Local Coastal Slope Monitoring Analysis

# Interpretation Report 2
# December 2013 to May 2014

Prepared for
## Scarborough Borough Council

November 2014

CH2MHILL®

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# Summary of findings

This is the second report in the new phase of coastal slope monitoring along the Scarborough Borough Council frontage that covers the period between November 2013 and July 2014. This phase of coastal slope monitoring continues that previously undertaken by Mouchel Ltd between July 2009 and June 2012.

A principal issue arising from the first report in this study was a concern over the integrity of a number of installations and the quality of inclinometer monitoring data received. Detailed checks have since been conducted. At most locations the tests suggest that while some inclinometer tubes are distorted good quality data can be recorded. At a limited number of locations, the inclinometers are blocked or deformed meaning random errors occur. Repairs should be attempted at these locations. Future monitoring of inclinometers requires extreme care to ensure good quality data are received.

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, but exceptionally high water levels and potential ground movements have been recorded at some locations, most notably at Scalby Ness.

- Robin Hoods Bay: inclinometers BH2 and BH4 are both partially blocked and require repair; piezometer BH3a records rising water level
- Scalby Ness: inclinometers C002, C004 and BH7 reveal shearing and ground movement at depth. A site visit to this location is recommended to determine the spatial extent of surface instability and implications to properties. Piezometers P1a, P2a record no data while P4a, P4b and WS5 require checks of equipment.
- Scarborough North Bay: data from inclinometer BH10 appear unreliable which requires inspection and maintenance and data check. Piezometer BH9b shows rising water levels.
- Scarborough South Bay: small movements were indicated by BH12 at Spa Chalet and AA07 at Holbeck Gardens. The ground at these locations should be checked over the wet winter period. Data from inclinometers BH103 and 105 are unreliable and require maintenance/checks. Piezometers 1spa and 19b have water at the highest level on record; H5, BH18a, BH18b and BH19a are unreliable and require checking; 5spa, BH106a, BH106b, BH104a and BH15 are all dry or exceptionally low and require integrity checks; BH3a has a damaged cable and BH4b has a broken data logger that requires maintenance; BH3b has possible water ingress and its cap requires maintenance.
- Filey: BH4 has water at the highest level on record; CPBH04 and BHB are unreliable and should be checked to ensure surface water is not entering the borehole; CPBH06b, CPBH08b and CPBH09b all have logger errors and require maintenance / checking.
- Flat Cliffs: possible ground movement or slope deformation was indicated at C1 and by the acoustic inclinometer C1A. Water was at ground level in B1 which needs checking to ensure surface water is not entering the borehole.

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 of 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 second set of data analysis. The report is presented as a stand-alone document.

## 1.2 Aims and objectives of monitoring

The principal objective of the monitoring programme is to provide home- and land-owners with information on instability 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 preceding 6 months monitoring data in the context of the historical record
- To highlight the implications of the data to coastal instability risk

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 Cafe | 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 | 92 | 1 |

*a single inclinometer and a diver piezometer with barometric diver was added at St Nicholas Cliff in 2014, between collect 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 (this report) |
| Data set 3: June 2014 to November 2014 | Report 3: February 2015 |
| 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 inception 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 risk, 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 present an interpretation of the new monitoring data. Comment is made on any relationships between rainfall, groundwater and ground movement, and the implications of the new data with regard to cliff instability risk.

## 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 'high risk' wet 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 repaired.

*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. For the purposes of this analysis, data are presented on a monthly basis. The full dataset is referred to if required.

This 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.

Battery failure in 2013 means there is a c. 6 week gap in the record between 23 May and 6 August. This period was characterised by exceptionally warm and dry conditions.

## 2.2 Rainfall

Monthly rainfall data between September 2011 and July 2014 are summarised in Figure 2.1.

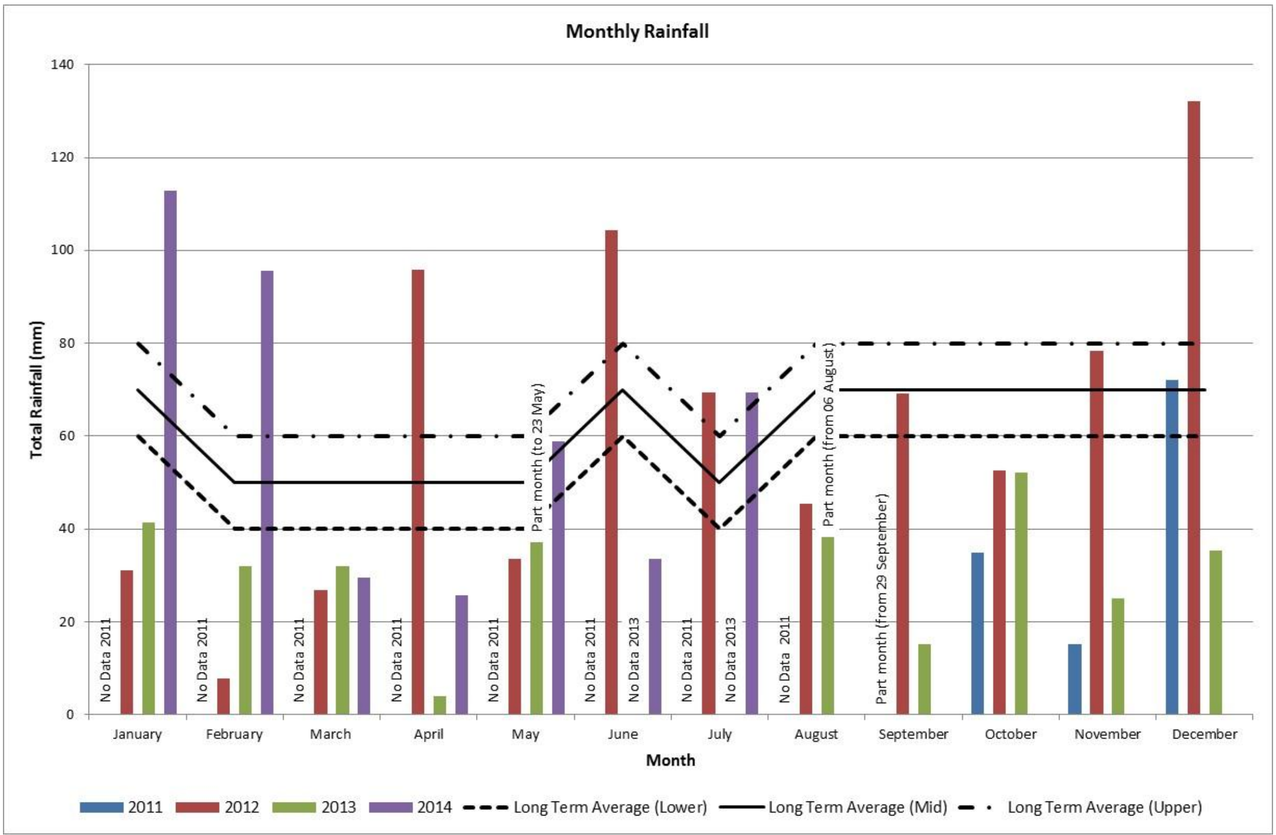


*Figure 2.1. Rainfall records at the Flat Cliffs met station (October 2011 to July 2014)*

Long-term monthly averages, maxima and minima (1981 to 2010) from Met Office records are indicated on the plot to provide context. The data highlight the following:

- Limited data from 2011 indicates dryer than average conditions in October and November and typically high rainfall in December.
- 2012 was an unusually wet year, with a reversed pattern of seasonal rainfall. Data from 2012 indicates exceptionally low rainfall in the early part of the year, from January to March, with December the only wet month of the 2011/12 winter. In contrast, the spring and summer were

particularly wet, with April and June 2012 receiving almost twice the long-term average rainfall and higher than average rainfall in July. Late 2012 was also wet, with above average rainfall in November and the highest recorded monthly rainfall of any month falling in December. It is likely that the wet summer had limited effect on slope stability at the time because the atypically dry winter will have resulted in relatively low groundwater levels for the time of year. However, the sustained high rainfall through the autumn and winter will have raised groundwater levels above average levels by the end of 2012.

- 2013 was a dry year and the data shows below average rainfall in all months (NB no data were recorded during June and July). The pattern of rainfall shows limited seasonality, with April, September and November having unusually dry conditions. It is likely that groundwater levels were low through much of the year.
- In 2014, January and February were substantially wetter than average. March, April and June were much drier than average, and rainfall in May and July was about average.

The seasonal pattern of rainfall is summarised in Figure 2.2. In the chart, 'winter' comprises the months of December, January and February and therefore spans the calendar year. The timing of 6 monthly monitoring reports coincides with the summer-autumn and winter-spring periods. The data indicate:

- The spring, summer and autumn 2013 periods were considerably drier than that experienced in 2012 (this pattern is unaffected by the missing data from June and July that were dry months).
- In contrast, the winter of 2013 was wetter than 2012 and represents the most recent period of significantly wet weather.
- Groundwater levels during the preceding July to December 2013 monitoring period are likely to have been low.
- During the winter 2013/14 period, rainfall has been higher than previous winters and may have led to some recovery of groundwater levels during the current monitoring period. Due to the data gap beginning in late May 2013, it is difficult to be sure how rainfall levels during that period compared to spring 2014. However, rainfall during spring and summer 2014 is more likely to represent conditions closer to average. This is confirmed by UK Met Office rainfall anomaly maps.

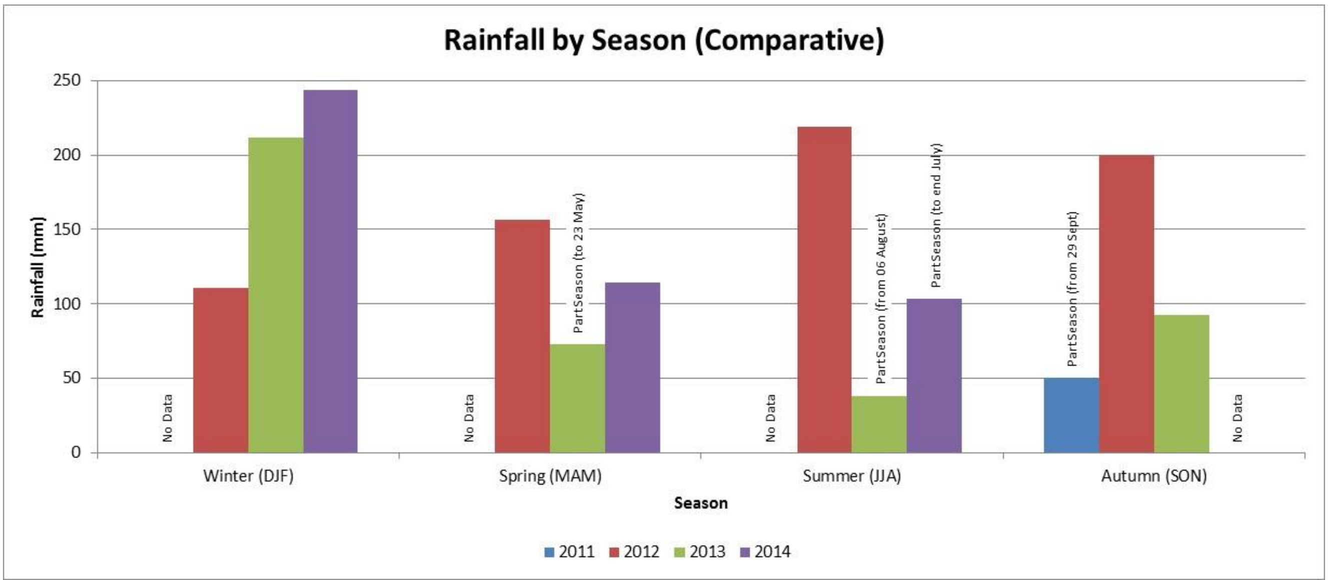


*Figure 2.2. Seasonal rainfall totals.*

Daily rainfall totals for each year monitored are provided in Figures 2.3, 2.4, 2.5 and 2.6. These plots clearly show the exceptionally wet spring, summer and autumn of 2012 (which can be seen from Fig 2.1

continued into December 2012) and contrasting dry conditions of 2013. The data for the most recent period of monitoring, covering the first half of 2014 shows (Figure 2.6):

- The wettest days occurred on 5 February, 9 May and 5 July, with 5 July being the wettest day when just over 25mm of rain fell.
- March and April were particularly dry, with no individual day experiencing rainfall more than 5mm.

### 2.2.1 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 high 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 in sites of relatively higher permeability where groundwater responds rapidly to rainfall, to a period of months at locations of lower permeability.

