Local Coastal Slope Monitoring Analysis

Interpretation Report 3
June 2014 to November 2014

Prepared for

Scarborough Borough Council

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CH2MHILL®

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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 is the third report in the new phase of coastal slope monitoring along the Scarborough Borough Council frontage that covers the period between June and November 2014. The previous reports are CH2M HILL (2014a and b). This phase of coastal slope monitoring continues that previously undertaken by Mouchel Ltd between July 2009 and June 2012.

The met station located at Filey Flat Cliffs failed in September 2014, but the Council were not aware until December 2014. A repair was completed on 10 February 2015. This means there is an incomplete record of rainfall for the current monitoring period. However, Met Office records have been obtained and presented that show the North Yorkshire coast experienced drier than average conditions over the period.

Monitoring locations that have been classified as Orange or Red in this assessment are summarised below. In general, these classifications relate to missing data or required maintenance of piezometers and/or their data loggers, but high or rising water levels have been recorded at some locations.

- Robin Hoods Bay: inclinometers BH2 and BH4 are both partially blocked. Repairs using a jet-flush are were undertaken in February 2015. Piezometer BH3a water levels have remained at a high level since Oct 2013.
- Scalby Ness: inclinometers C002, C004 and BH7 have recorded no movement in the current monitoring period. A site visit to this location undertaken in December 2014 indicated widespread reactivation has occurred in the landslide and the Council are undertaking periodic site visits to document any subsequent movement. No data can be downloaded from piezometer P1a due to equipment error. Records from piezometer P4b suggest a systematic error and from WS5 suggest the borehole is dry, which may be due to loss of borehole integrity.
- Scarborough North Bay: data from inclinometer BH10a are unreliable. This borehole was cleaned using a jet-flush in February 2015.
- Scarborough South Bay: Data from several inclinometers have recorded unreliable data in the past and will be jet flushed in February 2015. Piezometers 5Spa and G1a are dry; 108a and b that were installed mid-slope above the Spa record high and rising groundwater levels. Piezometer BH15 at the Clock Café is dry. At South Cliff Garden, piezometers BH 18a and b, and Bh3b record several spikes in the data, which could be error or periodic surface water ingress. No data have been recorded at BH19a since installation and it is recommended that the data be checked and equipment repaired if possible. Piezometer D2b has not recorded data since October 2013 due to a problem with the data logger. The cable of the datalogger at Bh3a has been cut and requires repair. Piezometer Bh4b in Holbeck Gardens also has a faulty datalogger.
- Filey: Piezometers BH4, CPBH01a and CPBH08a have recorded the highest water levels on record. No data could be downloaded from CPBH02a during the current monitoring period due to equipment problems. Data from CPBH09b and CPBH10b require maintenance checks to dataloggers.

SECTION 1

1 Introduction

1.1 Background to study

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

A comprehensive programme of data collection and analysis was commenced by the Council in October 2008, when SBC awarded Mouchel Ltd a contract to design a monitoring strategy for the coastline. Mouchel's recommendations were adopted by SBC and a four-year contract for regular data collection and monitoring reports was awarded. The 7th and final of these reports covered the period up to spring 2012, and was issued in August 2012 (Mouchel 2012).

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

SBC invited tenders on 24 July 2013, with separate contracts for data collection and data analysis being let. Contracts were awarded on 3 September 2013 to JBA Consulting Ltd and Halcrow Group Ltd (a CH2M HILL company), for data collection and data analysis respectively. JBA undertook the first data collection exercise in November 2013 and the first data analysis report was issued by CH2M HILL in March 2014.

The second set of data was received from JBA in August 2014. This report provides the third set of data analysis. The report is presented as a stand-alone document.

1.2 Aims and objectives of monitoring

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

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

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

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

In addition, the ultimate aim of the study is:

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

Table 1.1. Monitoring locations and devices.

Location	Inclinometers	Acoustic Inclinometer	Piezometers	Weather station
Runswick Bay	4	0	0	0
Whitby West Cliff	1	0	0	0
Robin Hood’s Bay	2	0	4	0
Scalby Ness	4	0	14	0
Scarborough North Bay – Oasis Café	2	0	3	0
Scarborough North Bay – The Holmes	2	0	6	0
Scarborough South Bay	17*	1	38*	0
Filey Town	4	0	24	0
Filey, Flat Cliffs	4	1	4	1
TOTAL	40	2	93	1

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

1.3 Programme of work

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

Table 1.2. Programme of data collection and reporting

JBA Monitoring Period	CH2M HILL (Halcrow) Analysis Report
Data set 1: June 2012 to November 2013	Report 1: March 2014
Data set 2: December 2013 to May 2014 (data received 1 Aug 2014)	Report 2: November 2014
Data set 3: June 2014 to November 2014	Report 3: March 2015 (this report)
Data set 4: December 2014 to May 2015	Report 4: August 2015
Data set 5: June 2015 to November 2015	Report 5: February 2016
Data set 6: December 2015 to May 2016	Report 6: August 2016
Optional 2 year extension	Optional 2 year extension

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 HILL with the inclinometer and ground water data presented as graphs, ready for interpretation. The following graphs are provided in Appendices to this report:

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

user error has occurred, it is carried through all cumulative plots, potentially giving misleading results. Errors can usually be identified by comparison to incremental displacement plots.

- Inclinometer absolute position – this plots the absolute position of the inclinometer casing when viewed vertically. While it does not give information on the rate of movement, it highlights the direction of any deformation and can be used to assess error in the data.
- Groundwater data from piezometer divers or data loggers – these data are plotted as a continuous line showing groundwater level fluctuation relative to Ordnance Datum (OD).
- Groundwater data from monitoring wells – these data are plotted as single points, showing groundwater level relative to OD at a particular point in time. They provide an independent check of piezometer data or water level information from boreholes that do not have automatic data logging capability.

The scope of Halcrow'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.
- 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 recommended to determine whether or not the data were accurate, the source of any errors, and the implications to cliff instability risk management. For most inclinometers, the checks comprised an additional site visit to take three consecutive readings to determine whether the error was systematic, or random. At some locations, where potential ground movement was indicated, the checks comprised monthly readings over the winter period to document any changes in ground movement and to explore the potential for error in the data. Four scenarios are identified that may cause error:

- **Distortion of the inclinometer tube**, can occur a few months after installation, causing a sinuous pattern of incremental readings. The cause of the distortion is unclear, but often correlates with granular strata (i.e. sands and gravels and not tills), suggesting it may be due to groundwater washing out the grout leading to loss of support of the casing. Given the sinuous pattern of distortion along a significant length of casing it is unlikely that natural ground movements are the cause. The test data have a consistent pattern, indicating that the deformation does not cause random errors. This means the BH is still capable of recording potential future ground movements.
- **Real movement along a discrete shear surface** at depth, leading to deformation of the overlying soil column and associated casing. This results in a sinuous pattern of change in the upper part of the BH above the shear surface and overlying *in situ* material. The BH is still capable of recording movement so should be closely monitored, with close attention paid to movement at the shear surface.
- **Blockage/damage to inclinometer** casing leading to random errors, usually near the base of the BH. While data at the location of random error is not reliable, readings from the rest of the BH can be interpreted with confidence. However, caution is needed interpreting cumulative movement plots, which will be affected by compounding of the random error.
- **Noise in the data**, representing normal instrument error that is exaggerated by incorrect scaling of the plot. Incremental movements of 2 to 3mm for a 40m deep borehole are within the 'instrument error' and cannot be interpreted as ground movement. However, more significant movement shown in cumulative readings is likely to represent real movement.

The results of these checks are documented in Table 1.4. In most cases, the error is systematic and represents minor settlement of the borehole casing that gives rise to a sinuous pattern of deformation. Provided these boreholes are read carefully e.g. ensure that the inclinometer probe does not come free of the key ways, ground movements should still be detectable. At locations where random errors are reported, it is likely that the borehole is partially blocked or damaged, leading to the probe coming away from the key ways. In these instances, there is low confidence in the resulting data and the boreholes should be checked and repaired if possible.

Table 1.4. Results of inclinometer integrity testing

BH	Location	30 Jan 2014	6 March 2014	30 April 2014	28 May 2014	26 June 2014	11 August 2014
BH2	Robin Hood's Bay		Upper 22m of BH damaged, leading to random error				
BH4	Robin Hood's Bay		Systematic error due to minor settlement				
BH11	Scarb N Bay Holms		Consistent error. BH deformed between 9 and 13m depth				

BH	Location	30 Jan 2014	6 March 2014	30 April 2014	28 May 2014	26 June 2014	11 August 2014
AA04	Scarb S Bay		Minor movement at 29 to 30m depth evident despite noise				
BH12	Scarb S Bay		Systematic sinuous error due to minor settlement of BH				
BH13	Scarb S Bay		Systematic sinuous error due to settlement of BH from 32 to 61m depth				
BH14	Scarb S Bay		Systematic sinuous error due to settlement of BH below 28m depth				
BH16 (BH damaged and read in error)	Scarb S Bay	Random error. Blocked or damaged key way					
BH16A	Scarb S Bay		Systematic sinuous error due to settlement of BH	Systematic error. No change.	Systematic error. No change.	Systematic error. No change.	Systematic error. No change.
BH17	Scarb S Bay		Systematic sinuous error due to settlement of BH				
BH20	Scarb S Bay	Systematic sinuous error.	Systematic sinuous error due to settlement of BH	Systematic error. No change.	Systematic error. No change.	Systematic error. No change.	Systematic error. No change.
BH6	Filey Town		Consistent error. Blockage at base of BH				
C1	Flat Cliffs		Consistent sinuous error.				

SECTION 2

2 Weather Summary

2.1 Introduction

A meteorological station has been operational at Flat Cliffs, central Filey Bay, since 29 September 2011. The device records wind speed and direction, air temperature, humidity, air pressure, rainfall and rainfall intensity every 15 minutes. The Filey dataset is used for comparison with all coastal slope monitoring data in order to identify relationships. It is taken to be representative of the whole Scarborough Borough Council frontage although it is accepted that micro-climate effects do lead to local variations in weather.

The meteorological station failed in early September 2014 and had not been repaired at the time this report was compiled; repairs are scheduled and the equipment is expected to be fully functional by early February 2015. Continuous rainfall data are only available for June and July of the current monitoring period; regional Met Office reports have been obtained for the period of absent data between Sep-Nov 2014. Despite this significant data gap, it is not thought that the monitoring programme has been adversely affected because the weather during autumn/winter 2014 was exceptionally dry and mild.

This period was characterised by exceptional warmth (autumn 2014 was the 3rd warmest on record since 1910) and slightly below average amounts of rainfall in Yorkshire. Met Office weather summaries for England are provided below:

- September 2014 was dominated by high pressure, bringing plenty of fine and settled weather. Temperatures were largely above average, although easterly winds meant that daytime temperatures on the east coast were relatively suppressed. Rainfall was limited, though there were a few heavy showers at times during the second half of the month. Rainfall was well below average in most places, with less than 20% of the long-term average over large swathes of the country, and an overall UK figure of just 23% of average (Figures 2.1 and 2.2). This was provisionally the driest September in a series since 1910, though only slightly drier than 1959. It was also the driest calendar month for the UK since August 1995.
- October 2014 was predominantly unsettled, with strong winds and rain a recurring feature, but these winds were generally from a southerly direction so it was mild, especially in the second half. Rainfall was above average, most especially over Cumbria, but with less in the way of rain during the final third of the month (Figures 2.3 and 2.4). The mean temperature for the month was provisionally 1.9 °C above the 1981-2010 average, making it the equal-seventh warmest October in a series since 1910. Rainfall overall was 115% of average but parts of Cumbria received more than twice the normal rainfall amount. Sunshine amounts were below average for central and western areas, with an overall figure of 91% of average.
- November 2014 was generally unsettled, with rain or showers and strong winds at times, but with temperatures often above average (Figures 2.5 and 2.6). The last few days became drier, allowing fog to form on some nights. The mean temperature for the month was provisionally 1.4 °C above the 1981-2010 average, making it the equal fourth warmest November in a series from 1910. Rainfall overall was 121% of average; the wettest areas were in the south and east, with north-west England drier than average.
- December 2014 comprised alternating spells of colder and milder weather, with frosts common between 3rd and 8th and again between 26th and 30th but some very mild weather at other times. A vigorous depression brought stormy weather around 9th to 12th, after which the weather was milder until Christmas. The last few days were mostly clear, sunny and frosty. The mean temperature for the month was provisionally 0.7 °C above the 1981-2010 average. Rainfall overall was 83% of average; the driest areas were across north-east England and toward the south coast, with less than 50% in a few places (Figures 2.7 and 2.8).

