Flat Cliffs stability assessment and management plan

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Ground investigation and monitoring report

Scarborough Borough Council

31 May 2012

Halcrow

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Document history

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1.1	16/07/2012	With client comments	Paul Fish	Paul Fish	Roger Moore

Contents

1 Introduction

1.1 Context

Flat Cliffs is a privately owned residential settlement located on coastal slopes in Filey Bay, south of the town of Filey. The settlement includes around 50 homes, some of which are permanent residences, and a Yorkshire Water pumping station. The settlement is served via a single access road down the cliffs and through a privately owned holiday park at Primrose Valley. The Shoreline Management Plan policy for Flat Cliffs is no active intervention and therefore Scarborough Borough Council (SBC) does not propose to undertake works in the area.

This study has been undertaken by SBC in their position as risk management authority. The study has been conducted to fulfil SBC's duty of care to residents and inform them of expected levels of risk. The report is intended to help residents' take an adaptive approach to the risks they face from cliff instability and coastal erosion and the guidance on risk management provided herein. Information on possible engineering schemes is beyond the scope of this document and no guidance on promoting private defences or drainage systems is provided.

The DEFRA-approved Filey coastal defence strategy study (Halcrow, 2002) confirmed that Flat Cliffs was formed of thick and variable glacial sediments prone to cliff instability, landslip and coastal erosion. The investigation indicated a variety of cliff failure mechanisms in operation, with differing degrees of activity. The work also highlighted the sensitivity of Flat Cliffs to the continued effects of coastal erosion and groundwater, which act to unload the toe of the landslide and trigger ground movement and landslip, respectively. The site has been monitored over the period 2002 to present under the strategic coastal and geotechnical monitoring programmes.

Cliff stability analysis of the northern part of the site, centred on the access road, indicates the slopes here have a small margin of stability against failure based on average groundwater conditions. Evidence of tension cracks and ongoing settlement of the road indicate that pre-failure of the cliffs has occurred. The analysis indicated that only a small rise in groundwater level could result in major failure of the Flat Cliffs with consequential damage and risk to the access road, properties and safety of residents.

The state-of-knowledge from the Halcrow (2002) ground investigation report confirmed a series of credible landslide hazards at the site, particularly in the north. However, some uncertainty remains about the ground model and exact mechanism of landsliding due to the restricted scope of the Halcrow (2002) investigation, poor recovery of core at some locations and the subsequent malfunction of *in situ* geotechnical monitoring.

Scarborough Borough Council (SBC), therefore, commissioned Halcrow to undertake a ground investigation and stability report in 2011 to develop a better understanding of the hazards and risk posed by ground instability to the residents and assets within the privately-owned site. This report informs the requirements for ongoing *in situ* monitoring to provide forewarning of ground movement, and recommends an evacuation plan is prepared for the council and emergency services in the event a significant landslip occurs.

1.2 Terms of reference

Halcrow were commissioned to provide technical services for a series of defined tasks (see Section 1.3). The contract is operated under Option C, dispute resolution W2 and secondary Options X2, X9, X10, X11, Y(UK)2, Y(UK)3 and Z of the NEC3 Professional Service Contract, June 2005.

1.3 Scope of services

The scope of services comprises the following tasks:

- A desk study review of existing information and recently collected data including monitoring records, building and planning control records, geotechnical data and statutory services.
- The design, procurement and management of a specialist ground investigation contractor to undertake a subsurface investigation at the site and install monitoring equipment as required. The investigation is to include engineering logs of the soils encountered during drilling and sampling of materials for geotechnical testing.
- Detailed topographic, geomorphological and damage surveys to provide information on the nature and extent of current instability.
- Analysis and interpretation of monitoring data, existing and new borehole records, mapping and geotechnical data to develop a revised landslide model for the site.
- Slope stability analysis (using Slope/W software) of pre-determined cross sections to establish the current stability of the slope, the likely mechanism of failure and the future sensitivity of slope to increases in groundwater level and sea cliff retreat.
- A review of the existing monitoring regime, recommended future monitoring and identification of any further actions required.
- Development of an emergency action plan which could be implemented at the site should significant instability be detected. The plan requires information on communication issues, emergency access and egress routes and evacuation procedures.

1.4 Sources of information

The data sources used in the preparation of this report comprise the following:

- A series of historical reports made available by SBC which include: Filey Bay Coastal Strategy Study, the shoreline management plan, building and planning records, previous ground investigation reports and monitoring interpretation reports.
- Historical and contemporary aerial photographs and Ordnance Survey maps from SBC archives and English Heritage. These data have been used to better understand the chronology of landsliding, quantify cliff recession and document the development of the site over the past c. 150 years.
- Geological information from the British Geological Survey, including:

- 1:250 000 solid/drift and offshore, sheet 54N 02W;
- 1:50 000 solid/drift sheet 55 (1998), 1:63 360 sheet 54 ;
- 1:10 000 solid sheets 18SW, 08SE, 08NE, 08NW; and
- memoirs of the British Geological Survey.

2 Site description

2.1 Site location

Flat Cliffs are located in Filey Bay, North Yorkshire, close to the Primrose Valley Holiday Park. The site is approximately 2 km south of Filey town at grid reference E512270 N478380. The site known as Flat Cliffs has been occupied since the 1920s and now comprises around 50 residential properties, many with permanent occupancy. These properties have utilities service connections and are accessed by a single private road at the north end of the site. The access road to Flat Cliffs forms part of the privately owned Primrose Valley estate. None of these private roads are adopted by the Local Authority.

The study area falls within the scope of the Cell 1 Regional and Geotechnical Monitoring Programmes commissioned by SBC and has been subjected to regular beach and cliff surveys, site inspections and data analysis (Royal Haskoning and Halcrow 2010a, b; Mouchel 2009, 2012). The SMP2 for the area was completed by Royal Haskoning in 2007 and advises a policy of no active intervention for the site.

2.2 Geology and geomorphology

2.2.1 Geology

Filey Bay is shaped almost entirely in glacial sediments that form cliffs c. 40m high. The bay is underlain by Cretaceous and Jurassic rocks that generally do not crop out above sea-level. The margins of the bay are formed by harder, older rocks, with Upper Cretaceous Chalk cropping out to the south at Flamborough Head and Upper Jurassic limestones and sandstones cropping out to the north at Filey Brigg (BGS 1967). The bedrock at Flat Cliffs is Kimmeridge Clay but is only encountered at c. 20m below Ordnance Datum.