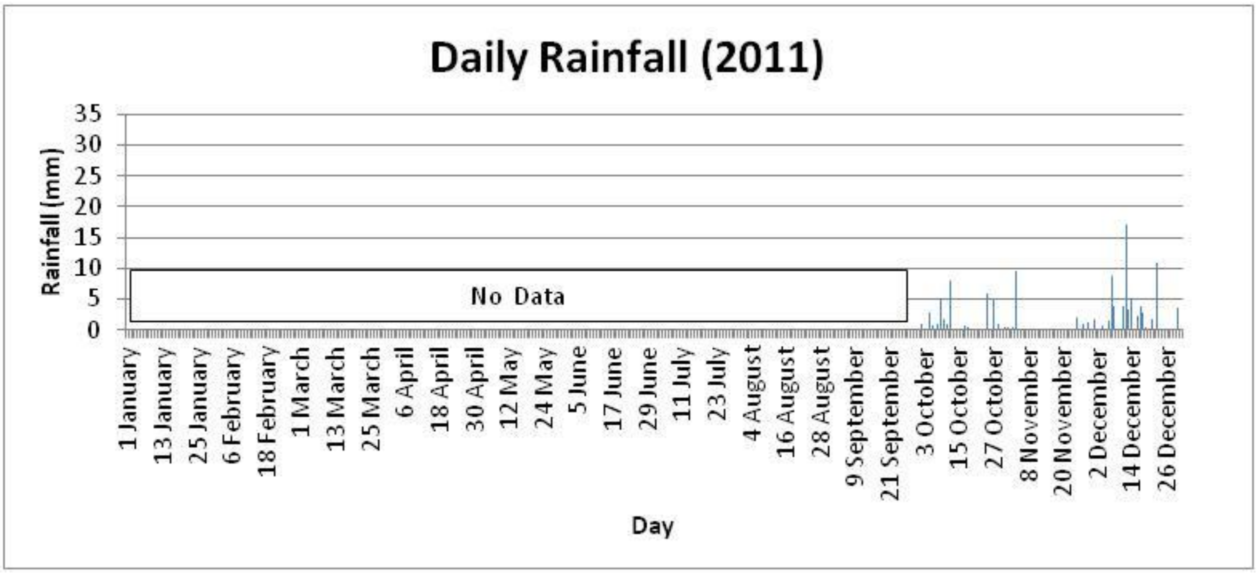


*Figure 2.3. Daily rainfall recorded at Flat Cliffs during 2011.*

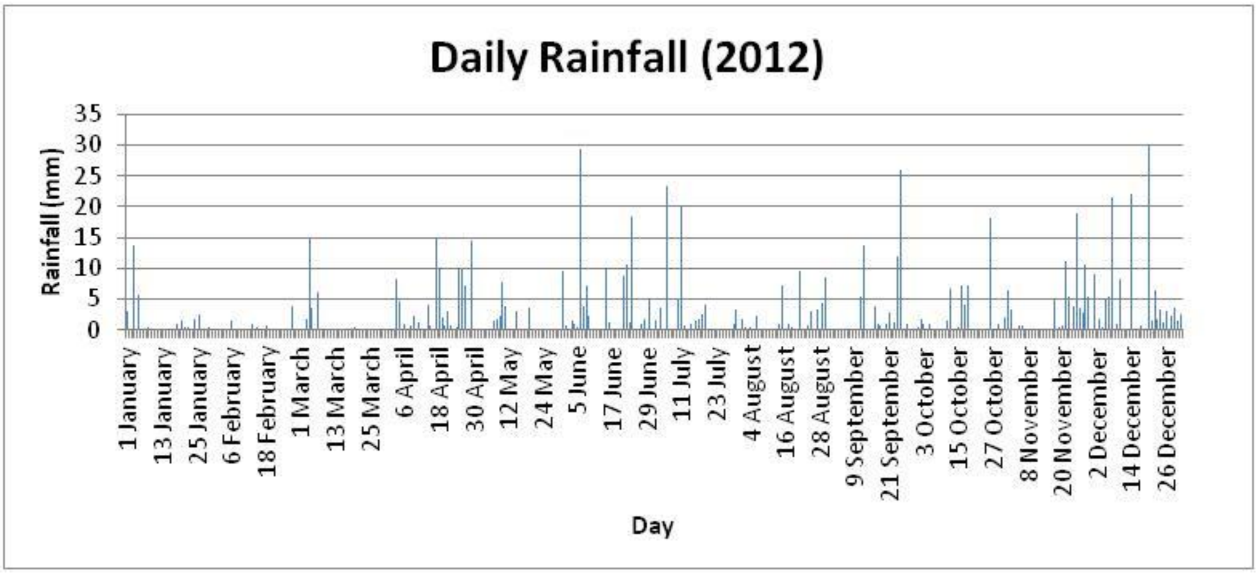


*Figure 2.4. Daily rainfall recorded at Flat Cliffs during 2012.*

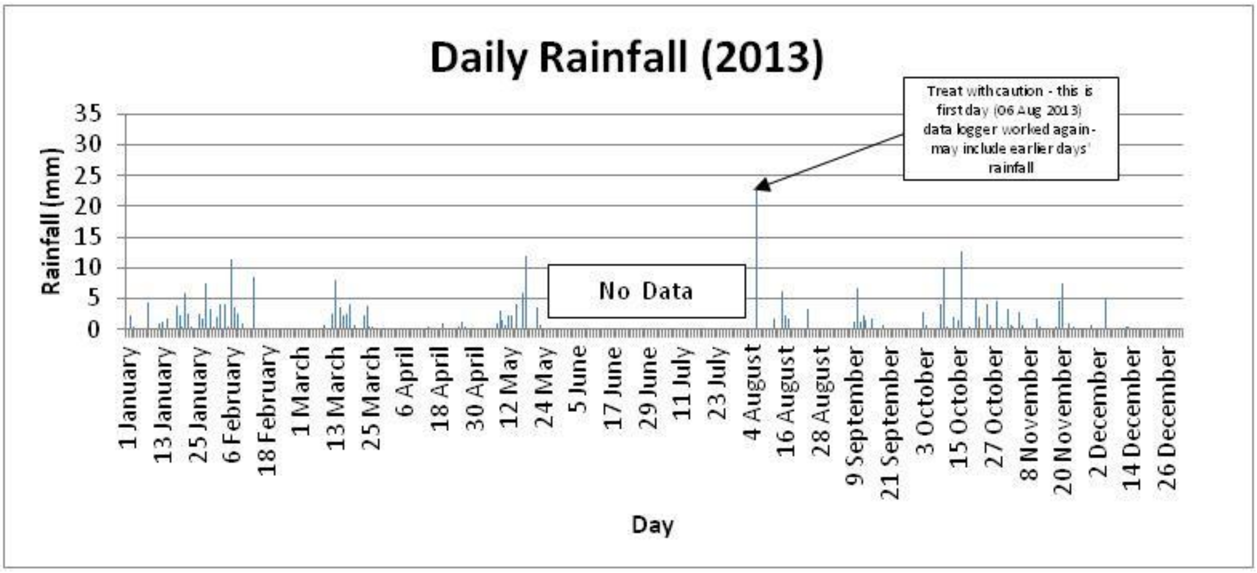


*Figure 2.5. Daily rainfall recorded at Flat Cliffs during 2013.*

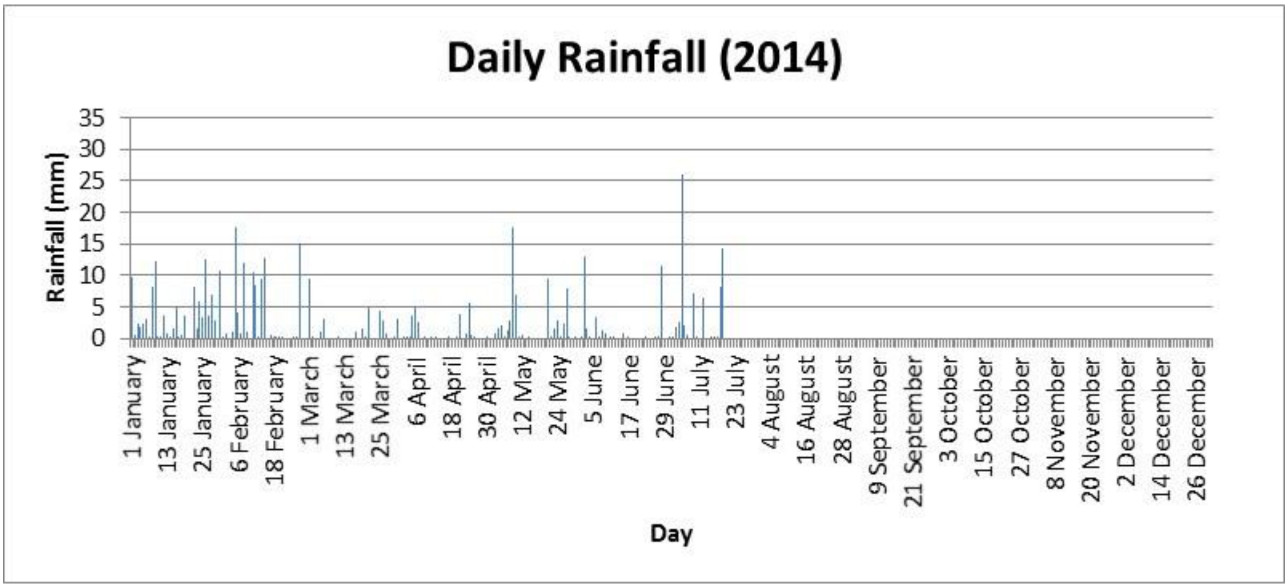


*Figure 2.6 Daily rainfall recorded at Flat Cliffs during 2014 (to end July).*

The weather records for the SBC frontage span a short time period, but do include the particularly wet year of 2012. Significant ground movements only occurred over the monitoring period 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) | |
| **September** | 80 | 0.14 (part month) | 69 | 15 | |
| **October** | 80 | 35 | 53 | 52 | |
| **November** | 80 | 15 | 78 | 25 | |
| **December** | 80 | 72 | 132 | 6 | |

## 2.3 Temperature

Air temperature is presented in Figure 2.7 showing minimum, maximum and mean for each month. The data show a later seasonal decline in temperatures in autumn of 2011. The temperature dropped below 0°C during February 2012 and January 2013. The data for June and July 2013 are missing and as a result the particularly warm weather experienced during the summer of 2013 was not recorded. Data for 2014 indicates a mild winter, with minimum temperatures rarely dipping below freezing, and average temperatures increasing earlier in the year in February, rather than March as in the previous two years.

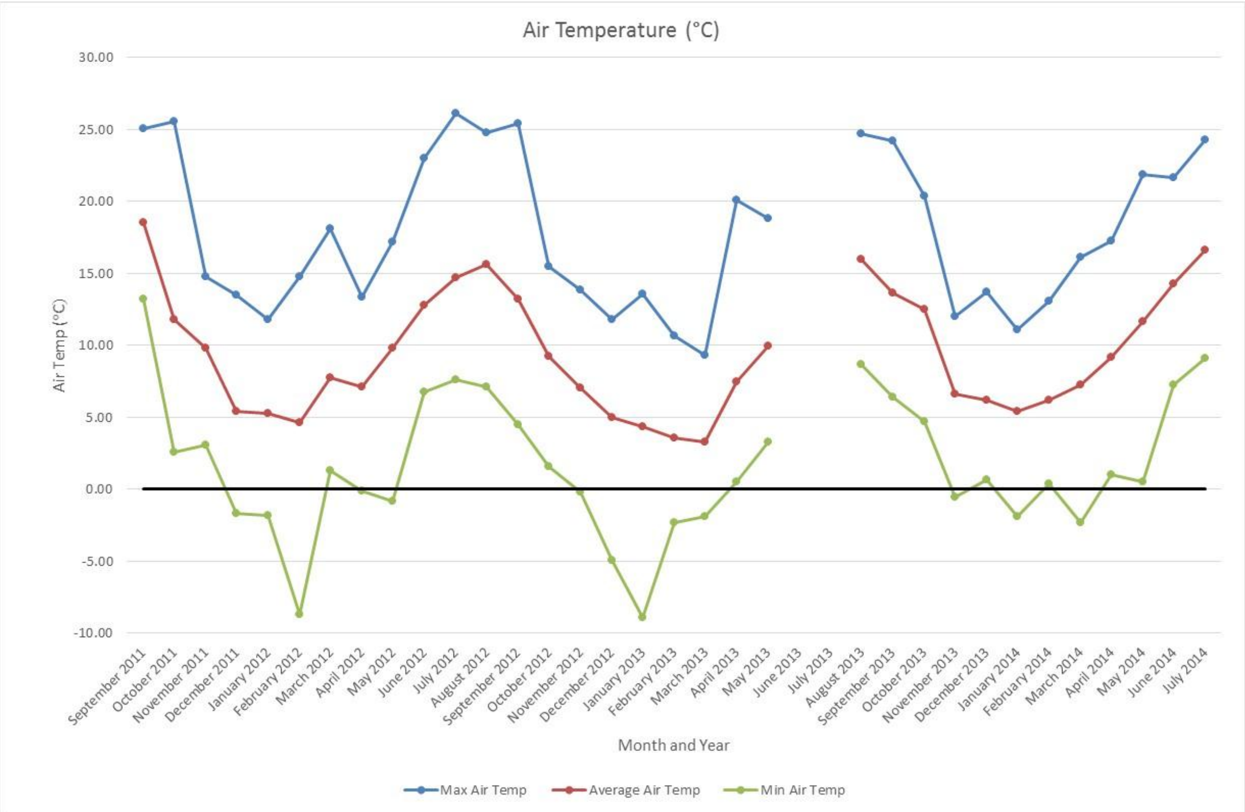


*Figure 2.7. Record of air temperatures recorded at Flat Cliffs*

## 2.4 Wind and storms

Wind speed is summarised in Figure 2.8 that shows the maximum speed recorded in each month period and the Beaufort scale storm force thresholds. The September 2011 and December 2013 records are incomplete and June and July 2013 records are missing.

The winter of 2012-2013 had particularly high wind speeds compared to the rest of the data record, with all of the months experiencing Force 4 or 5 winds. The highest wind speed recorded was 17.5mph in March 2013, which is the only month to record a Force 5 wind. The rest of 2013 had a similar pattern to 2012 in terms of the magnitude of wind speed with winter being windier than summer.

Overall the recorded wind speeds are comparatively low, but this is likely to reflect the relatively sheltered location of Flat Cliffs. The wind speeds during December 2013, when the east coast of the UK experienced a significant storm surge event, were only Force 4 at Flat Cliffs and overall the winter 2013-14 period was much less stormy that 2012-13.

Wind speed and direction for 2012 and 2013 are shown in Figures 2.8 and 2.9. Figures 2.10 and 2.11 provide a comparison of the winters for 2012/13 and 2013/14, and a comparison of the springs for the same period are provided in Figures 2.12 and 2.13. Each unit on the frequency scale represents a 15 minute period in the weather station record.

The wind roses for 2012 and 2013 are similar, and show that onshore winds from all westerly directions, NNW and SSW, are the most common and rarely exceed 3m/s, but that the strongest winds are offshore, from the east, where they can exceed 6m/s. Overall, 2013 experienced more frequent and higher speed winds. There is considerable variation in direction of the most frequent and strongest winds when viewed on a seasonal basis.

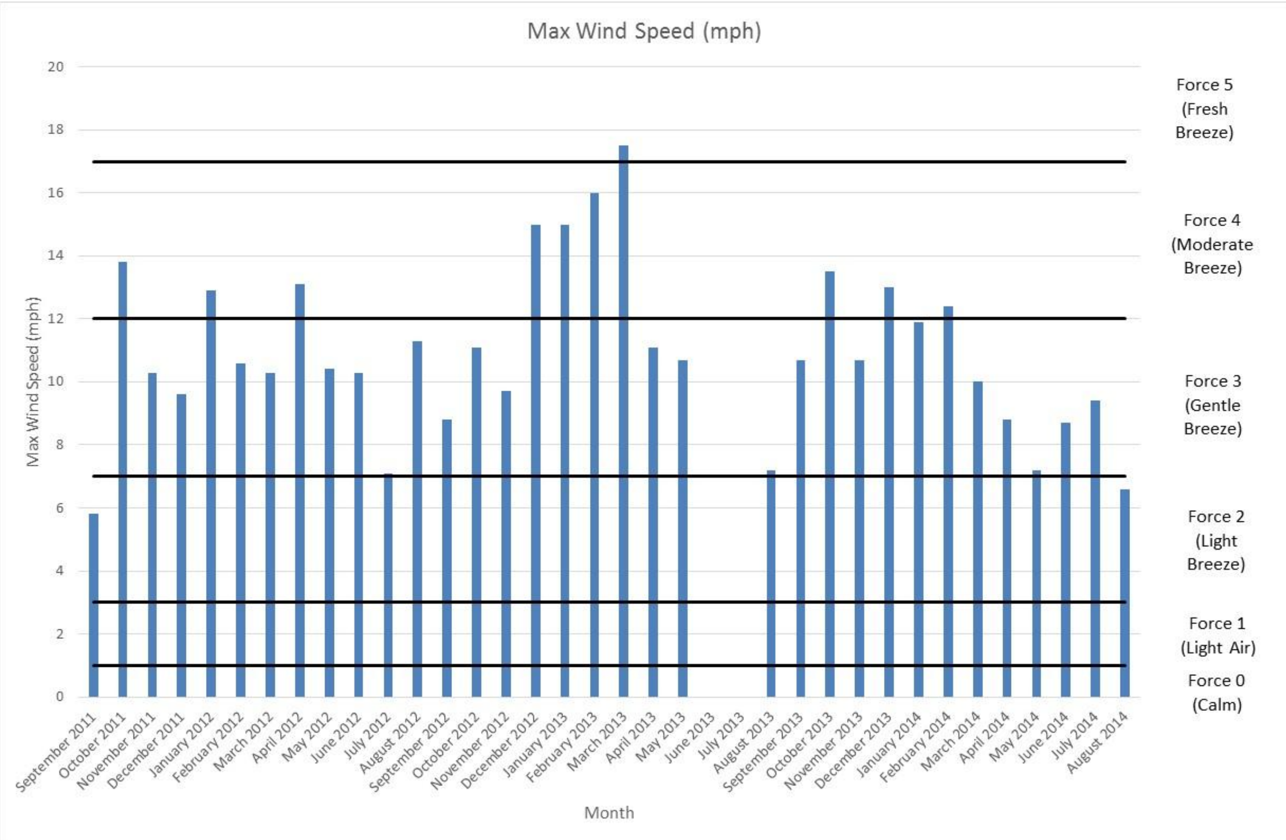


*Figure 2.8. Maximum monthly wind speeds recorded at the Flat Cliffs met station. Equivalent Beaufort scale categories are presented on the right of the chart.*

In comparison, winter 2013-14 and spring 2014 show an absence of the strong easterlies, with the pattern in winter 2013-14 being especially notable by the low strength but the dominance of comparatively light winds from the south. This is a possible explanation for the warm and wet January and February of 2014.