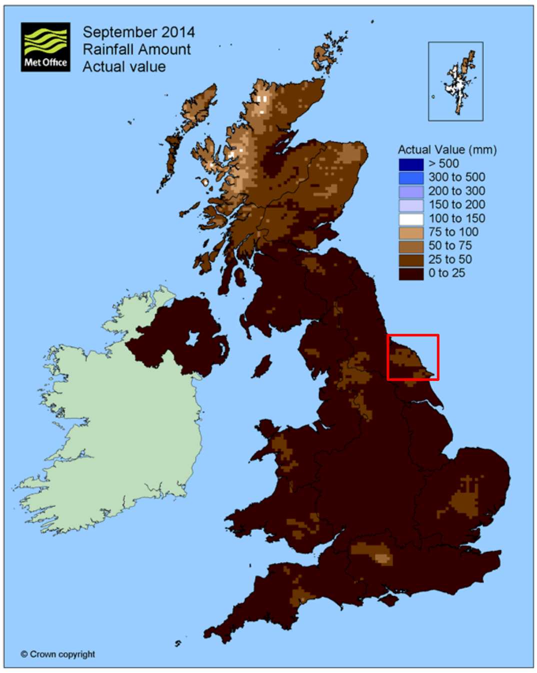

Figure 2.1. September 2014 rainfall

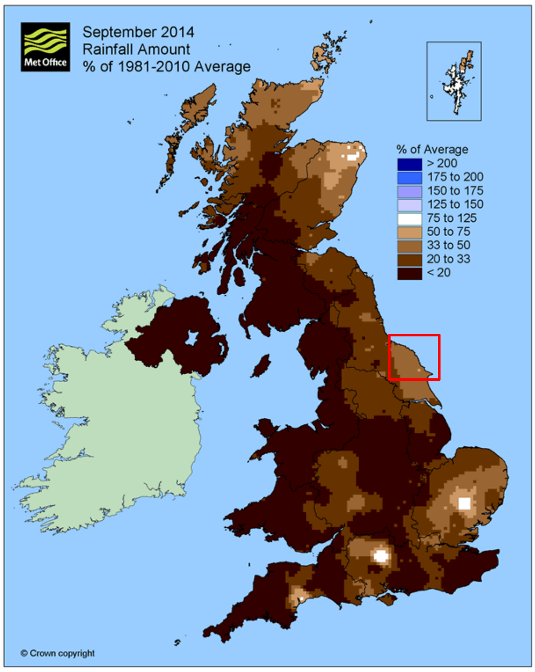

Figure 2.2. September 2014 rainfall as a percentage of the 1981-2010 average

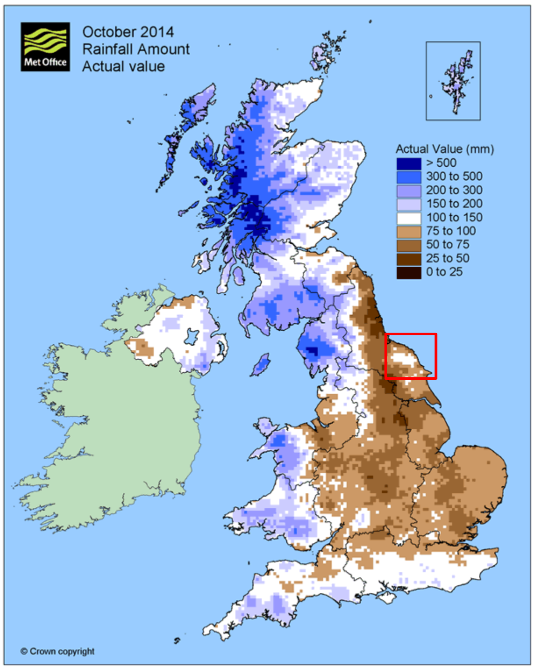

Figure 2.3. October 2014 rainfall

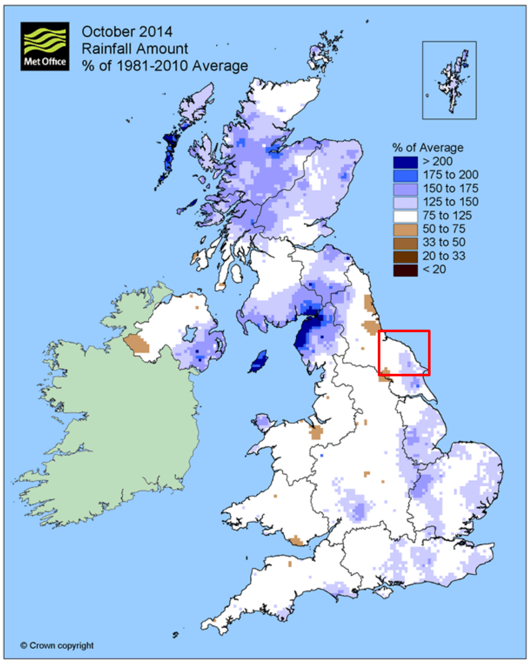

Figure 2.4. October 2014 rainfall as a percentage of the 1981-2010 average

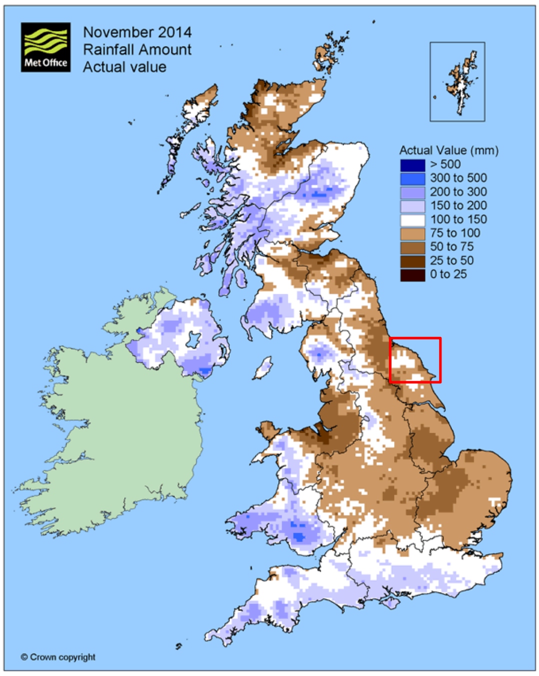

Figure 2.5. November 2014 rainfall

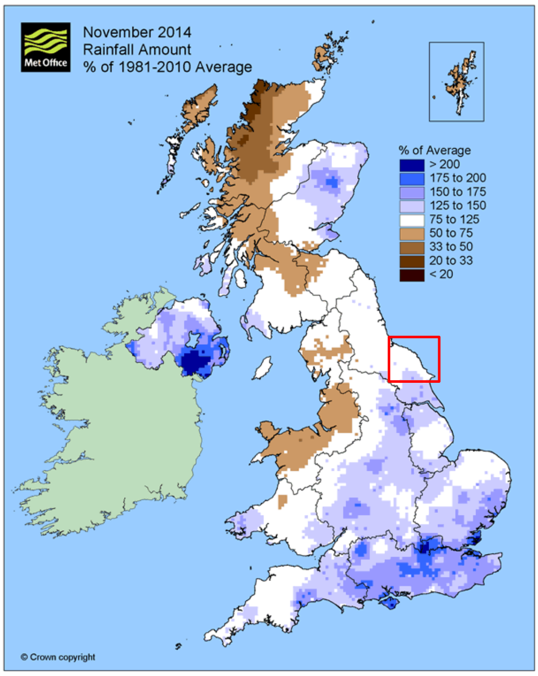

Figure 2.6. November 2014 rainfall as a percentage of the 1981-2010 average

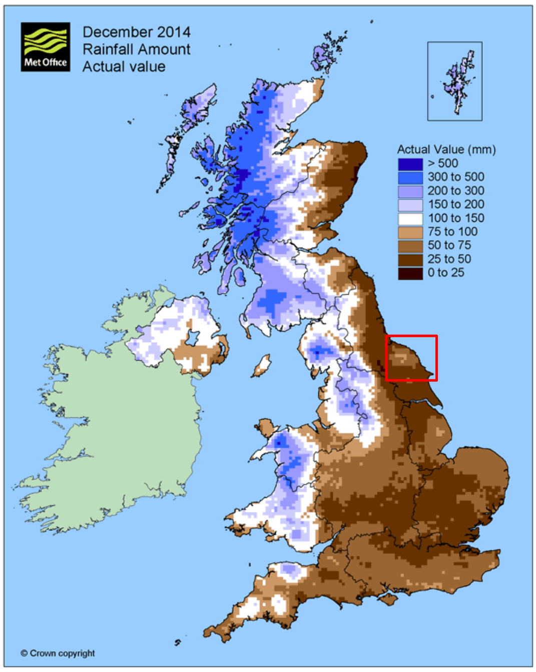

Figure 2.7. December 2014 rainfall

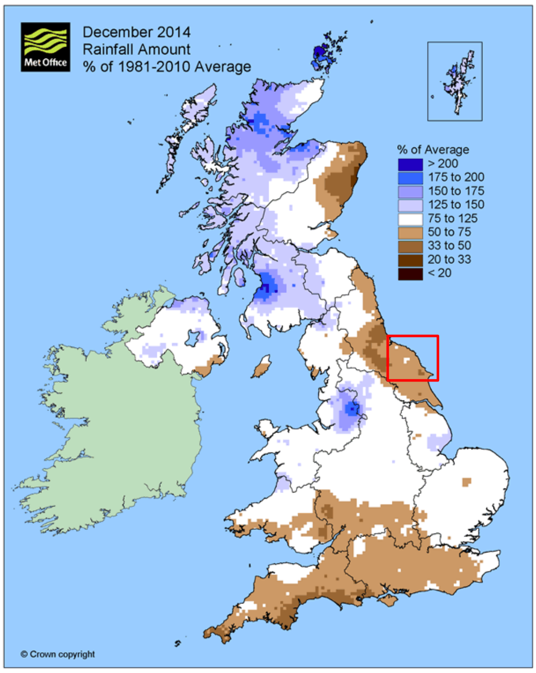

Figure 2.8. December 2014 rainfall as a percentage of the 1981-2010 average

2.1.1 Rainfall and landslides

The relationship between rainfall and the occurrence of landslides is known to be 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 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 span a short time period, but do include the particularly wet year of 2012. The only 'significant' ground movements at this time were recorded in BH7 at Scalby Ness, suggesting that the antecedent rainfall threshold levels were not achieved throughout much of the frontage. As cliff instability has not yet been observed at most locations, the antecedent rainfall time period is also unknown.

Monthly rainfall totals are provided in Table 2.1. The highest rainfall in a single month was 132mm, recorded in December 2012. This suggests if there was a one month antecedent rainfall relationship, the threshold level would be greater than 132mm.

Two and three month antecedent rainfall periods have been calculated from the available dataset. The data suggest a two month antecedent rainfall period threshold is in excess of 210mm and a three month threshold is greater than 263mm.

Table 2.1. Monthly rainfall recorded at Flat Cliffs met station

Month	Rainfall (mm)				
	Long-term mean (upper range)	2011	2012	2013	2014
January	80	No Data	31	41	113
February	60	No Data	8	38	96
March	60	No Data	27	32	29
April	60	No Data	96	4	26
May	60	No Data	34	37 (part month)	59
June	80	No Data	104	No Data	34
July	60	No Data	70	No Data	70
August	80	No Data	45	38 (part month)	0*
September	80	0.14 (part month)	69	15	0 (part month)
October	80	35	53	52	No Data
November	80	15	78	25	No Data
December	80	72	132	6	No Data

*No rainfall recorded in August but we are unclear about the accuracy of this data.

2.2 Summary

The weather data collected to date highlights the following:

- 2012 was exceptionally wet, particularly in the months of April, June, July, November and December.
- 2013 was dry. After an unusually stormy spring period the temperatures remained high throughout the summer and rainfall in all months was below average.
- January and February 2014 were much wetter than average, and the period March to July 2014 was comparatively dry.
- While no data were recorded from early September 2014 to February 2015, a review of Met Office records shows the Autumn 2014 period was characterised by drier than average conditions.

SECTION 3

3 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 is currently the subject of 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, in progress).

3.2 Ground model and monitoring regime

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

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

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

3.3 Historical ground behaviour

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

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

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

3.4 New data

All monitoring data at Runswick Bay is at the Topman End landslide, and is solely intended to monitor the effectiveness of the piles installed in the late 1990s to stabilise the slope. Water-levels within inclinometer tubes installed in the piles were recorded under the previous Mouchel contract. This has not been continued to the current phase of work as it was recognised that the data were of limited value and potentially misleading. Inclinometer data are summarised in Table 3.2. These data indicate:

- No movement in the piles. Apparent small movements at the base of A001 are assumed to be erroneous but should be monitored in future reports.

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 1 status	Movement from late 2013 to mid 2014	Movement from mid to late 2014
A001	Data collected from within 22m deep concrete pile near the top of the slope. The data indicates Incremental movements of up to 4mm have occurred between 20 and 22m depth. This suggesting cumulative movement of the whole pile of c. 20mm. However, the cumulative movements are not ordered through time, which suggests no significant movement has been recorded at the base of the hole		Apparent displacement of 1.5-3mm at the base of the pile since November 2013. There is no consistent progressive movement in the same direction indicating no significant movement.	Incremental movements are less than 1 mm during the monitoring period and are 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.		No change since November 2013. The apparent minor cumulative (<2mm) change at the ground surface is not significant.	Incremental movements are less than 1 mm during the monitoring period and are 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.		No change since November 2013. Apparent movements at all depths <0.5mm is not significant.	I Incremental movements are less than 1 mm during the monitoring period and are 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.		The erroneous data described in the previous report have been corrected, confirming no change here since readings began.	Incremental movements are less than 1 mm during the monitoring period and are insignificant.

SECTION 4

4 Whitby West Cliff

4.1 Site description

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

4.2 Ground model and monitoring regime

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

4.3 Historical ground behaviour

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

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

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

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

4.4 New data

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

Table 4.2. Summary of inclinometer data from Whitby West Cliff

Borehole	Summary of past data	Report 1 status	Movement from late 2013 to mid-2014	Movement from mid to late 2014
BH02	The inclinometer is 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.		No change since late 2013. All apparent incremental movements are <1mm and show no consistent progressive pattern and are therefore not significant.	Incremental movements are less than 1 mm during the monitoring period and are 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.

5 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 June 2014 is summarised in Tables 5.2 and 5.3.

No inclinometer data were recorded during the monitoring period. Both boreholes have previously provided erroneous data and maintenance (jet-flushing) is planned before the next data are collected.

The piezometer data show:

- Water levels in most locations vary by a small amount and have an inconsistent relationship with rainfall, with one borehole showing a slight rise in water level.
- BH3a, which is a shallow piezometer, shows a small fall in water level but overall the water level has remained high.

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

Borehole	Summary of past data	Report 1 status	Movements from late 2013 to mid 2014	Movements mid to late 2014
BH2	The borehole is 41m deep but inclinometer records are only provided for the upper 22m. Ground level is c. 55.1m OD. Readings have been taken between March 2010 and May 2012 and show up to 15mm incremental displacement, particularly at 5 to 15m depth on the A-axis and up to 80mm displacement between 8 and 21m depth on the B-axis. This pattern of movement is hard to explain and is likely to represent accumulated error.		The readings taken in July 2014 show a very similar pattern to previous readings. The apparent displacement prior to 11/12/2011 is likely to be erroneous. **It is recommended that an integrity check is completed and a new baseline is taken against which future displacements can be compared.**	Incremental movements are less than 1mm. Apparent deflection in cumulative plot is a result of compounding of errors. **It is recommended that an integrity check is completed and a new baseline is taken against which future displacements can be compared.**
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. Readings taken between March 2011 and May 2012 indicate incremental movements of up to 18mm on the A-axis and 25mm on the B-axis at a depth of 20 to 30m, within the siltstone bedrock. The data also indicate incremental movements of c. 15mm within the glacial sediments. Cumulative movement plots suggest error in the data and it seems likely that the readings taken since 17 June are error as no evidence for significant ground movement has been reported or observed on site.		The incremental plot shows that displacements of up to 5mm have occurred since the baseline measurement was taken, but that there has been very little change since 17 June 2011. It is likely that these apparent movements result from erroneous readings. **It is recommended that an integrity check is completed and a new baseline is taken against which future displacements can be compared.**	Incremental readings ae the same as those recorded since 2013. Apparent deflection in cumulative plot is a result of compounding of errors. **It is recommended that an integrity check is completed and a new baseline is taken against which future displacements can be compared.**

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

Borehole	Summary of past data	Report 1 status	Movement later 2013 to mid 2014	Movements mid to late 2014
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. Once equilibrated, water levels rose by 2.7m from May 2010 to June 2011. Levels then fell back by 1.3m to May 2012.		Since the last reading in October 2013, groundwater levels have risen by 0.05m and remain below the peak recorded in June 2011.	Water levels are unchanged since July 2014.
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 37.6m OD from March 2010 to Nov 2011. Between Nov 2011 and May 2012, levels rose by 1.2m reflecting the wet months of Dec 2011 and/or April 2012		Since the last reading in October 2013, groundwater readings have fallen by 0.04m	Water levels are unchanged since July 2014.

Borehole	Summary of past data	Report 1 status	Movement later 2013 to mid 2014	Movements mid to late 2014
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.		Since October 2013, water levels have continued to rise, but at a slower rate than seen in the period prior to October 2013. Levels have risen by 11.5m between June 2012 and June 2014, which seems erroneous and probably caused by ingress by surface water. **It is recommended that this location be checked and repaired**.	Since July 2014, water levels have fallen by c. 2m to the position of Oct 2013, but still remain high compared to the baseline.
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.		The water level has remained constant since May 2012 at a long term average of 56m OD.	The water level has remained constant since May 2012 at a long term average of 56m OD.

5.5 Causal-response relationships

A subtle relationship between rainfall and groundwater levels, particularly in the shallower piezometer BH1a, is observed for the wet December of 2011 and the wet summer of 2012. However, the dry conditions of 2013 are not reflected in the groundwater data, suggesting surcharge of groundwater from local sources may be occurring. 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, such as that of 5 July 2014 that may have caused the short-lived high groundwater level recorded on 7 July 2014.

5.6 Implications and recommendations

The groundwater data indicates a continuation of past patterns at Robin Hood's Bay. BH3a shows a continued rise in groundwater, but this is thought to represent ingress of surface water. This location requires investigation and repair of inclinometers and piezometers.

Previous work by Mouchel has noted that piezometer tubes have progressively become shallower, suggesting ingress of sediment. It is therefore recommended that all four 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.

6 Scalby Ness

6.1 Site description

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

6.2 Ground model and monitoring regime

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

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

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

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

6.3 Historical ground behaviour

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

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

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

6.4 New data

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

*Table 6.2. Summary of inclinometer data at Scalby Ness. *Surface elevations and borehole depths calculated from digital elevation model.*

Borehole	Summary of past data	Report 1 status	Movement late 2013 to mid 2014	Movement mid to late 2014
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, which becomes more sandy below 24.5m OD, and 3m of sandstone/mudstone bedrock. Cumulative plot almost vertical and incremental plot reveals no displacements of the inclinometer tube greater than 2mm.		None evident. No movements >1.5mm	Incremental movements are less than 1 mm during the monitoring period and are 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. Cumulative plot is almost vertical and incremental plot reveals no displacements of the inclinometer.		The incremental plot shows displacements of up to 10mm near the base of the borehole, which gives rise to a significant apparent cumulative displacement. This is considered to be error in reading or a blockage in the borehole. **This site should be investigated and the blockage removed or instrumentation repaired if necessary.**	Incremental movements are less than 1 mm during the monitoring period and are insignificant. Previous movements bear the base of the borehole are likely to be error.
L3(C004)	Borehole is ca. 17m deep and situated in the midslope of CBU3. Surface elevation is 13.4m OD therefore borehole extends to c. -3.6m OD through 8.5m of glacial sediment, and 8.5m of mudstone and sandstone that is weathered in the upper 3m. Cumulative plot is almost vertical with the exception of a large apparent displacement between June 2011 and December 2011 and minor (<5mm total displacement) near the surface, possibly due to surface creep.		Apparent continuation of relatively shallow surface creep that extends to ca. 2m BGL (11m OD).	Incremental movements are less than 1 mm for most of the borehole during the monitoring period and are insignificant. Slightly greater movement of c. 1.5mm in the top 2 to 3m may relate to soil creep or collapse of the borehole casing.

Borehole	Long-term Pattern	Report 1 status	Movement late 2013 to mid 2014	Movement mid to late 2014
BH7	Borehole is c.20.5m deep and situated in the mid-slope of CBU2. Surface elevation is c. 16.7m OD and the borehole extends to c.-3.8m OD through 13m of glacial sediment and 7.5m of sandstone /mudstone bedrock. The cumulative plot shows around 20mm of displacement in positive A axis direction between Feb 2011 and June 2011, above the contact between sandstone bedrock and gravelly sand at c.4.7m OD. Subsequent readings show alternating displacements of up to 20mm in both positive and negative B axis directions indicating possible cross slope movements of the upper, unconsolidated strata.		Since November 2013 there has been significant ongoing displacement along the shear surface, which lies c. 1m above the contact between bedrock and gravelly sand at ca. 4.7m OD (12m bgl). The cumulative displacement is c. 25mm. An interim reading on 5 March 2014 indicates the majority of movement occurred between Nov 2013 and Mar 2014 and that movement to July 2014 has been limited. **It is recommended that a site inspection be undertaken to determine the spatial extent of instability and the associated risk to properties**	Incremental movements are less than 1mm and therefore insignificant. There has been no additional movement along the shear surface at c. 11 to 12m depth.

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

Borehole	Long-term Pattern	Report 1 status	Change late 2013 to mid 2014	Change mid to late 2014
P1a	Automated piezometer. Tip at appox.25.65m OD*. Surface elevation at c. 35.6m OD* (cliff top above CBU 1, co-located with P1b). Fluctuates between 27.5 and 28.5m OD, with rapidly rising and falling peaks linked to higher rainfall and subsequent dry periods.		No data were available from this piezometer due to equipment error. Data will be provided in the third report.	No data. Problem downloading data since 15 Oct 2013.
P1b	Automated piezometer. Tip at c. 18.1m OD*. Surface elevation at c. 35.6m OD (cliff top above CBU 1, co-located with P1a). Relatively steady ground water level at ca.18.5m OD although fluctuations up to ca. 19.0m OD occur.		Steady at 18.5m OD	Steady at 18.5m OD
P2a	Automated piezometer. Tip at c. 25.6m OD*. Surface elevation at c. 34.7m OD* (cliff top above CBU 2, co-located with P2b). Fluctuates		Fluctuating pattern between c 27 and 28m OD. Water levels declining to the end of Dec 2013, then increased sharply to a peak of 27.9m OD in Feb 2014. Since this peak, water levels have fallen	Continuation of past trends. The period is marked by subtly falling water levels.