The geological sequence at Flat Cliffs was assessed by a ground investigation undertaken in February to March 2001 (Norwest Holst, 2001). The results were interpreted by Halcrow (2002). These established that all boreholes terminated within glacial sediments, at depths between 22.5 and 35.0 m below ground level (equivalent to +13.09 m Ordnance Datum [OD] to -12.36 mOD). Despite fragmentary core recovery, the data revealed that the site is underlain by glacial sediments comprising diamicts with localised and discontinuous stratified sands and gravel (meltwater deposits). The glacial sediments have a maximum recorded thickness of 35 m (-12.4m OD), but could exceed this given that none of the boreholes encountered the underlying Kimmeridge Clay. The contact between the glacial sediment and Kimmeridge Clay at Flat Cliffs is therefore indicated to be an unknown depth beneath the base of the cliffs and beach.

Past research (Edwards, 1981) has attempted to divide the glacial sequence into a clay-rich Upper Till Series and a fine sandy-silt Lower Till Series that are separated by sand and silts up to 3 m thick, but this stratigraphy was not recognized in the 2001 investigation (Halcrow, 2002).

2.2.2 Geomorphology

The Filey Bay strategy study (Halcrow, 2002) divides the cliffs of Filey Bay into a series of behaviour units (CBUs) that describe cliffs of similar morphology, composition and processes (Lee and Clark, 2002). Further details of the CBUs and hinterland geomorphology were derived from a geomorphological mapping assessment undertaken in February 2001. This exercise recorded the cliff morphology and allowed a preliminary ground behaviour model to be derived. The geomorphological mapping recorded evidence for various types of landslide mechanism including: relatively deep-seated rotational and non-rotational landslides and shallower mudslides. A new geomorphological map of Flat Cliffs is presented in Section 3.

2.3 Development history

There are very few records of the history of development at Flat Cliffs. Occupation of Flat Cliffs was first started as a number of temporarily occupied holiday homes. Over time these have been replaced with more substantial properties of permanent occupancy. Many of these properties have service connections to the main utilities. The local authority has not adopted the area as it forms part of the Primrose Valley estate which is privately owned.

Historical Ordnance Survey maps record the timing and nature of developments at Flat Cliffs since the early 20th century. No records earlier than the first edition Ordnance Survey map of 1854 were available for review. A summary of the main stages of development is provided in Table 1.

Table 1. Development history derived from historical OS mapping

Date	Development
1854	Flat Cliffs is agricultural land with no development
1893	Flat Cliffs is agricultural land with no development
1913	No development has occurred at Flat Cliffs. Swimming baths and one other building have been built within 150m of the cliff top at the north end of the site, as well as South Cliff house (200 m from the cliff top), and an associated access track.
1929	14 buildings and associated tracks have been built within the north end of Flat Cliffs, as well as three buildings within 100m of the cliff top. Development has also occurred along Long Whins Gill, to the north of Flat Cliffs.
1958	An additional 19 buildings have been developed (since 1929) within Flat Cliffs, and the track has been extended southwards, to service this development. Increased development has also occurred to the north of Flat Cliffs, within 250 m of the cliff top. A holiday camp has also been developed approximately 200m from the cliff top south of Flat Cliffs.
1973	An additional seven buildings have been developed (Since 1958) at Flat Cliffs, as well as a number of roads. Development has also occurred on the cliff top at Flat Cliffs, including permanent buildings, and a caravan park and associated infrastructure. The holiday camp has also extending towards the cliff top.
2010	Three additional buildings have appeared since the 1973 mapping in the Flat Cliffs area (to the south). The buildings from the holiday camp have been removed, and the area is now a caravan park, where some permanent development has occurred.

2.4 Cliff event history and damage records

Table 2 summarises the available reports of past ground movements or adverse impacts on properties at Flat Cliffs. No records were available prior to 2001 when investigations were carried out as part of the Filey Bay Coastal Defence Strategy Study. Discussions with residents of Flat Cliffs provide anecdotal evidence of historical cliff instability and erosion at the site.

Table 2. Flat Cliffs event chronology and impacts

Date	Cliff changes	Source
Unspecified (pre-2002)	• Cracking and subsidence of access road • Heave of the pipeline along the shoreline	Halcrow (2002) (Anecdotal evidence from Flat Cliffs residents' association)
July 2004 (Observation date. Activity may have been earlier)	• Damage to property and infrastructure throughout the Flat Cliffs development, most pronounced in extent and severity at the northern end of the development • Non-rotational failure at the north of Flat Cliffs beneath access road shows slow downslope translation • Cliff top shows forward tilt and cracking indicative of translation • Bench beneath property no. 12 shows evidence of differential rates of downslope movement • Bench between property no. 5 and no. 11 shows differential rates of backtilting • Bench beneath property no. 18 shows areas of resurfacing and arcuate areas of settlement	Halcrow records from 2004
September 2009	• Localised toe erosion • Fresh cracking in access road and older cracks in walls	Halcrow (2010a)

Consultation with the Flat Cliffs Residents' Association has provided anecdotal evidence of previous instability in connection with cracking and subsidence of the steep access road into Flat Cliffs, and the possible heave of a pipeline located along the shoreline. Reference was also made to privately installed drainage works along the access road to prevent flooding and ponding of the level area adjacent to property No. 9.

Taken as a whole, the observations indicate ongoing gradual ground movements associated with settlement, translation or rotational movement. Evidence is most marked where structures cross landslide boundaries and are subject to differential rates of movement. There is no evidence on the timing of failures, but the ground model would indicate movement is probably associated with elevated ground water levels and enhanced toe erosion, both associated with wet and stormy winter periods.

3 Ground model

3.1 Previous ground investigation

Previous ground investigation reports in the vicinity of Flat Cliffs have been located together with the associated borehole and laboratory test results. A summary of these investigations is provided in Table 3. Norwest Holst Soil Engineering Ltd carried out a ground investigation at Flat Cliffs during February and March 2001 (Norwest Holst, 2001) comprising five rotary wireline boreholes drilled to 24m to 35m depth; piezometers and inclinometers were installed in some boreholes. The boreholes revealed a mixed sequence of clayey tills, sands and gravels but there was inconclusive evidence as to the precise depth of slip surfaces; monitoring results from the inclinometers over the subsequent period have also been inconclusive. Sampling and testing of materials and groundwater monitoring were used to inform stability analysis.

