sand associated with shallow surface creep.	Incremental movements are less than 2 mm during the monitoring period, which is insignificant. No further movement along shear surface at c. 11 to 12m depth. Very minor displacement up to c. 2m depth within sand associated with shallow surface creep.

\*Surface elevations and borehole depths calculated from digital elevation model

**Table 6.3. Summary of groundwater data at Scalby Ness.**

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
P1a	Automated piezometer. Tip at approx.25.65m OD*. Surface elevation at c. 35.6m OD* (cliff top above CBU 1, co-located with P1b). Fluctuates between 27.5 and	27.1m OD 28.9m OD 1.8m									Data not downloaded since October 2015. Collect on next site visit.	<b>No data available.</b> Data logger communication error. Collect on next site visit.

	28.5m OD, with rapidly rising and falling peaks linked to higher rainfall and subsequent dry periods.										
<b>P1b</b>	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 since October 2015. Collect on next site visit.	<b>No data available.</b> Data logger communication error. Collect on next site visit.
<b>P2a</b>	Automated piezometer. Tip at c. 25.6m OD*. Surface elevation at c. 34.7m OD* (co-located with P2b). Fluctuates between 27.5 and 28.5m OD with peaks overlying a general trend of increasing water. Peaks and general trend correspond to the Filey rainfall record.	27.3m OD 28.7m OD 1.4m								Groundwater levels rise to 28.3m OD in March 2017, and fall gradually to 27.7m OD by May 2017.	<b>No data available.</b> Data logger communication error. Collect on next site visit.
<b>P2b</b>	Automated piezometer. Tip at c. -0.6m OD*. Surface elevation at c. 34.7m OD* (co-located with P2a). Prior to Oct 2009, ground water levels appear generally steady at c. 1.2m OD, except for fluctuations up to 2.5m OD in late 2007/early 2008. Records are absent between Oct 2009 and Mar 2010, after which levels are steady at around 2.5m OD.	0.9m OD 3.5m OD 2.6m								Readings remain steady at 2.4m OD.	<b>No data available.</b> Data logger communication error. Collect on next site visit.
<b>P3</b>	Automated piezometer. Tip at c. 10.5m OD*. Surface elevation at c. 30.7m OD. Steady at around 14.6-14.7m OD until Oct 2009.	14.2m OD 17.5m OD 3.3m								Data not downloaded since May 2016. Collect on next site visit.	<b>No data available.</b> Data logger communication error. Collect on next site visit.

	Apparent recalibration between Oct 2009 and Mar 2010 after which groundwater levels are again steady at ca.17.2-17.3m OD									
<b>P4a</b>	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							Groundwater levels rise to 13.9m OD in March and gradually fall to 13.3m OD by May 2017 in a saw-tooth pattern following previous readings.	<b>No data available.</b> Data logger communication error. Collect on next site visit.
<b>P4b</b>	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. Piezometer may need recalibration.	<b>No data available.</b> Data logger communication error. Collect on next site visit.
<b>WS4</b>	Tip at 9.9m OD. Surface elevation at 16.3m OD (midslope, CBU 2). Fluctuations from c. 10m OD to c.15m OD in response to long-term/seasonal rainfall patterns. Limited response to short-lived rainfall peaks.	10.0m OD 15.4m OD 5.4m							Groundwater level falls by 1.3m to 12.5m OD.	Groundwater level has fallen slightly to 12.2m OD.
<b>WS5</b>	Tip at 6.5m OD. Surface elevation at 11.3m OD (lower slope, CBU 2). Fluctuates between 6.5m OD and 7.5m OD between	6.5m OD 9.7m OD 3.2m							Borehole no longer functioning.	Borehole no longer functioning.

	September 2010 and June 2011 (low in summer/early autumn, high in winter).										
<b>WS6</b>	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 13.4m OD.	Groundwater level has remained steady at 13.4m OD.	
<b>B6</b>	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).	9.9m OD 13.8m OD 3.8m							Borehole dry. <b>Check piezometer integrity.</b>	Groundwater levels have fallen to a historical low at 9.9m OD.	
<b>B9</b>	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 level rises by 0.5m to 15m OD.	<b>No data available.</b> Access to borehole restricted as site is overgrown. Data should be collected on next site visit.	
<b>Sn2a</b>	Tip depth at c. 13.9m OD*. Surface elevation at 16.35m OD* (co-located with SN2b). Likely that past results for 2a and 2b confused or tip depth for Sn2a incorrect;groundwat	12.5m OD 13.3m OD 0.8m							Borehole dry. <b>Check piezometer integrity.</b>	Borehole dry. <b>Check piezometer integrity.</b>	

	er elevations not possible for tip depth stated.											
<b>Sn2b</b>	Tip depth at c. 8.35m OD*. Surface elevation at 16.35m OD* (co-located with SN2a). Likely that past results for 2a and 2b confused or tip depth for Sn2a incorrect. Sn2b shows groundwater levels between 1.6m OD and 11m BGL during 2011 and 2012.	10.3m OD 12.8m OD 2.5m									Groundwater levels fall by 2m to 10.8m OD.	Groundwater level falls slightly to 10.6m OD.

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

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- Auto-piezometers in boreholes P1a, P1b, P2a, P2b, P3, P4a and P4b all had data logger communication errors and therefore no data was collected for this monitoring period. Data loggers should be checked and communication errors resolved. Data should be collected on the next site visit.
- No data is available for piezometer in borehole B9. Access is restricted due to the site being overgrown at the time of data collection. This issue should be addressed and the data downloaded during the next site visit. Piezometer B9 showed significant increase in groundwater level in the previous monitoring period, and this trend should be reviewed in the next monitoring report.
- Piezometer in boreholes Sn2a was dry and its integrity requires checking on next site visit.
- Groundwater levels have fallen or remained steady in all other boreholes. Groundwater levels in borehole Sn2b have stabilised following significant drop in the previous monitoring period.
- The response to the extreme rainfall on 23 August was not identifiable given the intervals between data collection at the non-automated piezometers. The automated piezometer data is unavailable for this monitoring period; however, it should be reviewed following collection for the next monitoring report.

## 6.5 Causal-response relationships

The majority of shallow piezometers at Scalby Ness closely reflect the pattern of rainfall. Following a dry start to 2012, the spring and summer were exceptionally wet and the latter half of 2012 was wet. Peaks in groundwater were recorded during April, May July and December 2012. Overall, 2013, 2014, 2015 were drier than average. Piezometers installed with data loggers recorded falling 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 2017, 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 followed and have either fallen or remained steady from May 2016 to November 2017, which includes covers a period of above average rainfall for summer 2017.

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

The inclinometers in BH7 and L2 show significant periodic sub-surface movement. BH7 is the most pronounced and indicates movement on an existing shear surface in glacial sediments above sandstone bedrock. Movement occurred between November 2013 and March 2014, associated with a period of high groundwater levels (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 remained steady or fallen overall in the area. Rising water levels in Sn2b experienced from early to mid-2016 have returned to levels well below the historical high and remain steady. The earlier rise in groundwater suggested a discharge from cliff top developments or a natural response to the localised movement at the slope toe, though no movements were recorded in adjacent inclinometers. In addition, auto-piezometers in boreholes P1a, P1b, P2a, P2b, P3, P4a and P4b all had data logger communication errors, which require checking and readings to be re-taken on the next site visit. Piezometer in borehole Sn2a was dry and its integrity requires checking on next site visit. At borehole B9, overgrown vegetation that currently blocks the access path should be removed to enable access.

# 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**

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

## 7.4 New data

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

The new data indicate:

- No significant ground movements recorded in any of the inclinometers.
- Groundwater data show a continuation or slight increase in recent low levels. This is in response to wetter than average summer and drier autumn.
- Groundwater data show a continuation of, or further reduction in, recent low levels. This is in response to a drier than average winter and spring period. Short lived peaks in rainfall occurred in June and September and were recorded in BH3p, with a short lag.

- Elevated and increasing water levels in BH4p reflect the wetter than average conditions over this monitoring period. Sub-weekly fluctuations are atypical during drier months and may reflect local sources of groundwater from cliff top properties.

Table 7.2. Summary of inclinometer data at Oasis Café

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
<b>BH3</b>	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.
<b>BH4</b>	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 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 the rising trend in groundwater level over this period should be monitored. There is potential ingress of water from cliff top developments suggested by fluctuating groundwater levels during drier than average months.



**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 November 2017	
			1	2	3	4	5	6	7	8		
<b>BH2p</b>	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, fluctuating weekly up to 0.5m. Groundwater levels falling in March 2017 to 8.1m OD and rise stabilising to average of 8.4m OD.	Continuation of past pattern fluctuating weekly around an average of 8.2m OD. Groundwater level spikes on 23 August 2017 to 8.5m OD, coincident with high daily rainfall values.
<b>BH3p</b>	Tip depth at 12.4m OD. Situated in the midslope. Manual dip readings from Sept 2009 to Dec 2011 show fluctuation between ca. 13.8m OD (June 2010) and 14.7m OD (Dec 2010). Final manual reading May 2012 shows substantial rise to 17.6m OD, reflecting high rainfall during spring 2012.	13.5m OD 16.7m OD 3.2m									Groundwater levels remain around 14.1m OD, peaking up to 15.9m OD in January and March, steadily falling to May 2017.	Groundwater levels rise slightly to an average of 14.5m OD, peaking in mid-June and mid-September at 15.3m OD. Groundwater peaks on 25 August to 15.1m OD, possibly a lagged response to the 23 August rainfall event. Groundwater levels remain well below historical high.
<b>BH4p</b>	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 18.8m OD. Groundwater falls to 18.4m in late February, however through until May 2017 remains at an elevated position.	Continuation past cyclical pattern with sub-weekly variation. Groundwater levels have gradually risen to an average of 19m OD, briefly falling in mid-September to 18.7m OD. There are no clear response to the 23 August rainfall event.

## 7.6 Causal-response relationships

The higher than average rainfall in early winter 2015/2016 is reflected by elevated groundwater levels which fall in response to drier than average conditions which follow into 2017. On 23 August 2017 extremely heavy rainfall occurred, coinciding with a spike in groundwater levels at borehole BH2p, however this occurs only once in the record during high rainfall events. Borehole BH2p has an

unclear response to rainfall and/or tides. Shallow piezometer BH3p shows a very rapid response to rainfall events (which probably explains the spikes on 10 Aug and 8 Oct 2014, and 9 May and 12 Dec 2015, 3 Jan and 27 August 2016). Although a peak in groundwater in response to the 23 August rainfall event is evident, it is muted when compared to other high rainfall events. 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.

# Scarborough North Bay – The Holms

## 8.1 Site description

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

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

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

## 8.2 Ground model and monitoring regime

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

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

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

The monitoring regime at The Holms comprises:

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

## 8.3 Historical ground behaviour

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

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

<b>Observations in Mouchel 2012 (covering 6 month period between Dec 2011 and June 2012)</b>	<b>Total change observed between July 2009 and June 2012</b>
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 November 2017.

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 the exception of borehole L1a, which shows a slight increase.
- Borehole BH09a had data logger communication error and therefore no data was collected for this monitoring period. The data logger should be checked and communication errors resolved. Data should be collected on the next site visit.
- Piezometer BH9b is no longer functioning and the logger has been removed.

**Table 8.2. Summary of inclinometer data at The Holms**

Borehole	Summary of past data	Report Status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
<b>BH10A</b>	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.
<b>BH11</b>	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 and wet June and August 2017. The piezometers at The Holms show a lagged response to these conditions with only BH8a showing a rapid response to May 2015, March and November 2016 rainfall. Levels have fallen during winter 2016/2017 following months of dry conditions, and have since stabilised following a wet summer in 2017. Other boreholes show a continuation of past fluctuating or steady levels of groundwater, suggesting they respond to several months' antecedent rainfall. Over the whole record, BH8b shows a different pattern of gradual highs followed by sharp falls, however movements are not shown in the inclinometer upslope at BH10A. There is no clear response in any of the boreholes to the extreme rainfall event experienced on 23 August 2017.