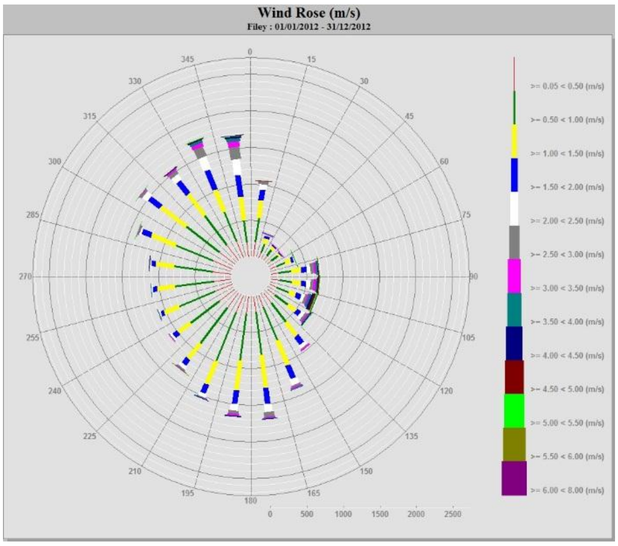


*Figure 2.9. All data from 2012*

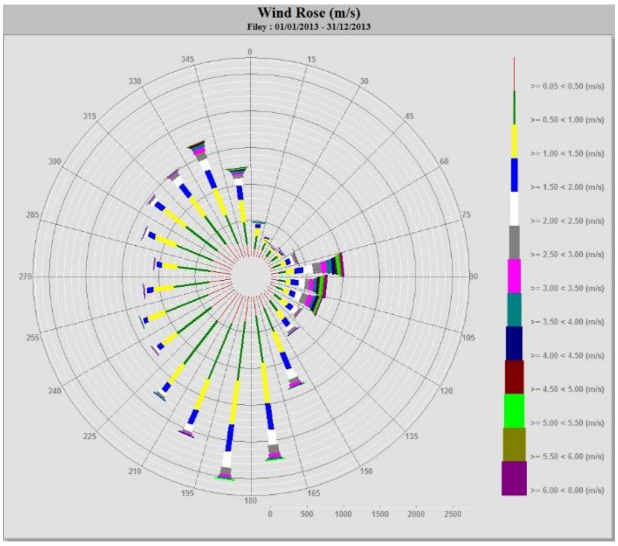


*Figure 2.10. All data from 2013*

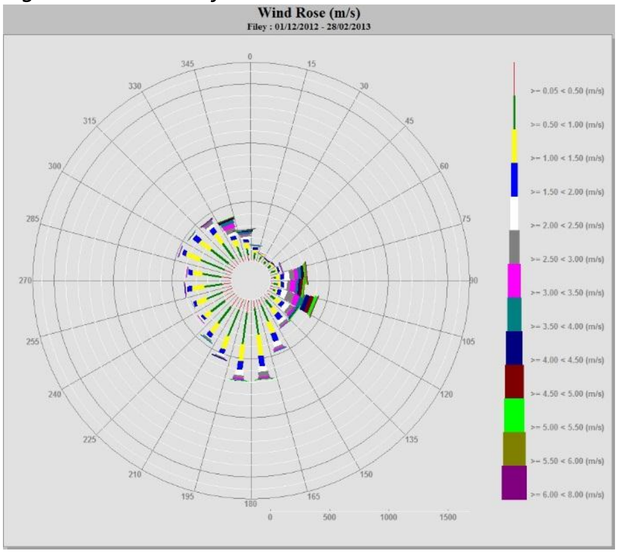


*Figure 2.11. Winter 2012-13 (Dec, Jan and Feb)*

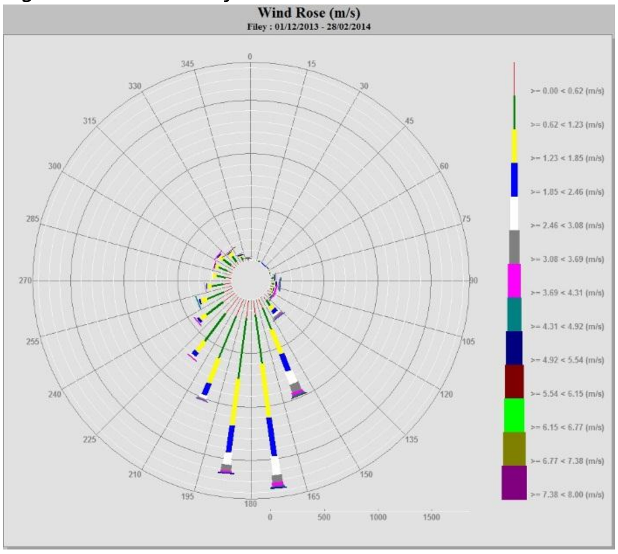


*Figure 2.12. Winter 2013-2014 (Dec, Jan and Feb)*

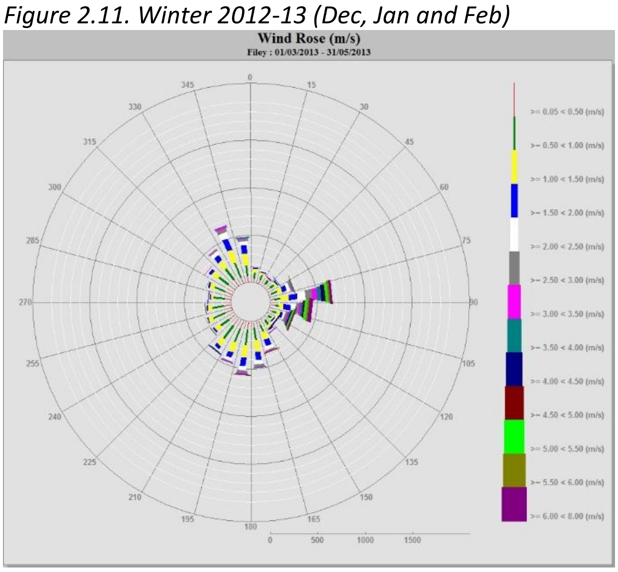


*Figure 2.13. Spring 2013 (March, April and May)*

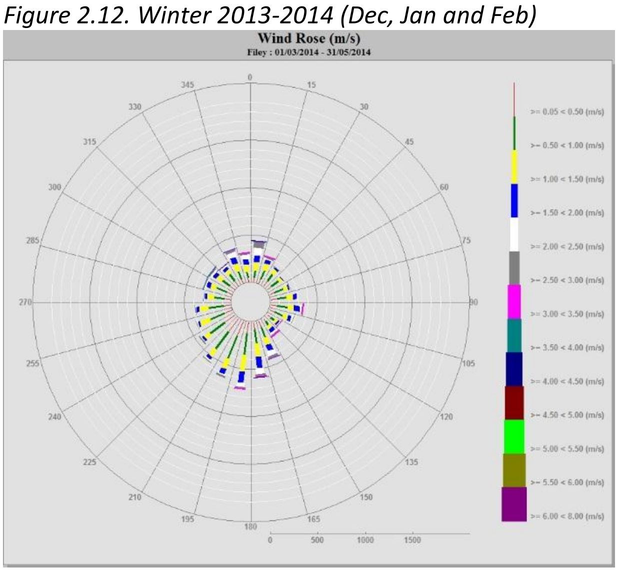


*Figure 2.14. Spring 2014 (March, April and May)*

## 2.5 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 particularly 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 has been comparatively dry.

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. |

Total observed movement since first

## 3.4 New data

All monitoring data at Runswick Bay is at the Topman End landslide, and is solely intended to monitoring 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 there was concern over the accuracy of these data 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

*Table 3.2. Summary of inclinometer data at Runswick Bay*

| Borehole | Summary of past data | Report 1 status: mid 2012 to late 2013 | Movement from late 2013 to mid 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 | No change recorded between Dec 2011, May 2012 and Nov 2013. | 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. |
| 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 recorded between Dec 2011, May 2012 and Nov 2013. | No change since November 2013. The apparent minor cumulative (<2mm) change at the ground surface is not significant. |
| 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 recorded between Dec 2011, May 2012 and Nov 2013 | No change since November 2013. Apparent movements at all depths <0.5mm is not significant. |
| A004 | Data collected from within 10.5m deep concrete pile near the bottom of the slope. The data indicates no significant movement in the pile up to Dec 2011. | Incremental displacement of c. 15mm in May 2012 and Nov 2013. These data are assumed to be erroneous as no ground movements have been reported on site. Inclinometer integrity check and quality of repeat readings to be reviewed. | The erroneous data described in the previous report have been corrected, confirming no change here since readings began. |

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# 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 | Movement to late 2013 | Movement from late 2013 to mid-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. | The most recent inclinometer reading was taken on 5 November 2013 and revealed no significant change since the previous reading in May 2012. Incremental change since the last reading is <1mm, and the total cumulative change down the full length of the tube is <5mm. These readings are not significant and are within the range of error expected for inclinometers. | No change since late 2013. All apparent incremental movements are <1mm and show no consistent progressive pattern and are therefore not significant. |

## 4.5 Causal-response relationships

The recommendation by Mouchel (2012) for future monitoring at Whitby West Cliffs was 'No additional measures recommended other than continue to observe and monitor the coastal slopes for additional slope failures and development of any existing failures particularly west towards Sandsend'. The new data do not change this recommendation.

## 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.

SECTION 5

# 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.

The inclinometer data show:

- The readings represent error in data capture or problems with the borehole. It is recommended that an integrity check be completed and a new baseline is taken against which future displacements can be compared.

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 significant rise in water level that is likely to be caused by ingress of surface water. It is recommended that this location be checked and repair undertaken.

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

| Borehole | Summary of past data | Movement to late 2013 | Movements from late 2013 to mid 2014 |
|---|---|---|---|
| BH2 | The borehole is 41m deep but inclinometer records are only provided for the upper 22m. Ground level is c. 55.1m OD (derived from LiDAR). 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. Cumulative movement plots suggest deformation along the whole length of the borehole until June 2012, where movement was limited to the upper 15m of the borehole and was particularly marked in B-axis where a total 1500mm deformation was recorded. This pattern of movement is hard to explain and is likely to represent accumulated error. | No readings were taken in 2013 as the borehole could not be accessed.<br>Historical readings require careful assessment. | The readings taken in July 2014 shows a very similar pattern to previous readings. The apparent displacement prior to 11/12/2011 is likely to be erroneous.<br>**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. Records between 01 March 2011 and 17 June 2011 indicate no change. However, two subsequent readings also taken on 17 June indicate displacements of up to 300mm on the a-axis and 1000mm in the B-axis in the upper 25m. The reading by Haskoning on 29 May 2012 indicates more significant movement along the whole borehole. 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 reading taken on 5 Nov 2013 indicates incremental movement of up to 15mm at depths of 5m and 23m below ground level. These displacements are indicated in both the A and B axes. Cumulative plots indicate total displacement at ground level is up to 700mm, which is most likely to be error. This reading is assumed to be erroneous as no evidence for significant ground movement has been reported or observed on site.<br>Inclinometer integrity check and quality of repeat readings to be reviewed. Activity at this location will be reviewed in the next phase of monitoring. | 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.<br>**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 | Movement to late 2013 | Movement later 2013 to mid 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 May 2012, water levels have risen by 1.7m, bringing them back to the long-term average. This occurred despite the dry conditions experienced over this time, which cannot be easily explained by the natural groundwater response to rainfall. | Since the last reading in October 2013, groundwater levels have risen by 0.05m and remain below the peak recorded in June 2011. |
| 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 May 2012, water levels have risen by 1.0m, bringing them to their highest levels since records began. This occurred despite the dry conditions experienced over this time, which cannot be easily explained by the natural groundwater response to rainfall. | Since the last reading in October 2013, groundwater readings have fallen by 0.04m |
| 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 the last reading in May 2012, water levels have risen sharply by 9.8m to 54.2m OD. This is unprecedented in the historical data at this location and occurred at a time of very dry weather and therefore may not be due to rainfall | 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**. |
| 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. | Since May 2012, water level has remained constant at the 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 high groundwater level recorded on 07 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.