The ground investigation provided evidence that Flat Cliffs comprises a variety of landslide mechanisms of contrasting age and degree of activity. Given the restricted scope of the ground investigation there was uncertainty with regard to the sub-surface geometry, which partly reflect the limited number and distribution of boreholes and also the difficulties of recovery of core from the highly variable glacial tills at the site. Results of stability analysis demonstrated a decline in stability of Flat Cliffs from the continued effects of toe erosion and retreat of the sea cliffs leading to reactivation of coastal landsliding and consequential losses this will cause. The northern section of Flat Cliffs was identified as a critical area vulnerable to landslip; the main access route into the Flat Cliffs traverses this section.

3.2 The 2011 ground investigation

A ground investigation was conducted at Flat Cliffs between the 26th July and 8th September 2011. The scope and position of the ground investigation was specified by Halcrow (Figure 1) and comprised the following:

- Six boreholes (two cable percussive and four drilled using rotary open-hole and coring techniques)
- *In-situ* standard penetration testing
- Disturbed and undisturbed sampling for laboratory testing
- Installation of inclinometer and vibrating wire piezometers with subsequent monitoring of instruments. An acoustic inclinometer was also installed for research purposes
- Installation of permanent ground movement markers, and
- Installation of an automatic weather station.

The boreholes were drilled to a range of depths to confirm the nature and variability of the geological materials and landslide stratigraphy across the site.

Table 3. Previous ground investigations in the vicinity of Flat Cliffs

Report	Objectives	Borehole depths
Filey Bay Coastal Defence Strategy Study (March 2001)	Investigation of coastal landslip at Flat Cliffs including stability analysis	5 rotary wireline boreholes 24-35m depth
Report on Investigation of ground conditions at Primrose Valley. Patrick Parsons Consulting Engineers (Sept. 1993)	Investigation of ground conditions at the site of proposed new clubhouse	BH1, 10m BH2, 10m BH3, 5.1m Vane shear tests
Further Report on Investigation of ground conditions for proposed Family Club at Primrose Valley. Patrick Parsons Consulting Engineers (Nov. 1993)	Investigation of ground conditions between site of proposed new clubhouse and coastal cliffs	BH1, 30m BH2, 30m Vane shear tests
Flat Cliff Sewer Diversion, Primrose Valley, Filey. Yorkshire Water Enterprises Ltd., Parts 1-3 (May 1991 to Aug. 1992)	Investigation, monitoring and stability analysis of ground conditions at the site of proposed sewer infrastructure development	BH1, 8m BH2, 13m BH3, 16m BH4, 25m BH5, 25m BH6, 25m 3 trial pits Inclinometers
The Pastures, Filey. Yorkshire Water (Oct 1991)	Investigation of route alignment of proposed new sewerage system connecting new housing estate	BH1, 6m BH2, 8m BH3, 8m BH4, 8m BH5, 8m BH6, 8m BH7, 9m BH8, 9m BH9, 9.5m BH10, 12m BH11, 8m
Fellsway, Sandhill Lane, Filey. Robert Horne & Partners (Sept. 1995)	Investigation of ground conditions for a development site	BH1, 5m BH2, 5m 1 trial pit
Church Ravine, Filey. Soils Engineering Services (Nov 1985)	Investigation of slope stability beneath footpath	BH1, 10m BH2, 10m

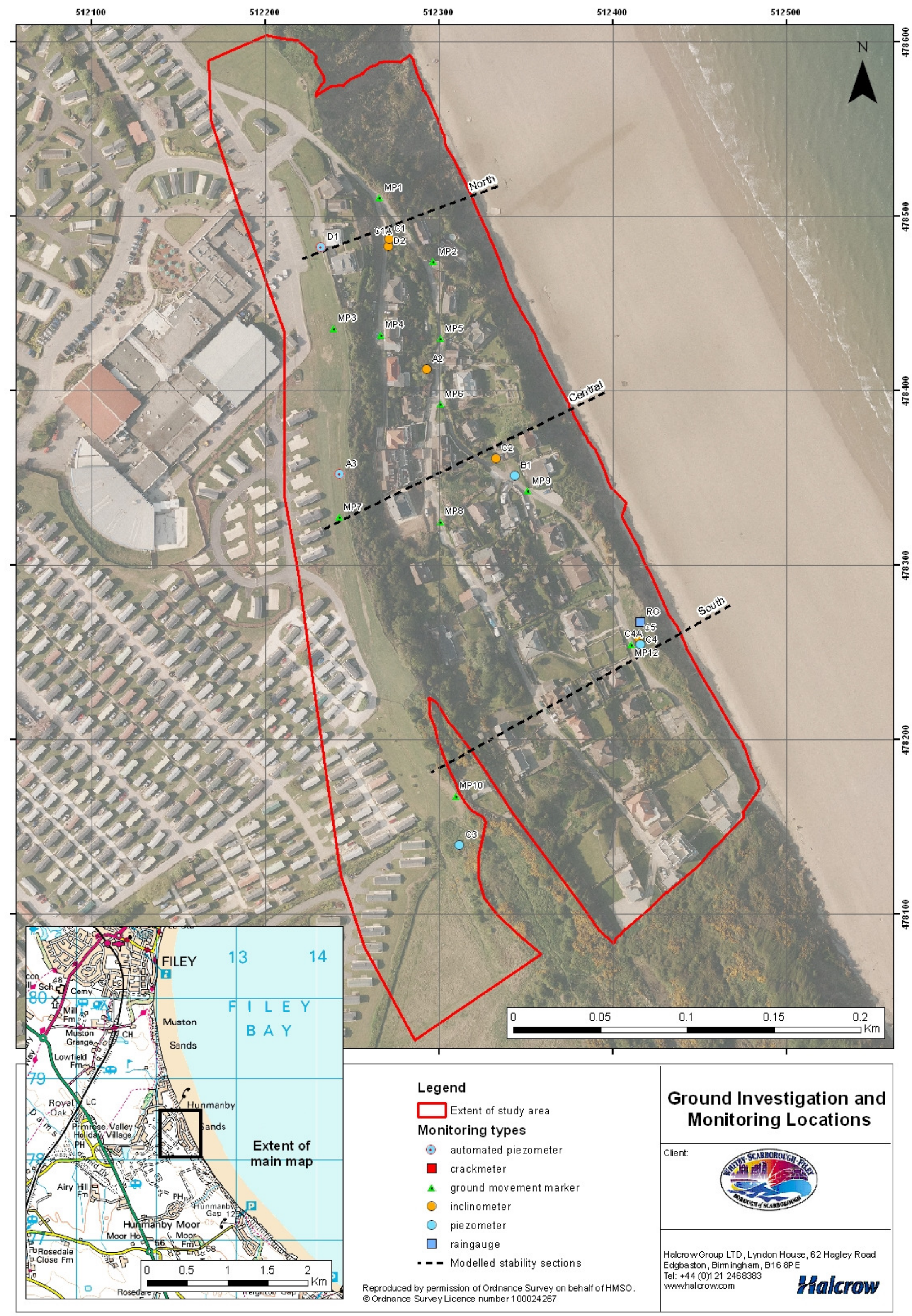


Figure 1. 2011 Ground investigation plan

3.3 Site instrumentation

Each borehole was fitted with either an inclinometer to measure subsurface ground movements, or a standpipe piezometer to monitor groundwater levels (Table 1). The standpipe piezometers were later fitted with automatic recording vibrating wire piezometers which download hourly groundwater readings to a data logger. A Vaisala WXT520 automatic weather station was installed to provide continuous recording of meteorological parameters. The weather station logs monitoring records to a secure website in real time.