## 8.6 Implications and recommendations

The data logger in borehole BH09a should be checked and have communication errors resolved. Data should be collected on the next site visit.

**Table 8.3. Summary of groundwater data at The Holms**

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
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. 0.5m in February.  Groundwater levels show an average decrease throughout the monitoring period, from 1.3m OD to 0.6m OD. Groundwater levels peak in late December 2016 to c. 1.3m OD, and are lowest during late February at 0.5m OD.	Continuation of past cyclical patterns, with 2 to 3 week variations of up to c. 0.3m in June and September.  Groundwater levels show an average increase throughout the monitoring period, from 0.6m OD to 0.9m OD. Groundwater levels peak in September to 1m OD, reflecting two months antecedent rainfall, and are lowest during June at 0.5m OD. There is no clear response to the extreme rainfall event on 23 August.
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 fallen from 4.3m OD in December 2016 to 4.1m OD in May 2017. Groundwater level falls close to the historical low at 3.8m OD in late February 2017, and rapidly rise again to steady levels. 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.	Continuation of 2 to 3-week cyclical pattern, with variations up to 0.5m in June.  Groundwater levels show a falling trend, averaging around 3.9m OD. Lowest recorded levels occur during June and September. These levels have not occurred since December 2013. There is no clear response to the extreme rainfall event on 23 August.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
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 fall during this monitoring period from an average of 10.5m OD in Dec 2016 to 10.3m OD in May 2017. Large cyclical variation occurs between January and March by 0.5m, close to historical lows. 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.	Groundwater levels remain relatively steady over the monitoring period, around an average of 10.4m OD. Variation of up to 0.5m occurs during June and September, where groundwater levels fall rapidly to 10m OD and return to more stable levels. There is no clear response to the extreme rainfall event on 23 August.
BH8b	Tip depth at 3.16m OD. BH top at 31.16m OD, co-located with BH8a. Groundwater levels dropped from an initial high of 17.3m OD at installation in Sept 2010 to a low of 9.55m OD in Feb 2011. Levels then gradually rise through 2011 to c. 10.6m OD in Dec 2012 before a sharp rise to 22.2m OD by May 2012. This shows a similar rainfall-influenced pattern to BH8a.	9.4m OD 14.5m OD 5.1m									Groundwater levels continue a saw-tooth pattern, rising to 11.7m OD between Dec and Feb, then rapidly falling to 10m OD, remaining steady.	Groundwater levels continue a saw-tooth pattern, rising to 11.7m OD between June and September, then rapidly falling to 9.7m OD in October and remaining stable. There is no clear response to the extreme rainfall event on 23 August.
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									Data retrieved for previous and current monitoring period shows groundwater falls until December 2016, after which levels rise in January to 18.7m OD. Levels remains steady at an average of 15.9m OD until May 2017.	No data available. Data logger communication error. Collect on next site visit.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
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 gradual fall 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 longer functional. Piezometer should be repaired.	Borehole no longer functioning. Logger removed.



# Scarborough South Bay

## 9.1 Site description

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

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

## 9.2 Ground model and monitoring regime

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

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

The areas being monitored comprise, from north to south:

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

These areas include both pre-existing landslides and 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 November 2017
		1	2	3	4	5	6	7	8	
FR01	FR01 is situated above Foreshore Road in front of the Grand Hotel at 11.43m OD. The borehole is c.20m deep with its base at c.-8.5m OD and passes through c.10.5m of made ground and 9.5m of fine grained glacial sediments. FR01 has been monitored since 16 June 2014.								Readings show less than 1mm movement and are not significant.	Readings show less than 1mm movement and are 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 November 2017	
			1	2	3	4	5	6	7	8		
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.	6.6m OD 8.4m OD 9m									Continuation of past cyclical pattern, with groundwater levels averaging at 7.6m OD.	Continuation of past cyclical pattern, with groundwater levels falling rapidly to historical low of 6.6m OD mid-August and remaining at an average of 6.8m OD. Groundwater spikes on 23 August to 7.3m OD, however well within range of previous records.

No ground movement is recorded at this site and water levels have fallen to a new historical low.

#### 9.4.2 Spa Chalet (MU 22/1)

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

Table 9.4 Summary of inclinometer data at Spa Chalet

Borehole	Summary of past data	Report Status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
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 November 2017	
			1	2	3	4	5	6	7	8		
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									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.	No data recorded for monitoring period, unable to connect to data logger. Last data recorded in May 2016. This site requires attention.
BH12a	Tip at 3.6m AOD. High degree of variability, with rapid fluctuation about a mean water level of c. 3.6m above OD. Peak water levels are c. 3.9m 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. Fluctuation ranges from 3.3 to 3.9m OD, averaging 3.6m OD. Large cyclical variation occurs between January and March 2017, close to the historical low.	Range of fluctuations within past limits and linked to tidal cycles. Groundwater levels remain steady. Fluctuation ranges from 3.3 to 3.7m OD, averaging 3.6m. Large cyclical variations occur in September, close to the historical low. There is no clear response to the extreme rainfall event on 23 August.

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 November 2017	
		1	2	3	4	5	6	7	8		
AA04 (G2)	40.5m deep borehole penetrating 34.5m of glacial sediments and 6m of sandstone/siltstone bedrock.									No significant movement.	No significant movement.

	Ground level is 47.62m OD, base of hole is 7.12m OD.										
BH13	61m deep borehole inland of the headscarp that penetrates 52m of glacial sediment and 9m of sandstone bedrock. Ground level is 53.93m OD, base of hole at -7.07 OD. Deflection of up to 80mm in the upper 35m (i.e. above 19m OD) of the borehole associated with creep.								No significant movement.	No significant movement. Pattern of recorded movement appears erroneous and it is likely the borehole is blocked and requires clearing.	
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 movement.	No significant movement.	
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 movement.	No significant movement.	
BH109	15m deep borehole that passes through 9m of glacial sediment and 6m of sandstone/mudstone bedrock. Ground level is 31.6m								No significant movement.	No significant movement.	

	OD, base of hole is 16.6m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm.										
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 movement.	No significant movement.
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 December 2016 and September 2017 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.	AE measurements between March 2017 and February 2018 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 November 2017	
			1	2	3	4	5	6	7	8		
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									Groundwater levels reach the historical high at 17.6m OD in December 2016. Levels slightly decrease towards May 2017, averaging 17.3m OD, with large rises and falls in March close to the historical low of 16.8m OD.	Groundwater levels decrease slightly, averaging 17.2m OD. There is a cyclical sub-weekly pattern, where groundwater varies up to 0.3m, falling to 16.9m OD in September. There is no clear response to the extreme rainfall event on 23 August.
H2b	Located near the headscarp of the Spa landslide. Tip at 11.1m AOD. 3 to 7 day	12.0m OD 13.0m OD 1.0m									No change in pattern, groundwater levels steadily fluctuate around an average of 12.6m OD. In March	No data available. Data logger communication error.

	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 on 3 June 2013 and 7 July 2013, minimum of 12.3m OD on 14 December 2012.							2017, groundwater levels fluctuate greatest between 0.5m.	Repair/collect on next site visit.
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						Water levels follow a saw-tooth pattern, with a sharp rise and gradual fall that fluctuates between 22.2m OD and 22.7m OD. This pattern and range reflected the past data. The rapid rises in groundwater coincide with heavy rainfall in April and May, however some peak rainfall events recorded in the summer do not show the same response in groundwater levels. In the period since May the magnitude of change is greater and water levels are elevated between 21.6m OD and 22.7m OD. A sharp peak in groundwater level in February is assumed to be error.	Water levels follow a saw-tooth pattern, with a sharp rise and gradual fall that fluctuates between 21.7m OD and 22.7m OD. This pattern and range reflected the past data.  The rapid rises in groundwater occur following two months antecedent heavy rainfall however some peak rainfall events recorded in the summer do not show the same response in groundwater levels. The 23 August event may be reflected in the rapid rise in groundwater level during October.
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	6.7m OD 11.9m OD 5.2m						Groundwater levels rise to 9m OD in May 2017, though well below historical high.	Borehole dry. <b>Check piezometer integrity.</b>

	2008 and Aug 2009.										
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 during the winters of 2010 and 2011.	7.2m OD 12.1m OD 4.9m								Groundwater levels rise slightly to 10.1m OD in May 2017.	Groundwater levels rise slightly to 10.4m OD in October.
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 fall slightly to 11.8m OD in May 2017.	Groundwater levels rise slightly to 12m OD in October.
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 fall slightly to 11.4m OD in May 2017.	Groundwater levels rise slightly to 11.6m OD in October.
G3	Located near the base of the cliff. Tip at 13.6m OD. Complex pattern comprising c. 7 month period	13.2m OD 14.4m OD 1.2m								Groundwater level increased slightly by March 2017 and remains steady at an average of 13.4m OD.	Groundwater level rises slightly to 13.6m OD in October.



	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 13.5m 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							Borehole dry. <b>Check piezometer integrity.</b>	Borehole dry. <b>Check piezometer integrity.</b>
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, greatest between January and March 2017 at 0.5m. Average groundwater level c. 4.5m OD.	Continuing cyclical pattern overlain onto steady groundwater levels during the monitoring period. Fluctuations within range of previous records, falling in mid-September by 0.3, and increasing to 4.6 in October. Average groundwater level c. 4.5m OD. There is no clear response to the extreme rainfall event on 23 August.
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	12.0m OD 12.8m OD 0.8m							Continuing cyclical pattern in groundwater levels. Reaches new historical high in December 2016 at 12.8m OD, and fluctuates between January and March up to 0.7m. Groundwater levels averaging 12.6 in	Continuing cyclical pattern, shows falling groundwater levels from June to October to an average of 12.4m OD. Groundwater levels fall rapidly in September to 12.1m OD, close to historical

	OD. Water levels highest in late Feb 2012 when they reached 12.7m OD. Sub-weekly fluctuations were up to 0.5m in the period Oct 2012 to Mar 2013.								May 2017. Nearby inclinometer BH101 shows no significant ground movement.	low. There is no clear response to the extreme rainfall event on 23 August.
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							Groundwater level shows a net decrease during the monitoring period. A significant drop in groundwater of c.0.5m levels occurs in February. This is assumed to be a systematic error. Between February and May water levels increase slightly by 0.2. Water levels decrease gradually into June, averaging 42.1m OD, within the historical range. <b>Check piezometer integrity</b>	Groundwater level is steady around an average of 42.1m OD. There is no clear response to the extreme rainfall event on 23 August.
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. <b>Check piezometer integrity</b>	Borehole dry. <b>Check piezometer integrity</b>
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							Borehole dry. <b>Check piezometer integrity</b>	Groundwater level at historical low of 19.2m OD.