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.<br>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 | Movement to late 2013 | Movement late 2013 to mid 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 ca.2.5m OD. It passes through 29m of glacial sediment, which becomes more sandy below 24.5m OD, and 3m of sandstone/mudstone bedrock.<br>Cumulative plot almost vertical and incremental plot reveals no displacements of the inclinometer tube greater than 2mm at any level within the borehole. | None evident | None evident. No movements >1.5mm |
| **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.<br>Cumulative plot is almost vertical and incremental plot reveals no displacements of the inclinometer tube greater than 2mm at any level within the borehole. | None evident | The incremental plot shows displacements of up to 10mm in the sandstone with mudstone bands 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 because displacements of similar magnitude occur in both axis directions and a similar pattern of change, but with a much smaller magnitude, is recorded in past readings. **This site should be investigated and the blockage removed or instrumentation repaired if necessary.** |
| **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.<br>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. The former apparent movement is likely to be an accumulation of error, as later readings show the inclinometer as nearly vertical. The latter is relatively moderate and possibly due to surface creep. | Possible continuation of surface creep identified in earlier period. | Apparent continuation of relatively shallow surface creep that extends to ca. 2m BGL (11m OD). |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid 2014 |
|---|---|---|---|
| **BH7** | Borehole is ca.20.5m deep and situated in the mid-slope of CBU2. Surface elevation is approximately 16.7m OD therefore borehole extends to ca-3.8m OD extending through 13m of glacial sediment and 7.5m of sandstone/mudstone bedrock.<br>The cumulative plot shows around 20mm of displacement in positive A axis direction between February 2011 and June 2011, above the contact between sandstone bedrock and gravelly sand at ca.4.7m OD. The extent of this displacement along the A axis reduces between June 2011 and December 2011 as displacement in the negative B axis direction occurs. Subsequent readings appear to show alternating displacements of up to 20mm in both positive and negative B axis directions indicating possible partly cross slope movements of the upper, unconsolidated strata. | Original shear has only displaced a small amount. However, displacement of up to 20mm in the positive b axis direction indicating either cumulative error or cross slope displacements occurs, particularly just above the contact between the gravelly sand layer and the sandy till at 3.5m BGL (4-5mm of movement). | 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.<br>**It is recommended that a site inspection be undertaken to determine the spatial extent of instability and the associated risk to properties** |

*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 | Change to late 2013 | Change from late 2013 to mid 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 peaks in May 2012 and December 2012, linked to higher rainfall during this period. Very rapid fluctuations occur particularly between Aug 2011 and July 2012, in response to individual heavy rainfall events. Rapid fall in groundwater levels linked to drier antecedent conditions and drainage. This rapid fluctuation becomes less after July 2012. | Since the December 2012 peak, whilst not without fluctuation, groundwater levels show a generally declining trend. | No data were available from this piezometer due to equipment error. Data will be provided in the third report. |
| **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 between Sept 08 and March 2009. | Steady at ca. 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 between 27.5 and 28.5m OD with peaks in April and July 2012 overlying a general trend of increasing water levels to a peak in Dec 2012. These peaks and general trend of increase tie in well with the Filey rainfall record. | After some initial fluctuations in early 2013, groundwater levels show a general trend of continual decline, particularly after June 2013. | Fluctuating pattern. 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 declined and stabilised around 27.7m OD, with a brief small rise and fall in early June 2014. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid 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 recalibration of the instrument appears to have occurred as groundwater levels are steady after that point (but with minor fluctuations) at around 2.5m OD. | No change – steady at ca. 2.5m OD to October 2013. | No change – steady at ca. 2.3-2.4m OD to July 2014 |
| **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 October 2013. | No change – steady at ca 17.2-17.3m OD to July 2014. |
| **P4a** | Automated piezometer. Tip at c. 8.3m OD*. Surface elevation at c. 17.0m OD (midslope in CBU2, co-located with P4b). Fluctuating pattern occurs between June 2004 and Feb 2009 with lows at around 12m OD (a base level) 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. After this, the base level appears to show a decline, but this is also associated with breaks in the record. After the more complete record resumes in September 2010 the same 'flashy' pattern of steep rising limbs and gentler falling limbs as seen before occurs, but with lows around 11.0m OD and peaks around 12.5 to 13.0m OD. Substantial peaks occur in Jan 2011, May 2012 and December 2012. NB. Before the break in the record in October 2009, groundwater levels were almost exactly the same as those in P4b. However, after that point, whilst following almost exactly the same pattern, ground water levels appear to be around 0.3m lower than in P4b. | The peak achieved in December 2012 was the largest, relative to the base level showing an increase in ground water level of nearly two metres. However, after some initial fluctuations in 2013, ground water levels in this piezometer have continually fallen to around 11.3m in October 2013, reflecting the drier than average weather of 2013.<br>The departure in groundwater levels from that monitored in P4b should be checked to ensure there is not a calibration issue. | 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.<br>**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.** |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid 2014 |
|---|---|---|---|
| **P4b** | Automated Piezometer. Tip at c. 6.35m OD*. Surface elevation at c. 17.0m OD (midslope in CBU2, co-located with P4a). Fluctuating pattern occurs between June 2004 and Feb 2009 with lows at around 12m OD (a base level) 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. After this, the base level appears to show a decline, but this is also associated with breaks in the record which may indicate calibration issues. After the more complete record resumes in September 2010 the same 'flashy' pattern of steep rising limbs and gentler falling limbs as seen before occurs, but with lows around 11.3m OD and peaks around 12.8 to 13.2m OD. Substantial peaks occur in Jan 2011, May 2012 and December 2012. It should be noted that before the break in the record in October 2009, groundwater levels were almost exactly the same as those in P4a. However, after that point, whilst following almost exactly the same pattern, ground water levels appear to be around 0.3m higher than in P4a. | The peak achieved in December 2012 was the largest, relative to the base level showing an increase in ground water level of nearly two metres. However, after some initial fluctuations in 2013, ground water levels in this piezometer have continually fallen to around 11.3m in October 2013, reflecting the drier than average weather of 2013.<br><br>The departure in groundwater levels from that monitored in P4a should be checked to ensure there is not a calibration issue. | 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.<br><br>**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.** |
| **WS4** | Tip at 9.9m OD. Surface elevation at 16.3m OD (midslope, CBU 2). Initially rises from ca. 10m OD to ca.15m OD between October 2010 and February 2011, then falls by June 2011 to ca. 13.7m OD, before rising again to ca15.2m OD in December 2011 which shows a pattern of high winter groundwater levels and lower summer levels. This pattern continues with groundwater levels in May 2012 recorded as ca. 13.7m OD despite heavy rainfall April 2012. | October 2013 groundwater level lower still at ca. 12.7m OD, indicating an overall decline in response to drier weather of 2013. Mirrors decrease in WS6 over same period. | July 2014 groundwater level at ca. 12.5m OD indicating a slight decline. |
| **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. | Groundwater level in October 2013 was ca. 9.7m OD, the highest indicated from all measurements of this borehole and in spite of drier conditions in 2013. This will be reviewed in the next monitoring assessment. | 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** |
| **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. | Decrease in groundwater level between May 2012 and October 2013 from high of 14.3m OD to ca. 13.2m OD, mirroring decrease in groundwater levels seen in WS4. | Groundwater levels showed a very slight (0.1m) decline since the last measurement in October 2013 |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid 2014 |
|---|---|---|---|
| **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). | Decrease in ground water level after December 2011 from 11.5m OD to 10.4m OD in October 2013 | Increase in groundwater level between October 2013 and July 2014 from 10.4m OD to 10.8m OD. Still lower than peak recorded values. |
| **B9** | Tip at 9.25m OD. Surface elevation at 17.8m OD (upper slope, CBU2). Fluctuation between ca. 10.0m OD and 12m OD except for substantial peaks in January 2008 (13.8m OD) and May 2008 (13.4m OD). Most recent peak in December 2011 at 11.5m OD. | Decrease in groundwater level between May 2012 and October 2013 from 15.2 to 14.7m OD. | Increase in groundwater level between October 2013 and July 2014 from 14.7m OD to 15.0m OD. Still lower than peak recorded values. |
| **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. | No data (cover locked and bolts rusted shut). When access gained, recommend tip depths verified and earlier records corrected. | Data from July 2014 at a similar level to that recorded between Dec 2009 and May 2012. |
| **Sn2b** | Tip depth at c. 8.35m OD*. Surface elevation at 16.35m OD* (midslope CBU2, co-located with SN2a). Likely that results for 2a and 2b confused or tip depth for Sn2a incorrect, as groundwater elevations for 2a not possible for tip depth stated. Notwithstanding that 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. | No data (cover locked and bolts rusted shut). When access gained, recommend tip depths verified and earlier records corrected. | Data from July 2014 at a similar level to that recorded between Dec 2009 and May 2012. |

The new data indicate:

- Significant ongoing movements were recorded in BH 7 between November 2013 and March 2014 (Figure 6.2). More limited movement is also indicated in borehole L2.
- Whilst not exceptionally high compared to the December 2012 peaks, shallow piezometers with a sufficiently resolute record indicate that groundwater levels reached a peak in mid-late February 2014.
- 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 Mouchel's final monitoring report in the summer of 2012, much of the rainfall in the study area has been atypical. Following a very dry start to 2012, the spring and summer were exceptionally wet and the latter half of 2012 was also wet. 2013 was comparatively very dry. 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 moderate peaks in groundwater level are reached by mid-late February 2014 before declining and stabilising at a lower level.

Deeper piezometers have a longer lag between rainfall and groundwater response. Those with data loggers show a much more muted response and those without dataloggers tend to show peaks in May 2012, or in earlier winter periods, with the likely December 2012 peak being absent due to the lack of monitoring at that time. The exception to this rule is WS5 which appears to show a rising groundwater level towards 2013 but was dry in July 2014.

The inclinometers in BH7 and L2 show significant sub-surface movement. BH7 is the most pronounced and indicates movement on an existing shear plane just above the sandstone bedrock in glacial sediments. This movement occurred between November 2013 and March 2014, and is likely to be associated with the period of high groundwater levels (nearby piezometers P4a and P4b show elevated groundwater peaking in mid-February 2014). This suggests a threshold groundwater level for movement occurred.

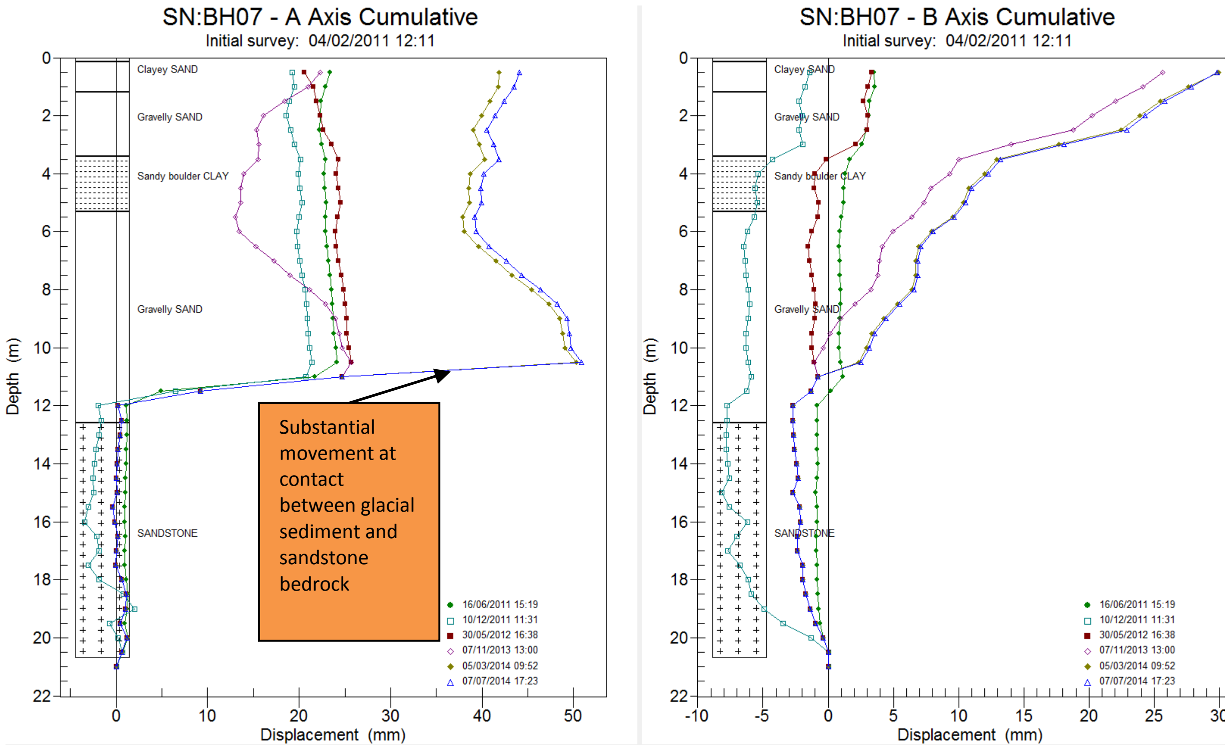


*Figure 6.2. Inclinometer data at Scalby Ness BH07*

# 6.6 Implications and recommendations

Shallow piezometers appear to show a strong relationship between rainfall and groundwater. This relationship is not as evident in the deep piezometers installed in bedrock, probably due to lag effects. Significant ground movement was detected in BH7 between November 2013 and March 2014. Comparison with data from nearby piezometers BHP4a and BHP4b suggests that movements coincided with a period of elevated groundwater levels following prolonged periods of heavy rain in January and February 2014. The precise relationship between rainfall and ground movement is unclear because more significant rainfall has occurred in the past, for example the spring of 2012 and the winter of 2012/13, which are not associated with ground movement.

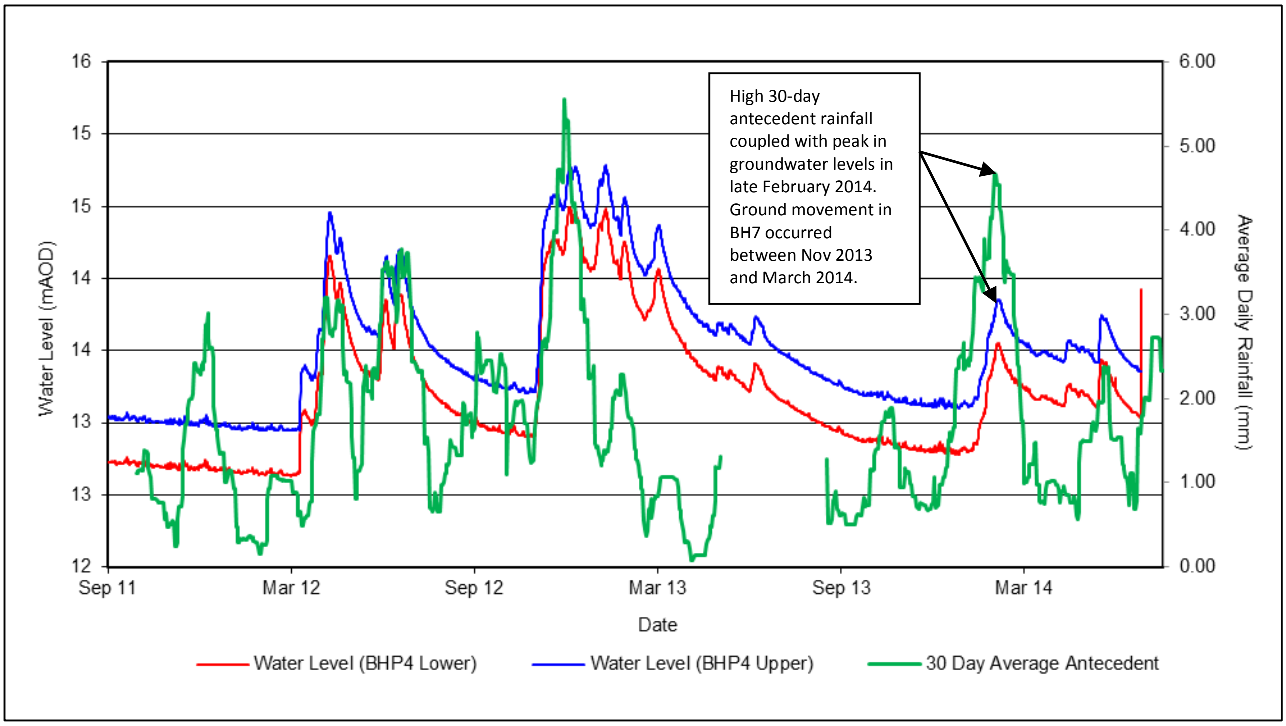


*Figure 6.3: 30-Day antecedent rainfall and groundwater levels in piezometers BHP4a and BHP4b. 30-day antecedent average daily rainfall is, on any given day, the average rainfall from that day and the preceding 29 days.*