In addition to these new monitoring locations, boreholes drilled during the 2001 Norwest Holst investigation were retrofitted with slimline vibrating wire piezometers and mini dataloggers (Table 4).

Table 4. Monitoring installed as part of the 2011 ground investigation

Borehole	Installation	Depth
C1	Inclinometer	25.00m BGL
C1A	Acoustic inclinometer (managed by Loughborough University)	25.00m BGL
C2	Inclinometer	19.00m BGL
C3	2x 25mm standpipes with vibrating wire piezometers	14.50m and 24.50m BGL
C4A	25mm standpipe with vibrating wire piezometer	15.50m BGL
C5	Inclinometer	16.00m BGL

Permanent ground movement marker points were installed throughout the site to monitor long-term change. The baseline location of these monitoring points is provided in Table 5.

3.4 Site stratigraphy

Engineering borehole logs were prepared in accordance with BS EN 14688-1:2002, BS EN 14688-2:2004 and also, where there is no conflict with European standards, in accordance with BS5930:1999. The detailed borehole logs are presented in the ground investigation factual report (AEG, 2012; Volume I).

The ground investigation confirmed a series of clayey till, sands and gravels. Although stratification was sometimes observed within the sand and gravel horizons it was generally not possible to correlate between individual boreholes. This is not surprising in glacial deposits where meltwater deposits are generally discontinuous. Furthermore, landsliding is likely to have displaced and/or removed horizons. Occasional core loss also complicates the interpretation.

No shear surfaces were identified in the borehole samples and therefore the position of landslide shears has been inferred from historical inclinometer data, surface geomorphology and material characteristics. Inclinometer data from the 2011 ground investigation has yet to reveal any significant subsurface movement.

Table 5. Permanent ground movement marker positions

Point	Easting (m)	Northing (m)	Elevation (mOD)
MP1	512265.870	478510.635	26.068
MP2	512296.985	478473.950	19.717
MP3	512239.426	478435.736	34.840
MP4	512266.575	478431.810	25.642
MP5	512300.826	478429.760	18.085
MP6	512300.993	478392.185	18.454
MP7	512242.521	478327.400	36.049
MP8	512301.085	478324.660	23.414
MP9	512351.262	478342.314	14.996
MP10	512309.960	478167.242	34.159
MP12	512410.971	478254.334	11.622

3.5 Hydrogeology and groundwater

The hydrogeology is being monitored using a series of automated vibrating wire piezometers. The instruments were installed at varying depths within the glacial sediments to establish the presence of groundwater at various levels within the glacial deposits, and their potential influence on ground instability.

Piezometer records over the period November 2011 to April 2012 indicate that all instruments are functioning and have equilibrated showing a response to prevailing groundwater conditions. A summary of groundwater levels and data plots is provided in Appendix A.

Five groundwater samples were obtained for testing for a range of contaminants on 12 September 2011. Four samples were from within the exploratory holes B1, C3 (shallow and deep samples) and C4 and one (SWS1) from a surface water location at beach level (Figure 2). The testing of samples was undertaken by Derwentside Environmental Testing Services and the results are summarised in Table 6. The Bathing Water Regulations 1991 indicate a maximum of 10,000 coliform counts per 100ml are considered acceptable, based on data provided in Investigation and rectification of drainage misconnections: Good Practice Document, Water UK/Environment Agency; Version 1.1 (January 2009).

In general the level of contamination encountered in the groundwater is not considered to be significant, the only exceptions being the coliform count in three of the five samples tested. Exploratory holes C3 (shallow and deep) and C4 recorded over 8000 coliform counts per 100ml, which is indicative of sewage contamination.

Figure 2. Groundwater sample locations and wastewater infrastructure

C3 and C4 are in close proximity to the Yorkshire Water pipeline and pumping station located at the southern part of Flat Cliffs. A leak in the Yorkshire Water wastewater pipeline above Flat Cliffs was reported on 26th March 2011 when untreated waste was observed issuing to the beach near the Whitehouse access steps to the south of Flat Cliffs. Yorkshire Water immediately investigated the site and subsequently repaired a blockage in a private sewer originating from the holiday camp. This sewer has now been adopted into the Yorkshire Water network. Water quality samples taken by Yorkshire Water in March 2011 highlighted elevated levels of coliform contamination on the beach in the vicinity of the outfall and beach access steps (Table 6, Figure 2).

The repair works were underway to remedy the leak before the ground investigation and collection of groundwater samples for testing in September 2011. The results recorded during this study may represent a residual contamination from the leakage and repair works. However, the source of present contamination is not proven and could originate from ongoing septic tank discharges from private properties. Consequently it is not possible to link these results to a specific cause or point source.

In order to resolve outstanding uncertainty over sources of contamination, it is recommended that re-sampling and testing is undertaken at all locations.

Table 6. Water quality guidance and test results

Faecal coliform guide (presumptive coliforms/100ml)	Guide levels for polluted surface water outfall contamination	Sample location and results
<500	Background levels – watercourse	B1 (12 Sept 2011) SWS1 (12 Sept 2011) Filey Beach (26 March 2011)*
500 - 999	Low or intermittent contamination	
1,000 – 9,999	Evidence of sewage contamination	C3 shallow (12 Sept 2011) C3 deep (12 Sept 2011) C4 (12 Sept 2011) Flat Cliffs Beach immediately south of outfall (26 March 2011)* Flat Cliffs Beach immediately north of outfall (26 March 2011)*
10,000 – 99,000	Inadequately treated sewage levels	Flat Cliffs outfall adjacent to beach access steps (26 March 2011)*
>100,000	Untreated sewage and health risk potential	

* Yorkshire Water sample data collected immediately the leak was reported.