Borehole	Long-term Pattern	Report 1 status	Change late 2013 to mid 2014	Change mid to late 2014
	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.		and stabilised around 27.7m OD, with a brief small rise and fall in early June 2014.	
P2b	Automated piezometer. Tip at c. -0.6m OD*. Surface elevation at c. 34.7m OD* (cliff top above CBU 2, co-located with P2a). Prior to October 2009, ground water levels appear generally steady at ca. 1.2m OD, except for substantial 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.		No change – steady at c. 2.3-2.4m OD to July 2014	No change – steady at c. 2.4m OD
P3	Automated piezometer. Tip at c. 10.5m OD*. Surface elevation at c. 30.7m OD (cliff top above CBU3). Steady at around 14.6-14.7m OD until Oct 2009. Apparent recalibration between Oct 2009 and Mar 2010 after which groundwater levels are again steady at ca.17.2-17.3m OD		No change – steady at ca 17.2-17.3m OD to July 2014.	No change, with levels varying by c. 0.4m about a very gently dropping level of 17.2m. Recent trend shows consistent gentle fall from 17.3m OD in April 2013 to 17.2m in Oct 2014.
P4a	Automated piezometer. Tip at c. 8.3m OD*. Surface elevation at 18.6m OD (midslope in CBU2, co-located with P4b). Fluctuating pattern occurs between June 2004 and Feb 2009 varying around 12m to 13.6m OD. Peaks show steep rising limb and gentler falling limb characteristic of a response to heavy rainfall events. After this, the base level appears to show a decline.		Groundwater levels showed a continued declining trend until late December 2013 when levels reached 13.1m OD. Groundwater levels then rose to a peak of 13.8m OD in mid-February 2014 before declining to around 13.5m OD. **Groundwater levels continue to show a systematic departure from those monitored shallower in the same hole in P4b and should be checked to ensure there is not a calibration issue.**	Continuation of cyclical pattern of several month spacing with rapid rise followed by gradual falls. Recent period marked by variations. Decline from Feb 2014 continues to May 2014 when levels fell to 13.4m, before rising to a peak of 13.7m OD on 30 May. Levels then fall gradually to 13.1m by 30 Oct 2014 and then begin to rapidly rise on 1 Nov 2014.
P4b	Automated Piezometer. Tip at c. 6.35m OD*. Surface elevation at c. 18.6m OD (midslope in CBU2, co-located with P4a). Fluctuating pattern occurs between June		Groundwater levels showed a continued declining trend until late Dec 2013, reaching 12.8m OD. Levels then rose to a peak of 13.6m OD in mid-Feb 2014 before declining to around 13.5m OD since.	**The same pattern is shown in this lower piezometer as the upper device P4a, however the systematic offset of c. -0.3 recorded since early 2010 continues.**

Borehole	Long-term Pattern	Report 1 status	Change late 2013 to mid 2014	Change mid to late 2014
	2004 and Feb 2009 with lows at around 12m OD and peaks between 13.0 and 13.6m OD. Peaks show steep rising limb and gentler falling limb characteristic of a response to heavy rainfall events. Substantial peaks occur in Jan 2011, May 2012 and December 2012.		**Groundwater levels continue to show a systematic departure from those monitored deeper in the hole in P4a and should be checked to ensure there is not a calibration issue.**	Decline from Feb 2014 continues to May 2014 when levels fell to 13.1m, before rising to a peak of 13.4m OD on 30 May**. Levels then fall gradually to 12.8m by 3 Nov 2014 before rapidly rising to 14m OD Nov 2014.**
WS4	Tip at 9.9m OD. Surface elevation at 16.3m OD (midslope, CBU 2). Fluctuations from c. 10m OD to c.15m OD in response to long-term/seasonal rainfall patterns. Limited response to short-lives rainfall peaks.		July 2014 groundwater level at ca. 12.5m OD indicating a slight fall.	Water levels maintained at consistent level of 12.5m OD
WS5	Tip at 6.5m OD. Surface elevation at 11.3m OD (lower slope, CBU 2). Fluctuates between 6.5m OD and 7.5m OD between September 2010 and June 2011 (low in summer/early autumn, high in winter). Gap in record until May 2012 when groundwater level of ca. 9.0m OD recorded.		Piezometer was dry when measured in July 2014, indicating a fall of at least 9.7m since October 2013. This is difficult to reconcile with the past record and requires review in the next phase of monitoring. **This borehole should be investigated and repairs made if possible**	Borehole remains dry. **This borehole should be investigated and repairs made if possible.**
WS6	Tip at 9.72m OD. Surface elevation at 16.2m OD (midslope, CBU2). After an initial sharp rise post installation from ca. 10m OD to 12.5m OD, measurements from this piezometer show a gradual and uninterrupted increase to a high of 14.3m OD in May 2012.		Groundwater levels showed a very slight (0.1m) decline since the last measurement in October 2013	Groundwater levels constant at 13.1m OD
B6	Tip at 10.0m OD. Surface elevation at 18.55m OD (midslope, northern edge of CBU2). Pattern of substantial fluctuation, usually between 14m OD and 17m OD, with the exception of major low in August 2008 when installation may have been almost dry (groundwater level ca. 10m OD).		Increase in groundwater level between October 2013 and July 2014 from 10.4m OD to 10.8m OD. Still lower than peak recorded values.	Slight fall from July to Nov 2014 from 10.8 - 10.7m OD.
B9	Tip at 9.25m OD. Surface elevation at 17.8m OD		Increase in groundwater level between October 2013 and July	Fall in water levels from July to November 2014 from15.0 -

Borehole	Long-term Pattern	Report 1 status	Change late 2013 to mid 2014	Change mid to late 2014
	(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). Most recent peak in December 2011 at 11.5m OD.		2014 from 14.7m OD to 15.0m OD. Still lower than peak recorded values.	14.3m OD. This is the lowest level since December 2009.
Sn2a	Tip depth at c. 13.9m OD*. Surface elevation at 16.35m OD* (midslope CBU2, co-located with SN2b). Likely that results for 2a and 2b confused or tip depth for Sn2a incorrect, as groundwater elevations not possible for tip depth stated. Notwithstanding that, Sn2a shows groundwater levels around 12m BGL rising slightly to May 2012.		Data from July 2014 at a similar level to that recorded between Dec 2009 and May 2012.	Levels remain constant since 2010 at 12.5m OD
Sn2b	Tip depth at c. 8.35m OD*. Surface elevation at 16.35m OD* (midslope CBU2, co-located with SN2a). Historical data for 2a and 2b confused or tip depth for Sn2a incorrect. Sn2b shows groundwater levels around 11m BGL, but rising to ca. 10.6m BGL by Dec 2011 and falling slightly to 10.7m BGL by May 2012.		Data from July 2014 at a similar level to that recorded between Dec 2009 and May 2012.	Water levels show a fall between June and Nov 2014 from 10.9 mOD - 10.5 mOD. Water levels in this borehole vary little, but are at their lowest on record since Dec 2009.

The new data indicate:

- No ground movements recorded in any of the inclinometers.
- The period has been drier than average and water levels remain low, or have fallen further to achieve their lowest level (e.g. mid-slope holes Sn2b and B9).
- Water levels recorded in boreholes P4a and P4b follow the same pattern but at slightly differing levels, and it is recommended their calibration be checked.

6.5 Causal-response relationships

Since the summer of 2012, much of the rainfall in the study area has been atypical. Following a dry start to 2012, the spring and summer were exceptionally wet and the latter half of 2012 was also wet. 2013 was dry and 2014 was also drier than average. The majority of shallow piezometers at Scalby Ness closely reflect that pattern of rainfall, with those installed with data loggers showing peaks in April/May 2012, July 2012 and December 2012, and falling groundwater levels until December 2013, after which groundwater levels rise and peak in mid-late February 2014, before falling and stabilising at lower levels by late 2014.

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

The inclinometers in BH7 and L2 show significant 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) (Figure 6.2). Neither inclinometer recorded movement between June and November 2014, associated with low groundwater levels. As Figure 6.2 indicates, the 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 are not associated with ground movement, possibly due to slow borehole equilibration with the surrounding ground.

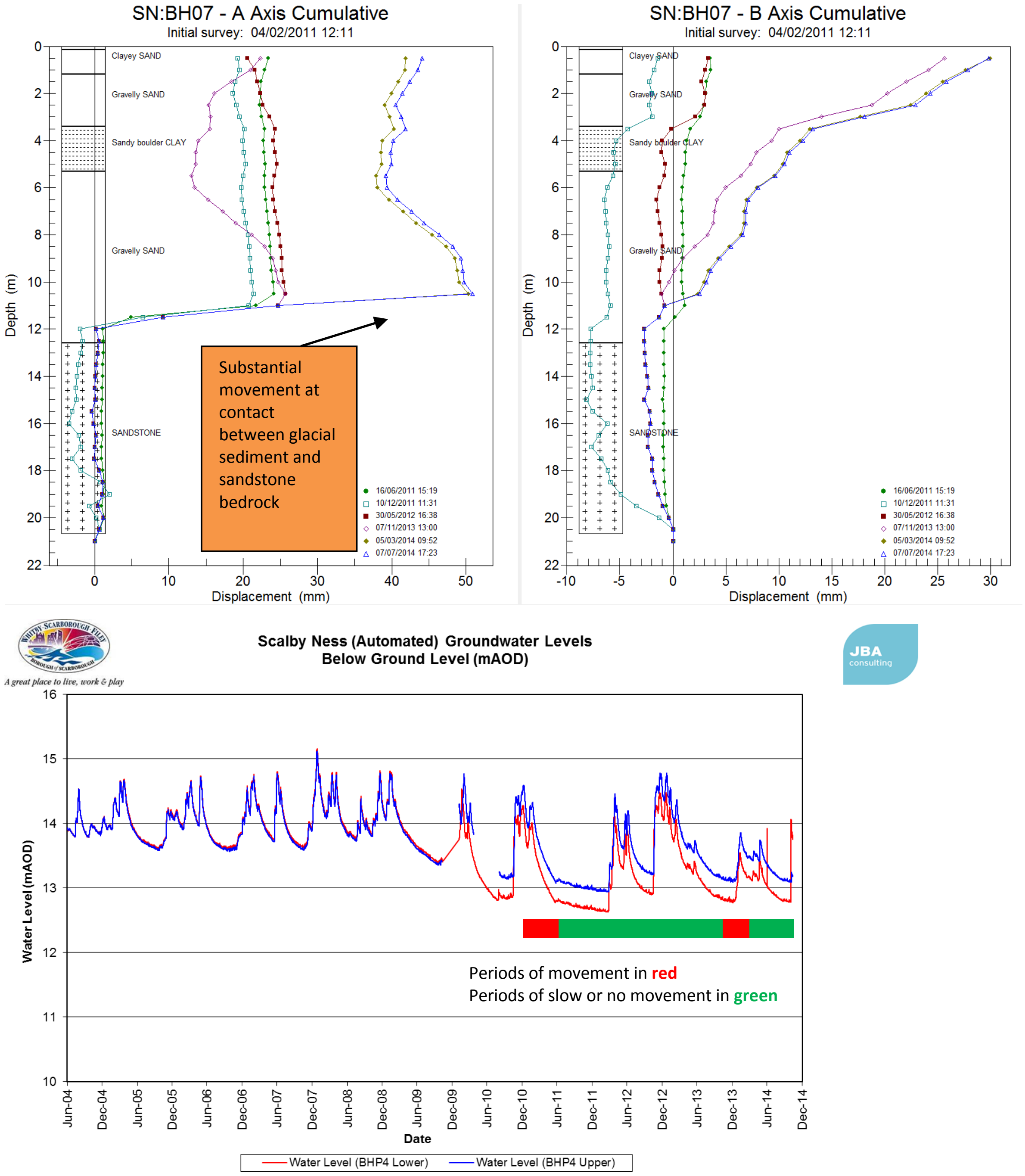

Figure 6.2. Correspondence of ground movement at inclinometer Scalby Ness BH07 and piezometer P4.

7 Scarborough North Bay – Oasis Café

7.1 Site description

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

7.2 Ground model and monitoring regime

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

7.3 Historical ground behaviour

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

Table 7.1. Summary of historical ground behaviour at Oasis Café

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

7.4 New data

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

7.5 Causal-response relationships

The winter 2013 to summer 2014 monitoring period was characterised by higher rainfall compared to the previous 6 months. The latter half of 2014 was slightly drier than average and water levels tend to show very slight falls with superimposed monthly fluctuations. The patterns seen in the past are still visible, with BH2p having an unclear response to rainfall and/or tides. Shallow piezometer BH3p continues to show a very rapid response to rainfall events (which probably explains the spikes on 10 Aug and 8 Oct), while only marginally deeper piezometer BH4p shows a lag response to prolonged periods of high rainfall. Groundwater levels in all boreholes remain below their peaks of winter 2012/13 and the inclinometers do not indicate movement.

Table 7.2. Summary of inclinometer data at Oasis Café

Borehole	Summary of past data	Report 1 status	Movement from late 2013 to mid-2014	Movement mid to late 2014
BH4	BH4 is situated on the cliff top and extends to ca.13.5m BGL. Ground level is 31.1m OD and the borehole extends to c 17.6m OD, penetrating 14m of glacial sediment and 3.5m of sandstone bedrock. Past readings show no significant ground movement.		July 2014 reading shows no significant change	Readings in November 2014 are insignificant, being less than 1mm.
BH3	BH3 is situated in the midslope and extends to c. 5.5m BGL. Surface elevation is 17.8m OD and the base of the hole is at c. 12.3m OD. The borehole extends through c. 3 m of glacial sediment before encountering 2.5m of mudstone, the uppermost metre of which is weathered. Past readings show no significant ground movement.		No significant change	Readings in November 2014 are insignificant, being less than 1mm. Apparent cumulative displacements are a result of compounding or small errors.

Table 7.3. Summary of groundwater data at Oasis Café

Borehole	Long-term Pattern	Report 1 status	Change from late 2013 to mid-2014	Change mid to late 2014
BH2p	Tip depth at 8.05m OD. Situated in the lower cliff. Manual dip readings from Sept 2009 to May 2012 show fluctuation between 8.0 and 8.5mOD from Sept to Dec 2009 followed by no change to December 2011. Groundwater level then rises to 8.5m OD by May 2012.		Groundwater levels rose to a peak in mid-Nov 2013 at around 8.6m OD, declined to late Dec 2013 rose to a peak of 8.5m in early Jan 2014. Levels then fell until mid-February 2014 before rising to a peak of 8.5m in mid-March. Subsequently, levels have fluctuated between 8.2 and 8.5m OD. Peaks not obviously coincident either with particularly high tides (e.g. the December 2013 storm surge event) or high rainfall events.	Continuation of past pattern. Water levels fall over summer 2014 to 8.1m OD in Aug 2014; rapidly rise to 8.4m OD in early Sept 2014. Levels then fall to c. 8.2m OD with fluctuations of c. 0.3m
BH3p	Tip depth at 12.4m OD. Situated in the midslope. Manual dip readings from Sept 2009 to Dec 2011 show fluctuation between ca. 13.8m OD (June 2010) and 14.7m OD (Dec 2010). Final manual reading May 2012 shows substantial rise to 17.6m OD, reflecting high rainfall during spring 2012.		Groundwater levels rose gradually from late Dec 2013 to a peak of 15.6m OD in late Jan. Levels then fluctuated about a generally falling trend to a low of 13.7m OD on 5 July 2014. Levels then rose sharply on 6 July 2014 to around 15.1m OD, following a day of very high rainfall on 5 July. Levels are well below their June and Dec 2012 and June 2013 peaks.	Continuation of past near-monthly cyclical pattern, but with significantly higher peak levels. Following the July 2014 peak of 15.1m OD, levels fell to 13.8m OD by early Aug then rose rapidly to an exceptional but short lived peak of 16.4m OD on 10 Aug 2014. The rise and fall pattern continued through 2014 with lows of 13.8m OD in late Sept and early Nov, separated by a peak of 16.4m OD on 8 October.

Borehole	Long-term Pattern	Report 1 status	Change from late 2013 to mid-2014	Change mid to late 2014
BH4p	Tip Depth at 17.0m OD. Situated at the cliff top. Manual dip readings from September 2009 to May 2012 show groundwater levels fluctuating between 18.0m to 19.3m OD with peaks in April 2010, December 2010 and May 2012.		Since October 2013, groundwater levels fell further during the dry conditions of 2013 to reach a low of c. 17.2m OD in late December and mid-February. Levels rose sharply in early March to c. 18.7m OD and have since fluctuated between 18.2m and 18.8m OD. Levels remain well below their February 2013 peak. The pattern continues to indicate the lag response of a bedrock aquifer to prolonged periods of high rainfall rain.	Continuation of past subtle cyclical pattern about average level around 18.7m OD. A subtle peak of 18.9m OD was achieved in mid-Sept, after which levels fell, albeit with considerable sub-weekly variations.

7.6 Implications and recommendations

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

Future reports should pay particular attention to the midslope piezometer (BH3p) which shows rapid response to rainfall conditions, but no associated ground movements to date.

SECTION 8

8 Scarborough North Bay – The Holms

8.1 Site description

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

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

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

8.2 Ground model and monitoring regime

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

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

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

The monitoring regime at The Holms comprises:

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

8.3 Historical ground behaviour

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

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

Observations in Mouchel 2012 (covering 6 month period between Dec 2011 and June 2012)	Total change observed between July 2009 and June 2012
Mouchel (2012) comments that no ground movement has been indicated at BH10A. They mention continued ground movements of around 14mm between 13 and 10m depth (ca. 46-43m OD) in BH11. They report erratic groundwater readings from BH8 and BH9 a and 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 2013.

Table 8.2. Summary of inclinometer data at The Holms

Borehole	Summary of past data	Status of report 1	Movements from late 2013 to mid-2014	Movements from mid to late 2014
BH10A	BH10A is c. 42m deep. Surface elevation of the borehole is 46.75m OD, therefore the base is at 4.75m OD. The borehole passes through.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. Moderate displacement (<4mm) is recorded in the negative B axis direction at 15m BGL (32m OD) within the sandstone between February and June 2011 but with little movement after that up to and including May 2012.		The inclinometer shows a similar pattern to that seen previously. The cumulative plot indicates significant displacement (several mm) in the B axis throughout the length of the tube, but this is likely to be an accumulation of measurement errors associated with the probe coming away from the key way **An inclinometer integrity check and careful collection of future readings is necessary.**	Similar pattern to before, with incremental movements <2mm throughout the borehole and more significant movements up to 4mm in the upper 5m. These readings are likely to be error and give rise to a cumulative plot that incorrectly suggests movement of c. 12mm at the top of the borehole. **Once this borehole is flushed it is recommended that future readings are recorded relative to a new baseline.**
BH11	BH11 is c.22m deep. Surface elevation of the borehole is at 55.86m OD therefore the base is at c.34m OD. The 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.		Sinusoidal deformation continues to be apparent within c. 4m of the weathered sandstone between 9 and 13m depth, but with no deformation above or below. It is likely that this relates to settlement of the borehole lining.	Sinusoidal deformation with the same pattern recorded in the past present within c. 4m of the weathered sandstone between 9 and 13m depth, but with no deformation above or below. It is likely that this relates to settlement of the borehole lining.