SECTION 7

# 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

*Table 7.2. Summary of inclinometer data at Oasis Café*

| Borehole | Summary of past data | Movement to November 2013 | Movement from late 2013 to mid-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.<br>Past readings show a series of very small displacements which cumulatively account for no more than 5mm of displacement at the surface, so no significant ground movement. | Nov 2013 reading shows no significant change | July 2014 reading shows no significant change |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **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.<br>The inclinometer plot shows very little displacement (<2mm in the cumulative plot) with the exception of the reading from December 2009 which shows a 3.5mm displacement in the positive A axis (upslope) direction at around 14.8m OD (3.0m BGL). However, the following reading from January 2009 shows the inclinometer near vertical with no displacement from the reading before December 2009 (November 2009). This reading is within the margin of error of the instrument. | No significant change | No significant change |

*Table 7.3. Summary of groundwater data at Oasis Café*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **BH2p** | Tip depth at 8.05m OD. Situated in the lower cliff. Manual dip readings from September 2009 to May 2012 show fluctuation from September to December 2009 between 8.0 and 8.5m OD followed by no variation to December 2011. Groundwater level rises to 8.5m OD by May 2012. | Results available from October 2012 onwards. Fluctuates between 8.0 and 8.6m OD. General trend is fall towards December 2012 and Rise toward August 2013, followed by slight fall to October 2013. This is contrary to the rainfall pattern and maybe influenced by tidal cycles or local surcharging of groundwater sources. | 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 but may reflect delayed responses. |
| **BH3p** | Tip depth at 12.4m OD. Situated in the midslope. Manual dip readings from September 2009 to December 2011 show fluctuation between ca. 13.8m OD (June 2010) and 14.7m OD (December 2010). Final manual reading May 2012 shows substantial increase in groundwater level to 17.6m OD, reflecting high rainfall during spring 2012. This would be just below the surface, which is at 17.8m OD. | Results from Oct 2012 to late 2013 indicate fluctuating levels with no obvious correlation to rainfall events. | 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 December 2012 and June 2013 peaks. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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. | In October 2012 groundwater levels were at c. 19.0m OD. Levels fluctuate but show a gradual rise towards a peak at around 19.4m OD in late Feb 2013. Levels are generally stable between 18.8 and 19.2m OD until early June 2013 when they fall rapidly to a low of around 18.4m OD in early July before rising again to around 19.1m in mid July 2013. From late July onwards, the data shows a steady fall in groundwater level to a low point of c. 17.7m OD by October 2013.<br>It is likely that this borehole is reflecting a lag response of the bedrock aquifer. | 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.<br>The pattern continues to indicate the lag response of a bedrock aquifer to prolonged periods of high rainfall rain. |

## 7.5 Causal-response relationships

During the winter 2013 to summer 2014 monitoring period, there has been higher rainfall compared to the previous 6 months. This is reflected in reversals of falling groundwater levels in boreholes BH3p and BH4p, but with less of an impact in BH2p. The patterns seen in the previous 6 month period are still visible, with BH2p not having a clear response to rainfall and/or tides. Shallow piezometer BH3p continues to show a flashy response to rainfall events 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 it is therefore unsurprising that inclinometers do not indicate movement. The impact of December 2013 storm surge does not appear to have had a strong influence on ground water levels at this site.

## 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 Cafe, 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 a flashy 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 (ca.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, ca. 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 ca.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 | Movement to late 2013 | Movements from late 2013 to mid-2014 |
|---|---|---|---|
| **BH10A** | BH10A is ca. 42m deep. Surface elevation of the borehole is 46.75m OD, therefore the base is at 4.75m OD. The borehole passes through (from surface to base) ca.2m of made ground, ca. 1m of clay and ca.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 (ca. 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 displacement recorded in the A axis focused around 42m OD continues between May 2012 and November 2013. However, the incremental change plot indicates movement in both negative and positive directions in the borehole, which is most likely reading errors.<br>**Inclinometer integrity check and quality of repeat readings to be reviewed.** | 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<br>**An inclinometer integrity check and careful collection of future readings is necessary.** |
| **BH11** | BH11 is ca.22m deep. Surface elevation of the borehole is at 55.86m OD therefore the base is at ca.34m OD. The borehole passes through 5m of slightly sandy clay and boulder clay (likely glacial till) before encountering weathered sandstone at about 51m OD until at 41m OD at which point intact sandstone bedrock is encountered.<br>The inclinometer readings show a series of progressively larger deformations of around 20mm in the both axes within the weathered sandstone. No deformation has yet occurred above this depth. | The same pattern continues with displacement increasing between May 2012 and November 2013 by a very small amount. | 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. |

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

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **L1a** | Tip depth at -8.03m OD. Situated on Royal Albert Drive (Marine Drive), co-located with L1a. Manual dip readings between June 2009 and May 2012 show relatively steady groundwater level around 5.2m OD but with greater variation in the earlier part of this period with a peak ca. 5.9m OD (June 2010) and a low of 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 nonetheless shows a higher piezometric level than BHL1b – this may indicate a confined aquifer under artesian pressure (albeit insufficient to reach the surface and flow).** | No data available from May 2012 to October 2012. Shows a cyclical pattern (likely tidally influenced) overlain onto a trend of generally declining groundwater levels from around 2.5m OD in October 2012 to around 1m OD July 2013, then rising slightly towards October 2013. | BHL1a continues to show a generally declining trend in groundwater levels, albeit with potentially tidally influenced cyclical variation. |
| **L1b** | Tip Depth at -2.97m OD. Situated on Royal Albert Drive (Marine Drive), co-located with L1a. Manual dip readings between June 2009 and May 2012 show relatively steady groundwater level around 1.9m OD, except for substantial apparent fall to this level at the beginning of that monitoring period from around 8.3m OD. However, the pattern of the rise to that level and subsequent fall indicates a monitoring issue rather than an actual substantial diversion from the usual range of groundwater levels experienced. | No data available from May 2012 to October 2012. Shows a cyclical pattern (likely tidally influenced) overlain onto a general trend of falling groundwater levels from around 4.50m OD in October 2012 to 4.25m OD to October 2013. | 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 |
| **BH8a** | Tip depth at 10.16m OD. Situated at 31.16m OD in the midslope at the Holms (Co-located with BH8b). Monitoring from September 2010 shows an initial sharp fall in level from 15.9m OD possibly due to installation, followed by gently falling water level to a low of 10.43m OD in June 2011. After this there is a gradual rise in water level through the autumn to December 2011 (as might be expected given the rainfall pattern) before a much steeper increase to 23.6m OD by May 2012, possibly as a result of the exceptional rainfall, relative to the average rainfall at that time of year. | No data available between May 2012 and October 2012. From October 2012 to July 2013 shows slight and gradual rise in groundwater levels from ca.10m OD to ca.10.5m OD before showing slight and gradual fall to around 10.3m OD by October 2013. Fluctuations are present but are quite subtle. | 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. |
| **BH8b** | Tip depth at 3.16m OD. Situated at 31.16m OD in the midslope at the Holms (Co-located with BH8a). Groundwater levels dropped from an initial high point of 17.3m OD at installation in September 2010 before dropping to a low of 9.55m OD in February 2011. Groundwater levels gradually rise throughout 2011 to around 10.6m OD in December 2012 before increasing substantially to 22.2m OD by May 2012. This shows a very similar pattern, likely influenced by heavy rainfall, to that shown in BH8a. | No data available between May 2012 and October 2012. Shows substantial rise in groundwater level from ca. 12m OD in October 2012 to ca.14.5m OD in April 13, before falling again to ca.12m OD in June 2013. Period from June to October 2013 shows increase in groundwater levels to ca.13m OD. | 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. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **BH9a** | Tip depth at 9.49m OD. Situated on the midslope bench in the north eastern part of The Holms at 33.49m OD (co-located with BH9b). Shows sharp increase after installation from ca. 11-12m OD to a high of 26.6m OD by February 2011 before falling to 24.3m OD in June 2011. Between June 2011 and December 2011 ground water levels rise again to around 27.0m OD before falling slightly again to 26.3m OD, contrary to what might have been expected given the rainfall during that period. | No data available between May 2012 and October 2012. Shows general pattern (with a notable exception in December 2012) of falling groundwater level from ca.23m OD in October 2012 to around 14m OD in June 2013. Sudden rise occurs in early June 2013 to around 17.45m OD before a pattern of decreasing groundwater level is resumed | Groundwater levels have been relatively steady between 23 and 24m OD since the last monitoring period, peaking in February 2014. |
| **BH9b** | Tip depth at 0.49m OD. Situated on the midslope bench in the northeast part of The Holms at 33.49m OD (co-located with BH9a). Shows sharp increase in ground water levels from around 10m OD after installation in September 2010 to around 25m OD in February 2011 (similar to BH9a). Continues to more gradually rise to around 26m OD in June 2011 before gradually falling to 23.2m OD in May 2012. This pattern is similar to the pattern of groundwater fluctuation recorded in BH9a, but contrary to that shown in BH8a and BH8b. | No data available between May 2012 and October 2012. Shows initial readings around 26m OD in October 2012 before showing sharp fluctuations overlying a general pattern of increase to a groundwater level of around 27m OD in December 2012. Groundwater stays near this level until early March 2013 before the water level falls relatively quickly throughout March 2013 to around 26m OD and then falls more gently to around 25.5m OD by late July 2013. In late July 2013, an instantaneous fall in groundwater level of ca.11m is shown, followed by fluctuating levels overlain onto a pattern of general decrease, with groundwater levels reducing to 13.73m OD by October 2013. The cause of this is unclear. | 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.<br>**Groundwater levels appear to show a moderate lag response to periods of high rainfall.** |

## 8.5 Causal-response relationships

Since the last monitoring report covering the period to late 2013, rainfall has increased relative to the comparatively dry year of 2013. 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. BH8b shows a different pattern of gradual rises followed by sharp falls, which may indicate a release of pore water pressure following slope movements, but this is not reflected in the inclinometer upslope at BH10A. BH9b shows a gradual rise towards the end of the latest monitoring period, and groundwater levels in this piezometer are approaching their highest levels since August 2013.

The 5th December 2013 storm surge does not have a distinctive signature in the groundwater levels at the Holms.

The relationship between 180-day (c. 6-month) antecedent rainfall pattern and groundwater level at BH8b is presented in Figure 8.2. A gap in the rainfall data between late May and early August 2013 means that the extent of the relationship through that period and the following 180 days (i.e. from late May 2013 until late January 2014 cannot be accurately determined.

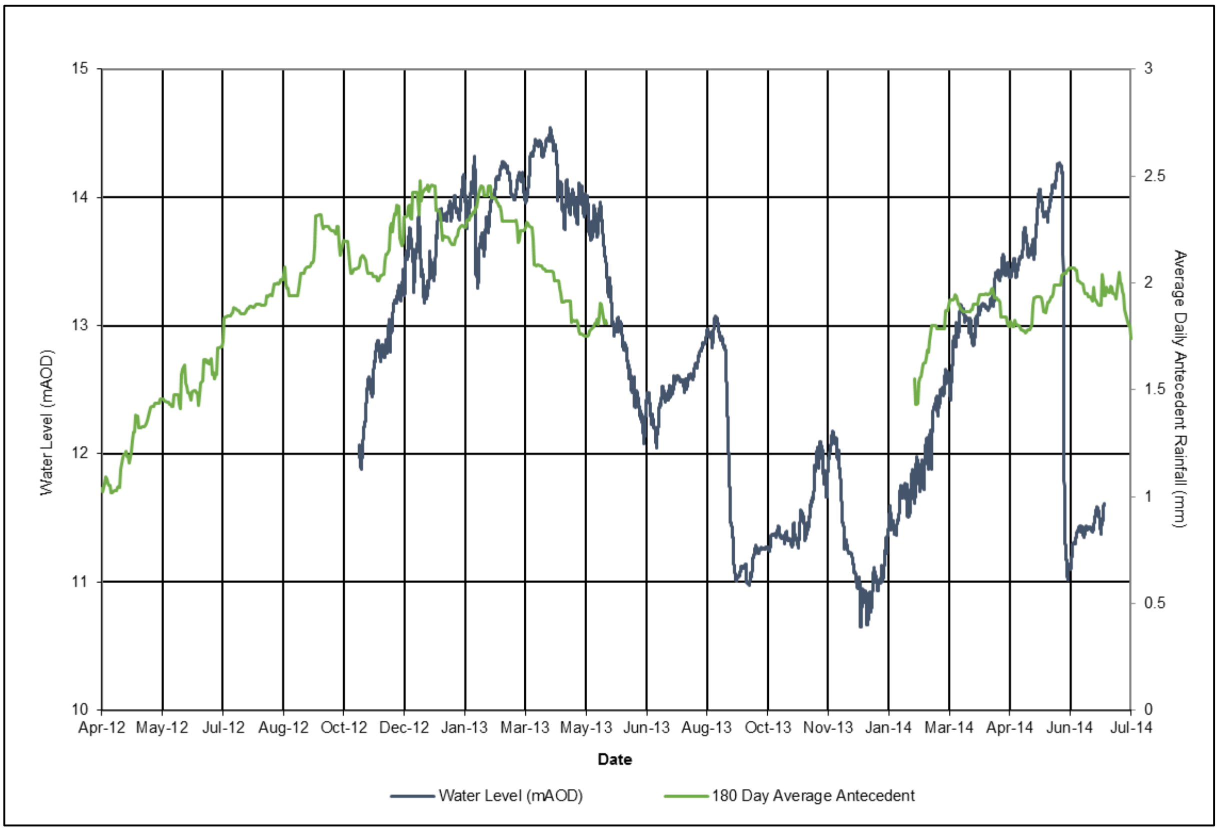


*Figure 8.2: Relationship between 180-day antecedent rainfall and groundwater level at BH8b.*

## 8.6 Implications and recommendations

The displacements recorded at BH11 should be checked to ensure their accuracy. Specific review of data from BH9b should be undertaken at the next review to establish whether the trend of increasing groundwater levels has continued.

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 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 | Movement to late 2013 | Movement from late 2013 to mid-2014 |
|---|---|---|---|
| FR01 | FR01 is situated above Foreshore Road in front of the Grand Hotel at 11.43m OD. The borehole is c.20m deep and therefore has its base at c.-8.5m OD. The borehole passes through c.10.5m of made ground before entering 9.5m of predominantly fine grained glacial sediments.<br>FR01 has been monitored since 16 June 2014. | N/A | No movement recorded during initial readings. |

*Table 9.3 Summary of groundwater data at St Nicholas Cliff*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **FR02** | FR02 has only 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. | No data | Distinct sub-weekly cyclical pattern of rising and falling groundwater level, overlain onto an approximately monthly pattern of changes in amplitude of the 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). |

## 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.

These data indicate:

- Possible incipient movement in the top 10m of material in BH12, although this is currently unclear and movements are minor. The borehole string has partially collapsed and become deformed between 30 and 40m depths. This movement occurred sometime following the first reading on 3 February 2011 and the second reading on 15 June 2011.
- Both piezometer datasets show weekly to sub-weekly variations of up to 1m with no clear underlying trend or pattern in water-levels. These variations are likely to reflect tidal variations, with the signature of the 5$^{th}$ December 2013 being particularly clear in the BHI2 record as a distinct spike in groundwater levels.
- Contrasting patterns of change with short-term variability, with BH12 indicating an increase and BH12a indicating a decrease in variability over the last 6 months. This is likely to reflect significant variability in permeability of the glacial sediments over short distances and does not correlate well with the period of dry weather experienced during the latter half of 2013.