BH108a	Deep piezometer tip located mid-slope. Solinst data logger. Record begins on 18 Dec 2012 and shows several sharp fluctuations that may be a response to rainfall events or ingress of surface water.	9.3m OD 31.4m OD 22.1m							Groundwater levels continue to fall over monitoring period to 23.1m OD by May 2017.	Groundwater levels continue to fall over monitoring period to 22.7m OD. There is no clear response to the extreme rainfall event on 23 August.
BH108b	Shallow piezometer tip co-located with deeper BH108a. Dry between Sept 2012 and Jan 2013.	25.6m OD 31.6m OD 6m							Borehole dry. <b>Check piezometer integrity</b>	Borehole dry. <b>Check piezometer integrity</b>
BH106a	Located at the cliff top. Solinst data logger. Borehole dry between Oct 2012 and Jan 2013.								Borehole dry. <b>Check piezometer integrity</b>	Borehole dry. <b>Check piezometer integrity</b>
BH106b	Located at the cliff top. Located at the cliff top. Borehole dry between Oct 2012 and Jan 2013.	n/a (dry)							Borehole dry. <b>Check piezometer integrity</b>	Borehole dry. <b>Check piezometer integrity</b>
BH104a	Located near the base of the slope. Solinst data logger.	5.0m OD 20.0m OD 15.0m							Groundwater levels remain steady at 4.3m OD. No fluctuation.	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 remains steady at 10.3m OD, which is close to historical high.	Groundwater level increased to 10.8m OD, close to historical high.
BH102a	Located at the base of the slope behind the seawall. Solinst data logger.	0m OD 2.6m OD 2.6m							Slight increase in average groundwater levels to 1.6m OD over monitoring period.	No data downloaded. Borehole filled with tarmac.
BH102b	Located at the base of the slope behind the seawall. Manual piezometer.	1.1m OD 2.1m OD 1.0m							Decrease in groundwater to 1.6m OD.	No data downloaded. Borehole filled with tarmac.

These data indicate:

- Inclinerometers show no significant movement in the monitoring period. Movements recorded in inclinometer in BH13 appear erroneous, and the borehole may be blocked.
- Most locations show continuation of past patterns or slight increases/decreases in water level over the monitoring period, with the exception of BH104b which indicates continued elevated groundwater levels towards the historical high. This trend should be reviewed in the next report. Almost all piezometers do not show a clear groundwater response to the extreme rainfall event on 23 August.
- Piezometers 1 Spa, 5 Spa, G1a, G1b, BH106a, BH106b and BH108b should be checked because they were dry. This equipment may be damaged and required attention to determine whether they can be repaired.
- 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. This trend should be reviewed in the next report.
- Piezometer data from H5 are now collected via telemetry, and show water levels follow the same saw-tooth pattern recorded previously. Sharp increases in groundwater level tend to occur in response to two months antecedent peak rainfall events. Heavy rainfall in June is reflected in the rapid rise during early August, and another rapid rise in October possibly in response to the extreme rainfall event on 23 August. This location should be checked and the trend should be reviewed in the next report.
- Boreholes BH102a and BH102b have been filled with tarmac and the piezometers are no longer functional.
- 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)

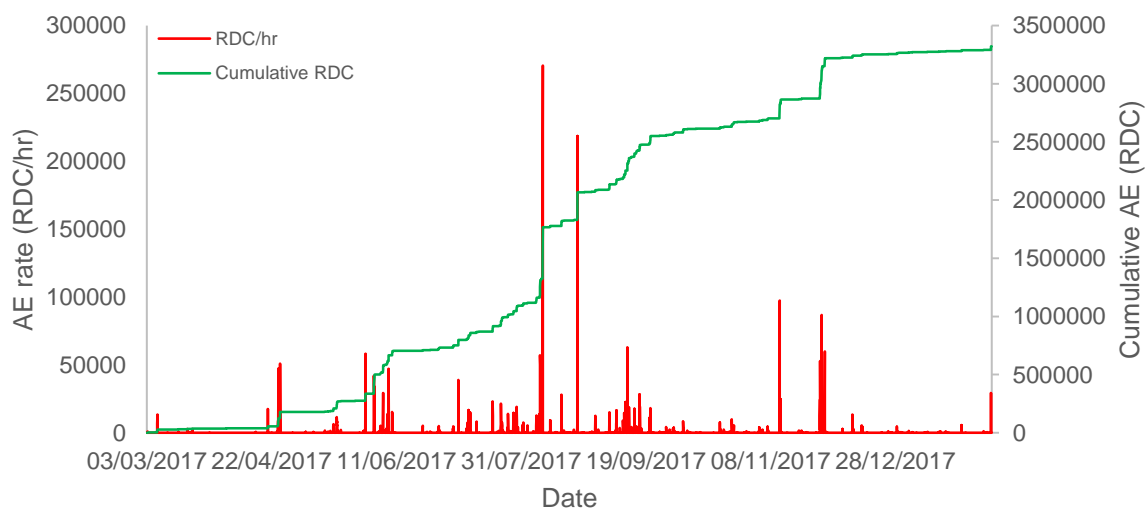


Figure 9.2. Cumulative AE (RDC) and AE rate (RDC/hr) time series at Scarborough Spa for the period March 2017 to February 2018.

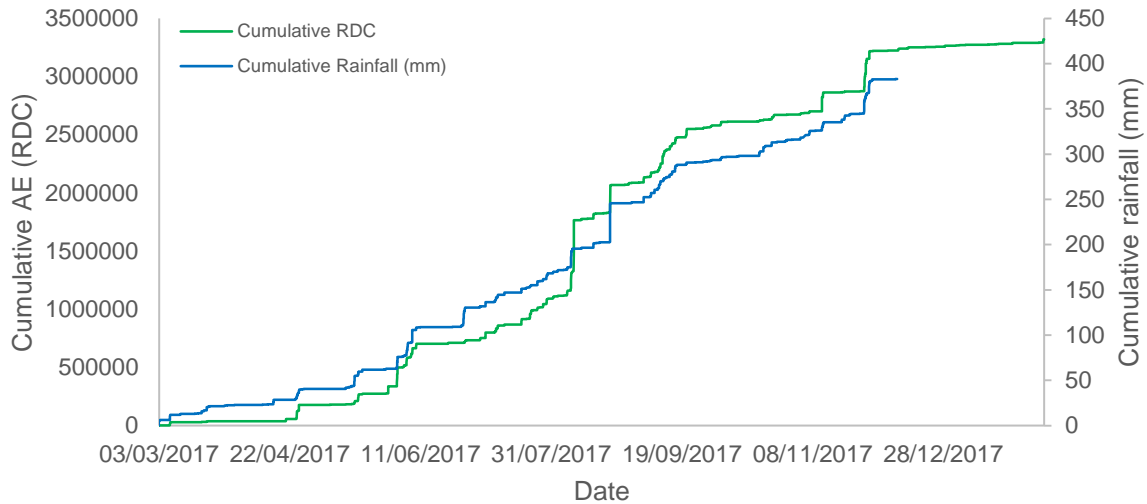


Figure 9.3. Cumulative AE (RDC) and cumulative rainfall time series at Scarborough Spa for the period March 2017 to February 2018.

### 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 November 2017	
		1	2	3	4	5	6	7	8		
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 data. Collect data on next site visit.	Readings are less than 1mm and therefore not significant.
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.									Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

Table 9.9. Summary of groundwater data at the Clock Café

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
BH15	Located inland of the landslide headscarp. No historical data	n/a									Borehole dry. Check piezometer integrity	Borehole dry. Check piezometer integrity

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 Cliff Gardens

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
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.	Readings are less than 1mm and therefore not significant.
BH17	50m deep borehole than penetrates 34m of glacial sediment and 16m of siltstone bedrock at the top of a mudslide embayment. Ground level is 57.46m OD, base of hole at 7.46m OD.									No significant change.	Readings are less than 1mm and therefore not significant.
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.	Readings are less than 1mm and therefore not significant.
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.	Readings are less than 1mm and therefore not significant.

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

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
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 42.6m OD 6.1m									Groundwater rises rapidly from an average of 34.5m OD in Dec to c. 39m OD in late February to March 2017, where it stabilises in an elevated position relative to earlier records.	Groundwater levels spike coinciding with high daily rainfall totals in June and August to 42.6m OD, a new historical high. In October, groundwater level falls to 36.1m OD.
BH18b	Tip at 23.8m OD near the base of the cliff and Rose Garden landslide. Pattern very similar to BH18a installed higher in the borehole	34.3m OD 42.4m OD 6.1m									Previous records show the same pattern and water levels as BH18a. These now differ over this monitoring period whereby there is only a slight rise in average groundwater levels to 34.8m OD, close to the historical low.	Previous records show the same pattern and water levels as BH18a. These now differ over this monitoring period whereby there is only a slight rise in average groundwater levels to 35m OD, close to the historical low. Groundwater level peaks to 36.4m OD on days coinciding with heavy rainfall.
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 62.4m OD 9.5m OD									Cyclical pattern with magnitude of variation ranging 0.7m averaging 52.9m OD. Peaks in groundwater levels in December 2016 and falls in February.	Cyclical pattern with magnitude of variation ranging 0.7m averaging 52.9m OD.  On 23 August, groundwater spiked well above the historical high to 62.4m. This coincides with a day of extremely heavy rainfall.
BH19b	Tip at 47.3m OD inland of the headscarp of the South Bay Pool landslide. Sub-metre variation	47.1m OD 53.4m OD 6.3m									Continuation of sub-weekly fluctuation of c. 1.m about monthly variation. Overall	Continuation of sub-weekly fluctuation of c. 1.m about monthly variation. Overall

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
	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.										steady decline, averaging 47.5m OD.	steady decline, averaging 47.5m OD.  On 8 June and 23 August, groundwater levels spiked to 49.9m OD and 53.4m OD respectively, coinciding with high daily rainfall totals.
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 0.5m.	Levels remain steady around 31.6m OD with sub-weekly fluctuations of up to 0.5m.  Groundwater spiked on 23 August coinciding with high daily rainfall totals, to 32.4m OD.
D2b	Tip at 41.5m OD at the headscarp of the South Bay Pool landslide. Pattern similar to that recorded by lower elevation tip, with sub-metre variation about mean of c. 45.8m OD. Slight peak in water level occurred in late Nov to late Dec 2012. Gap in data between April and Aug 2013.										No data, logger to be checked.	No data, logger to be checked.
Bh3a	Tip at 41.5m OD at a mid-slope position adjacent to the South Bay Pool landslide. Sub-metre variation about a mean value. Change occurs in Apr 2013, before which mean is 44.5m OD, after	Original logger: 43.6 44.8 1.2 Replacement logger: 45.6m OD 50.0m OD 4.4m									No data, logger to be checked.	No data, logger to be checked.



Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
	which it drops to c. 44m AOD.											
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									No data since May 2016, logger to be checked.	Levels remain steady around 10.6m OD with sub-weekly fluctuations of up to 0.5m. Groundwater spiked on 8 June and 23 August coinciding with high daily rainfall totals, increasing to 12.6m OD and 14.3m OD respectively.
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 gradually to 44.7m OD in Oct 2013	43.3m OD 46.5m OD 3.2m									Groundwater level gradually continues to fall to 43.5m OD in March, where it stabilises at 43.7 in May 2017.	Groundwater level gradually continues to fall to 43.5m OD, where it stabilises. There is no clear response to the extreme rainfall event on 23 August.
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 remain steady averaging c. 50.4m OD, except for a rapid fall in March 2017 by 0.5m.	Groundwater levels remain steady averaging c. 50.4m OD, except for a rapid fall in September by 0.4m. There is no clear response to the extreme rainfall event on 23 August.

These data indicate:

- No movement has been recorded in any boreholes at South Cliff Gardens.
- Overall, groundwater levels have mostly remained steady during the monitoring period; however, a number of piezometers exhibit a rapid response to high daily rainfall totals,

specifically on 8 June and 23 August. Groundwater spikes within borehole BH18a and to a lesser amount in deeper borehole BH18. Groundwater also spiked in deep boreholes BH19a and BH19b at/near historical highs, and to a lesser degree in D2a and BH3b. The spikes in groundwater level within boreholes BH19a and BH19b in response to the 23 August extreme rainfall event were much greater when compared to other spikes in groundwater occurring as a result of lesser rainfall events. In other boreholes, however, peaks in groundwater level were relatively similar. This suggests surface water ingress and the contractor should ensure that plastic caps are in place and that water cannot collect at the top of the boreholes. These piezometer data should be reviewed during the next monitoring period. There are no significant ground movement in nearby boreholes.