Table 8.3. Summary of groundwater data at The Holms

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
L1a	Tip depth at -8.03m OD, co-located with L1a. Manual dip readings from June 2009 to May 2012 show steady groundwater level around 5.2m OD with variation from 5.9m OD (June 2010) to 4.6m OD (March 10). This piezometer was also monitored between 1997 and 2000 and groundwater levels appeared to be lower (ca. 4m OD). NB the tip of this piezometer is deeper than BH1Lb, but shows a higher piezometric level that may indicate a confined aquifer under artesian pressure		BHL1a continues to show a generally declining trend in groundwater levels, albeit with potentially tidally influenced cyclical variation.	Ongoing short term cyclical variation (likely tidally influenced) is underlain by a c. 1m rise in groundwater levels between August and October. There was then a c. 0.3m fall from October to November 2014.
L1b	Tip depth at -2.97m OD co-located with L1a. Manual dip readings between June 2009 and May 2012 show relatively steady groundwater level around 1.9m OD.		BHL1b shows a fluctuating, cyclical pattern of groundwater levels between around 3.3m OD and 4.5m OD. Water levels peaked during the last monitoring period at 4.54m on 11 March. This is below the peaks seen in winter of 2012/13	Fluctuating, cyclical pattern continues well within range of previous variation.
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. After this there is a gradual rise to Dec 2011, reflecting wetter weather, before a sharp rise to 23.6m OD by May 2012, possibly as a result of the exceptional rainfall.		Limited variation, with levels between 9.7 and 10.6m OD. Rise in groundwater levels throughout Nov 2013 to a peak. On 1 Dec 2013. Levels then fall in Jan 2014 before rising to a peak in mid-June 2014.	Water level peaked at 10.65m OD on 22 July 2014, but has shown a general pattern of falling water level between July and November 2014 to c.10m OD with minor variation.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
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 very similar rainfall-influenced pattern to BH8a.		Pattern of gradual rises in level following by rapid falls. Groundwater levels fell in early Sept 2013 to c. 11m OD before a moderate rise that peaked in late November 2013 at 12.2m OD. Levels then fell to c. 11m OD in late December 2013 before a prolonged and gradual rise to a peak of 14.2m OD in early June 2014. There followed a sharp drop in groundwater levels to around 11m OD in summer 2014.	Groundwater reached lowest level on record at c.10m OD in mid-August 2014, but has continuously risen since, with only minor fluctuations, reaching c. 11.5m in mid-November 2014. This level is well below previous peaks.
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 slightly again to 26.3m OD.		Groundwater levels have been relatively steady between 23 and 24m OD since the last monitoring period, peaking in February 2014.	No change in water levels that have remained steady at c. 23.5m OD.
BH9b	Tip depth at 0.49m OD, surface at 33.49m OD co-located with BH9a. Shows sharp increase in ground water levels from c. 10m OD after installation in Sept 2010 to c. 25m OD in Feb 2011. Continues to gradually rise to c. 26m OD in June 2011 before gradually falling to 23.2m OD by May 2012. This pattern is similar to that recorded in BH9a, but contrary to that in BH8a and BH8b.		Groundwater levels fell to a low of around 9.3m OD in mid-December 2013 before rising to fluctuate between 14 and 16m OD between late January and early March 2014. Levels then fell to c. 10.3m OD before rising to between 12.0m and 13.5m OD in April 2014. Since early May 2014 groundwater levels have continued to show significant fluctuations about a general rise. **Groundwater levels appear to show a moderate lag response to periods of high rainfall.**	Initial fall in late July, followed by relatively large and irregular fluctuations with lows of c. 12.5m OD and peaks of up to c. 17.5m OD. Variation is within range of previous fluctuations**.**

8.5 Causal-response relationships

The weather was relatively dry and mild since the last monitoring report. The piezometers at The Holms show a mixed response to these conditions with L1a, L1b, BH8a and BH9a showing fluctuating, declining or steady levels of groundwater which remain below their earlier peaks. 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. BH8B has shown a pattern of consistently rising groundwater level during the current monitoring period, but levels remain well below historical peaks.

The lack of detailed weather records for the site while the met station is being repaired means improving the current understanding of relationships between rainfall and groundwater is not currently possible.

8.6 Implications and recommendations

Data from BH9b should be reviewed in the next report to establish whether the trend of rising groundwater levels continues.

SECTION 9

9 Scarborough South Bay

9.1 Site description

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

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

9.2 Ground model and monitoring regime

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

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

The areas being monitored comprise, from north to south:

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

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

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

9.3 Historical ground behaviour

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

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

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

9.4 New data

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

9.4.1 St Nicholas Cliff (MU 22A)

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

Table 9.2 Summary of inclinometer data at St Nicholas Cliff

Borehole	Summary of past data	Report 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
FR01	FR01 is situated above Foreshore Road in front of the Grand Hotel at 11.43m OD. The borehole is c.20m deep with its base at c.-8.5m OD and passes through c.10.5m of made ground and 9.5m of fine grained glacial sediments. FR01 has been monitored since 16 June 2014.	N/A	No movement recorded during initial readings.	No significant movement recorded.

Table 9.3 Summary of groundwater data at St Nicholas Cliff

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
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.	N/A	Water levels have a cyclical pattern of variation in elevation that is less than 0.5m. Distinct sub-weekly cyclical pattern of rising and falling groundwater level, overlain by a c. monthly pattern of changes in amplitude of sub-weekly variation. Probably reflects daily and neap/spring tidal cycles. Max ground water level c. 8.1m OD and minimum c. 7.7m OD (during spring tide).	Shows continuing responses to tidal cycles. However, this is overlain onto a slight trend of rising water levels from 7.7m OD in late August to 8.1m OD in mid-November, which is within the past range of values.

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

9.4.2 Spa Chalet (MU 22/1)

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

Table 9.4 Summary of inclinometer data at Spa Chalet

Borehole	Summary of past data	Report 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
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 creep along the whole length of the borehole with total displacement at the ground surface of c.10mm by 15 June 2011 and subsequent recovery. The nature of movement is likely to be error. 60mm displacement between 9.05m and 17.05mAOD in a sand and gravel horizon occurred between Feb and Aug 2011. This is likely to represent localised collapse of the casing.		Displacements of up to 3mm have occurred at 38m OD, where sandy gravelly clay sits above sand and gravel-rich strata. No movement lower in the borehole. Analysis of repeat test measurements taken in March 2014 concluded that while much of the borehole has been compromised, the reading offsets are systematic and therefore any change due to ground movement would be detected.	No significant movement.

Table 9.5. Summary of groundwater data at Spa Chalet.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
BHI2	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 tidal phases.		Range of fluctuations remain similar to those seen in the latter half of 2014. The signature of the 5th December storm surge is clearly visible as a spike when ground water levels achieved 2.25m OD, whereas tidal peaks are typically c. 1.5m OD	Range of fluctuations remain within past limits and linked to tidal cycles.
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.		Short term variability appears to have increased to levels comparable to those seen in late 2012.	Short term variability returned to previous (2012) levels after increase in late 2013 and early 2014.

No ground movement has been recorded and fluctuations in groundwater levels are within the ranges previously observed.

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 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
AA04 (G2)	40.5m deep borehole penetrating 34.5m of glacial sediments and 6m of sandstone/siltstone bedrock. Ground level is 47.62m OD, base of hole is 7.12m OD. No recorded change up to 30 May 2012 when Royal Haskoning recorded incremental change of 20mm to 30mm throughout the borehole.		Limited movement (<2mm) at around 15m OD since previous monitoring in 2011 is within tolerance of repeat readings. No additional movement at depth. Additional testing undertaken in March 2014 concluded compounding of small errors in historical readings had led to apparent deformation, but that limited deformation probably occurs in glacial sediments at 29 to 30m depth.	No significant movement.
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 of glacial sediment. Plots indicate movement occurred since the first reading on 3 Feb 2011 but are not always progressive. Small but significant movements (<20mm) are		Pattern shown is similar to earlier readings, with no change greater than the tolerance of repeat readings. Analysis of repeat test measurements taken in March 2014 concluded that while the lower part of the borehole had been compromised, the error was systematic and therefore any change due to ground	Apparent displacement of up to 150mm at the ground surface since last reading. The pattern of displacement relates to accumulation of measurement error throughout the BH where the sinuous pattern of change has become more exaggerated.

Borehole	Summary of past data	Report 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
	apparent in the lower 30m of the borehole, associated with a zone of fissures (i.e. below 23m OD). While the general pattern of displacements is that individually they have progressively enlarged up to December 2011, their direction is not consistent and therefore not indicative of a specific slip surface, or pattern of movement.		movement would be detected.	**Check integrity of borehole through repeat measurement.**
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.		Analysis of repeat test measurements taken in March 2014 concluded that while the lower part of the borehole below 28m depth had been compromised, the variance in readings was systematic and therefore any change due to ground movement would be detected. New data shows incremental movements up to 5mm in both A and B axes in the fine-grained materials at 45 to 50m depth (5 to 10m OD), which is due to loss of integrity of the borehole.	No significant movements since last reading, except at 37 - 38m depth where negative displacement of c. 5mm occurred. This reading is within a zone where the BH is compromised, resulting in a sinuous pattern, and is therefore likely to be error. **Review at next survey to see whether the possible minor movement at 37m to 40m depth has continued.**
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.		Incremental plot shows no significant movement greater than 1mm.	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.		All movements in incremental plot <2mm. Data integrity should be checked as cumulative plot shows increase in deviation from vertical in the B axis, but apparent recovery in the A axis. Apparent movements are small and not indicative of a distinct shear surface.	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.		All movements 2mm or less which are not significant.	No significant movement.
BH109	15m deep borehole that passes through 9m of glacial sediment and 6m of sandstone/mudstone bedrock.		All movements 2mm or less which are not significant.	Incremental movements are less than 2mm, but cumulative and plan view

Borehole	Summary of past data	Report 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
	Ground level is 31.6m OD, base of hole is 16.6m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm.			plots show markedly different patterns to those seen before, suggesting current reading may be erroneous. **This location should be reviewed in the next report once the BH has been flush cleaned.**
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.		Interim reading in March 2014 shows movements in incremental plot up to 5mm in both axes, but June 2014 reading shows recovery towards vertical. This suggests an error in data capture or that the integrity of the borehole is compromised.	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.		Acoustic emissions (AE) detected are most likely a response to rainfall events and groundwater seepage and not slope movement.	AE measurements during the period August 2014 to February 2015 do not show any significant slope movement, as the AE activity is relatively constant.

Table 9.7. Summary of groundwater data at the Spa

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
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. Maximum water level 17.6m OD on 4 June 2013, minimum of 16.9m OD on 15 March 2013.		No change to pattern, except slightly lower groundwater levels between December 2013 and March 2014.	Reduction in magnitude of fluctuation. Groundwater levels well within range of previous variation.
H2b	Located near the headscarp of the Spa landslide. Tip at 11.1m AOD. 3 to 7 day frequency fluctuation around mean of c. 12.7m OD with amplitude of c. 0.3m. No clear long term trend or temporal pattern. Maximum water level 12.9m OD on 3 June 2013 and 7 July 2013, minimum of 12.3m OD on 14 December 2012.		No change in the pattern.	No change in the pattern.
H5	Located near the base of the cliff. 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		Saw-tooth pattern of instantaneous rises in groundwater levels up to several metres followed by gradual falls since Jan 2014. Suggests a very sensitive response to rainfall or, more	Continued saw-tooth pattern of instantaneous rises and gradual falls.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
	water-levels rose by almost 1m in a day.		likely, an equipment error. Checks of the piezometer is recommended.	**Check piezometer integrity as this pattern did not occur prior to January 2014.**
1 spa	Located near the base of the cliff. Tip at 6.3m OD. Water levels fluctuate between c. 7m OD and c. 12m OD. High levels over 11m AOD occurred in May 2008, Dec 2009 to Apr 2009 with historical low of c.7m OD between Aug 2008 and Aug 2009.		Incomplete record. Level at 7.4m OD in Oct 2013 is near the historical low. Rises to 10.0m OD in June 2014.	Groundwater levels have risen slightly to 8.3m OD in Nov 2014. This remains well below the historical high.
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.		Incomplete record. 9.9m OD in Oct 2014 is near the historical low. It rises to 10.3m OD in July 2014, which is still near the historical low.	Slight fall in groundwater level to 10.2 m OD, which is near the historical low.
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.		Incomplete record. Groundwater at 12.0m in June 2014. This is similar to the last reading of 12m OD in Oct 2012, which is near the historical average.	Slight fall in groundwater level to c.11.9m OD in Nov 2014, remaining near the historical average.
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		Incomplete record. Similar pattern to 3 Spa continues. Groundwater at 11.9m in June 2014. This is similar to the last reading of 12m OD in Oct 2012, which is near the historical average	Slight fall in groundwater level to c.11.7m OD in Nov 2014, which remains near the historical average.
G3	Located near the base of the cliff. Tip at 13.6m OD. Complex pattern comprising c. 7 month period cycle of rising water level with superimposed sub-weekly fluctuations. 7 month cycle shows rise in water levels of c 1m from 13.3m OD in Oct 2012 to high of 14.4m OD in Feb 2013, falling to low of 13.5m OD in June 2013.		Cyclical pattern continues with apparent decrease in amplitude, leaving maximum and minimum groundwater levels within the range seen between Oct 2012 and late 2013.	Continuing pattern of cyclical fluctuation. Maximum and minimum levels within well within the range of previous fluctuation, but levels show a general fall in October 2014.
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.		No data recorded since May 2012 as the borehole is dry. Piezometer integrity check and quality of readings to be reviewed.	No data. Borehole dry since May 2012. **Check piezometer integrity.**
BH1a spa	Located at the toe of the Spa landslide. Tip at 2m OD. Sub-weekly fluctuation about mean around 4.4m. Water levels were at their highest during Jan and Feb 2012 when they were c. 0.5m higher than		Continued decrease in sub-weekly fluctuations. Peak in early March 2014 of ca. 4.8m OD but fluctuations within those seen before.	Continuing cyclical pattern overlain onto slight fall in groundwater levels since October 2014. Fluctuations still well within range of previous levels seen.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
	average. Sub-weekly fluctuations are c. 0.4m in the period Oct 2012 to Mar 2013.			
BH1b spa	Located at the toe of the Spa landslide. Tip at 10.1m OD. Similar pattern to BH1a. Sub-weekly fluctuation in water level about mean of c. 12.4m OD. Water levels highest in late Feb 2012 when they reached 12.7m OD. Sub-weekly fluctuations were up to 0.5m in the period Oct 2012 to Mar 2013.		Decrease in amplitude of fluctuations with peaks in March and May 2014 of around 12.6m OD. Groundwater levels generally higher than in late 2013 to early 2014, reflecting increased rainfall in 2014 compared to the same period in 2013. Levels have stabilised since recovering after 2013 around a mean level of ca. 12.5m OD.	Continuing cyclical pattern overlain onto slight fall in groundwater levels since October 2014. Fluctuations still within range of previous levels seen.
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.		Pattern of general increase, since a low in early Feb 2014 when levels dropped to 41.1m OD. Levels peaked at 42.0m in mid-May and mid-June, but were stable around 41.8m OD from June to Aug.	Continuing fluctuations of c. 0.2m overlying an overall trend of falling groundwater levels, reaching c.41.5m OD in November 2014.
G1a	Located inland of the cliff top. Dipped piezometer that shows consistent water levels of c. 53.5m OD since late 1997.		No change – consistent groundwater level of c.53.5m continues.	Borehole dry. **Check integrity of piezometer installation.**
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.		Consistent water level since previous recording at ca. 19m OD.	Consistent water level since previous recording at ca. 19m OD. No significant change.
BH108a	Deep piezometer tip located mid-slope. Solinst data logger. Record begins on 18 Dec 2012 and shows several sharp fluctuations that are possibly in response to rainfall events However fluctuations recorded by BH108b show an unexpected pattern, with sharp apparent rises in groundwater level up to ground level followed by a slower and decelerating drop. It is possible this pattern represents a sudden ingress of surface water into the installation which then slowly dissipates.		Data available from 5 Oct 2012 to Feb 2013 is characterised by sudden rises in level, often to ground level at 31.60m OD, followed by slower falls. Pattern is absent, or muted between Feb 2013 and late Oct 2013, but returns in late 2013 to early 2014. Typical base levels have fallen from c. 20m in late 2012 to early 2013, to c. 15m OD for the rest of 2013. This pattern matches the rainfall pattern. The single peak on 26/11/2013 does not fit the rainfall pattern, but appears in other boreholes. This may be a local weather effect.	Continuing pattern of rapid rises in water level with more gradual falls that probably relate to rainfall events, however base level shows a net rise since the last monitoring period. All peaks are at 31.6m OD, which is ground level, suggesting the borehole may be filling with water during storms. The base level to which groundwater levels fall after sharp rises has risen by c. 10m (from 15m to 25mOD) between late Sept 2014 and mid-Nov 2014. This base level is higher than previously seen and may indicate a net rise in groundwater levels.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
BH108b	Located mid-slope. Located mid-slope. Shallow piezometer tip that was dry between Sept 2012 and Jan 2013.		No change in reported groundwater level – steady at 25.06m OD since last reading.	Increase of c. 5m in groundwater level since last reading. This reflects the pattern seen in BH108a
BH106a	Located at the cliff top. Solinst data logger. Borehole dry between Oct 2012 and Jan 2013.		Borehole dry.	Borehole dry. **Check piezometer integrity**
BH106b	Located at the cliff top. Located at the cliff top. Borehole dry between Oct 2012 and Jan 2013.		Borehole dry.	Borehole dry. **Check piezometer integrity**
BH104a	Located near the base of the slope. Solinst data logger.		Data shows rapid spikes to ground level (20.2m OD) overlying a rise in the average base level of groundwater that rises to 12m OD in late December 2012, then falls to 5m OD through the middle of 2013. Water level fell below the diver and therefore may have been lower than 5m OD.	No change in water level since previous reading (steady at 5m OD).
BH104b	Located near the base of the slope. Manual piezometer tube. Borehole dry between Sept 2012 and Jan 2013. No data		Increase in groundwater level from 4.3m OD to 10.6m OD. However, this reading is similar to October 2012 and there are too few readings to determine if this is outside of the norm.	Slight fall in groundwater level to 10.3m OD.
BH102a	Located at the base of the slope behind the seawall. Solinst data logger. Reading will be reported in next report.		Data shows a short-term cyclical pattern that is likely to represent tidal variation. The variation is reduced after March 2014. A clear spike shortly after the December 2013 storm surge is included. There is an underlying pattern of slightly higher levels from late 2012 to mid-2013 with levels falling in late 2013 and early 2014. An anomalous spike present in other diver piezometers in this location on 26/11/2013 is present.	Continuing short term cyclical pattern, likely to be driven by tidal variation. Slight increase in magnitude of fluctuation in throughout monitoring period and an apparent rise in overall level after the previous measurement.
BH102b	Located at the base of the slope behind the seawall. Manual piezometer.		Slight fall in groundwater level to 1.2m, similar to October 2012 reading. Likely influenced by tidal cycle.	No significant change in groundwater level. Remains at c.1.3m OD.