*Table 9.4 Summary of inclinometer data at Spa Chalet*

| Borehole | Summary of past data | Movement to late 2013 | Movement from late 2013 to mid-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 recorded on 15 June 2011. 60mm displacement between 9.05m and 17.05mAOD in a sand and gravel layer in the glacial sediment occurred between Feb and Aug 2011. However, the nature of the movement is atypical of that to be expected on a slip plane. Readings since this time have indicated recovery of the borehole towards a more vertical position, with cumulative movement in the most recent reading being less than 2mm. Superimposed on this linear trend of decreasing deformation with depth is a sinuous pattern of deformation between 30 and 40m depth (18 to 8m OD) where up to 60mm of movement has occurred. This movement is within a lens of sand and gravel. | Recovery of the borehole towards a more vertical position, with cumulative movement to late 2013 of less than 2mm. | 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.<br>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. |

*Table 9.5. Summary of groundwater data at Spa Chalet.*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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. | Subtle pattern of increasing short-term variability between maximum and minimum levels through time, from c. 0.5m in late 2012 to c. 1m in late 2013. | 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 |
| 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. | Subtle pattern of decreasing short-term variability of water level from c. 0.4m in March 2013 to c. 0.2m in late 2013. This may reflect the drier conditions of 2013 compared to 2012. | Short term variability appears to have increased to levels comparable to those seen in late 2012. |

### 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 | Movement to late 2013 | Movement from late 2013 to mid-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. | This location was not read in 2013.<br>Inclinometer integrity check and quality of readings to be reviewed. | Limited movement (<2mm) at around 15m OD since previous monitoring in 2011 is within tolerance of repeat readings. No additional movement at depth.<br>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. |

| Borehole | Summary of past data | Movement to late 2013 | Movement from late 2013 to mid-2014 |
|---|---|---|---|
| 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 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. | Incremental movements on 6 Nov 2013 show displacements of up to 5mm in lower half of borehole (from 35m to 60m depth). Deflections in upper 35m are less than 2mm. Cumulative deflection indicated to be up to 60mm in the upper 35m of the borehole. **A site inspection was undertaken in December 2013. No observations of surface features such as cracks or ground heave indicative of slope movement were observed.**<br>Inclinometer integrity check and quality of repeat readings to be reviewed. | Pattern shown is similar to earlier readings, with no change greater than the tolerance of repeat readings.<br>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 movement would be detected**.** |
| 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. | Incremental movement of less than 1mm, which is within the tolerance of repeat readings. | 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**.** |
| BH101 | This 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 of the hole is -19.7m OD. The borehole shows small movement (<2mm) in its upper few metres between installation in Oct 2012 and Dec 2012. The movement is very small and in a cross-slope direction so may not indicate real long term progressive displacements. | Historical readings unavailable at current time therefore current reading cannot be compared to baseline.<br>Inclinometer integrity check and quality of readings to be reviewed. | Incremental plot shows no significant movement greater than 1mm. |
| 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. | Historical readings unavailable at current time therefore current reading cannot be compared to baseline. | 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. |

| Borehole | Summary of past data | Movement to late 2013 | Movement from late 2013 to mid-2014 |
|---|---|---|---|
| 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. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm. Historical readings unavailable at current time therefore current reading cannot be compared to baseline. | Historical readings unavailable at current time therefore current reading cannot be compared to baseline. | All movements 2mm or less which are not significant. |
| BH109 | 15m deep borehole that passes through 9m of glacial sediment and 6m of sandstone/mudstone bedrock. Ground level is 31.6m OD, base of hole is 16.6m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm. | Historical readings unavailable at current time therefore current reading cannot be compared to baseline. | All movements 2mm or less which are not significant. |
| BH105 | 45m deep borehole passing through 44m of glacial sediments an 1m of sandstone bedrock. Ground level is 41.75m OD and base of hole is -3.25m OD. Apparent displacements between installation in Oct 2012 and Dec 2012 are <1mm. | Historical readings unavailable at current time therefore current reading cannot be compared to baseline. | 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. |
| 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. | Recent measurements at the Spa are minor and are interpreted as being a response to water seepage through high permeability gravels lenses within the glacial sediments following rainfall. Ongoing monitoring will help these events to be filtered from the data and allow evidence for ground movement to be more clearly indicated. | Acoustic emissions (AE) detected are most likely a response to rainfall events and groundwater seepage and not slope movement. |

*Table 9.7. Summary of groundwater data at the Spa*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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 in pattern of variability about a mean level. | No change to pattern, except slightly lower groundwater levels between December 2013 and March 2014. |
| 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 pattern of variability about a mean level. | No change in the pattern. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| 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 water-levels rose by almost 1m in a day. | No change in pattern of falling water-level. | 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 likely, an equipment error. Checks of the piezometer is recommended. |
| 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. | Most recent reading of 7.4m AOD is near to the historical low, reflecting the dry conditions prevailing through 2013. | Groundwater levels now at their highest on record at 12.2m OD. |
| 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. | Most recent readings are near the long term average of c.10m AOD reflecting the dry conditions prevailing through 2013. | July 2014 reading shows a fall from the previous reading from ca. 10m OD to <9m OD. |
| 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. | Most recent readings are near the long term average value of c. 12m OD reflecting the dry conditions prevailing through 2013. | July 2014 water levels dropped to c. 7m OD, which is near the lowest levels on record. |
| 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 | Most recent reading are near the long term average value of c. 12m AOD reflecting the dry conditions prevailing through 2013. | July 2014 water level dropped to 6.3m OD, which is near the lowest levels on record. |
| 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. | No change in cyclical pattern. Recent readings have fluctuated about a mean of c. 13.7m. Sub-weekly fluctuations are up to 0.2m. | Cyclical pattern continues with apparent decrease in amplitude, leaving maximum and minimum groundwater levels within the range seen between Oct 2012 and late 2013. |
| 5 spa | Located near the base of the cliff. Tip at 9.4m OD. No correlation with the upper tip in this well. Data only recorded between Sep 2006 and May 2012, after which the hole is dry. Limited fluctuation between c. 8.5m and c.9.5m OD. | No data recorded since May 2012 as the borehole is dry.<br><br>Piezometer integrity check and quality of readings to be reviewed. | No data recorded since May 2012 as the borehole is dry.<br><br>**Piezometer integrity check and quality of readings to be reviewed.** |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| BH1a spa | Located at the toe of the Spa landslide. Tip at 2m OD. Sub-weekly fluctuation about mean around 4.4m. Water levels were at their highest during Jan and Feb 2012 when they were c. 0.5m higher than average. Sub-weekly fluctuations are c. 0.4m in the period Oct 2012 to Mar 2013. | Decrease in sub-weekly fluctuations from c. 0.4m up to Mar 2013, to c. 0.2 since Mar 2013. This probably reflects the dry conditions prevailing through 2013. | Continued decrease in sub-weekly fluctuations. Peak in early March 2014 of ca. 4.8m OD but fluctuations within those seen before. |
| 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. | Sub-weekly fluctuations reduced to c. 0.2 since Mar 2013, possibly reflecting the dry conditions prevailing through 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. |
| 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. | No change in pattern. | 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. |
| G1a | Located inland of the cliff top. Dipped piezometer that shows consistent water levels of c. 53.5m OD since late 1997. | Consistent level since previous recording reflecting the dry conditions of 2013. | No change – consistent groundwater level of ca.53.5m continues. |
| 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 level since previous recording, with elevation at c. 19m AOD. | Consistent water level since previous recording at ca. 19m OD. |
| BH108a | Located mid-slope. Located mid-slope. Shallow piezometer tip that was dry between Sept 2012 and Jan 2013. | No data. Piezometer integrity check and quality of readings to be reviewed. | No change in reported groundwater level – steady at 25.06m OD since last reading. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| BH108b | 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. | No data. Piezometer integrity check and quality of readings to be reviewed. | 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.<br>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.<br>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. |
| BH106a | Located at the cliff top. Solinst data logger. Borehole dry between Oct 2012 and Jan 2013. | No data. Piezometer integrity check and quality of readings to be reviewed. | Borehole dry. |
| BH106b | Located at the cliff top. Located at the cliff top. Manual piezometer tube. Borehole dry between Oct 2012 and Jan 2013. | No data. Piezometer integrity check and quality of readings to be reviewed. | Borehole dry. |
| BH104a | Located near the base of the slope. Solinst data logger. | No data. Piezometer integrity check and quality of readings to be reviewed. | 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. |
| BH104b | Located near the base of the slope. Manual piezometer tube. Borehole dry between Sept 2012 and Jan 2013. No data | No data. Piezometer integrity check and quality of readings to be reviewed. | 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. |
| BH102a | Located at the base of the slope behind the seawall. Solinst data logger. Reading will be reported in next report. | No data. Piezometer integrity check and quality of readings to be reviewed. | 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.<br>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. |

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| BH102b | Located at the base of the slope behind the seawall. Manual piezometer. | No data. Piezometer integrity check and quality of readings to be reviewed. | Slight fall in groundwater level to 1.2m, similar to October 2012 reading. Likely influenced by tidal cycle. |

### 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 | Movement to late 2013 | Movement from late 2013 to mid-2014 |
|---|---|---|---|
| AA10 (F2) | 30m deep borehole penetrating 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 (Royal Haskoning) is erroneous and should be removed from the plot. | Incremental movement of up to 4mm in the upper 5m of the borehole associated with shallow creep of glacial sediment and made ground. Data for base of the borehole is instrument error. | Continuation of minor creep in positive A axis direction in the upper 5m of glacial sediment. |
| AA11 (F4) | 20m deep borehole penetrating 8m of glacial sediment and 12m of siltstone/sandstone bedrock near the toe of the Clock Café landslide. Ground level is unclear and will be confirmed. Very low cumulative movement along whole length of borehole of up to 3mm is within tolerance of the device. | No change. Incremental movement of 1mm is not significant. | No change. All apparent movements <1mm and therefore not significant. |

*Table 9.9. Summary of groundwater data at the Clock Café*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| BH15 | Located inland of the landslide headscarp. No data found | Borehole dry.<br>Piezometer integrity check and quality of readings to be reviewed. | Borehole dry.<br>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.

### 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 | Movement to late 2013 | Movement late 2013 to mid-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 very slight progressive creep along the whole length of the borehole, with a maximum cumulative displacement of 5mm. | No change. Incremental movement of less than 1mm is not significant. | No change. No incremental movements >1mm. |
| 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 very slight progressive creep along the whole length of the borehole, with maximum cumulative displacement of 5mm. | 6 Nov 2013 data indicates incremental movement of up to 25mm**. A site inspection was undertaken in December 2013. No observations of surface features such as cracks or ground heave indicative of slope movement were observed.**<br>Inclinometer integrity check and quality of readings to be reviewed. | 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. |
| 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 very slight progressive creep along the whole length of the borehole with a maximum cumulative displacement of 5mm. Data recorded on 2 Feb 2011, 14 Jun 2011, 8 Dec 2011 (Mouchel) and 31 May 2012 (Haskoning) indicate significant cumulative displacement of up to 300mm, but pattern of change, with both positive and negative displacement suggests readings are erroneous. A site visit undertaken in Dec 2013 confirmed these readings are erroneous. | 6 Nov 2013 data revert to the original pattern of slight creep, with incremental movements at locations along the whole borehole of up to 5mm.<br>Readings taken on 30 Jan 2014 show positive and negative movements on both axes likely to be in error. The cause(s) of this error are being investigated.<br>Inclinometer integrity check and quality of readings to be reviewed. | Incremental plot indicates no significant change since last reading. |

| Borehole | Summary of past data | Movement to late 2013 | Movement late 2013 to mid-2014 |
|---|---|---|---|
| BH20 | 41m deep borehole that penetrates 27m of glacial sediments and 14m of sandstone bedrock within the body of a small landslide block. Ground level is 58.98m OD, base of borehole is 17.98m OD. Data indicates very slight progressive creep along the whole length of the borehole with a maximum cumulative displacement of 5mm. | **6 Nov 2013 data indicates deflection of 10 to 15mm from the ground surface to a depth of 30m in both the A and B axes that was not detected before**. This suggests development of a shear surface within the sandstone bedrock at 30m depth (29m OD) since the last reading in June 2012. Sinuosity in data is indicative of error in the reading, which is being checked.<br>Readings taken on 30 Jan 2014 shows ongoing deformation of the upper 31m on the A axis and significant movement of up to 10mm in the negative direction on the B axis. This could reflect a change in landslide behaviour but reading error is also possible.<br>Inclinometer integrity check and quality of readings to be reviewed. | Additional data provided in September 2014, the latest reading in which was taken on 15 September 2014, indicates no further movements in this borehole. |

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

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-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. | Since the last peak in water level (mid Aug 2013), water levels have gradually fallen to 35m OD, which is their lowest elevation since early November 2012 when records began. There have been no peaks of water level to interrupt this pattern gradual fall. This probably reflects the dry conditions prevailing through 2013. | Gradual increase in base readings from mid-December 2013 to mid-February 2014, with spikes in water level reaching ca. 42.5m OD.<br>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** |
| 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 higher elevation tip, with gradual fall of water level from 37m OD in mid Aug to 35.6 in mid Oct, reflecting the dry conditions prevailing through 2013. | 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. |
| BH19a | Tip at 53.8m OD inland of the headscarp of the South Bay Pool landslide. This piezometer has been dry since installation. | Dry.<br>Piezometer integrity check and quality of readings to be reviewed. | No data available. Contractor's notes indicate that there is an issue with the data logger.<br>Data logger and piezometer integrity to be checked. |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| 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. | Rapid rise of almost a metre to highest recorded elevation (from 47.5 to 48.3m OD) between 11 and 15 Oct 2013. This contrasts with the rainfall data and may reflect a local effect. | 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).<br>This pattern does not tie in well with the rainfall record and may reflect local effects. |
| D2a | Tip at 27.5m OD at the headscarp of the South Bay Pool landslide. Sub-metre variation about an average level of 40.5m OD. Periods where hole appears dry occurred regularly from late June to early July 2013, following which no data has been recorded. | No data downloaded since Jul 2013 due to a missing connection cable. This will be rectified in the next site visit. | Groundwater levels fell from a peak in late November 2013 until late December 2013, likely reflecting the dry conditions of 2013. Levels subsequently recovered until reaching a peak in mid-March at around 31.8m OD.<br>Groundwater levels show sub-metre variability around a mean groundwater level of 31.5m OD since late March. |
| 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. | Data since Aug 2013 continues previous pattern. | 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 change in pattern, with mean of c. 44m and variation of c. 0.2m | No data since October 2013. Contractor's notes indicate the cable has been cut and requires fixing. |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| 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. | No change in pattern, with mean of c. 10.5m and variation of c. 0.2m. Isolated peak in water level (12.5m AOD) on 15 Aug 2013. | Slight reduction in mean water levels in winter 2013/14 before recovering to levels seen previously.<br>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. |
| 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 | Continuation of recent falling trend. Level still c. 0.5m higher than at beginning of record in Oct 2012. This reflects the dry conditions prevailing through 2013 and suggests either this site is taking a particularly long time to recover from the wet conditions of 2012, or there is a local source of groundwater. | 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.<br>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. |
| 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. | No change in previous pattern of constant water-level. | Groundwater levels lower in late 2013/early 2014 and with shorter term variability than previously seen. Since March 2013, readings have returned to the same mean level and pattern of variability as seen before November 2013. |

These data indicate:

- The previous report indicated movement and shear surface within the sandstone/siltstone bedrock at an elevation of 29m OD in BH20. No ground movements were reported on site, although evidence of failures in the lower cliff and water seepage were mapped at this location in 2011. Periodic inspections at this location are recommended, particularly as winter approaches but readings since the last monitoring period indicate no further movement or development of this shear surface.
- No further movement is indicated in BH17 since the last monitoring period.
- Groundwater levels declined in response to the dryer-than-average conditions in 2013, but have since recovered to levels seen previously. BH19b is the only borehole showing a significant rise to a peak groundwater level higher than that seen in late 2012 and early 2013.
- 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 (See Figures 9.2 and 9.3).