3.6 Material properties

Laboratory testing of selected samples was scheduled on core samples selected for testing on site by Halcrow. Detailed laboratory results are presented in the ground investigation factual report (AEG, 2012; Volume II).

3.7 Geomorphological mapping and damage survey

A geomorphological field survey and landslide damage assessment was undertaken in the summer of 2011. The results are summarised in Figures 3 and 4.

Detailed geomorphological field mapping and interpretation has confirmed the presence of features first mapped during the Filey Bay strategy study (Halcrow 2002).

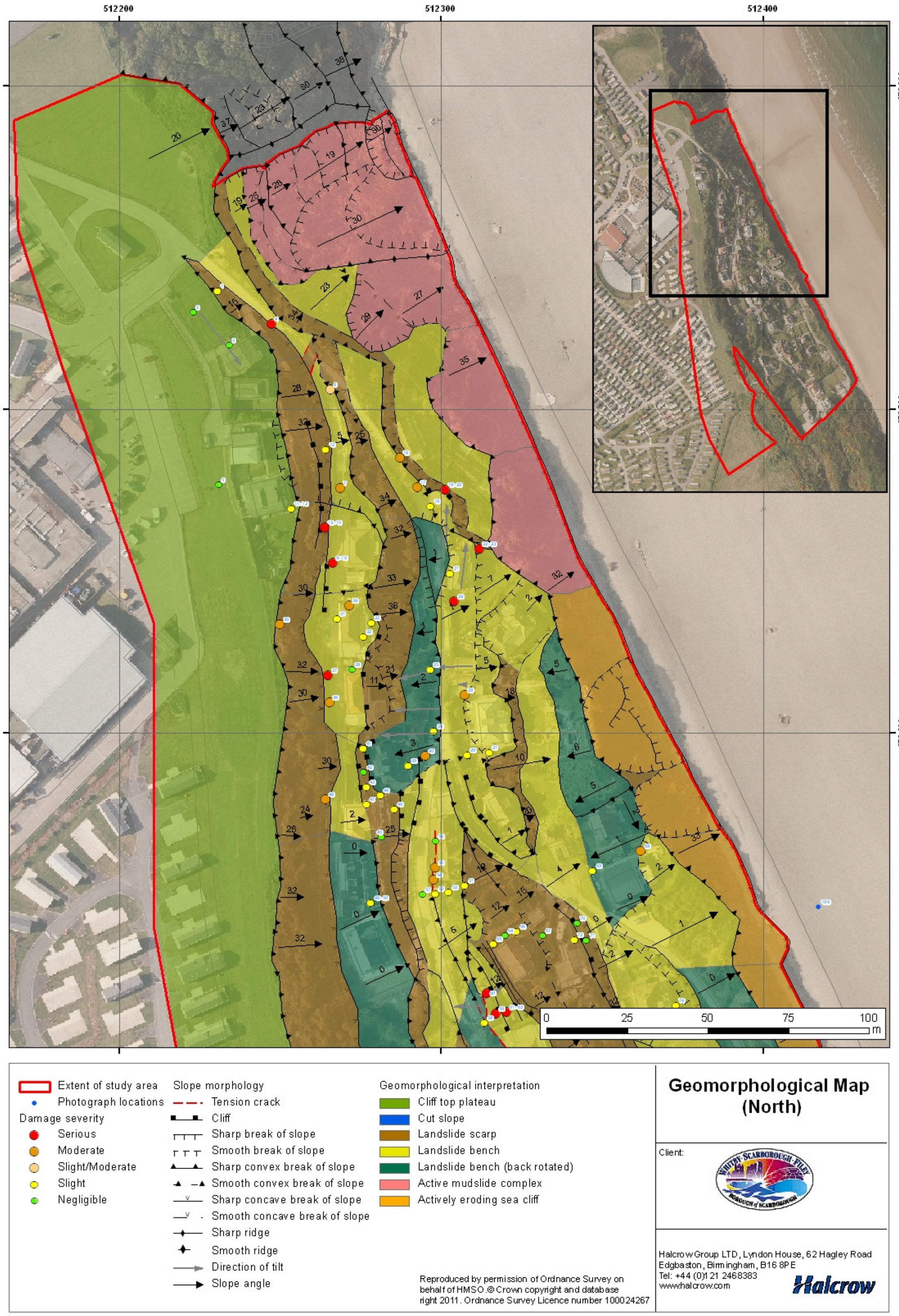


Figure 3 Geomorphological map and damage survey (Flat Cliffs north)