- Borehole piezometers D2b and BH3a should be checked and repaired.

#### 9.4.6 Holbeck Gardens (MU 22/7)

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

**Table 9.12. Summary of inclinometer data at Holbeck Gardens**

Borehole	Summary of past data	Report status								Change June to November 2017
		1	2	3	4	5	6	7	8	
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.								Readings are less than 1mm and therefore not significant.	Readings are less than 1mm and therefore not significant.

**Table 9.13. Summary of groundwater data at Holbeck Gardens**

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>Bh4a</b>	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. <b>Check integrity of piezometer.</b>	Unable to download logger data. <b>Check integrity of piezometer.</b>
<b>Bh4b</b>	Tip at 35m OD. Different pattern to records of shallower tip. Highly variable	31.8m OD 59.9m OD 26.7m									Unable to download logger data. <b>Check integrity of piezometer.</b>	Unable to download logger data. <b>Check integrity of piezometer.</b>

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

## 9.5 Causal-response relationships

Groundwater levels in South Cliff tend to show a slight increase or remain steady. Some piezometers with data loggers show a response to the peak rainfall event on 23 August event, however, the most common response is for elevated water levels during October, which suggests a lagged response to the event, and/or a relationship to the 5 or 6 month antecedent rainfall (Figure 2.6). 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 remained steady or increased slightly. Several show short-lived peaks in water level that suggests ingress of surface water during heavy rainfall. Checks should be made at these locations to ensure water-proof caps are in place. At South Bay Gardens in borehole BH18a, groundwater levels have risen to an elevated position relative to earlier records, however no significant ground movement was recorded by nearby inclinometers. This record should be reviewed during the next monitoring period to check whether this trend continues. Similarly, elevated groundwater levels in BH104b and H5 at Scarborough Spa should be checked and reviewed during the next monitoring period.

No data were collected at a number of piezometers including BH12 (Spa Chalet), H2b (Spa), D2b, BH3a (South Cliff Gardens), and BH4a and BH4b (Holbeck Gardens) due to data logger communication errors. Boreholes BH102a and BH102b at the Spa are have been filled with tarmac and are no longer functional. Boreholes 1 spa, 5 spa, G1a, BH106a, BH106b, BH108b (Spa) and BH15 (Clock Café) are recorded as dry. The integrity of piezometer tips should be checked and the next monitoring data reviewed, whether these trends continue.

Inclinometer data at borehole BH13 at the Spa appears erroneous. It is likely that the borehole is blocked and requires clearing.

# 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
<p>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.</p>	<p>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 &lt;5mm were noted in BH6 but no further movements have been identified.</p>

## 10.4 New data

Tables 10.2 and 10.3 summarise the inclinometer and piezometer data from Filey Town to June 2017.

These data indicate:

- No movement has been recorded in any boreholes at Filey Town.
- Water levels are generally stable or increasing slightly in most boreholes.
- Groundwater levels remain elevated in borehole CPBH01a near to the historical high, following a previous fall to lower levels. It is possible the borehole was flooded by surface water flows.
- Groundwater levels also remain elevated in boreholes CPBH02a, CPBH06a and CPBH10a. A rapid increase in groundwater levels occurs in CPBH10a following high daily rainfall totals on 8 August and remains elevated, however the extreme rainfall on the 23 August showed no clear response in the groundwater level.
- Boreholes BH4, CPBH02, CPBH08b and CPBH10b were dry.
- Data logger communication errors occurred at boreholes CPBH01b, CPBH04b, CPBH06b, CPBH08b and CPBH09b, and data was not downloaded for this monitoring period.

- Borehole CPBH03 (inclinometer) was obstructed and data were not downloaded for this monitoring period.

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

Table 10.2. Summary of inclinometer data at Filey Town.

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
<b>CPBH03</b>	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 data, borehole obstructed. Collect on next site visit.	No data, borehole obstructed. Collect on next site visit.
<b>CPBH05</b>	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.	Readings are less than 1mm and therefore not significant.
<b>CPBH07</b>	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.	Readings are less than 1mm and therefore not significant.
<b>BH6</b>	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.	Readings are less than 1mm and therefore not significant.

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

Table 10.3. Summary of groundwater data at Filey Town

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>BH5b</b>	Tip depth at 1.09m OD. Levels constant with limited fluctuation between 1.1m OD (Aug 2008) and 1.7m (Dec 2009).	1.1m OD 7.5m OD 6.4m									Groundwater levels fall slightly to 1.5m OD by May 2017.	Groundwater levels remain steady at 1.5m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>BH4</b>	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									Groundwater levels decrease to 20.6m OD by May 2017.	No data available. Borehole is dry. Repair/collect on next site visit.
<b>CPBH01a</b>	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									Groundwater level rises by 0.9m close to historical high at 26.1m OD.	Groundwater level falls slightly to 26m OD, and remains elevated close to the historical high.
<b>CPBH01 b (Diver)</b>	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. Manual dip readings at 33.9m OD, which suggests levels remain within the range of previous records.	Data logger communication error. Repair/collect on next site visit.  Manual dip readings at 34.1m OD, which suggests levels rise slightly within the range of previous records.
<b>CPBH02a</b>	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									Groundwater levels fall slightly to 4.9m OD, remaining at an elevated position.	Groundwater levels increase slightly to 5m OD, remaining at an elevated position.



Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>CPBH02 b (Diver)</b>	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, which is credible and reflects past records, but manual dip readings indicate borehole is dry. <b>Recommend installation integrity is checked.</b>	Water level steady at 8.6m OD, which is credible and reflects past records, but manual dip readings indicate borehole is dry. <b>Recommend installation integrity is checked.</b>
<b>CPBH04a</b>	Tip at 2.90m OD. Mean ground water level at 7.2m OD, with range of fluctuation between 7.02m OD (06/09/2012) and 7.33m OD (19/04/2012).	7.1m OD 32.9m OD 25.8m									Groundwater levels fall slightly to 7.1m OD.	Groundwater levels rise slightly to 7.2m OD.
<b>CPBH04 b (Diver)</b>	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									No data. Readings to be re-taken. Manual dip readings at 13.3m OD, which suggests levels are static.	Data logger communication error. Repair/collect on next site visit.  Manual dip readings at 13.3m OD, which suggests levels are steady and within the range of previous records.
<b>CPBH06a</b>	Tip depth at 0.13m OD. Mean groundwater elevation at 19.86m OD. Range between 18.85m OD (27/02/12) and 20.11 (20/12/12). Notable increase in Mar/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									No data, readings to be re-taken. Manual dip readings indicate groundwater levels rise slightly to 19.1m OD.	Groundwater levels rise to 19.4m OD.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>CPBH06 b (Diver)</b>	Tip depth at 8.63m OD. Steady at c. 18m OD except for sudden drop to around 14.5m OD and immediate recovery on 20/03/12 and 06/09/12 and sudden drop on 19/04/12 followed by a prolonged steady period at c. 15m OD before sudden recovery on 24/05/12 to 18m OD.	9.2m OD 19.1m OD 9.9m									No data. Readings to be re-taken.	Data logger communication error. Repair/collect on next site visit. Manual dip readings at 19m OD, which suggests levels are steady and within the range of previous records.
<b>CPBH08a</b>	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									Groundwater levels remain steady at 9.6m OD.	Groundwater levels rise slightly to 9.7m OD.
<b>CPBH08 b (Diver)</b>	Very steady with fluctuations over whole period only between 17.90m OD and 17.97m OD.	17.7m OD 19.3m OD 1.6m									No data. Readings to be re-taken. Dip meter data indicates borehole is dry. <b>Recommend installation integrity is checked.</b>	No data. Readings to be re-taken. Dip meter data indicates borehole is dry. <b>Recommend installation integrity is checked.</b>
<b>CPBH09a</b>	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									Groundwater levels rise slightly to 20.4m OD.	Groundwater levels fall slightly to 20.3m OD.
<b>CPBH09 b (Diver)</b>	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 fall to 20.1m OD, which is corroborated by dip meter data.	Data logger indicates water level is at 3m OD, however manual dip readings are at 19.4m OD, suggesting a data logger communication error. Repair/collect on next site visit.

Borehole	Long-term Pattern	Groundwater summary Min/Max/Range	Report Status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>CPBH10a (Diver)</b>	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, with gradual increase in underlying groundwater level. Peaks in March 2017 at c. 29.4m OD.	Groundwater rises in mid-August and remains at elevated position averaging 29.9m OD, close to the historical high. Rapid increase in August coincides with high daily rainfall totals on 8 August, however the response to the extreme rainfall event on 23 August is unclear.
<b>CPBH10b</b>	Tip depth at 11.92m. No data prior to October 2013 due to blockage by slip rod.	n/a (dry)									Borehole dry <b>Recommend installation integrity is checked.</b>	Borehole dry <b>Recommend installation integrity is checked.</b>

## 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. Muted antecedent rainfall responses are also noted in CPBH06a and CPBH09a. There is no clear response in groundwater level following the extreme rainfall event on 23 August in any of the boreholes. Most of the piezometers show steady groundwater levels or slight increases, reflecting the relatively wetter and mild conditions during the monitoring period. There has not been movement in inclinometers and therefore no relationships between groundwater and ground movement have been identified.

## 10.6 Implications and recommendations

No data are available for boreholes CPBH01b, CPBH04b, CPBH06b, CPBH08b and CPBH09b and require readings to be re-taken on the next site visit. Boreholes BH4, CPBH02, CPBH08b and CPBH10b were dry and require investigation and repair work where necessary. The rising trend in groundwater levels towards the historical high in CHBH10a should be monitored and reviewed in the next monitoring report. Groundwater levels in CPBH01a, CPBH02a and CPBH06a remain elevated and should also be reviewed in the next report to see whether this trend continues.

Borehole CPBH03 was obstructed during the site visit and data should be collected for the next monitoring report.



# Filey Flat Cliffs

## 11.1 Site description

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

## 11.2 Ground model and monitoring regime

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

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

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

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

## 11.3 Historical ground behaviour

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

Table 11.1. Summary of historical ground behaviour at Flat Cliffs

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

## 11.4 New data

Tables 11.2 and 11.3 summarise the monitoring results from inclinometers and piezometers at Flat Cliffs up to November 2017.

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 November 2017	
		1	2	3	4	5	6	7	8		
<b>A2</b>	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.	Readings are less than 1mm and therefore not significant.
<b>C1</b>	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.	Readings are less than 1mm and therefore not significant.
<b>C2</b>	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. Minor displacement extending to c. 1.5m depth, likely relatively shallow surface creep in glacial sediment.	No significant movement. Minor displacement extending to c. 1.5m depth, likely relatively shallow surface creep in glacial sediment.
<b>C5</b>	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. Minor displacement extending to c. 1m depth, likely relatively shallow surface creep in glacial sediment.	No significant movement. Minor displacement extending to c. 1m depth, likely relatively shallow surface creep in glacial sediment.

Borehole	Summary of past data	Report status								Change June to November 2017	
		1	2	3	4	5	6	7	8		
<b>C1A</b>	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 Dec 2016 and Sept 2017 do not appear to show significant slope movements. The periods of elevated AE activity could be indicative of deformations but of a very slow rate and magnitude. It is more likely that this increased AE activity was caused by extraneous noise (e.g. interference with the surface cover).  The periods of elevated AE activity could be indicative of deformations but of a very slow rate and magnitude. It is more likely that this increased AE activity was caused by extraneous noise (e.g. interference with the surface cover).	AE measurements between March 2017 and February 2018 do not appear to show significant slope movements. The periods of elevated AE activity could be indicative of deformations but of a very slow rate and magnitude. It is more likely that this increased AE activity was caused by extraneous noise (e.g. interference with the surface cover).  A specific event occurred at the end of November and lasting for 5 days, which coincides with a period of increased rainfall. It is possible that the detected AE during this period is indicative of slope movements, but again, slow rate and small magnitude.