These data indicate:

- Borehole BH109 shows possible minor ground movements. The accuracy of readings is unclear and the record should be reviewed once the borehole has been cleaned.
- Piezometers H5, 5 Spa, G1a and BH108a should be checked because they are dry or show rapid peaks in water level that reach ground level. These readings suggest the boreholes are being flooded.
- Acoustic emissions (AE) detected are most likely a response to rainfall events and groundwater seepage and not slope movements (Figure 9.2)

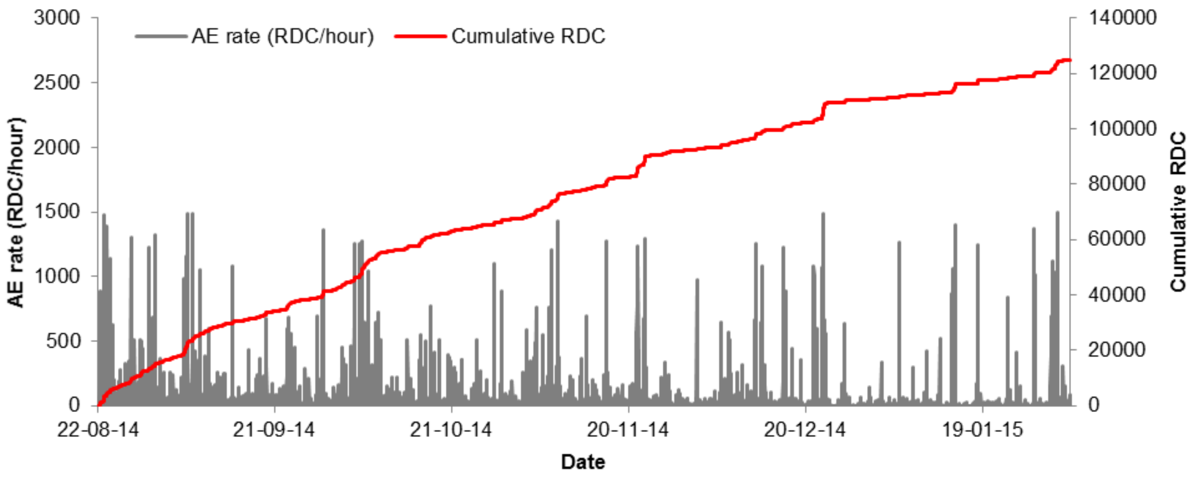

Figure 9.2. AE rate- and cumulative AE-time series measurements at Scarborough Spa for the period August 2014 to February 2014.

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 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
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.		Continuation of minor creep in positive A axis direction in the upper 5m of glacial sediment.	No significant change.
AA11 (F4)	20m deep borehole penetrating 8m of glacial sediment and 12m of siltstone/sandstone bedrock near the toe of the Clock Café landslide. Very low cumulative movement along whole length of borehole of up to 3mm is within tolerance of the device.		No change. All apparent movements <1mm and therefore not significant.	No significant change.

Table 9.9. Summary of groundwater data at the Clock Café

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
BH15	Located inland of the landslide headscarp. No historic data found		Borehole dry. Piezometer integrity check and quality of readings to be reviewed.	Borehole dry. **Piezometer integrity check and quality of readings to be reviewed.**

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 and its integrity should be checked.

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

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

Table 9.10. Summary of inclinometer data at South Bay Gardens

Borehole	Summary of past data	Report 1 Status	Movement late 2013 to mid-2014	Movements from mid to late 2014
AA08 (D3)	24m deep borehole that penetrates 12m of glacial sediment and 12m of siltstone/sandstone 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, with a maximum cumulative displacement of 5mm.		No change. No incremental movements >1mm.	No significant change.
BH17	50m deep borehole than penetrates 34m of glacial sediment and 16m of siltstone bedrock at the top of a mudslide embayment. Ground level is 57.46m OD, base of hole at 7.46m OD. Data indicate slight progressive creep along the whole length of the borehole, with maximum cumulative displacement of 5mm.		No change in pattern shown in the incremental data above deepest 2.5m of borehole within the siltstone. Sinuous pattern likely represents reading error and not ground movement.	No significant change.
BH16A	54m deep borehole than penetrates of 33m of glacial sediment and 21m of siltstone/sandstone bedrock inland of the Rose Garden rotational landslide. Ground level is 62.88m OD, base of hole is 8.88m OD. Data indicates slight progressive creep along the whole length of the borehole with a maximum cumulative displacement of 5mm. Field visit in Dec 2013 confirmed readings of 2011 and 2012 that suggested movement were error.		Incremental plot indicates no significant change since last reading.	No significant change.
BH20	41m deep borehole that penetrates 27m of glacial sediments and 14m of sandstone bedrock within the body of a small landslide. Ground level is 58.98m OD, base of borehole is 17.98m OD. Data indicates slight progressive creep along the whole length of the borehole with a maximum cumulative displacement of 5mm.		Additional data provided in September 2014, the latest reading in which was taken on 15 September 2014, indicates no further movements in this borehole.	No significant change.

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

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
BH18a	Tip at 26.8m OD near the base of the cliff and Rose Garden landslide. Complex pattern, with a number of clustered sub-weekly spaced peaks of water-level 4m to 5m higher than base readings. From Nov 2012 to May 2013 base readings were between 36.5 and 37m OD. Between May and August 2013 it has been higher at between 37.5 and 38m OD. Clusters of high water level occurred from 21 Nov to 24 Dec 2012, 15 Jan to 14 Feb 2013, 13 to 18 Mar 2013, 15 May to 28 Jun 2013 and 28 Jul to 15 Aug 2013. Between these peaks, levels rapidly drop to the typical 37m OD elevation then gradually drop a further c. 0.5m.		Gradual increase in base readings from mid-December 2013 to mid-February 2014, with spikes in water level reaching ca. 42.5m OD. Base readings fall to the end of the July. The elevated base level in winter 2013/14 ties in well with the wetter period shown in the rainfall record. The short-lived spikes in groundwater level may be indicative of a malfunction such as damage to the vibrating wire or water ingress. **The integrity of this installation should be checked**	Short-lived spikes in groundwater continue, but base level has fallen between July and November 2014 to around 35m OD. **Recommend integrity of installation is checked.**
BH18b	Tip at 23.8m OD near the base of the cliff and Rose Garden landslide. Pattern very similar to that recorded by higher elevation tip, with similar timing and magnitude of peaks and similar low elevation water level.		Pattern very similar to that recorded by the higher tip, including spikes which may be indicative of damage to the vibrating wire or water ingress. The integrity of this installation should be checked.	Pattern very similar to that recorded in BH18a above, including spikes which may be indicative of damage to the vibrating wire or water ingress. **The integrity of this installation should be checked.**
BH19a	Tip at 53.8m OD inland of the headscarp of the South Bay Pool landslide. This piezometer has been dry since installation.		No data available. Contractor's notes indicate that there is an issue with the data logger. Data logger and piezometer integrity to be checked.	No data. **Contractor's notes continue to indicate replacement of the data logger is required.**
BH19b	Tip at 47.3m OD inland of the headscarp of the South Bay Pool landslide. Sub-metre variation about an average level of 47.8 OD. Periods of slightly higher water level from Dec 2012 to Mar 2013, late May 2013 and early Aug 2013.		Lower groundwater levels between early December and early May, with sub-weekly variations of ca. 0.2m and a spike in levels to ca. 48.1m OD in early March. A general rise in water levels with much greater (0.5m) variations over slightly longer timescale. Groundwater levels peaked on 8 July 2014 at their highest level in the record (48.5m OD). This pattern does not tie in well with the rainfall record and may reflect local effects.	Relatively low groundwater levels (c. 47.4 to 47.6m) from late July to late Sept. Peak in groundwater level at 48.6m in Sept 2014 is highest on record but subsequent net fall in water levels until mid-Nov.
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		Groundwater levels fell from a peak in late November 2013 until late December 2013, likely	General pattern of a slight fall in groundwater level, with the exception of two short lived spikes in groundwater

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
	hole appears dry occurred regularly from late June to early July 2013, following which no data has been recorded.		reflecting the dry conditions of 2013. Levels subsequently recovered until reaching a peak in mid-March at around 31.8m OD. Groundwater levels show sub-metre variability around a mean groundwater level of 31.5m OD since late March.	level to over 32m OD in early October 2014.
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 since October 2013 as contractor unable to connect to data logger – integrity of the logger should be checked.	No data since October 2013 as contractor unable to connect to data logger. **Integrity of the logger should be checked.**
Bh3a	Tip at 41.5m OD at a mid-slope position adjacent to the South Bay Pool landslide. Sub-metre variation about a mean value. Change occurs in Apr 2013, before which mean is 44.5m OD, after which it is drops to c. 44m AOD.		No data since October 2013. Contractor's notes indicate the cable has been cut and requires fixing.	No data since October 2013. Contractor's notes indicate the cable has been cut and requires fixing.
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.		Slight reduction in mean water levels in winter 2013/14 before recovering to levels seen previously. Spikes in level coincide with drops in temperature during winter and increases in temperature during the summer which suggests they reflect ingress of surface water. The integrity of the piezometer should be checked.	Groundwater levels show slight reduction during autumn 2014. Spikes in water level with associated water temperature fluctuation continue but are of lower magnitude than previously. **Spikes in ground water level indicate that the integrity of the piezometer should be checked.**
E2a	Tip at 31.4m OD below the headscarp of the mudslide embayment. Cyclical long-term pattern with sub-metre fluctuations superimposed. Water levels rise from c. 44m AOD to 46.5m OD between Oct 2012 and late Feb 2013 thereafter they fall gradually to 44.7m OD in Oct 2013		Continued decline from peak of ca. 46.5m OD in Feb 2013 to early 2014. Since Feb 2014 levels have stabilised at 44.2m OD with subtle weekly to fortnightly variability. The data indicates a lag response to the wet conditions of 2012 and dry conditions of 2013 with stabilisation during average conditions in early 2014.	Continuing reduction in water level since summer 2014 to around 43.6m OD in mid-November 2014.
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.		Groundwater levels lower in late 2013/early 2014 and with shorter term variability than previously seen. Since March 2013,	Slight fall in water level throughout late autumn 2014. Overlain by pattern of minor fluctuations well within the range of previous

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
			readings have returned to the same mean level and pattern of variability as seen before Nov 2013.	fluctuation. No significant change.

These data indicate:

- No further movement has been recorded in any of the boreholes at South Cliff Gardens.
- Where a pattern can be determined from the data, all piezometers show a general fall in ground water level. However, there are several piezometers (BH19a, D2b, BH3a) for which there are no data due to data logger problems, and others (BH18a, BH18b and BH3b) should be checked as they show rapid spikes in water level which could be due to flooding or equipment malfunction.
- BH19a, D2b and Bh3a have not been read due to problems with the data loggers.
- Bh3b and BH18a show a pattern of spikes which are unlikely to be due to actual changes in groundwater level and appear to be associated with ingress of surface water during wet periods.

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 1 Status	Movement from late 2013 to mid-2014	Movements from mid to late 2014
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. Cumulative deformations of up to 10mm are also indicated at three elevations within the bedrock, but these may represent minor settlement of the borehole lining.		Small continuation of displacement at contact between glacial sediments and underlying bedrock at ca. 30m depth. Slightly larger (4mm in incremental plot) additional displacement in siltstone at c. 55m depth. These locations have previously shown smaller variation in both axes, which suggests that the BH is deformed.	Incremental movements at same depths seen before are less than 2mm and not significant.

Table 9.13. Summary of groundwater data at Holbeck Gardens

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
Bh4a	Tip at 31.5m OD. Complex pattern with periods of relatively stable water-level interspersed by rapid rises or falls to new levels up to 2m different. Occasional very short-lived peaks in level that are up to 8m higher than typical. Overall pattern since Oct 2012 is of falling water level. Oct 2012 to Mar 2013 shows period of mean level at 51 to 52m OD with numerous short-lived peaks of up to 59m OD. Water-levels then fall 47.5m OD in May 2013 and they remain relatively stable until late July when they rapidly rise from c. 49m and then gradually fall again.		Low point reached at c.48m OD in late Dec 2013,followed by progressive rises and falls between 49.8m and 49m OD in response to rainfall.	Limited, steady rises and falls in groundwater level within the range of previous fluctuations. No significant change.
Bh4b	Tip at 35m OD. Very different pattern to that recoded in shallower tip. Highly variable, but falling water level from mean of c. 50m OD in Oct 2012 to mean of c. 32m OD. Over this time there are rapid changes of elevation of c. 15m with short-term peak elevations of up to 58m OD and lows of down to 32m OD. Since Oct 2012, levels have been more consistent, with variation of up to c. 2m about a mean of c. 33m OD. A single short-lived peak occurred on 24 Apr 2013 when levels rose by 6m in a day.		Contractor's notes indicate this logger is currently not working. Last data presented was July 2013.	Contractor's notes indicate this logger is currently not working. Last data presented was July 2013. **Repair or replacement of data logger required.**

The data show fluctuations in groundwater levels within the range of previous fluctuation. Several piezometers need maintenance or replacement. Previously, the inclinometer installed at the cliff top indicated possible small movements at around 55m below ground level in a siltstone layer between two sandstone layers, which would be anticipated from experience at Holbeck Hall Hotel and other pre-existing landslides in South Bay. However, no evidence of continued movements is shown in the latest data.

9.5 Causal-response relationships

For the most part, groundwater levels show a limited fall or no change, reflecting the relatively mild and dry weather during late 2014. There is little evidence of movement in the inclinometers and no critical groundwater level thresholds have been identified during this period. However, several piezometers show a trend of rising water level which should be closely monitored.

9.6 Implications and recommendations

None of the inclinometers indicate any significant ground movement.

The majority of piezometers show a fall or no change in groundwater levels. Several piezometers (BH19a, D2b and BH3a at South Bay Gardens and BH4b at Holbeck Gardens) have issues with their data loggers and no data has been recorded at these locations for several months. Boreholes 5 spa, 106a and 106b at the Spa, and BH15 at the Clock Café are all dry. Several other piezometers (H5, BH108a, BH18a, BH18b and BH3b) show sharp rises and falls which are unlikely to be due to normal groundwater fluctuations. These locations should be checked, and any necessary repairs undertaken. BH108a and BH108b also show significant rises in groundwater levels and it is recommended that interim readings or downloads are taken from these installations to understand if that pattern has continued or reversed during the winter.

SECTION 10

10 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 stormwater 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 stormwater run-off around Glen Gardens and this also caused drainage to collapse leading to slope instability behind Royal Parade chalets and Crescent Hill (Mouchel, 2012). The unprotected cliffs to the north and the south of the town are susceptible to toe erosion by the sea and are actively retreating. Cliff behaviour units (CBUs) have been defined and their activity status classified under the Cell 1 Regional Monitoring Programme.

10.2 Ground model and monitoring regime

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

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

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

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

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

The monitoring regime at Filey Town comprises the following:

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

- Inland North – Groundwater monitoring near Church Cliff Farm, Pinewood Avenue and Parish Wood.
- Inland South – Groundwater monitoring near Filey Fields Farm, Long Plantation (west of Rivelin Way and Fewston Close) and Filey School.

10.3 Historical ground behaviour

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

Table 10.1 Summary of historical ground behaviour at Filey Town.

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

10.4 New data

Tables 10.2 and 10.3 summarise the inclinometer and piezometer data from Filey Town to August 2014.

*Table 10.2. Summary of inclinometer data at Filey Town. Note: *Surface elevation and borehole depth calculated from digital elevation model.*

Borehole	Summary of past data	Report 1 Status	Movement late 2013 to mid-2014	Movements from mid to late 2014
CPBH03	CPBH03 is 10m deep. Surface elevation is ca. 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. It is situated on Coble landing. Cumulative and incremental readings show very minor movements <2mm.		No displacement – all apparent incremental displacements <1mm	No significant movement.
CPBH05	CPBH05 is 10m deep. Surface elevation is ca.6.5m OD* therefore the borehole extends to ca. -3.5m OD* through glacial sediments. Cumulative displacements indicate movements of <2mm with no particular pattern.		No displacement	No significant movement.