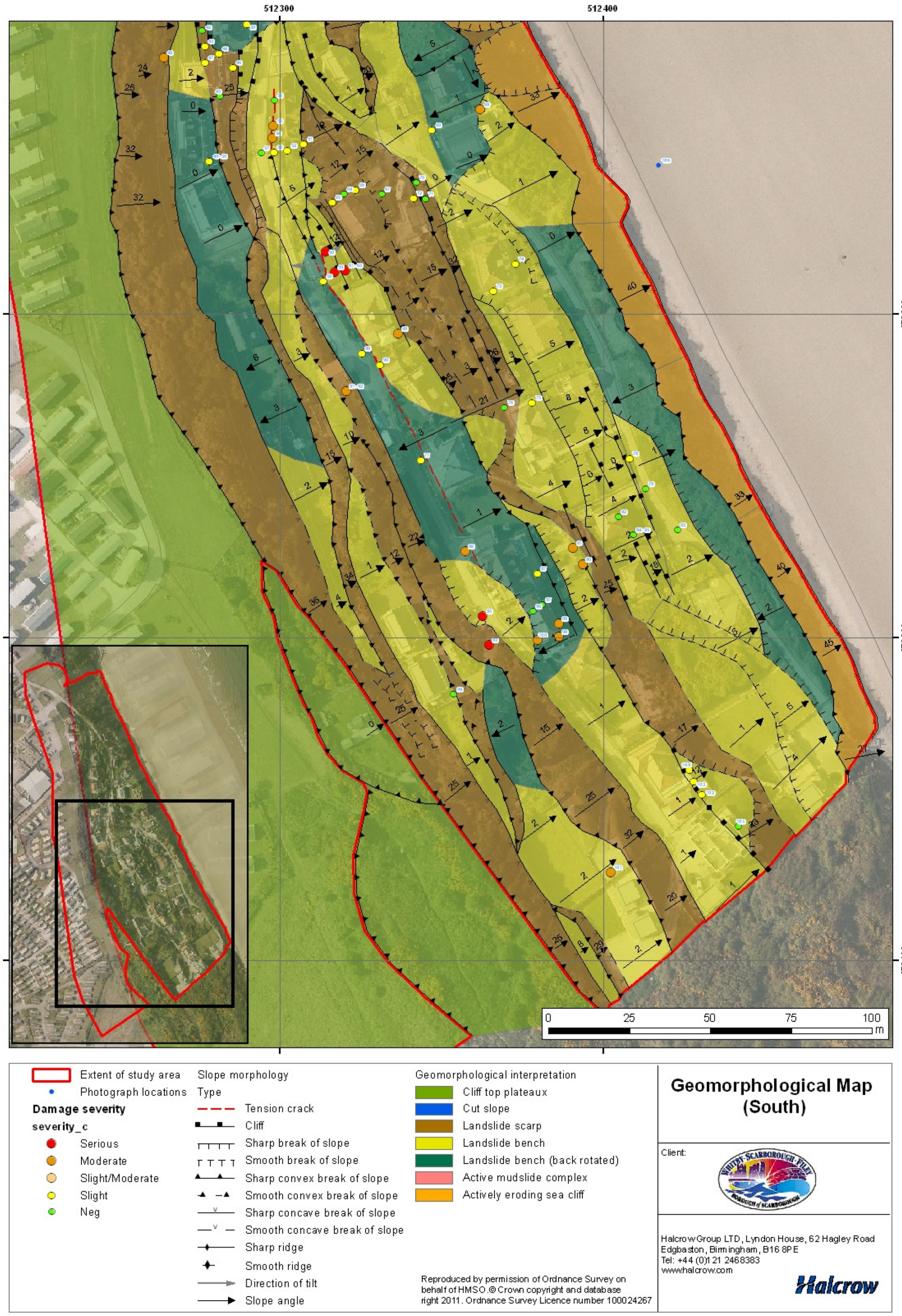


Figure 4. Geomorphological map and damage survey (Flat Cliffs south)

The field observations and mapping reveal that Flat Cliffs is formed of an undercliff that comprises a series of tiers of linear, discontinuous flat benches of less than 5 degrees separated by steep scarps that are typically over 20 degrees, but up to 35 degrees in places. The slope of the benches is generally seawards, but some show obvious back-tilting at angles of around 5 degrees. Properties have been constructed on the benches which offer the best sites for development and views across Filey Bay.

The benches and scarps within the undercliff complex are generally laterally continuous. The large upper bench in the south of Flat Cliffs has a long and continuous tension crack that follows the access road. The undercliff complex is separated from the flat slopes that characterise the inland area by a continuous, steep back scarp of around 30 degrees. The toe of the undercliff complex forms a steep sea-cliff that is typically over 30 degrees and locally up to 45 degrees. In the north of the site, this sea cliff slope is much wider and a series of mudslides have developed that extend almost to the main back scarp. No uncontrolled drainage was observed during field work, however it should be noted that the field survey was undertaken in the summer when the antecedent weather conditions were dry.

Review of remote sensing data collected as part of the Cell 1 monitoring programme shows that the coastline north of Flat Cliffs to Filey town is characterised by mudslides that occupy almost the whole sea-cliff slope, while south of Flat Cliffs, the undercliff morphology continues to an area of undeveloped coast that was formerly occupied by a holiday camp.

A landslide damage survey was undertaken at the same time as the geomorphological mapping exercise. Such surveys provide vital clues about ground behaviour and can be used with the geomorphology to confirm landslide extents, morphology and displacement rates, as well as inform assessment of hazards and risk. Damage points were mapped and classified according to a standard five-point scale ranging from serious to negligible. The results are shown in Figures 3 and 4 and full details are provided in Appendix B. The general standard of building and slope modification work at Flat Cliffs is such that observed landslip damage may in part be related to structural failures as much as it is ground movement. However, the data suggest that areas of greatest damage (serious and moderate) are associated with the steeper scarp slopes towards the back of the landslide system and the full extent of the undercliff forming the northern part of Flat Cliffs.

3.8 Historical coastal change

3.8.1 Datasets and error

The data used for historical shoreline change analysis is summarised in Table 7 and includes Ordnance Survey maps and aerial photographs. Maps showing the site in the 1940, 1967 and 1982 aerial photography are provided in Appendix C. The approach taken for the assessment was as follows:

- Historical data were assembled within a GIS
- In the GIS, cliff top and cliff toe positions were digitally mapped from each historical map or aerial photograph
- In the GIS, a series of cross shore profiles were established, one for each cliff behaviour unit (CBU)

- In the GIS, the distance from the landward end of each cross profile to the mapped cliff top/cliff toe position was measured for each dataset
- Measurements were transferred from the GIS to a spreadsheet and compared with measurements from different epochs of maps and photos to calculate magnitude and rate of change
- During the transfer from GIS to spreadsheet, sources of error were controlled with a series of checks to ensure mistakes could be identified and removed.

Table 7. Historical coastal change data sources

Data type	Date	Source
Aerial photography	2010	Cell One Aerial Survey 2010
Aerial photography	1982	National Monuments Record
Aerial photography	1967	National Monuments Record
Aerial photography	1940	National Monuments Record
Historical map	1971-73	Landmark
Historical map	1929	Landmark
Historical map	1893	Landmark
Historical map	1854	Landmark

Flat Cliffs was divided into five units for the purposes of this assessment. This allows spatial variation in the rate of cliff top, sea cliff and cliff toe position to be analysed (Figure 5).

Table 8. RMSE values of historical data

Data type	Date	RMS error
Historical map	2010	0 (OS Mastermap)
Historical map	1971-3	5.71
Historical map	1929	9.42
Historical map	1893	6.44
Historical map	1854	6.85
Aerial photo	2010	0.1
Aerial photo	1982	2.18
Aerial photo	1967	3.92
Aerial photo	1940	2.17

When comparing epochs of data, knowledge of the accuracy of spatial positioning is imperative when reporting rates of shoreline change. The accuracy of the datasets is described using root mean square errors (RMSE) which describe the difference between the grid reference of features observed in historical maps and photos and their known grid references. The RMSE values of the historical maps used in this assessment are shown in Table 8. The combined RMSE values for time periods of historical data are summarised in Table 9.

Figure 5. Location of transects used for coastal change analysis. Profiles 25 to 29 are reported here. Other profiles have been reported under the Filey town coastal slope study.