Table 11.3. Summary of groundwater data at Flat Cliffs

Borehole	Summary of past data	Groundwater summary Min/Max/Range	Report status								Change June to November 2017	
			1	2	3	4	5	6	7	8		
<b>B1</b>	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 at 13.4m OD, well below historical high.	Groundwater level rises slightly to 13.5m OD.

<b>D1</b>	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 (Mar 2010). Peaks of 28.2m OD in July 2012 and 24.5m OD in early Jan 2012. Mean base groundwater level is 18 to 18.5m OD.	18.1m OD 29.9m OD 11.8m OD								Groundwater peaks at 21m OD in Jan and fluctuates up to 0.5m around an average of 18.6m OD.	Groundwater levels rise slightly throughout monitoring period to an average of 19m OD. There is no clear response to the extreme rainfall event on 23 August.
<b>A3</b>	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. Groundwater levels remain steady around c. 18m OD.	No significant change with continuation of 4 to 6 week fluctuations. Groundwater levels remain steady around c. 18m OD. There is no clear response to the extreme rainfall event on 23 August.
<b>C4a</b>	Tip depth at - 3.7m OD. Monitored since Sept 2011. Levels vary between 7.5m OD and 8.4m OD in response to short and medium term tidal cycles (ca. 6 hourly and 4-weekly).	7.5m OD 8.5m OD 1.0m								No data collected since May 2016. Readings to be re-taken.	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 December 2016 and September 2017 do not show significant slope movements. The periods of elevated AE activity, which are shown by periods of increased gradient of the cumulative RDC record, could be indicative of deformations but of a very slow rate and small magnitude. However, it is more likely that this increased AE activity was caused by extraneous noise (e.g. interference with the surface cover). However, a specific event occurred at the end of November and lasting for 5 days, which coincides with a period of increased rainfall (Figure 11.3) and is after the last inclinometer survey. It is possible that the detected AE during this period is indicative of slope movements, but again, slow rate and small magnitude.
- Groundwater data show no significant change. At borehole D1 near the top of the slope adjacent to the main access road water levels remain steady after decreasing significantly since winter 2015/16. There is no clear response to the extreme rainfall event on 23 August in any of the boreholes.
- No data collected at piezometer in borehole C4a, and requires readings to be retaken.

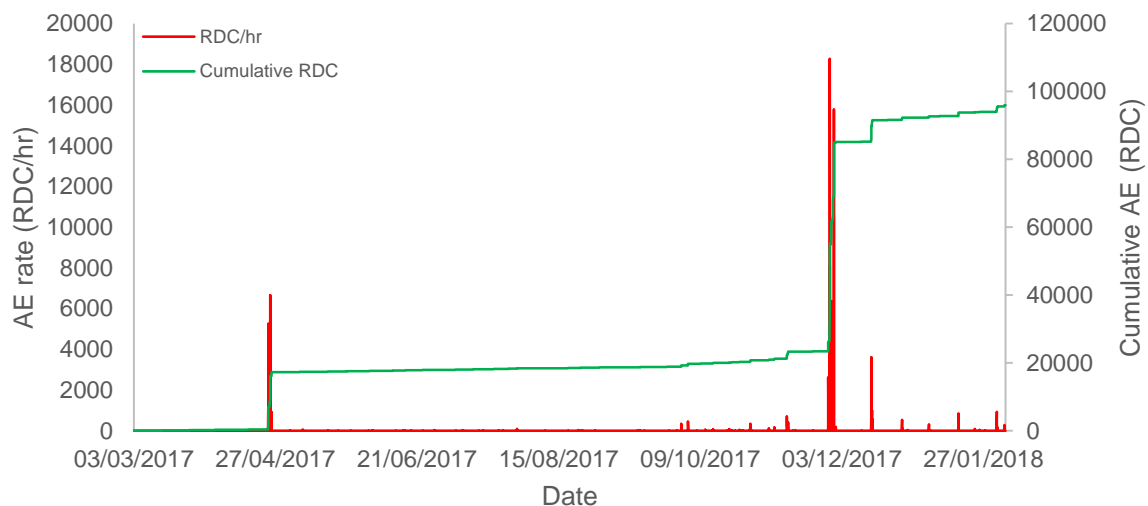


Figure 11.2 Cumulative AE (RDC) and AE rate (RDC/hr) time series at Flat Cliffs, Filey for the March 2017 to February 2018.

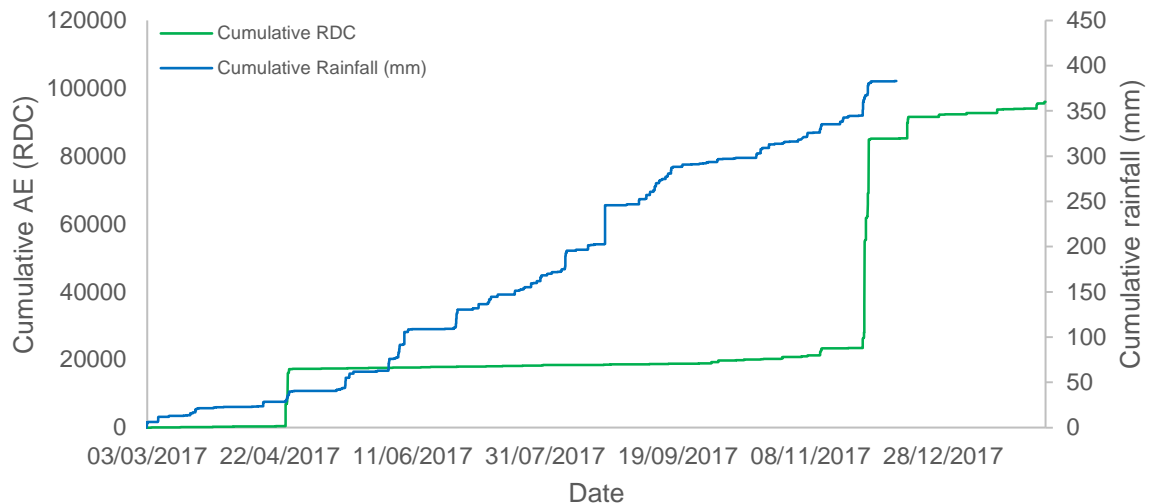


Figure 11.3 Cumulative AE (RDC) and cumulative rainfall time series at Flat Cliffs, Filey for the period March 2017 to February 2018.

## 11.5 Causal-response relationships

No relationship is identifiable between ground movements and rainfall as no substantial ground movements have occurred. Acoustic emissions data indicates low rate and slow magnitude movement in borehole C1a at the end of November 2017 lasting for 5 days coincident with a period of high rainfall. However, there was no significant movement recorded during the extreme rainfall event on 23 August. 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. The beginning of the monitoring period experienced above average rainfall. The data from borehole D1 record a peak in July 2017, which may be in response to a month antecedent rainfall. B1 gradual increase in groundwater level follows a month antecedent rainfall. There is no clear response in groundwater levels to the extreme rainfall event on 23 August 2017.

## 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 publicly 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.

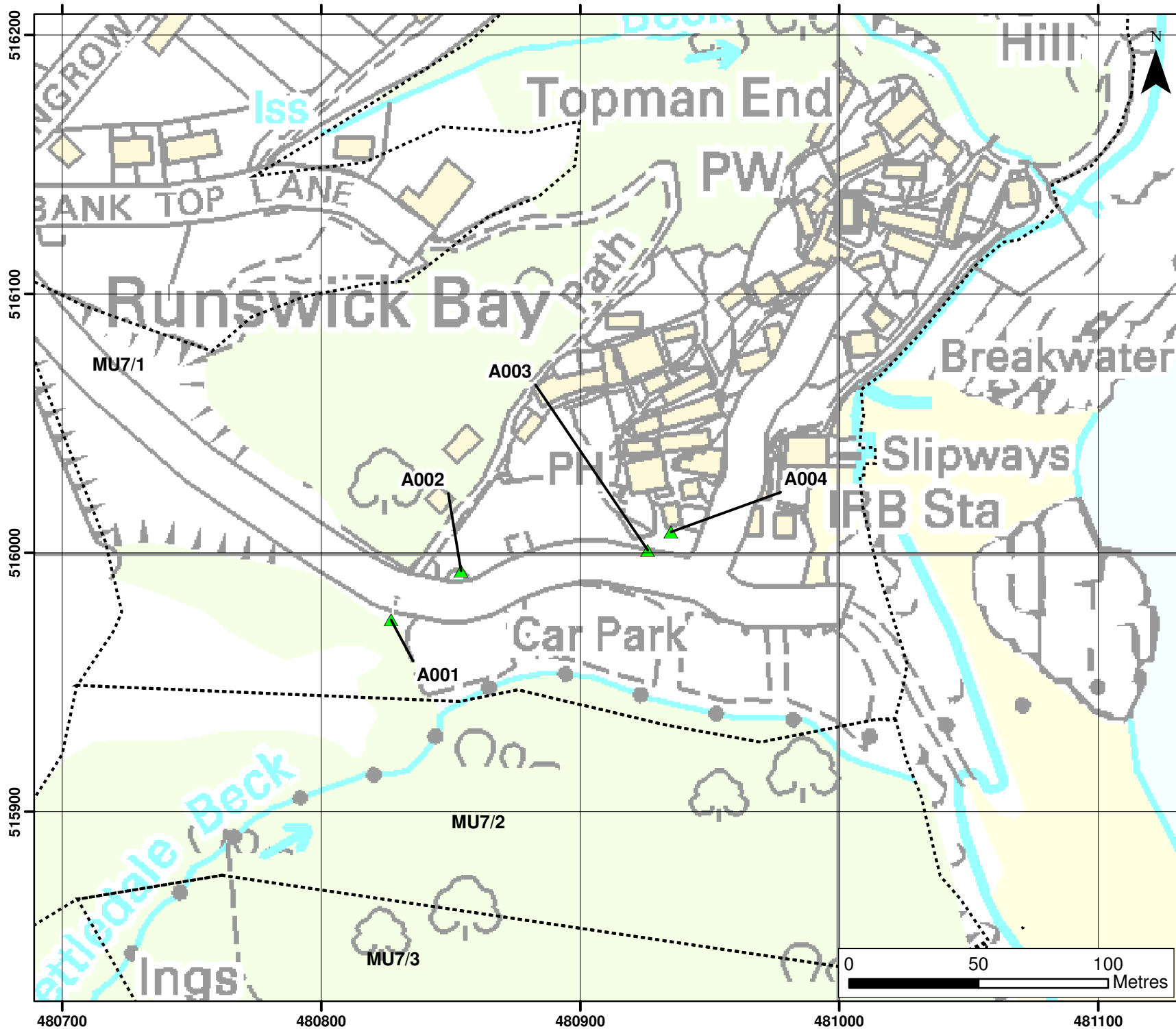
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# Appendix A