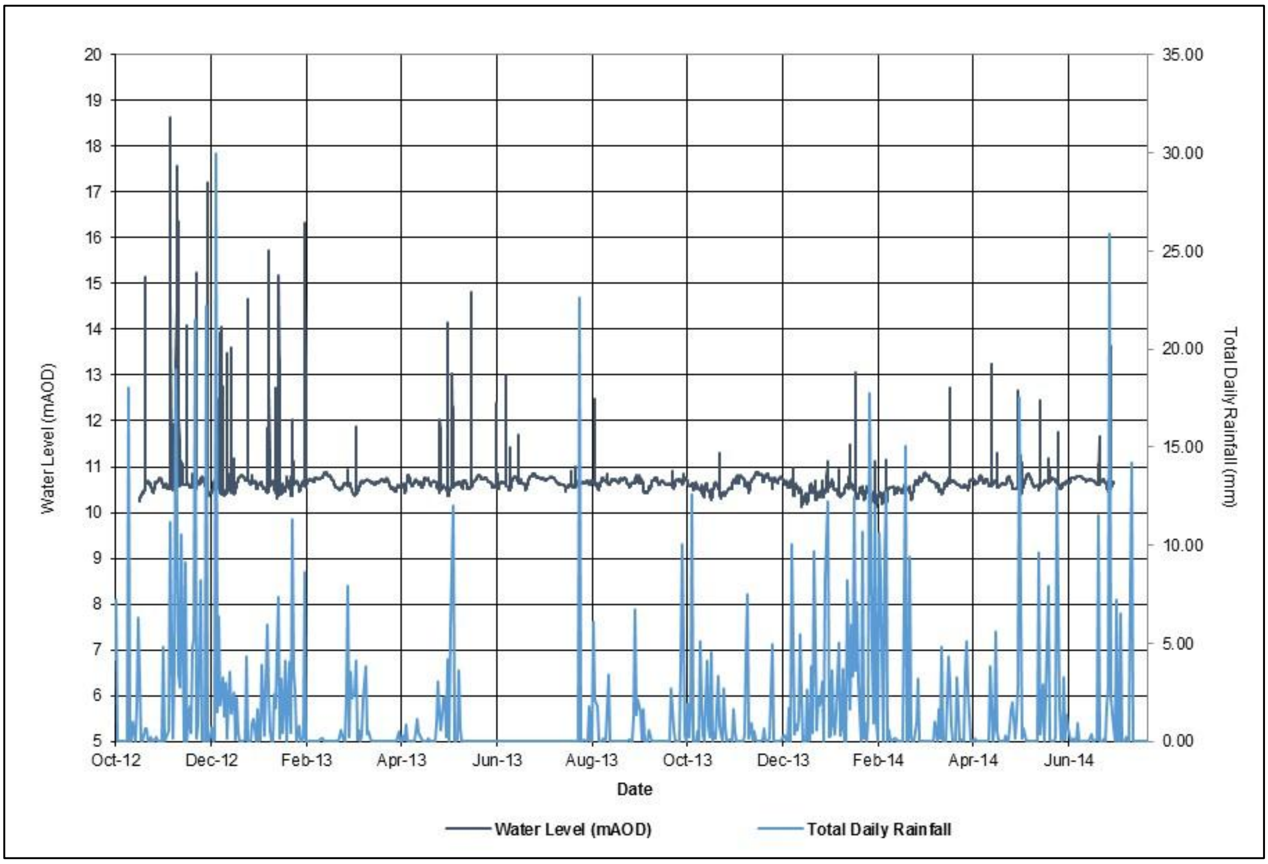


*Figure 9.2: Spikes in groundwater in BH3b compared to total daily rainfall from Flat Cliffs. Note a limited correlation between days with higher rainfall and spikes in groundwater level.*

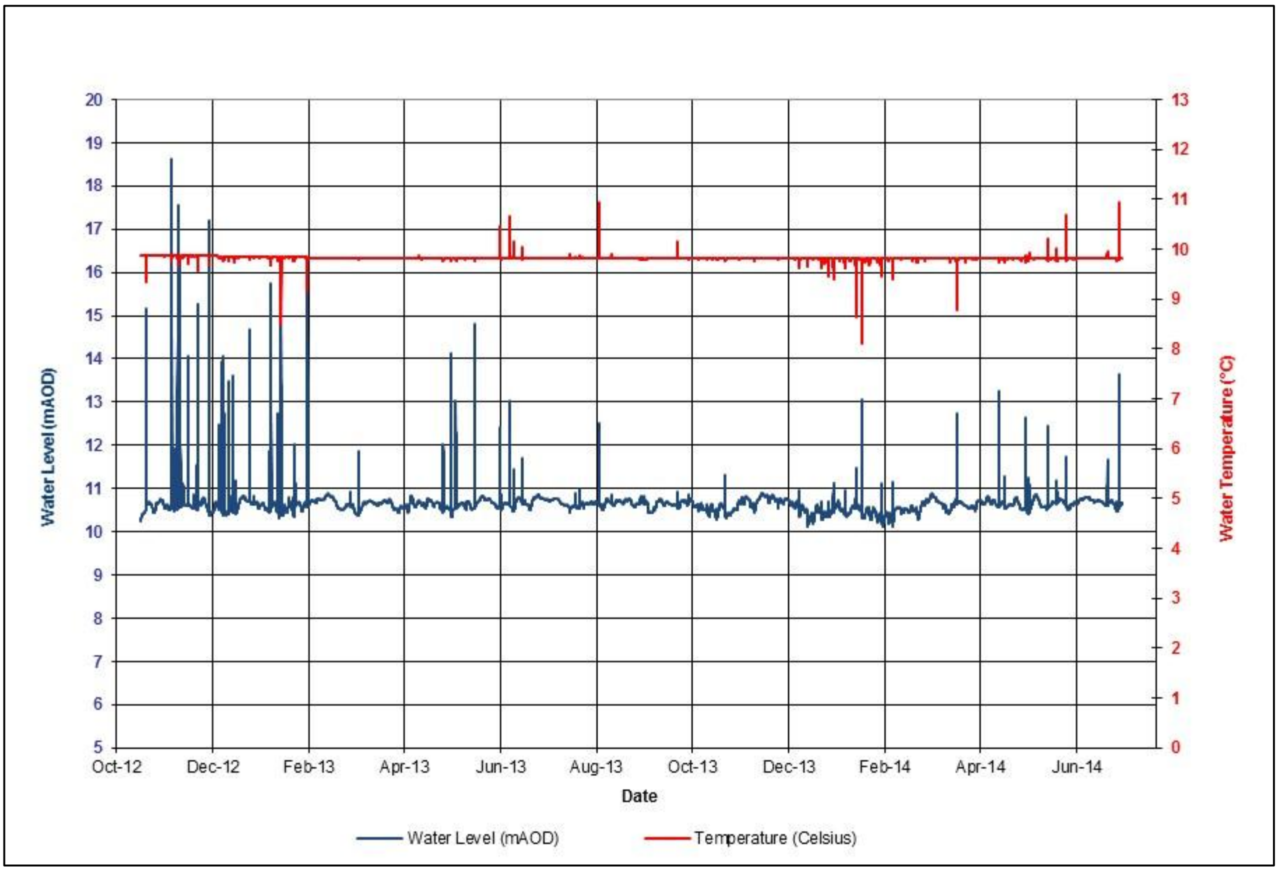


*Figure 9.3: Correlation between peak groundwater levels and changes in temperature. During summer groundwater temperature rises at the time of water-level peaks, while during winter groundwater temperature drops. The relationship during spring and autumn is more muted and the direction of change is less consistent, but the timing of the changes still correlate with the apparent peaks in groundwater level.*

### 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 near the slope top (Tables 9.12 and 9.13).

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

| Borehole | Summary of past data | Movement to late 2013 | Movement from late 2013 to mid-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. | Displacements measured on 5 Nov 2013 were negligible and within the tolerance of the equipment and method. | 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 ca. 55m depth. These locations have previously shown smaller variation in both axes, which suggests that the BH is deformed. Close attention to this location is recommended to determine whether the data indicates ground movement or is related to minor settlement of the borehole. |

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

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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. | Continuous and gradual fall from c. 49m c 48m OD. These levels are among the lowest recorded and reflect the dry conditions prevailing through 2013. | Low point reached at ca. 48m OD in late Dec 2013,followed by progressive rises and falls between 49.8m and 49m OD in response to rainfall. |
| 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. | Continuous water level with sub-metre variation since May 2013. | Contractor's notes indicate this logger is currently working. Last data presented was July 2013. |

The data show increases in groundwater levels at this location. The biennial coastal inspection in August 2014 did not identify any evidence of recent slope movement at this site. However, the inclinometer installed at the cliff top indicates 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.

## 9.5 Causal-response relationships

Since the last monitoring period in late 2013, which was characterised by an atypically wet 2012 and atypically dry 2013, the rainfall has returned to a more typical pattern and the groundwater responses show close agreement.

This pattern suggests that adverse effects of the very wet spring of 2012 were partly mitigated by the preceding dry conditions during the winter of 2011/12, which meant ground water levels were not raised significantly above normal levels. The continuation of wet weather during the latter half of 2012 is likely to have caused groundwater levels to rise, but not to a threshold level above which instability is triggered. The dry conditions of 2013 have allowed water levels to fall back to normal or lower-than-normal levels.

## 9.6 Implications and recommendations

Data from BH20 at South Cliff Gardens suggests development of a shear surface at depth but the reading is unreliable due to random errors that may be due to settlement of the borehole. The location should be visually inspected at times of wet weather to determine the cliff instability risk. Other inclinometers indicate no change or gradual slow creep. A new inclinometer was installed at St Nicholas Cliff (FR01) during this phase of monitoring and a set of baseline readings recorded.

Piezometer data that were previously unavailable due to missing barometric pressure data have now been recovered. Problems in downloading data were encountered at BH19a, D2b and BH3a at South Bay Gardens, but this will be remedied during the next phase of monitoring. The data logger at BH4b at Holbeck Gardens is not functioning and needs repair. Boreholes 5 spa, 106a and 106b at the Spa, and BH15 at the Clock Café are all dry, which may indicate a problem with the monitoring equipment. These locations should be checked, and any necessary repairs should be undertaken.

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 includes 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 up 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 | Movement to late 2013 | Movement late 2013 to mid-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 | No displacement – all apparent incremental displacements <1mm |
| **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 significant displacement | No displacement |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-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. | Readings from November 2013 show no significant change in this borehole since the last reading in September 2012. | No movement. All apparent displacements in incremental plot <1mm. |
| **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 from November 2013 indicate significant recovery towards vertical in the A axis direction. These readings do not reveal any significant ground movement. | 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**. |

*Table 10.3. Summary of groundwater data at Filey Town*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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 (August 2008) and 1.69m (December 2009). | Levels almost the same in October 2013 as they were at the last measurement in May 2012. | Levels steady at c. 1.3m 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 December 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. | Pattern of increasing groundwater level has continued with latest reading (October 2013) showing groundwater at 20.7m OD. This is within the range seen in the past. | Sharp increase in groundwater level to 25m OD from previous level ca. 20.7m OD. |
| **CPBH01a** | Tip at 16.93m OD. Situated on the cliff top to the north of the Sailing Club road. The readings for this piezometer are sporadic between September 2011 and it often shows as 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. | Ground water levels have reduced to 17.28m OD as of 17/10/2013, reflecting the comparatively dry spring, summer and early autumn of 2013. | Levels steady at ca.17.3m OD. |
| **CPBH01b (Diver)** | Tip at 32.63m OD. Situated on the cliff top to the north of the Sailing Club road. Steady in early 2012 around 33.2m OD followed by fluctuating rise towards 34.1m OD on 08 June 2012. Sudden drop on 11 June 2012 to 33.4m with immediate recovery to 33.7m OD. Fluctuating rise thereafter to 34.2m with noticeable sudden increases on 11/07/2012 and 15/08/2012 to around 34.2m OD. Fluctuating decline to around 33.7m OD in mid October 2012. Steady but sharp increase to 34.0m on 01/10/2012, with equivalent decline afterwards before sharp fluctuations and general increasing trend in December 2012, culminating in maximum groundwater elevation of 35.0m OD on 14 December 2012. | Generally declining pattern from December 2012/January 2013 high of ca. 35m OD to around 33.3m OD in October 2013. No particular spikes of note. | 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. |

| Borehole | **Long-term Pattern** | **Change since to late 2013** | **Change from late 2013 to mid-2014** |
|---|---|---|---|
| **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 September 2012 at 3.57m. Maximum groundwater elevation at 5.23m OD on 19/04/2012. | No data. Piezometer integrity check and quality of readings to be reviewed. | Level fallen slightly to 4.9m OD. |
| **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 December 2012 (to 20.0m OD). Smaller spikes (to less than 9.7m OD in late November/early December 2012). | No data. Piezometer integrity check and quality of readings to be reviewed. | Very little fluctuation. Level steady around 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). | No data. Piezometer integrity check and quality of readings to be reviewed. | Water at ground level. Check piezometer integrity to ensure surface water cannot access the borehole. |
| **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 December 2012 although dip in December 2012 reads significantly higher (16.3m OD). | No data. Piezometer integrity check and quality of readings to be reviewed. | Stable groundwater level at ca. 13.4m OD. |
| **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 December 2012 at the end of a very wet spring, summer and winter. | Ground water levels show slight decline to 19.99m OD on 17/10/2013 from December 2012 high point. | Continued decline in ground water level to 18.88m OD. |
| **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 ≈15m OD before sudden recovery on 24/05/2012 to 18m OD. | Notable step change in December 2012 reflecting very wet conditions around this time to around 19.3m OD. Slight and gradual decline to around 19.0m on 09 April 2013 when sudden drop to 17.14m occurs. Immediate recovery to around 19.1m. Slight increase to around 19.3m OD in June 2013 then steady at around 19.3 to October 2013. | 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.<br>**Check data logger and diver integrity**. |
| **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. | Groundwater levels show reduction from high of 9.46m OD in Dec 2012 to 8.74m OD on 17/10/2013. | Slight increase in groundwater level to 9.43m OD, which matches peak levels of Dec 2012. |