Table 9. Combined RMSE values of historical data

Time period	Data	Combined RMSE
1854-2010 (maps)	Maps – long-term	0.04
1929-2010 (maps)	Maps – medium-term	0.12
1970s-2010 (maps)	Maps – short-term	0.16
1940-2010 (photos	Photos – long-term	0.03
1967-2010	Photos – medium-term	0.09
1982-2010	Photos – short-term	0.08

3.8.2 Long term change

Results of the assessment of coastal change from historical maps and aerial photography is summarised in Tables 10 and 11. The combined RMSE for the 1854 and 2010 maps suggests that any rate of change of less than 0.04m/yr over this time frame cannot be assumed to represent real change. Measured changes from the majority of shoreline profiles exceed this value however.

Cliff top recession at Flat Cliffs has been minimal over the long term historical map record. CBUs 26, 27 and 29 do not show any change in cliff top position outside of the RMS error bounds. This would suggest that the headscarp of the large landslide systems at Flat Cliffs has not retreated over the last c. 160 years. The exception is CBU 25 where a cliff top recession rate of 0.22m/yr has been observed.

Cliff toe recession has been ongoing within all CBUs within the range of 0.11 to 0.15m/yr recession. The position of the sea cliff has also receded over the long term, by between 0.11 and 0.22m/yr. The greatest sea cliff recession was measured at CBU 25. Generally, this would suggest there has been a steepening of the overall cliff profile at Flat Cliffs.

Table 10. Cliff retreat rates from historical maps.

Profile	Cliff top retreat rate (m/yr)			Cliff toe retreat rate (m/yr)		
	Long term (1854-2010)	Medium term (1929-2010)	Short term (1970s-2010)	Long term (1854-2010)	Medium term (1929-2010)	Short term (1970s-2010)
25	0.22	0.32	0.77	0.12	0.24	0.20
26	0.03	0.17	0.28	0.11	0.17	0.06*
27	0.00	0.04*	0.05*	0.15	0.13	0.08*
28	0.05	0.10*	0.18	0.11	0.12	0.07*
29	0.04	0.13	0.13*	0.13	0.19	0.06*

**indicates rates of change that are smaller than the calculated error*

Table 11. Cliff retreat rates derived from historical aerial photographs.

Profile	Cliff top retreat rate (m/yr)			Cliff toe retreat rate (m/yr)		
	Long term (1940-2010)	Medium term (1967-2010)	Short term (1982-2010)	Long term (1940-2010)	Medium term (1967-2010)	Short term (1982-2010)
25	0.01*	0.01*	0.01*	0.11	0.00*	0.12
26	0.03*	0.04*	0.08*	0.13	0.00*	0.06*
27	0.35	0.21	0.22	0.00*	0.00*	0.14
28	0.19	0.00*	0.00*	0.00*	0.00*	0.08*
29	0.19	0.00*	0.21	0.05	0.00*	0.13

**indicates rates of change that are smaller than the calculated error*

In the historical photo data, CBUs 25 and 26 have not shown a significant rate of cliff top retreat since 1940. The recession rates within the remaining units are variable, ranging from 0.19m/yr for units 28 and 29, to the highest rate of 0.35m/yr for unit 27.

Activity at the cliff toe has been less significant over this timeframe. Units 27 and 28 show no significant change in cliff toe position and the other units at Flat Cliffs show recession rates of 0.13m/yr and less. The sea cliff was not distinguishable from the 1940 aerial photography and so has not been mapped or included in this assessment of shoreline change.

3.8.3 Medium term change

Results of the assessment of coastal change from historical maps and aerial photography is summarised in Tables 10 and 11. The combined RMSE for the 1929 and 2010 maps indicates that any rate of change of less than 0.12m/yr over this time period cannot be taken to represent real change.

Cliff top retreat within the area of Flat Cliffs has been most notable over the medium term at CBU 25. Here, there has been 0.32m/yr cliff top recession. The other units have experienced lesser rates, with no significant change at all recorded for CBUs 27 and 28.

The pattern of change at the cliff toe has also been variable. The greatest retreat (0.24m/yr) was again recorded at CBU 25. The other units have experienced lesser recession rates, with no significant change recorded at CBU 28.

The sea cliff position here appears to have shown more recession than either the cliff top or cliff toe, with rates of retreat in the range 0.20 to 0.44m/yr. The greatest rate of sea cliff recession was recorded at CBU 25, suggesting that this has been the most active CBU at Flat Cliffs over the medium term.

In the aerial photographs, units 25, 26, 28 and 29 show no significant change in cliff top position since 1976 at Flat Cliffs. In contrast, unit 27 has shown quite a high cliff top recession rate of 00.21m/yr.

At the cliff toe, no significant recession has been measured within any of the units. It is suggested that this results from the poor spatial positioning of the 1967 aerial photography in this vicinity, rather than a real absence of activity here.

The sea cliff was not distinguishable from the 1940 aerial photography and so has not been mapped or included in this assessment of shoreline change.

3.8.4 Short term change

Results of the assessment of coastal change from historical maps and aerial photography is summarised in Tables 10 and 11. The combined RMSE for the 1971/3 and 2010 maps suggests that any rate of change of less than 0.16m/yr cannot be taken to represent real shoreline change.

Within the Flat Cliffs area, the measured rates of cliff top recession are variable. At the northern end of the site CBU 25 has experienced a large amount of cliff top retreat at a rate of 0.77m/yr between 1971/3 and 2010. High rates of recession were also measured here over the medium and long term. The cliff top at CBU 26 receded at a rate of 0.28m/yr and at CBU 28 by 0.18m/yr. No significant change was observed at CBUs 27 and 29.

The majority of CBUs along this frontage experienced no significant change in the cliff toe position over the short term. The exception is the more active unit 25, which retreated at a rate of 0.20m/yr. On-going retreat of the position of the sea cliff was also measured at Flat Cliffs. This is particularly notable at CBU 29, where the sea cliff recession rate was measured to be 0.51m/yr.

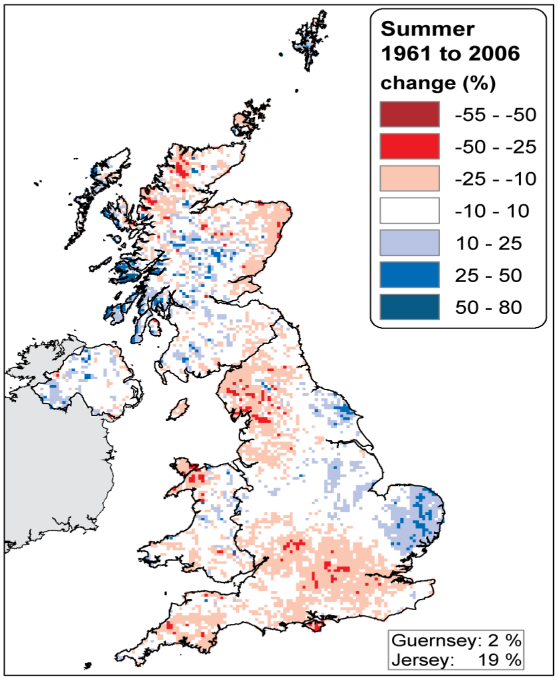
A variable pattern of cliff top recession has been measured for the Flat Cliffs frontage using the historical aerial photography. Most units show no significant change in cliff top position outside the bounds of error. The exceptions are units 27 and 29 which show similar rates of cliff top recession at 0.22 and 0.21m/yr respectively.