## 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

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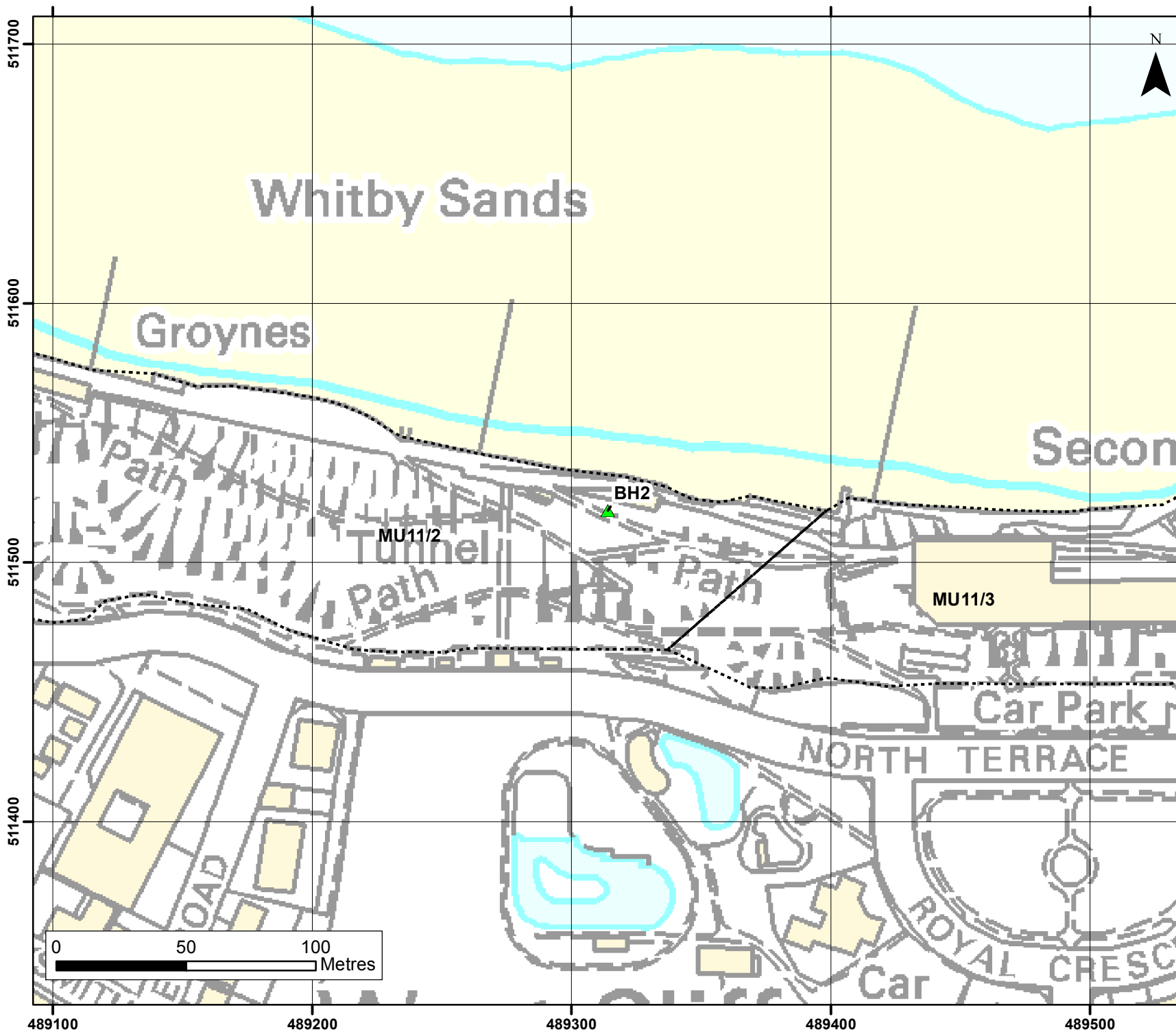
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**Figure 3.1 Location of slope monitoring at Runswick Bay**

**CH2MHILL<sup>®</sup>**  
**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  
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**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

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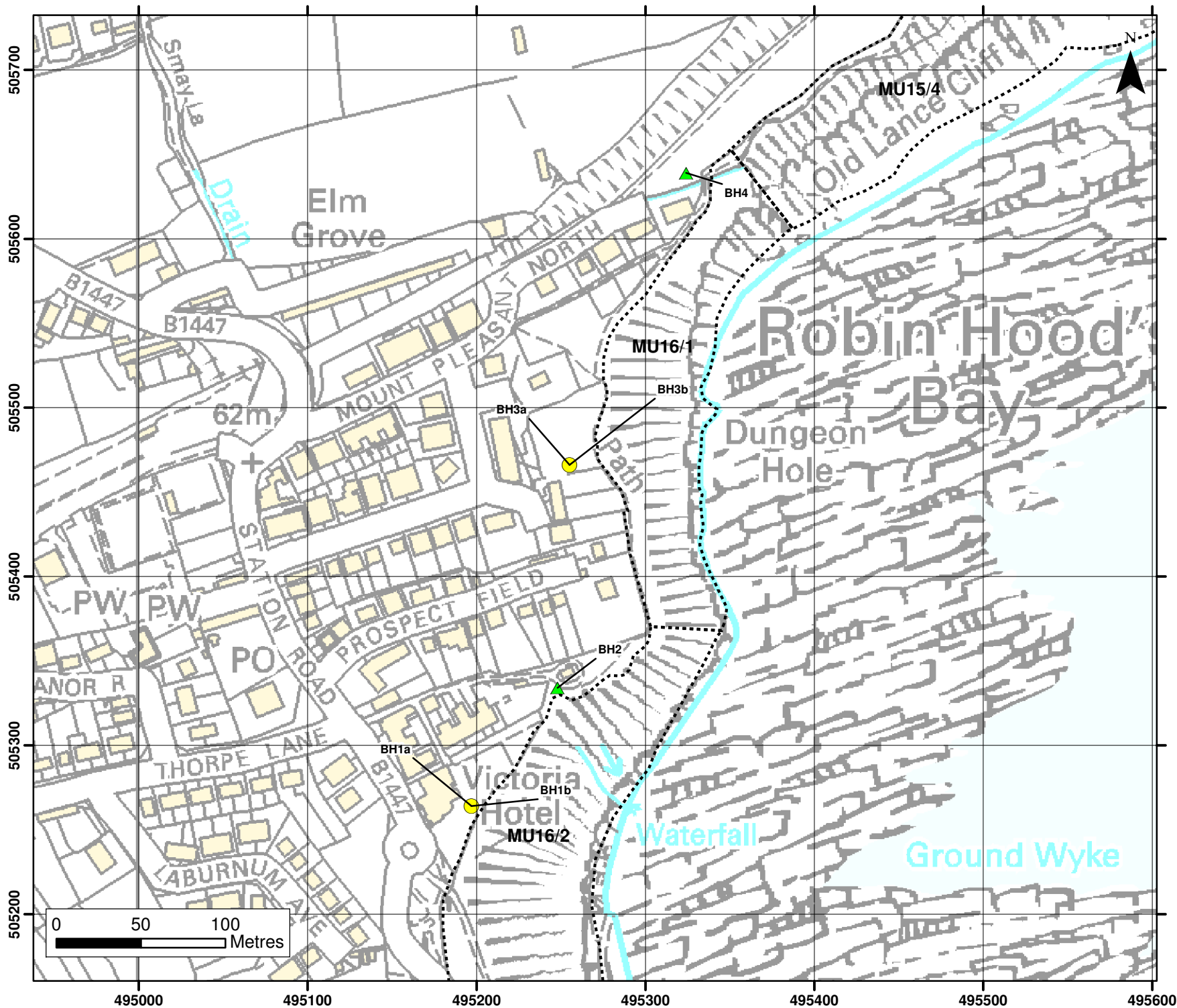
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**Figure 4.1 Location of slope monitoring at Whitby West Cliff**

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**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

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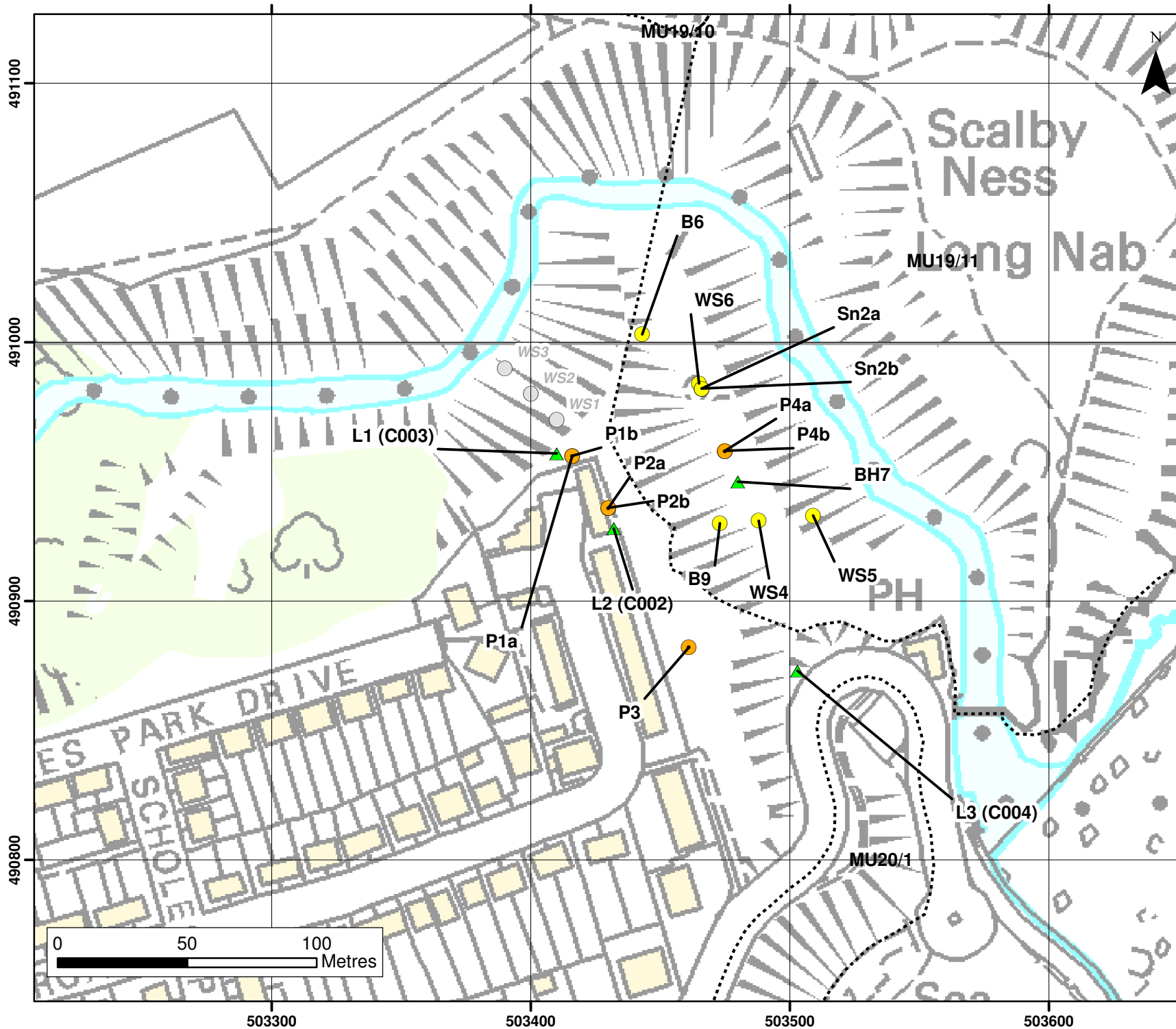
**Figure 5.1 Location of slope monitoring at Robin Hood's Bay**

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### 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