Borehole	Summary of past data	Report 1 Status	Movement late 2013 to mid-2014	Movements from mid to late 2014
RCBH07	CPBH07 is 20m deep. Surface elevation is at ca. 5m OD* therefore the borehole extends to ca. -15m OD through glacial sediments. Only very minor (<2mm, cumulative) displacements without any particular pattern are recorded in this borehole.		No movement. All apparent displacements in incremental plot <1mm.	No significant movement.
BH6	BH6 is 30m deep. Surface elevation is ca.27.4m OD* therefore the base of the hole is ca. -2.6m OD. The borehole extends through glacial sediment. Cumulative displacement plots show displacements of around 10mm in a negative B axis direction between September and December 2009.		Readings in March and July 2014 both show significant negative displacement at the base of the borehole, which is thought to be due to blockage. Potential blockage should be investigated and repaired.	Large apparent displacement due to blockage is still present at base of borehole but otherwise no significant movement. **Potential blockage should be investigated and repaired.**

Table 10.3. Summary of groundwater data at Filey Town

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
BH5b	Tip depth at 1.09m OD. Situated on the sea front road ('The Beach'). Early large fluctuations indicated following installation (July/August 2008) but since then has remained relatively constant with limited fluctuation between 1.09m OD (Aug 2008) and 1.69m (Dec 2009).		Levels steady at c. 1.3m OD	Levels steady 1.3 - 1.4m OD
BH4	Tip at 18.07m OD. Situated at the cliff top towards the southern end of The Crescent. Major fluctuations (>27m OD to <20m OD 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 since albeit showing an increase in groundwater levels to 20.2m OD in May 2012.		Sharp increase in groundwater level to 25m OD from previous level ca. 20.7m OD.	Slight rise to 25.5m OD which is close to the highest levels previously seen.
CPBH01a	Tip at 16.93m OD. Situated on the cliff top north of the Sailing Club. The readings for this piezometer are sporadic between Sept 2011 and are often dry. Mean groundwater 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.		Levels steady at ca.17.3m OD.	Sharp rise in groundwater level to 25.23m OD. Latest reading is highest on record.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
CPBH01b (Diver)	Tip at 32.63m OD. Situated on the cliff top north of the Sailing Club road. 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 groundwater elevation of 35.0m OD on 14 December 2012.		Groundwater level fell until late Dec 2013, reaching a low of around 33.2m OD. Levels rose to early February and stabilised at c. 34.3m OD. This pattern reflects the rainfall record**.**	Fluctuations within range of previous readings, except for substantial peak on 10th Aug 2014 when level rose to c. 34.8m OD followed by a rapid fall to c. 34m OD.
CPHB02a	Tip at 1.57m OD. Situated on the cliff top to the north of Coble Landing. Mean groundwater elevation at around 5m OD with minor fluctuations except for a reading in Sept 2012 at 3.57m. Maximum groundwater elevation at 5.23m OD on 19/04/2012.		Level fallen slightly to 4.9m OD.	No data. Correct equipment not available during site visit.
CPBH02b (Diver)	Tip at 8.17m OD. Situated on the cliff top to the north of Coble Landing. Generally steady around 8.7m OD except for significant spikes in on 06 July 2012 (to 15.6m OD) and 07 Dec 2012 (to 20.0m OD). Smaller spikes (to less than 9.7m OD in late Nov/early Dec 2012).		Very little fluctuation. Level steady around 8.7m OD	No change. Water level steady at c.8.7m OD.
CPBH04a	Tip at 2.90m OD. Situated on the Cliff Top immediately to the north of Church Ravine. 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).		Water at ground level. Check piezometer integrity to ensure surface water cannot access the borehole.	Large fall in groundwater level to c. 7.3m OD.
CPBH04 (Diver)	Tip at 9.9m OD. Situated on the Cliff Top immediately to the north of Church Ravine. Steady around 13.5m OD until Dec 2012 although dip in Dec2012 reads significantly higher (16.3m OD).		Stable groundwater level at ca. 13.4m OD.	Gradual rise in groundwater level since July 2014.
CPBH06a	Tip depth at 0.13m OD. Situated to the on the cliff top towards the northern end of The Crescent. Mean groundwater elevation at 19.86m OD. Range between 18.85m OD (27/02/2012) and 20.11 (20/12/2012). Notable increase in March/April 2012 suggesting groundwater recovery followed the dry period late autumn of 2011 and winter of 2011/2012 rising to highest point in Dec 2012 at the end of a very wet year.		Continued decline in ground water level to 18.88m OD.	Slight rise in groundwater level, but overall similar to historical record at c. 13.5m OD.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
CBPH06b (Diver)	Tip depth at 8.63m OD. Situated on the cliff top towards the northern end of The Crescent. Relatively steady at around 18m OD except for sudden drop to around 14.5m OD and immediate recovery on 20/03/2012 and 06/09/2012 and sudden drop on 19/04/2012 followed by a prolonged steady period at c. 15m OD before sudden recovery on 24/05/2012 to 18m OD.		Sudden drop of ca. 4m coincident with last dipped reading in Nov 2013. These sudden drops are common in the record, and are coincident with manual readings. Since late 2013 there has been a gradual rise in level to late Feb 2014 that stabilised at c. 14.7m OD. Check data logger and diver integrity.	Slight rise in groundwater level from 14.3 to 14.4m OD, with short-lived peak of 16.6m OD on 10 August 2014. Along with similar peak in CPBH01b, this suggests a rapid response to rainfall in these piezometers.
CPBH08a	Situated on the cliff top immediately to the north of Martin's Ravine, 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.		Slight increase in groundwater level to 9.43m OD, which matches peak levels of Dec 2012.	Continuous rise in groundwater level of c. 2m to 11.4 m OD since last reading. Levels now significantly higher than historical peak of 2012.
CPBH08b (Diver)	Situated on the cliff top immediately to the north of Martin’s Ravine. Very steady with fluctuations over whole period only between 17.90m OD and 17.97m OD.		Generally steady water level at c. 17.9m OD, with subtle rise and fall in mid-February 2014. Subtle spikes in level in late May and early June 2014 may relate to rainfall peaks in the weather record. Contractor’s report indicates the data logger is full and stopped recording on 5 June. It should be visited and maintained.	Slight rise of groundwater level between July and November 2014, from atypical low of c. 17.8 to historical position of 17.9m OD..
CPBH09a	Tip depth at 0.64m OD. Situated on the cliff top near the northern part of the golf course. Mean groundwater elevation is 20.27m OD and ranges between 19.86m OD (01/08/2012) and 20.98m OD (06/09/2012).		Slight fall in groundwater levels to 20.4m OD	No significant change in groundwater level. Remains constant at c.20m OD.
CBPH09b (Diver)	Tip Depth at 17.74m OD. Situated on the cliff top near the northern part of the golf course. 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 October and mid-December 2012.		No diver data available due to malfunction. Manual reading indicates water level at 20.4m OD, which is 0.1m lower than at the last manual reading in October 2013. It is recommended that this instrument is checked.	No data due to ongoing problems with the diver and connecting to the data logger. **Repair of diver and installation required.**

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
CPBH10a (Diver)	Tip depth at 23.82m OD. Situated on the cliff top near the northern part of the golf course. Shows a pattern of relatively sharp increases to a peak over 1 to 7 days, followed by more gentle decreases in levels over several weeks, to around 28.5m OD. Comparison to rainfall records indicates that this borehole has a comparatively 'flashy' response to rainfall, with lag times reducing towards the end of 2012 probably because earlier rainfall events aided the recovery of groundwater levels following a dry period. Maximum peak is 30.8m OD in late Dec 2012.		Follows a similar pattern to CPBH01b, peaking at around 30m OD in mid-February. However, groundwater levels in at this depth have fallen since then to around 29.1m OD	Rapid rise in groundwater level on 10 August 2014, peaking at 29.5m OD on 12 August 2014, followed by more gradual decline. Suggests slight lag but still rapid response to rainfall event. Gentle and gradual rise from late September to mid-November 2014.
CPBH10b	Tip depth at 11.92m. Situated on the cliff top near the southern part of the golf course. No data prior to October 2013 due to blockage by slip rod.		Contractor's notes state no reading was taken.	Borehole dry **Recommend installation integrity is checked.**
BHA	Tip depth at 27.62m OD. Situated to the North of Pinewood Drive/Wooldale Drive on the northern edge of the town. No previous data available at present		09/07/2014 – Slight rise in groundwater level to 36.58m OD	Subtle rise to 36.9m OD
BHB	Tip depth at 30.97m OD. Situated in the northern corner of the field to the northeast of Cherry Tree drive and Sycamore Road on the northern edge of the town. No previous data available at present		09/07/2014 – Water at ground level. Piezometer integrity check to ensure surface water cannot access the borehole	Subtle rise to 40.4m OD.
BHC	Tip depth at 32.87m OD. Situated near Long Plantation on the south west edge of the town. No previous data available at present		09/07/2014 – Small increase in ground water level of 0.3m to 42.0m OD.	No significant change. Steady at 42.0 to 42.1m OD.
BHD	Tip depth at 21.57m OD. Situated between the golf course car park and the railway line. No previous data available at present		09/07/2014 – Small increase in groundwater level of 0.4m to 31.2m OD.	No significant change. Steady at c. 31.2m OD.
TP3	Tip depth at 29.73m OD. Situated immediately to the north of Church Cliff Farm. No previous data available at present		09/07/2014 – Slight decrease in water level to 32.4m OD	No significant change. Steady at c. 32.4m OD.
TP6	Tip depth at 33.85m OD. Situated in to the north of Filey Fields Farm on the northwest edge of the town. No previous data available at present		09/07/2014 – Slight decrease in level to 36.1m OD	No significant change. Steady at c. 36m OD.
TP8	Tip depth at 39.81m OD. Situated in the northern corner of Filey School's playing field near the end of Midhope Way on the south west edge of the town. No previous data available at present		09/07/2014 – Small increase in water level to 43.3m OD.	Significant fall of c. 6.4m.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
TP9	Tip depth at 45.35m OD. Situated near the south west boundary of Filey School's playing field. No previous data available at present		09/07/2014 – Small increase in water level to 50.6m OD.	No change. Steady at 51.6m OD

10.5 Causal-response relationships

Most of the piezometers show steady groundwater levels or subtle rises, with the exception CPBH01a and CPBH08a which increases in water level of several metres. Boreholes CPBH01b, CPBH06b, CPBH08b and CPBH10a show peaks in groundwater level on 10th October 2014, indicating rapid response to an intense rainfall event. No relationships between groundwater and ground movement have been identified.

10.6 Implications and recommendations

Inclinometer at BH6 requires maintenance and careful reading to avoid errors at the base of the hole that may relate to a blockage.

There are problems with piezometers and/or data loggers at CPBH09b and CPBH10b that should be investigated and repaired if possible. Future groundwater levels in CPBH01a and CPBH08a should be carefully monitored to understand the cause of unexplained peaks recorded in the current data.

SECTION 11

11 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 July 2014.

*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 1 Status	Movement to from late 2013 to mid2014	Movements from mid to late 2014
A2	A2 is 27.5m deep (surface elevation at 17.93m OD) and extends through glacial sediment. Moderate movements (<5mm cumulative) between Dec 2009 and Dec 2010 which increase by a further c. 10mm by June 2011. Incremental plot indicates the largest downslope movement is focused on a shear zone at c. 6m to 7m OD		No movement has taken place – data indicates an apparent recovery towards vertical.	No significant movement has taken place since the last measurement.
C1	C1 is c. 25m deep. Surface elevation is 25.7m OD* the base of the hole is c. 0.7m OD. It shows very minor (<2mm cumulative) displacements up to and including October 2012.		Inclinometer baseline reading reset to Nov 2013. Subsequent readings continue to indicate displacement at c.15m depth. Incremental displacements are <5mm	No further displacement.
C2	C2 is c. 21m deep. Surface elevation is at 16.5m* and the borehole extends to -4.5m OD through variable glacial sediments. All displacements to Oct 2012 within the margin of instrument error		No significant movement recorded.	No significant movement recorded.
C5	C5 is c. 16m deep. Surface elevation is 12.0m OD* and the borehole extends to -4.0m OD passing through variable glacial sediments. The inclinometer shows no movement to October 2012 apart from very minor (<2mm cumulative at the surface) displacements in the uppermost 1.5m of material		Previously identified movement appears to have been error. Latest reading shows no significant movements. Contractor's report notes borehole requires cleaning.	No significant movement recorded.

Borehole	Summary of past data	Report 1 Status	Movement to from late 2013 to mid2014	Movements from mid to late 2014
C1A	Acoustic inclinometer. The Acoustic Emissions (AE) monitoring has not detected any movement of the landslide to the end of 2012. Precipitation levels were low from September 2011 until April 2012 and therefore stability of the landslide is not unexpected. It does not appear that the higher than average rainfall in the period April to Dec 2012 has resulted in slope movements, but there may be a lag between rainfall, elevated groundwater levels and ground movements of some months. The AE monitoring and inclinometer measurements are consistent		Elevated levels of AE for the period January 2014 to February 2014 are indicative of deformation, however; no such movement was detected in the adjacent inclinometer It is possible that this AE was generated by small magnitude deformations within the active waveguide column due to straining internally within the slide mass (i.e. not shear surface deformation).	AE measurements during the period August 2014 to February 2015 reveal no significant slope movement.

Table 11.3. Summary of groundwater data at Flat Cliffs

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
B1	Tip Depth at -7.64m OD. Situated in the central part of the site on the lower part of the cliff. 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.		09/07/2014 - Water level at 15.6m OD (ground level). Only manual readings possible still at this piezometer.	1.6m fall in groundwater level since last monitoring period to 14m OD
D1	Tip depth at 15.61m OD. Situated on the cliff top in the northern part of the site, upslope of the access road. Monitored since May 2002. Groundwater levels show large fluctuations between 15.7 m OD (Sept 2008) and 38.4m OD (March 2010). Borehole fitted with data loggers since autumn 2011 that have recorded 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.		Groundwater level c. 18.3m OD. Small peak in levels to c. 19.6m OD in late Feb 2014, but well below groundwater levels seen in previously.	No significant change. Ground water levels steady at 18 - 19m OD. Minor, short-lived peaks in water level noted.
A3	Tip depth at 6.37m OD. Situated on the cliff top in the central part of the site. Monitored since March 2001. Manual dip meter readings show relatively static ground water level at around 18.75m OD except for peaks in July 2001 (19.8m OD) and Dec 2010 (21.4m OD) and a low in July 2008 of 11.63m OD (possibly a measurement error). Vibrating wire piezometer installed in Sept 2011 shows static groundwater level of c. 18.0m OD with minor fluctuation.		No significant changes – static at ca. 18m OD.	No significant change. Small fluctuations around 18m OD noted. Small fall in average level from mid October 2014.

Borehole	Long-term Pattern	Report 1 Status	Change from late 2013 to mid-2014	Change from mid to late 2014
C4a	Tip depth at -3.7m OD. Situated on the lower cliff at around 11.8m OD in the south of the site. Monitored since September 2011. Long term trend very steady with fluctuations between ca.7.5m OD and 8.4m OD in response to short and medium term tidal cycles (ca. 6 hourly and 4-weekly).		Continued clear reflection in tidal cycle. Clear evidence of the effect of the 5 Dec 2013 storm surge as a peak in groundwater levels at 8.5m OD, as opposed to a normal tidal peak of c.8.3m OD.	No significant change. Continued clear reflection of tidal cycle. All peaks around 8.3m and average level around 8.0m OD.

The new data indicate:

- No evidence for ground movements is shown by inclinometers.
- Acoustic inclinometer data for the period August 2014 to February 2015 do not show any significant slope movement (Figure 11.2). Fluctuations in the data represent rainfall-induced groundwater flows interacting with the wave guide.
- Groundwater data show no significant change, except for a 1.6m fall in water level at piezometer B1 , reflecting the below average rainfall experienced in the region.

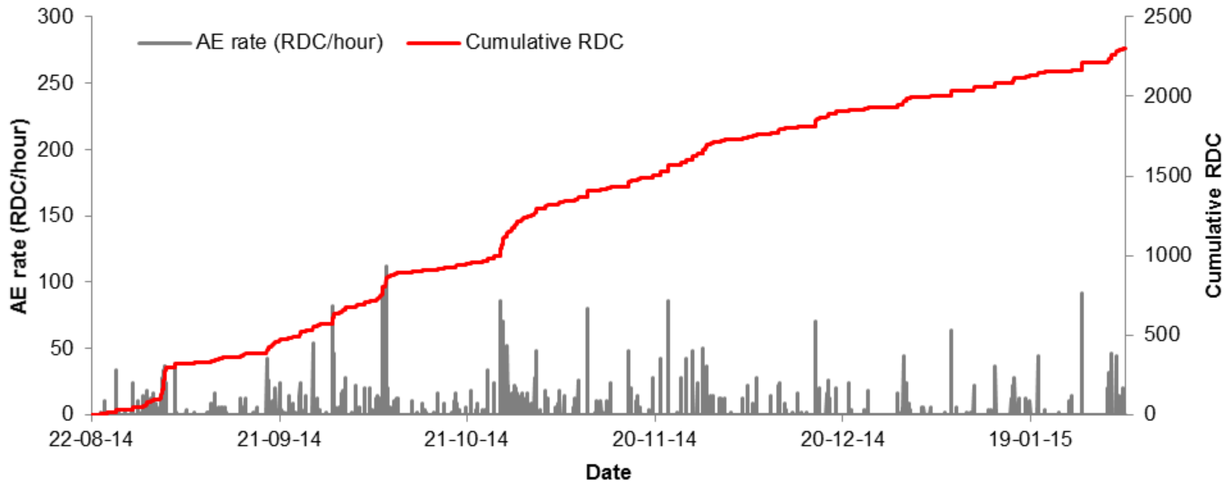

Figure 11.2 Acoustic emission (AE) rate- and cumulative AE time series measurements at Flat Cliffs for the period August 2014 to February 2015

11.5 Causal-response relationships

No relationship is identifiable between ground movements and rainfall as no substantial ground movements have occurred. However, borehole D1 appears to show a response to above average rainfall in January and February 2014 and borehole C4a clearly shows the effect of the 5 December 2013 storm surge on groundwater levels as the highest peak in the record. The lack of rainfall data covering the current monitoring period means this relationship cannot be further investigated.

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.