| Borehole | **Long-term Pattern** | **Change since to late 2013** | **Change from late 2013 to mid-2014** |
|---|---|---|---|
| **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. | Small but noticeable step change increase in level to 18.08m OD in mid-late Dec 2012 probably reflecting very wet conditions around this time, then level until a small decrease in level to 18.06m which continues to most recent readings in mid-October 2013 | 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.<br>**Contractor's report indicates the data logger is full and stopped recording on 5 June. It should be visited and maintained.** |
| **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). | Since the December 2012 reading, groundwater levels appear to have increased slightly to 20.78m OD on 17/10/2013, achieving a level close to the high of 20.98m OD seen in September 2012. | Slight fall in groundwater levels to 20.4m 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. The periodic manual dip readings mirror the readings from the automatic diver readings with the exception of readings in June and December 2012 which deviate by >500mm. There is a general trend of slight decline towards June 2012 followed by a rise towards peaks in late October and mid-December 2012. | Levels appear to drop slightly following the late 2012 high to around 20.0m OD for the first few months of 2013 but then begin to rise from early April 2013 onwards to fluctuate around 20.5m OD by early June 2013. After mid-July 2013, water levels fluctuate wildly between 20.5m OD and 13.7m OD within hours indicating possible instrumentation issues.<br>It is recommended this instrument is checked. | 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.<br>**It is recommended that this instrument is checked.** |
| **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 (over a day to a week) followed by more gentle decreases in levels (over several weeks). Sharp increases occur around 13/02/2012, 02/03/2012, 02/04/2012, 25/04/2012, 03/06/2012, 23/06/2012, 05/07/2012, before a prolonged and substantial steady decline from a peak of >29.55m OD to around 28.5m OD. A small sharp increase in levels to around 29.0m OD follows with limited and steady fluctuation before a large increase over 10 days in late November 2012, which ultimately peaks at around 30.9m OD (except for a spike likely to be associated with a manual associated with a dip reading) around 21-23/12/2012. Comparison to rainfall records indicates that this borehole has a comparatively 'flashy' response to increased rainfall, with lag times seeming to reduce towards the end of 2012, likely because earlier rainfall events aided the recovery of groundwater levels following a dry period (and therefore had a smaller impact on overall levels). | Following the peak in groundwater levels in late December 2012, groundwater levels declined by early October 2013 to around 28.3m OD, similar to those levels experienced prior to the wet Spring, Summer and Winter of 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 |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-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 sliprod. | Dry on 17/10/2013. Piezometer integrity check and quality of readings to be reviewed. | Contractor's notes state no reading was taken. |
| **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 | 17/10/2013 – groundwater level at 36.31m OD | 09/07/2014 – Slight rise in groundwater level to 36.58m 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 | 17/10/2013 – dry. Piezometer integrity check and quality of readings to be reviewed. | 09/07/2014 – Water at ground level. Piezometer integrity check to ensure surface water cannot access the borehole |
| **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 | 17/10/2013 – groundwater level at 41.74 | 09/07/2014 – Small increase in ground water level of 0.3m to 42.0m 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 | 17/10/2013 – groundwater level at 30.80m OD | 09/07/2014 – Small increase in groundwater level of 0.4m to 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 | 17/10/2013 – groundwater level at 32.38m OD | 09/07/2014 – Slight decrease in water level to 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 | 17/10/2013 – groundwater level at 36.40m OD | 09/07/2014 – Slight decrease in level to 36.1m 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 | 17/10/2013 – groundwater level at 43.21m OD | 09/07/2014 – Small increase in water level to 43.3m OD. |
| **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 | 17/10/2013 – groundwater level at 49.35m OD | 09/07/2014 – Small increase in water level to 50.6m OD. |

## 10.5 Causal-response relationships

Since the last monitoring report, which covered the period to late 2013, there has been above average rainfall in January and February but other months have been near to or below average. Most of the piezometers show steady groundwater levels or a slight changes, with the exception of BH4 which shows a sharp increase of >4m since late 2013. 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 potential or known issues with either piezometers or their data loggers at CPBH06b, CPBH08b and CPBH09b which should be investigated and rectified to ensure as continuous a record as possible.

The 5 December 2013 storm surge is not represented in the piezometer or inclinometer 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 | Movement to late 2013 | Movement to from late 2013 to mid2014 |
|---|---|---|---|
| **A2** | A2 is 27.5m deep (surface elevation at 17.93m OD) and extends through glacial sediment. Moderate movements (<5mm cumulative) between December 2009 and December 2010 which increase by a further ca.10mm by June 2011. Small fluctuating movements in the opposite direction to the general trend occur through to June 2012. Incremental plot indicates the largest downslope movement is focused on a shear zone at ca. 6m-7m OD | The pattern of movement is very similar to those seen over the whole period for which results are available for this inclinometer, with incremental change of less than 5mm. | No movement has taken place – data indicates an apparent recovery towards vertical. |
| **C1** | C1 is ca. 25m deep. Surface elevation is 25.7m OD* therefore the base of the hole is ca. 0.7m OD*. C1 shows only very minor (<2mm cumulative) displacements up to and including October 2012. | Substantial displacement (ca.27mm) indicated in the A axis at around 11.5-11.0m OD, with deformation in both positive and negative directions on both axes. This suggests the probe has come away from its keyway. Careful recording of data in the future will clarify the position. | Inclinometer baseline reading reset to Nov 2013. Subsequent readings continue to indicate displacement at c.15m depth. Incremental displacements are <5mm |
| **C2** | C2 is ca. 21m deep. Surface elevation is at 16.5m* therefore the borehole extends to -4.5m OD* through variable glacial sediments. All displacements to October 2012 were extremely minor (<2mm) and indicated oscillation around the vertical on both the A and B axis, possibly due to minor shrink and swell effects. | No significant movement recorded. | No significant movement recorded. |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| C5 | C5 is ca. 16m deep. Surface elevation is at 12.0m OD* therefore the borehole extends to -4.0m OD* and passes 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 | Significant displacement appears to have occurred between October 2012 and November 2013 in the uppermost 3m. However, movement is recorded in both the A and B axes. Careful recording of data in the future will clarify the position. | Previously identified movement appears to have been error. Latest reading shows no significant movements.<br>Contractor’s report notes borehole requires cleaning. |
| 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 December 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 | The AE response at Filey at the end of January 2014 is indicative of straining of the gravel column in response to slope movement. However, the inclinometer reading from Nov 2013 shows no movement. The generation mechanism of this AE response is currently inconclusive and will be better understood with data from the next monitoring period. Note: inclinometer readings suggest the probe came away from the keyway and therefore results are inconclusive. | 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). |

*Table 11.3. Summary of groundwater data at Flat Cliffs*

| Borehole | Long-term Pattern | Change to late 2013 | Change from late 2013 to mid-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 ca. 11.2 m OD and 15.6m OD with peaks in July 2003, April 2004 and December 2010. Groundwater level at 12.9m OD in May 2012. | Groundwater level has risen from 12.9m in May 2012 to 15.64m OD in November 2013, despite drier 2013.<br>No data logger is present so only manual readings are possible. | 09/07/2014 - Water level at 15.6m OD (ground level).<br>Only manual readings possible still at this piezometer. |

| Borehole | Long-term Pattern | Change since to late 2013 | Change from late 2013 to mid-2014 |
|---|---|---|---|
| **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 (September 2008) and 38.4m OD (March 2010); lows occurred in November 2009 and June 2011 and peaks in January 2008 and March 2010. Borehole was fitted with a data logger in September 2011 which recorded a relatively static groundwater level around 18.9m OD to 19.0m OD. This stopped recording in January 2012 and was replaced with a new piezometer on 24/05/2012 which immediately recorded a sharp increase in groundwater level from 19.2m OD to around 22.3m OD. | Fluctuations in level between c. 23 and 28m OD that have a close relationship to rainfall.<br>Peak of 24.9m OD on 13/06/2012, following heavy rainfall on 05/06/2012.<br>Peak on 28/06/2012 that followed heavy rainfall on 24/12/2012.<br>Peak of 28.2m OD on 07/07/2012 following heavy rain on 06/07/2012. | 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. |
| **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 December 2010 (21.4m OD) and a low in July 2008 of 11.63m OD (which is possibly a measurement error as pre- and after readings were 18.75m OD). A vibrating wire piezometer was installed in September 2011 and shows a static groundwater level of ca. 18.0m OD with minor fluctuation. | No significant changes in groundwater level since September 2012 – static at ca. 18.0m OD, although manual dip reading shows a slightly lower (17.85m OD) groundwater level. | No significant changes – static at ca. 18m OD. |
| **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). | No change, continues to reflect tidal cycle with fluctuations of same magnitude. | Continued clear reflection in tidal cycle. Clear evidence of the effect of the 05 December 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. |

The new data indicate:

- No firm evidence for ground movements is shown by inclinometers. However, apparent movements are again occurring at the same depth as movements previously attributed to measurement errors in inclinometer C1. We recommend this inclinometer is measured more frequently to identify if these apparent movements are continuing.
- Acoustic inclinometer data suggests some strain in the borehole occurred between January and February 2014 (Figure 11.2), but ground movements were not indicated in adjacent inclinometer borehole C1. The results may indicate strain within the slope material, but do not indicate development of a shear surface.
- Groundwater data show stable groundwater levels, although a small but clear peak in late February 2014, almost certainly as a result of a wetter than average January and February has occurred in borehole D1 and borehole C4a shows a clear response to the storm surge of 5 December 2013.

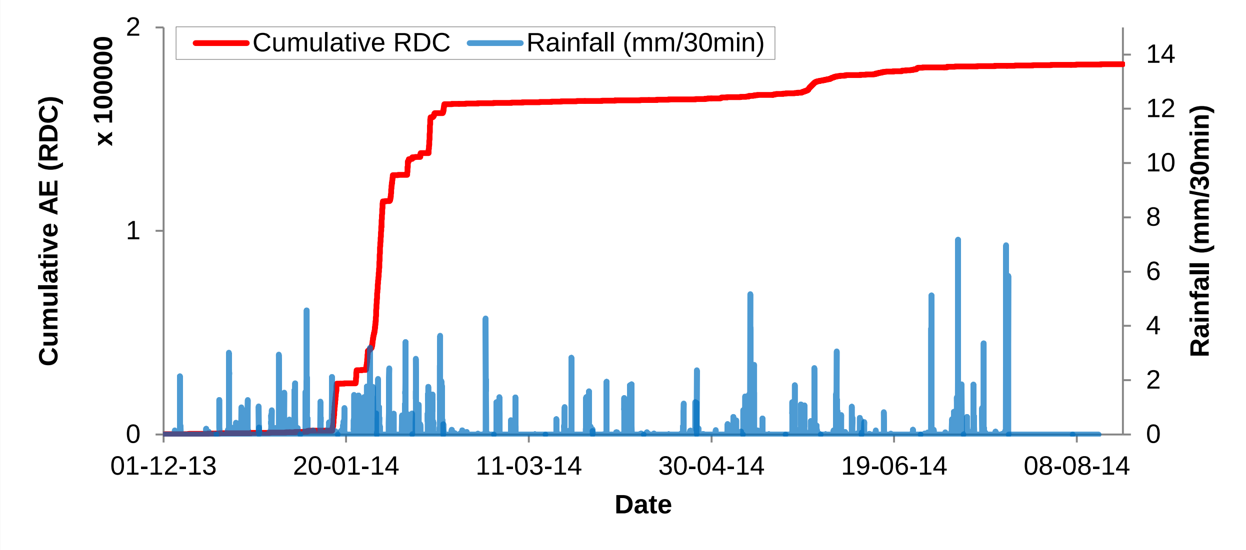


*Figure 11.2 Acoustic emission (AE) rate (RDC/hour),cumulative RDC and rainfall at Flat Cliffs*

## 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 (Figure 11.3).

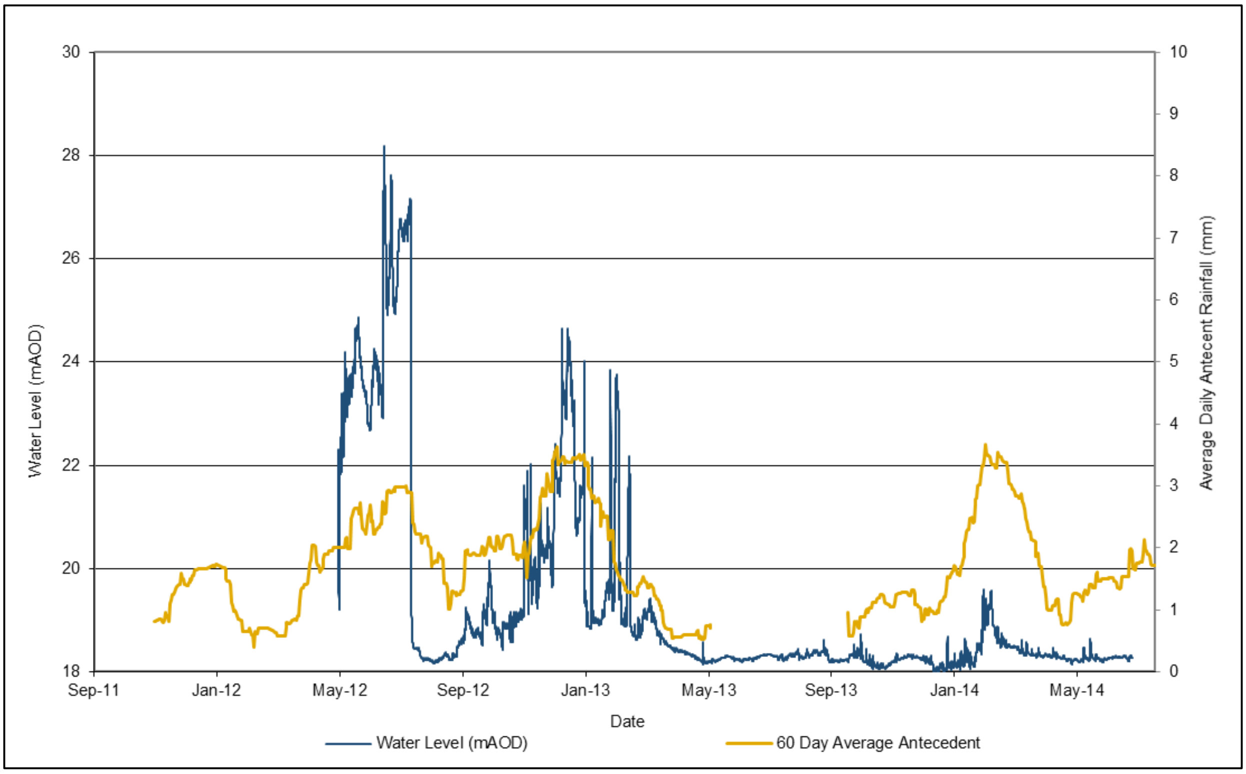


*Figure 11.3: Relationship between 60-day antecedent rainfall and groundwater levels in borehole D1.*

## 11.6 Implications and recommendations

The relationship between groundwater levels in piezometer D1 and movements in inclinometer C1 is unclear, but it is possible they are related and careful monitoring is recommended. Groundwater levels in Piezometer D1 show a strong relationship with rainfall and this relationship should be specifically reviewed in future reports to refine understanding of that relationship.

# 12 References

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

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

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

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

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

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

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

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

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

# Appendix A
# Digital data