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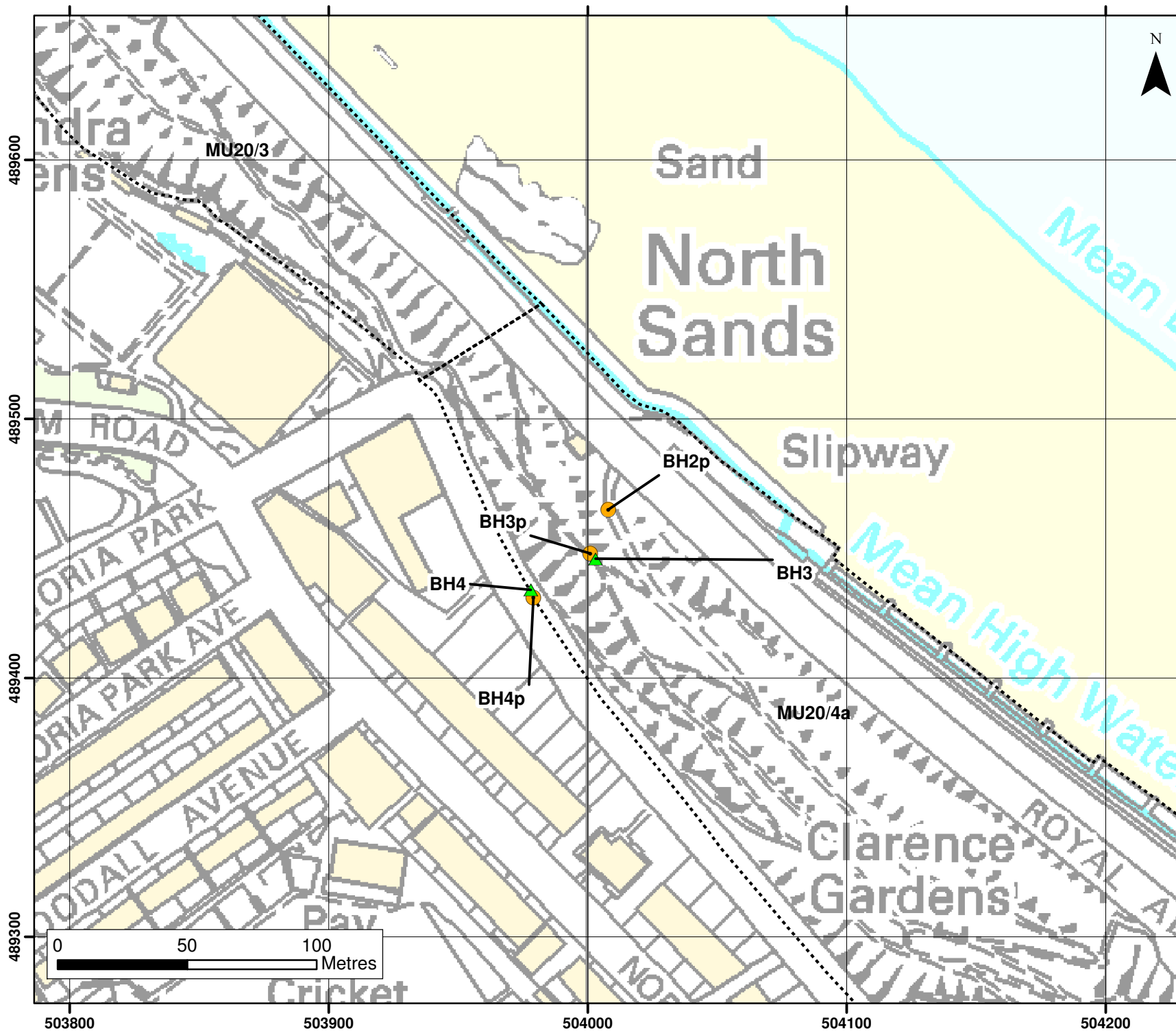
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**Figure 6.1 Location of slope monitoring at Scalby Ness**

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**Legend**

**Active**

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

**Inactive**

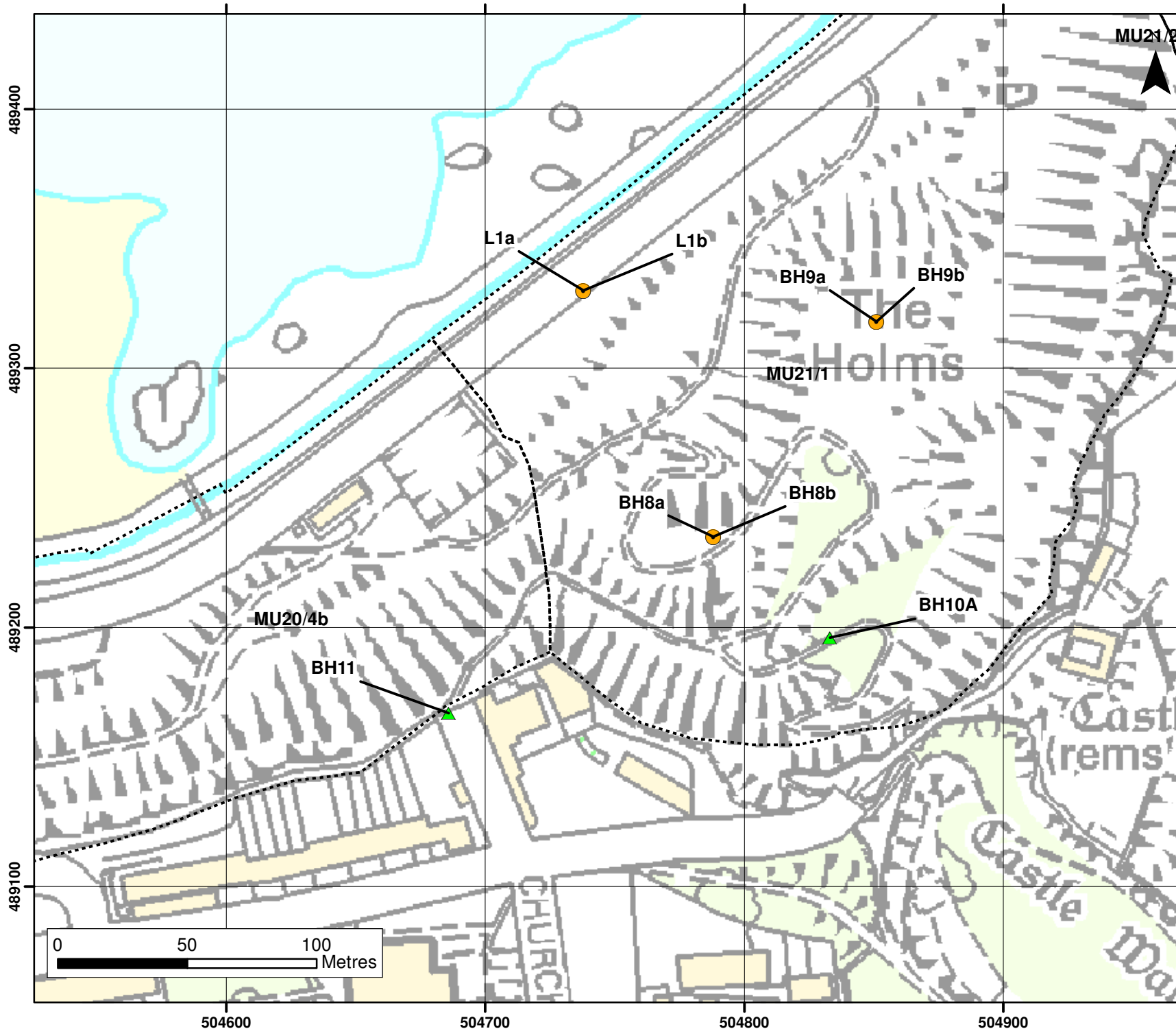
- ▲ Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)
- Cliff behaviour unit

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

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**Legend**

**Active**

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

**Inactive**

- ▲ Inclinator
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- ⊗ Piezometer (with diver)
- Cliff behaviour unit

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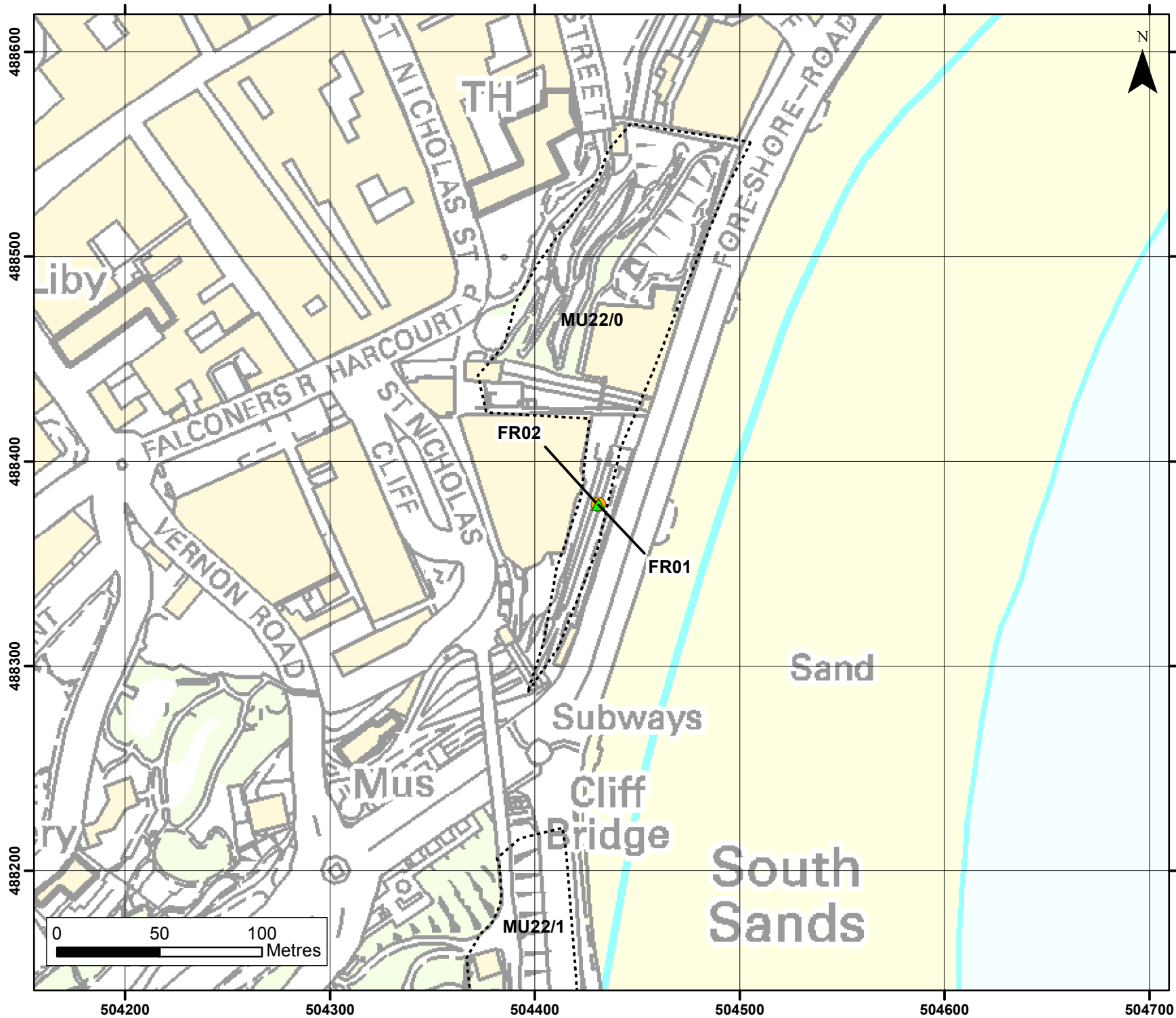
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**Figure 8.1 Location of slope monitoring at Scarborough North Bay (The Holms)**

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**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