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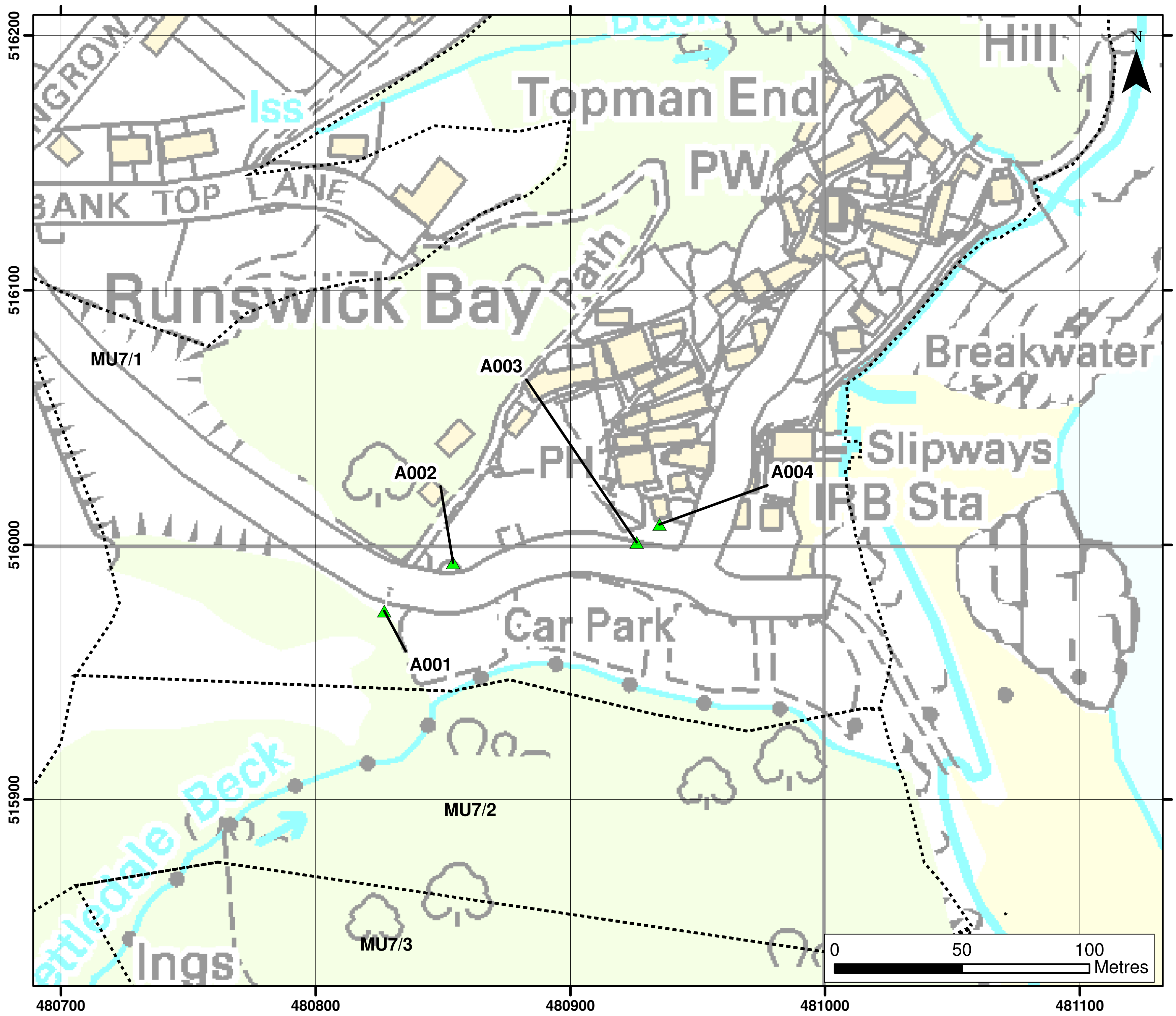

Legend

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

Client: Scarborough Borough Council

Project: Scarborough Borough Council Geotechnical Monitoring

Figure 3.1 Location of slope monitoring at Runswick 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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Figure 4.1 Location of slope monitoring at Whitby West Cliff

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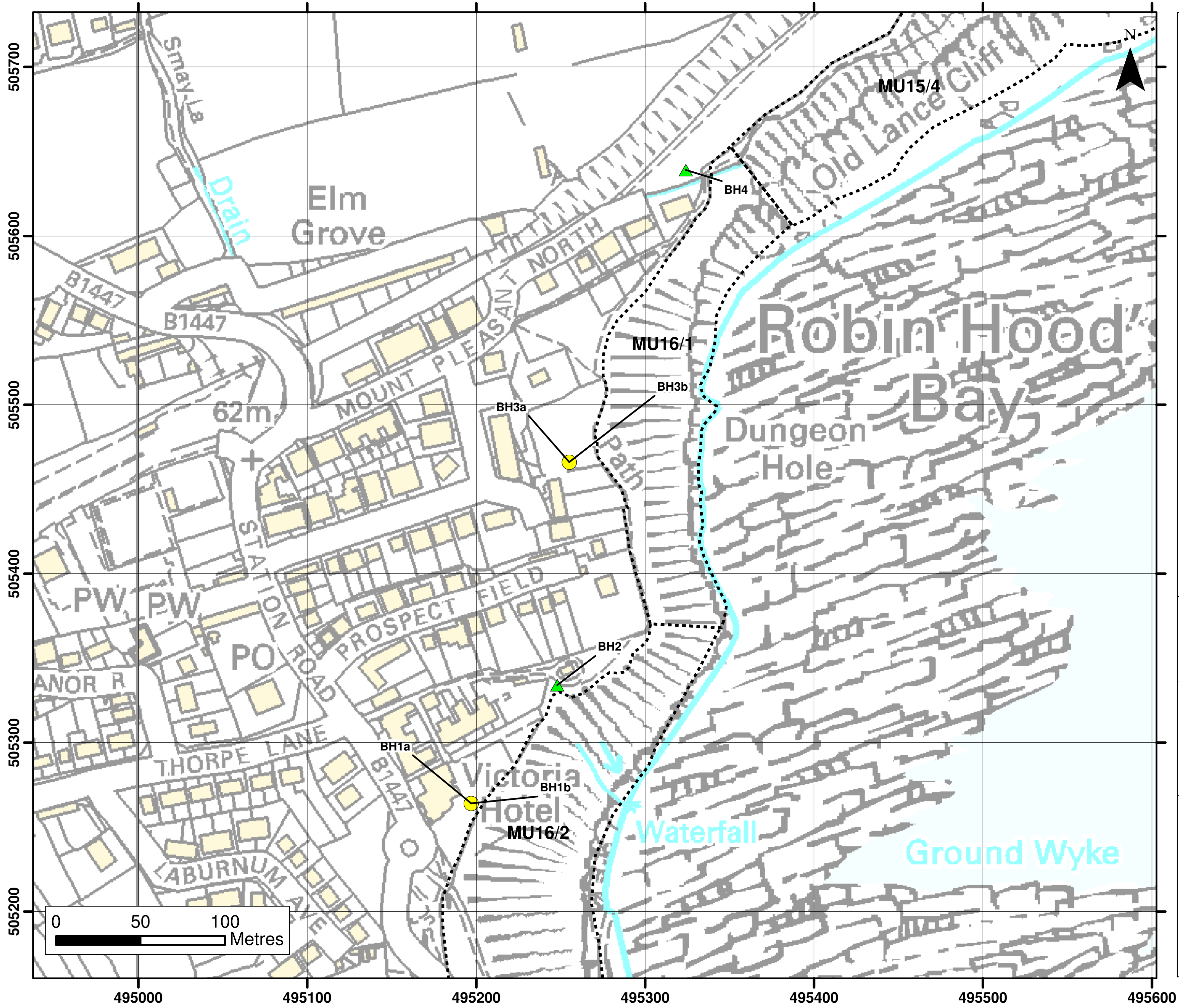

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Active

- 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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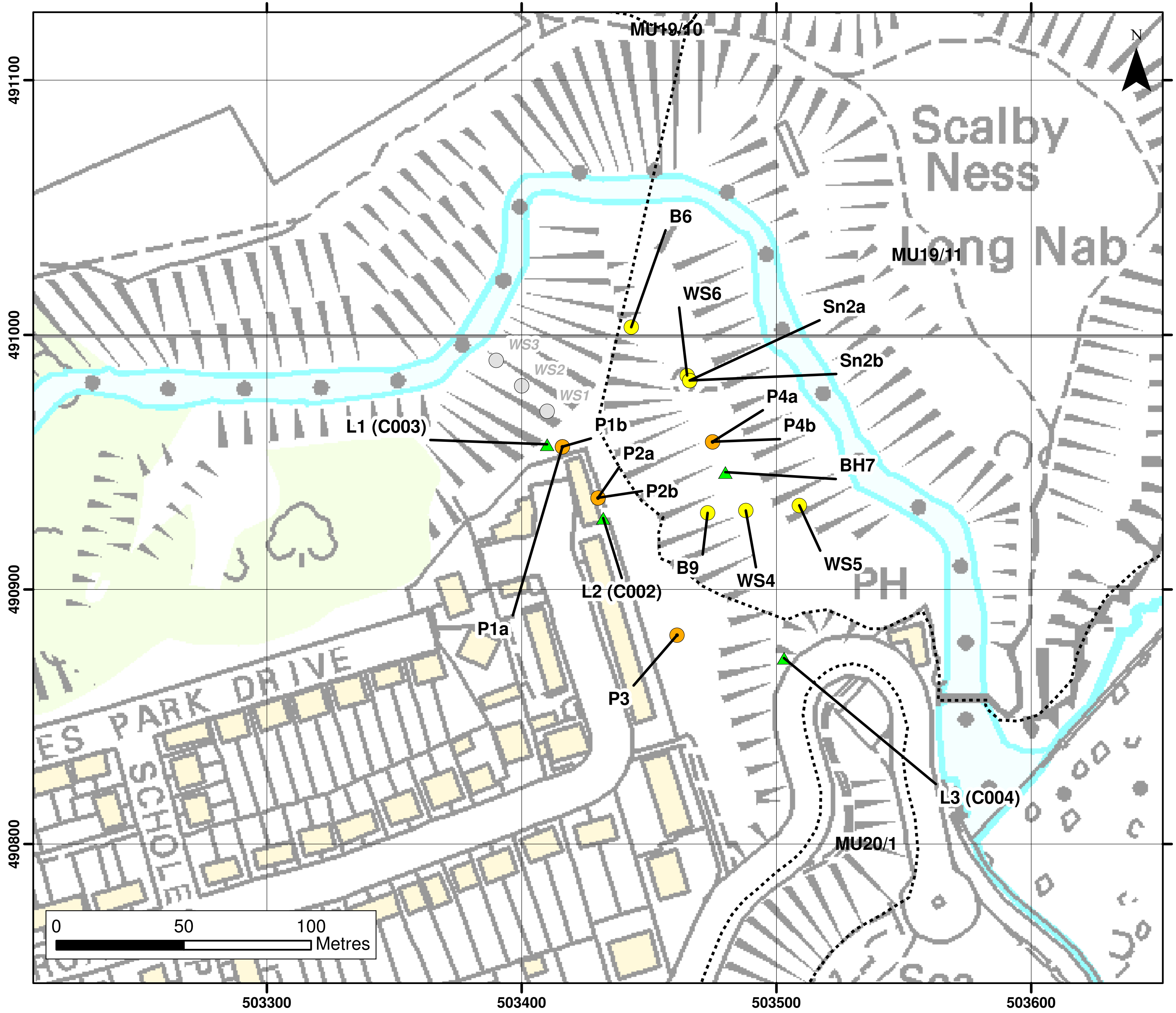

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- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

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

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Figure 6.1 Location of slope monitoring at Scalby Ness

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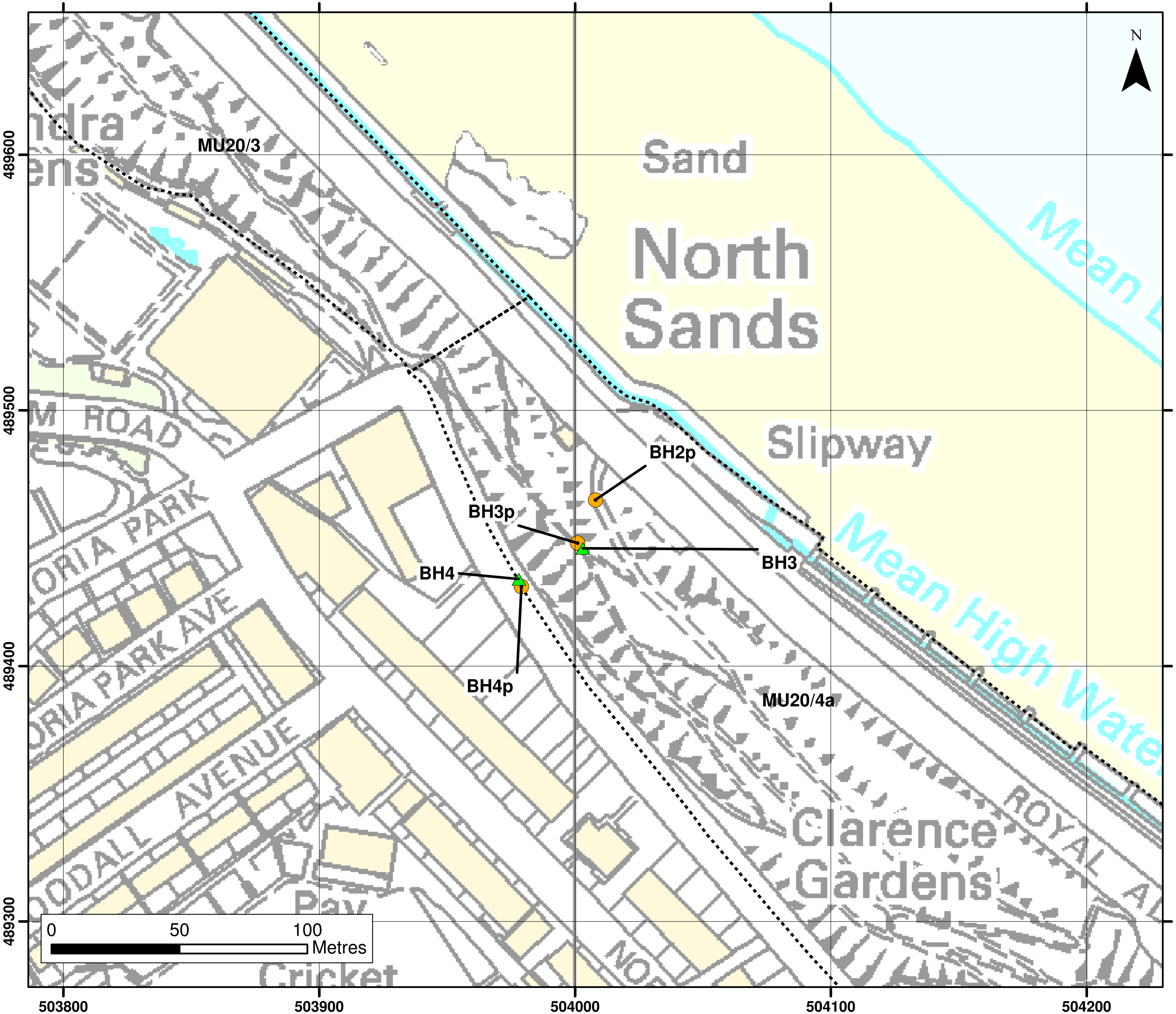

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- Piezometer (with data logger)
- Piezometer (with diver)

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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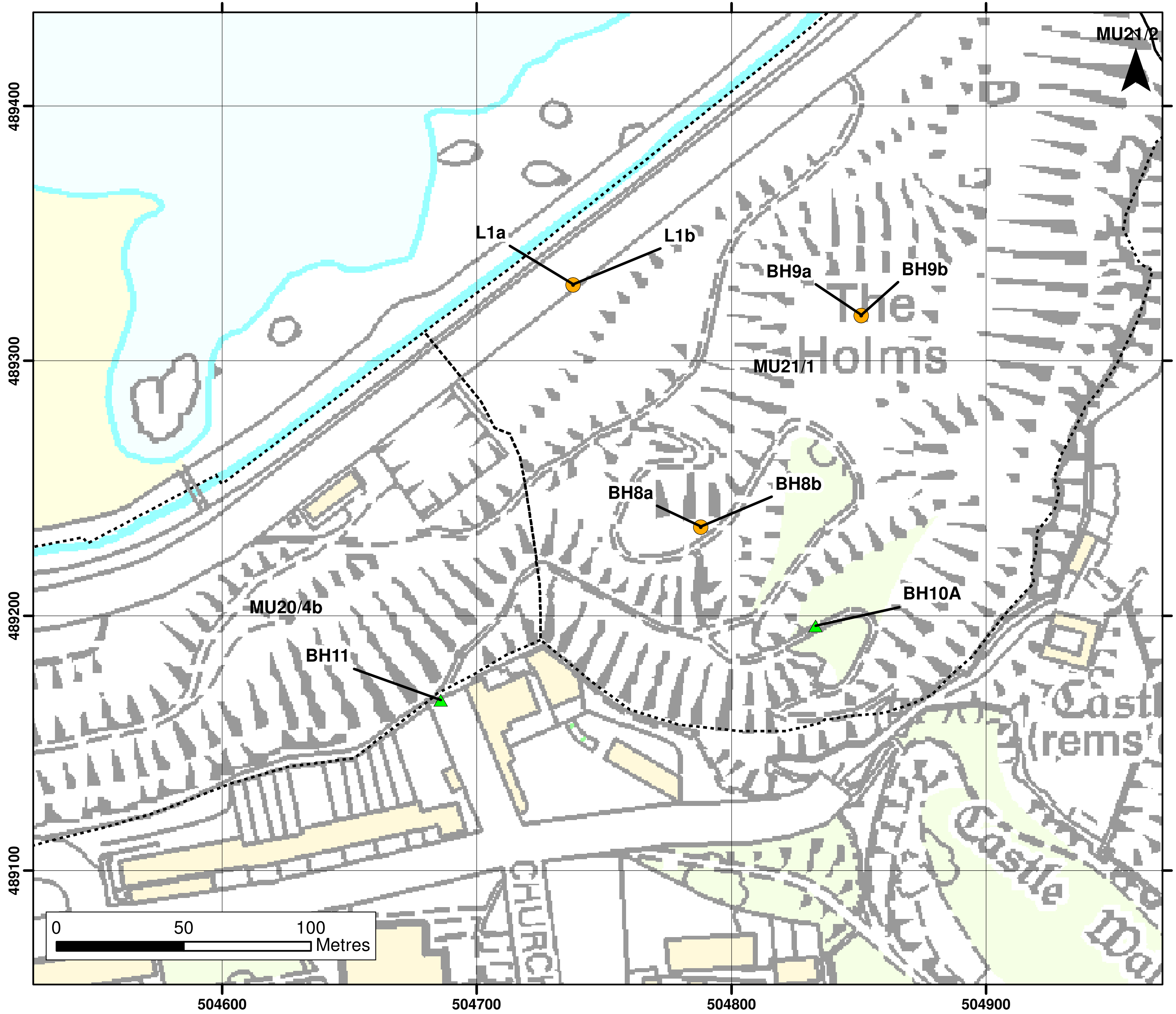