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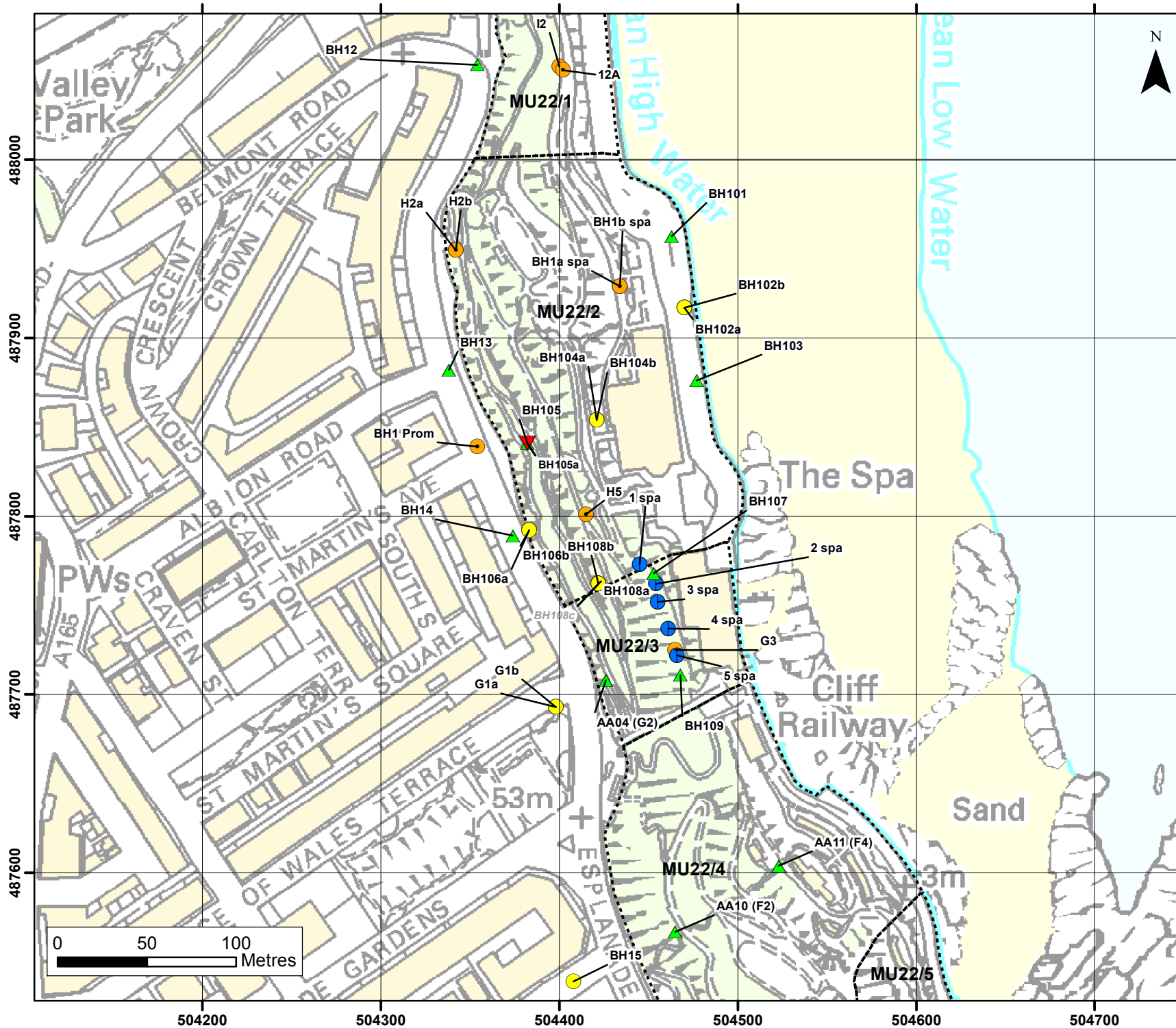
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**Figure 9.1A Location of monitoring at Scarborough South Bay**

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**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

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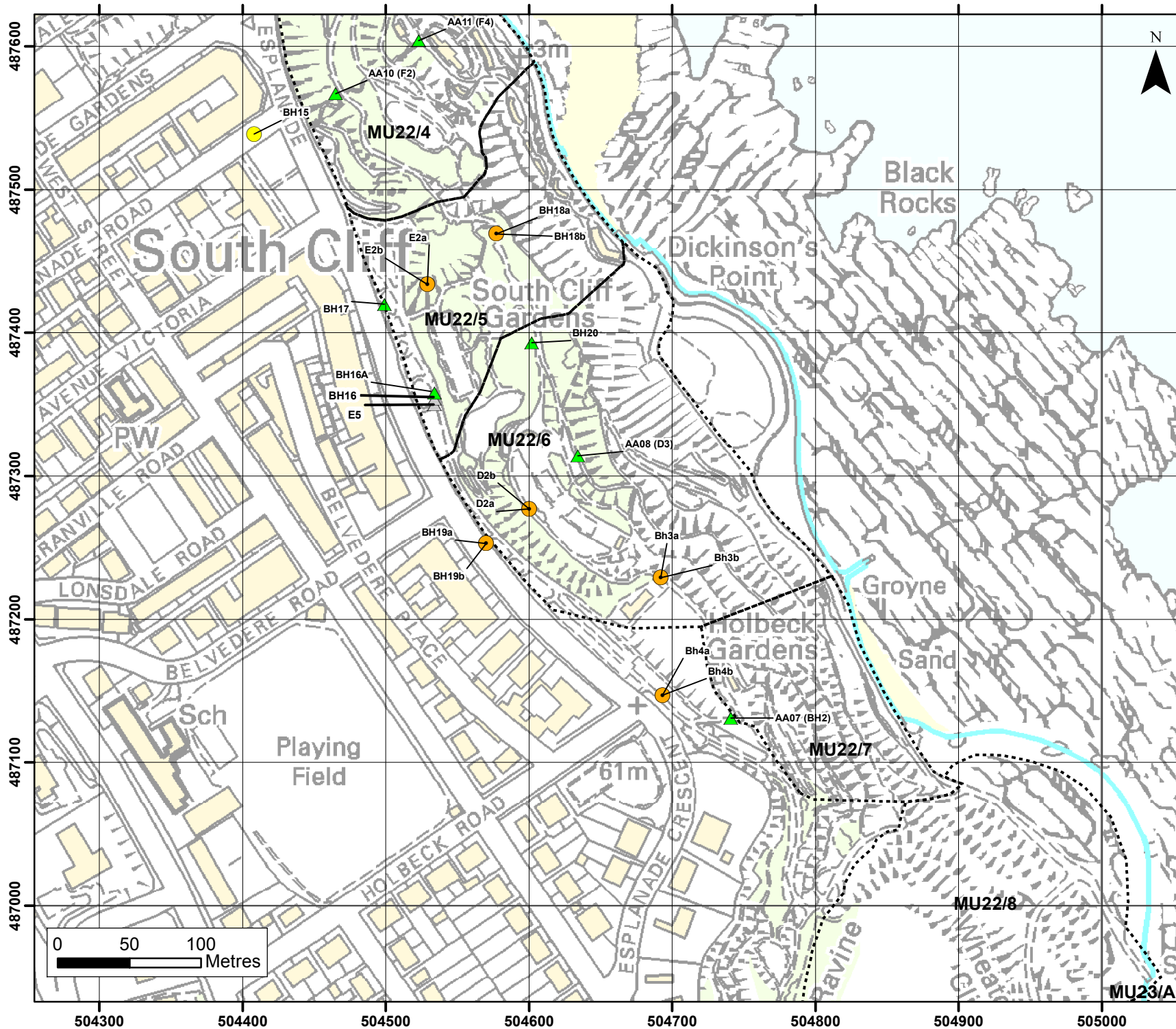
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**Figure 9.1B Location of monitoring at Scarborough South Bay**

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**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)
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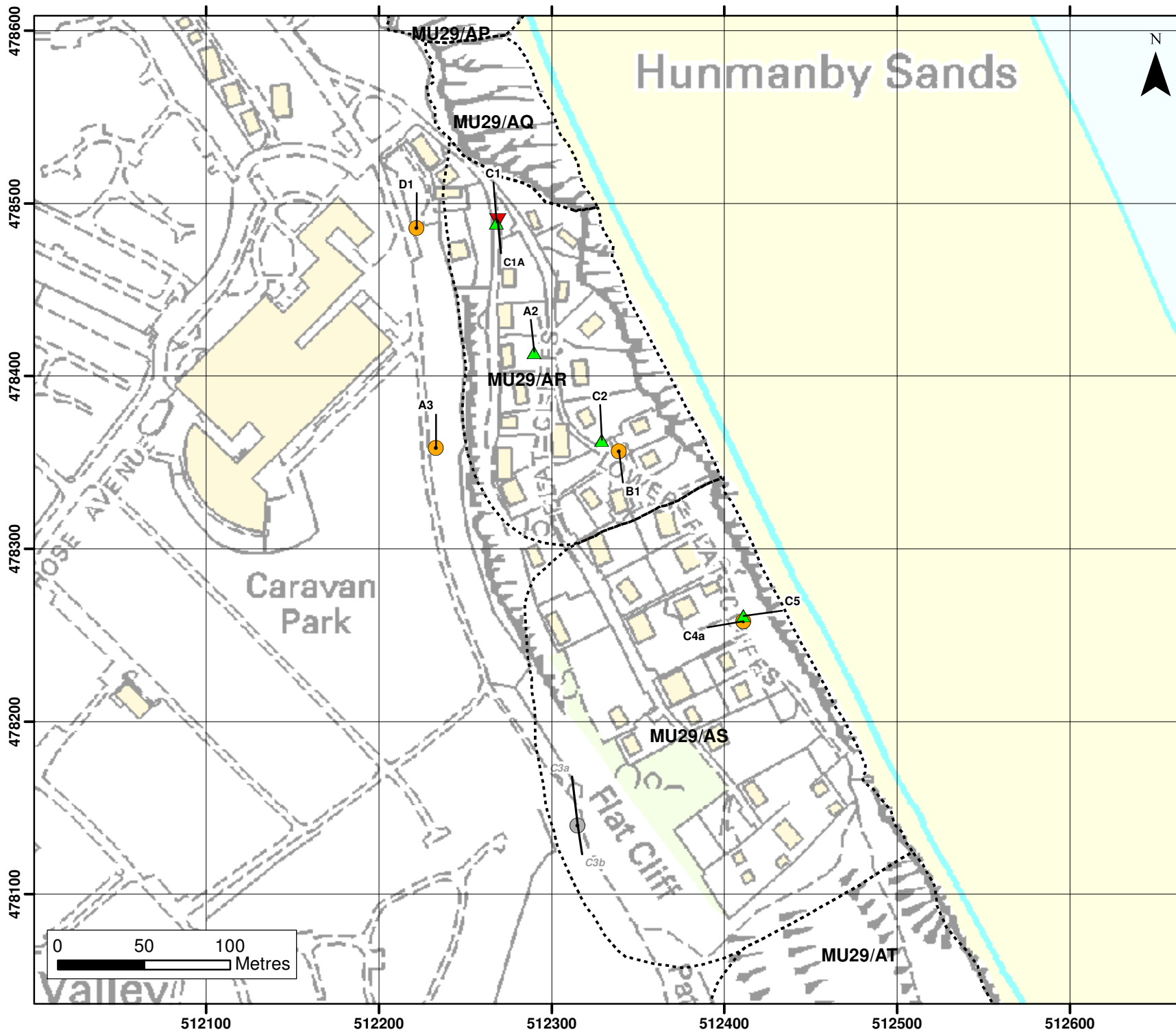
**Figure 9.1C Location of monitoring at Scarborough South Bay**

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**Halcrow**

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**Legend**

**Active**

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

**Inactive**

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

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**Figure 11.1 Location of slope monitoring at Filey Flat Cliffs**

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