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Active

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

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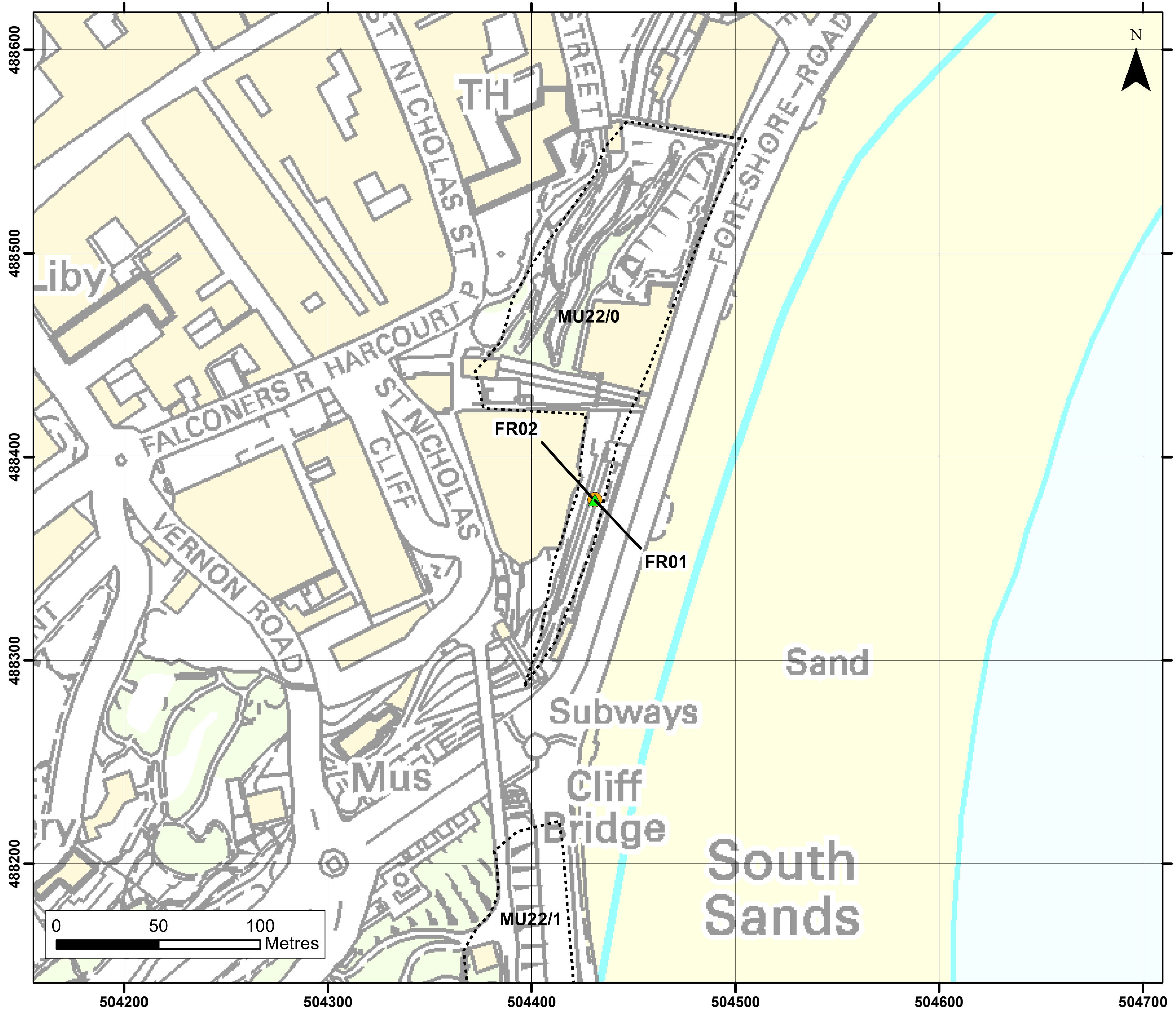

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- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

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

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Figure 9.1A Location of monitoring at Scarborough South Bay

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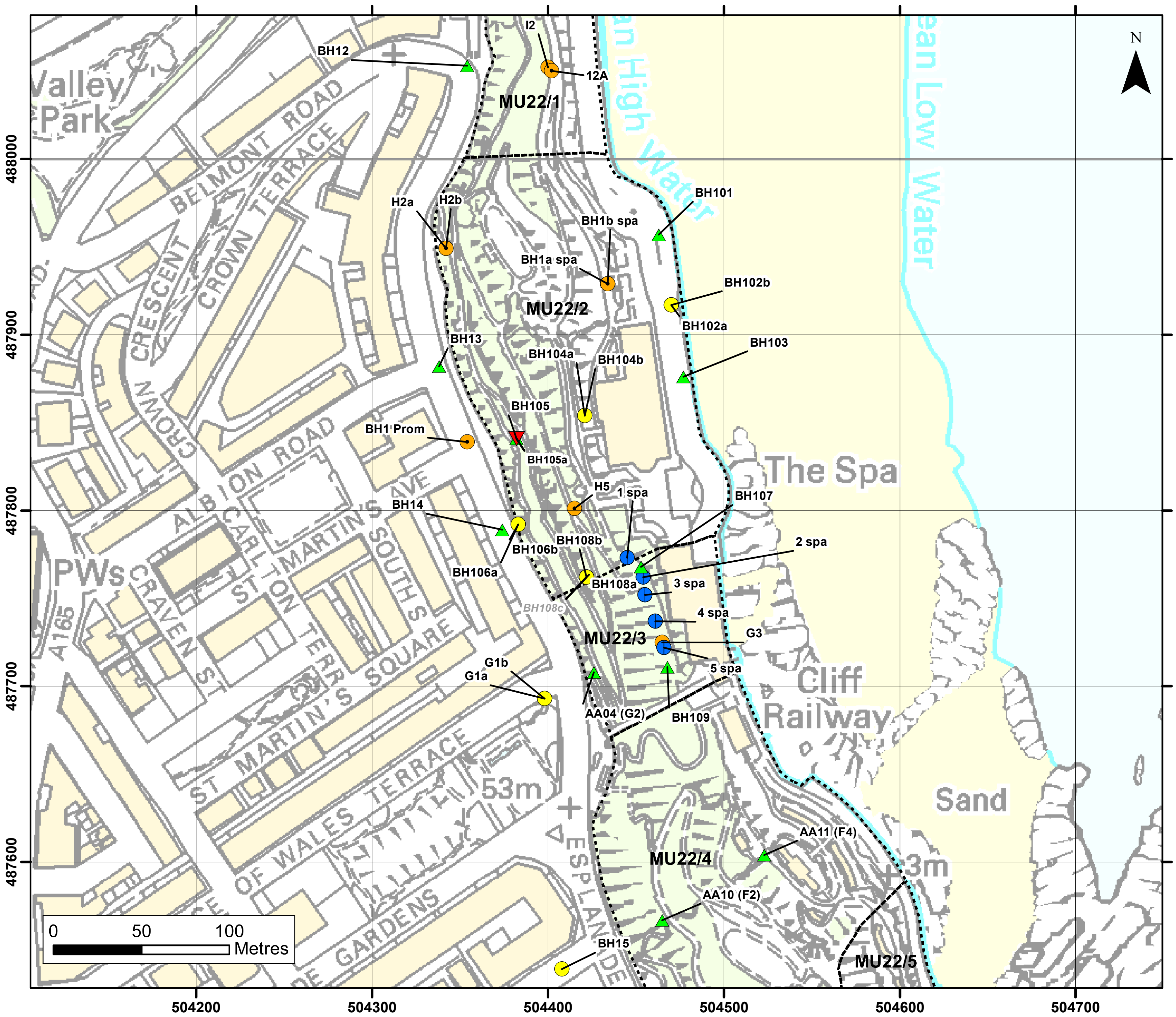

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Active

- 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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Figure 9.1B Location of monitoring at Scarborough South Bay

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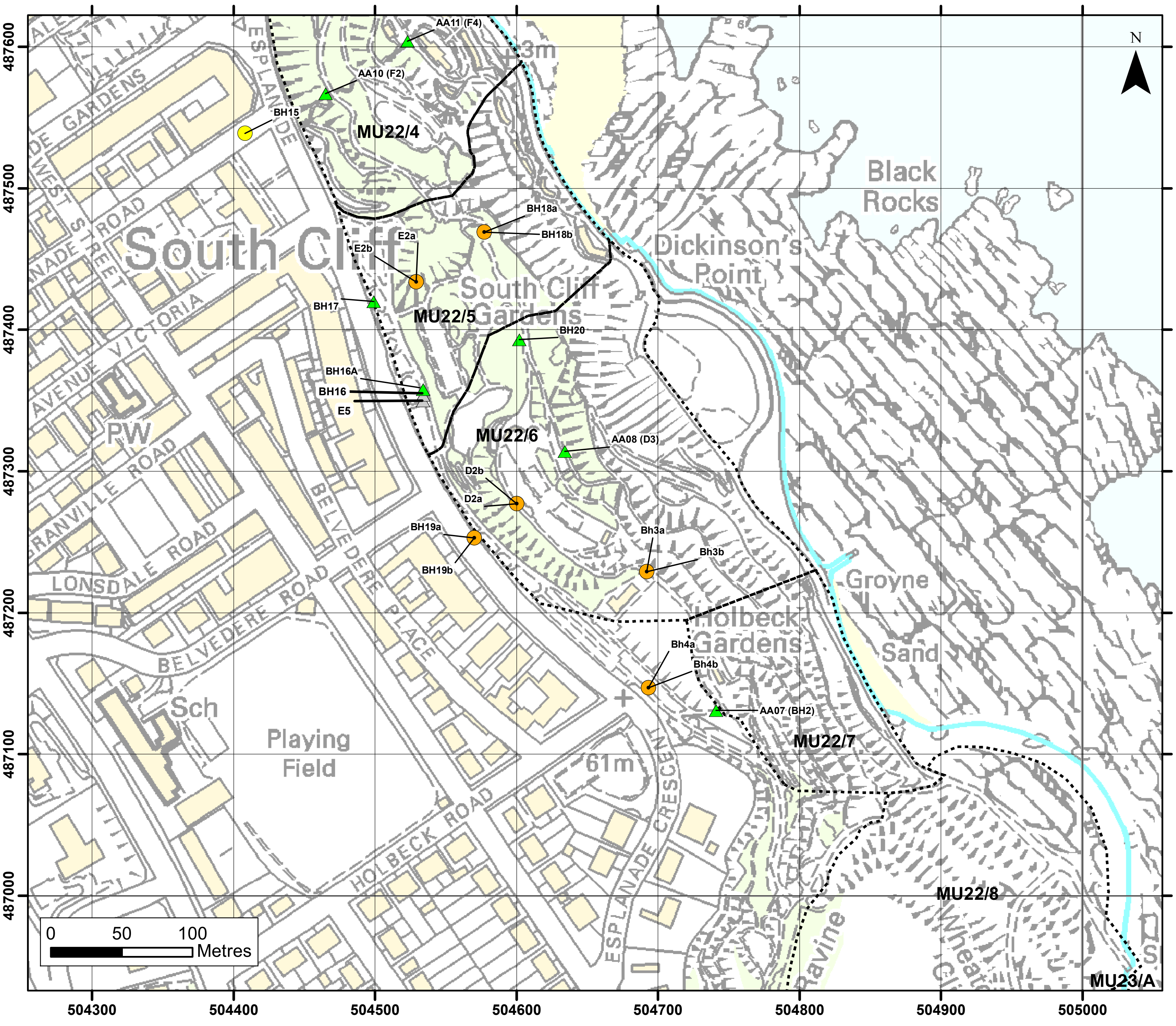

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Active

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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 9.1C Location of monitoring at Scarborough South Bay

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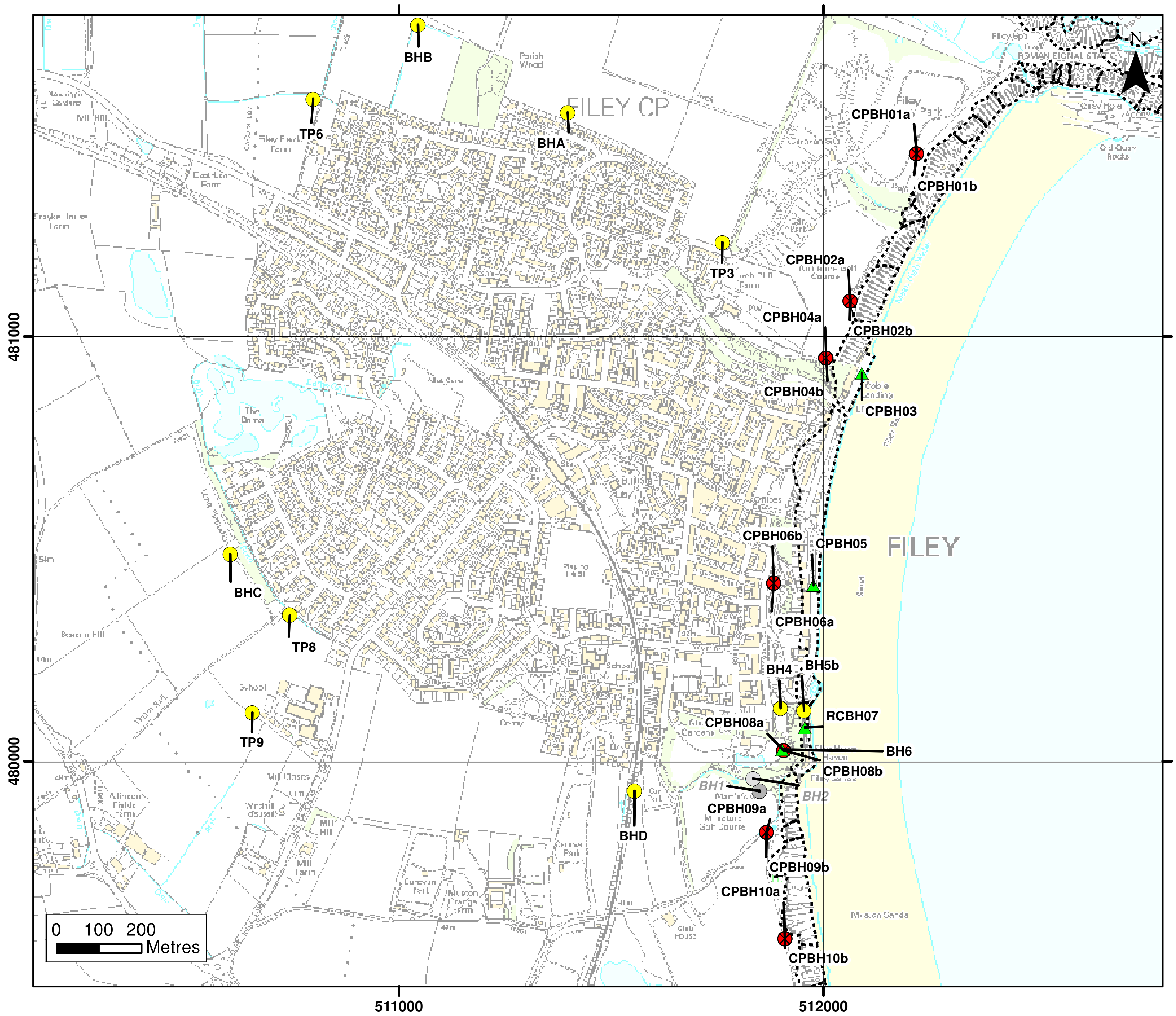

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Active

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- 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 10.1. Location of slope monitoring at Filey

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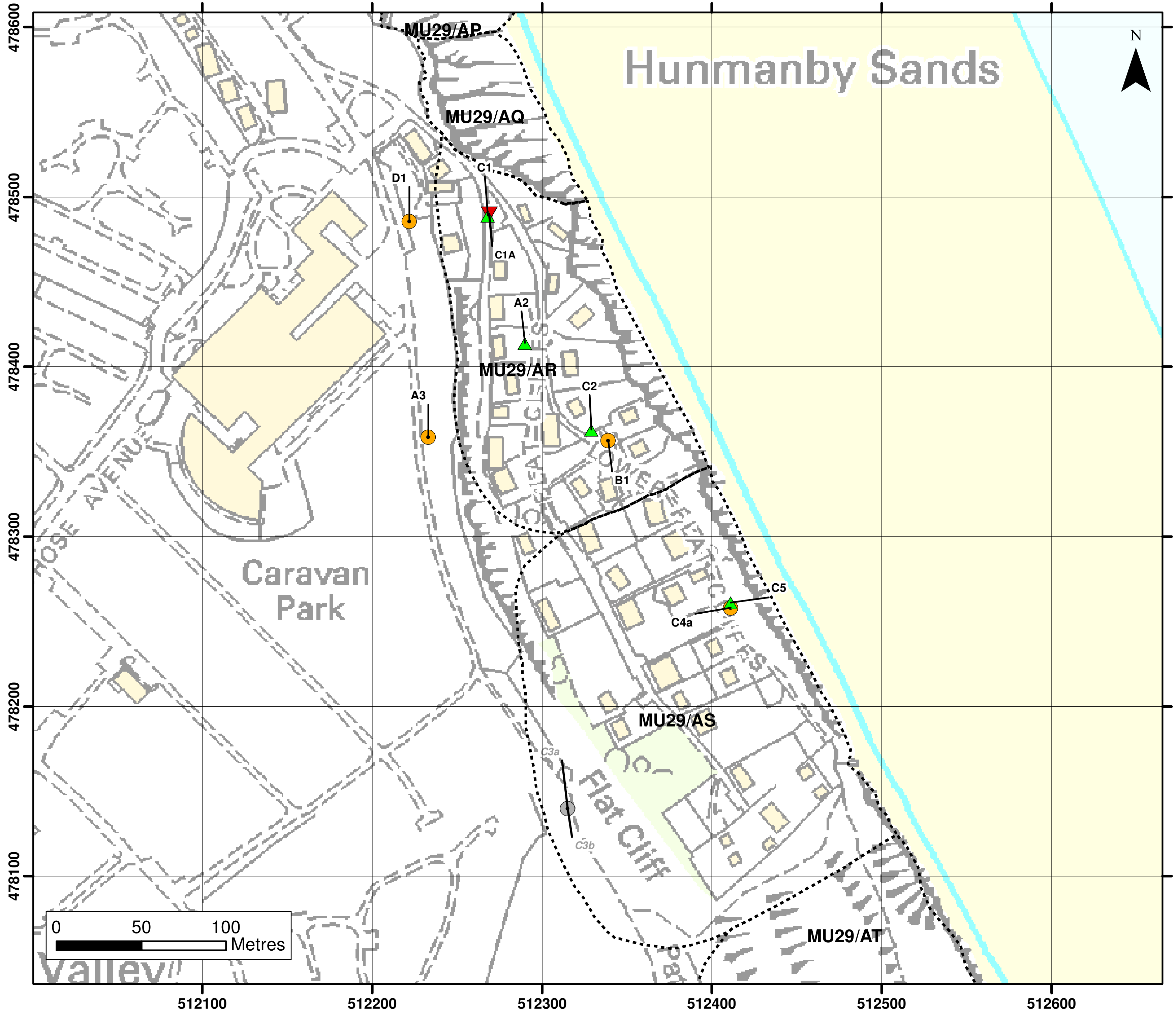

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- Inclinometer
- Monitoring well
- Piezometer (not automated)
- Piezometer (with data logger)
- Piezometer (with diver)

Inactive

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

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Figure 11.1 Location of slope monitoring at Filey Flat Cliffs

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Appendix A
Digital data