At the cliff toe, no significant change is observed within units 26 and 28. The remaining units show a consistent rate of cliff toe recession of 0.12-0.14m/yr since 1982. The sea cliff was not distinguishable from the 1940 aerial photography and so has not been mapped or included in this assessment of shoreline change.

3.9 Climate change projections

Climate change projections for the next 100 years are available from UKCP (UK Climate Programme). Changes in summer and winter rainfall over the last c. 50 years have been assembled by UKCP (Figure 6) and show that the North Yorkshire coast has become up to 25% wetter. This pattern of increasing rainfall is expected to continue over the next 100 years.

Sea-level projections are also provided by UKCP and data for Filey Bay is presented in Figure 7. The graph shows projections for the three emissions scenarios (high, medium and low) and for the 5, 50 and 95 percentiles. Taken as a whole, the projections indicate a range of sea-level rise of c. 0.2 to 0.9m above 1990 levels in the next 100 years. There is considerable uncertainty over sea-levels beyond 100 years, which are largely dependent on the timing and extent of melting of polar ice caps. However, a credible worst case scenario is for 20m of sea-level rise within the next 1,000 years.



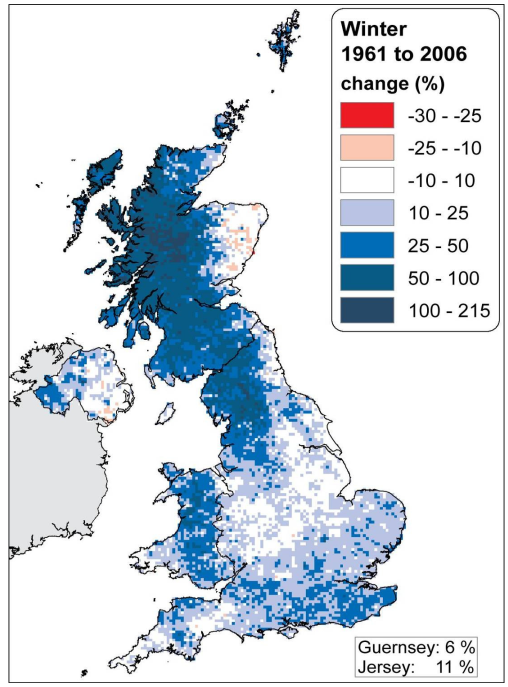


Figure 6. Change in summer and winter rainfall in the United Kingdom 1961 to 2006 (UKCP09, 2011)

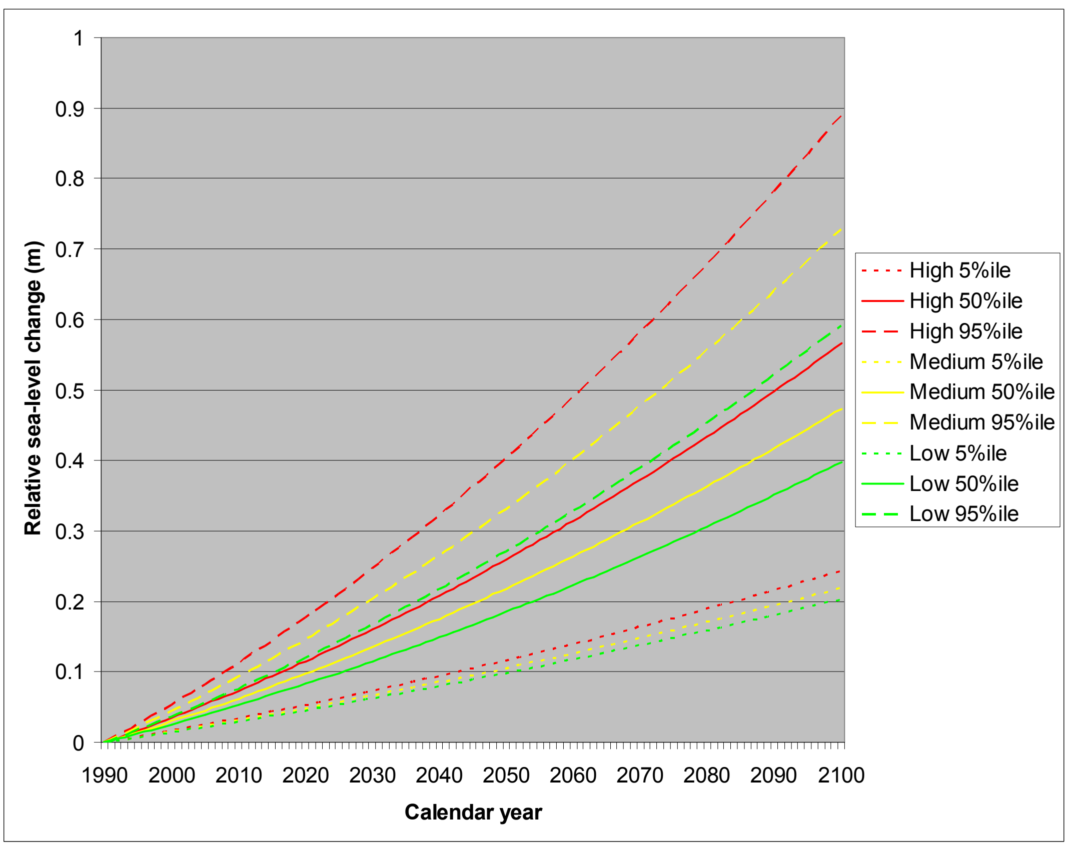


Figure 7. Relative sea-level rise projections for Filey Bay (UKCP09)

The probable impacts of sea-level rise and climate change on Filey Bay include:

- Increased effective rainfall leading to excess surface water run-off and groundwater levels that trigger more frequent mudslides and erosion (Moore et al. 2010)
- Raised sea-levels causing waves to break higher up the beach/cliff leading to increased rates of cliff toe erosion (cf Lee 2011)

3.10 Projected future coastal change

Based on the historical datasets presented above and taking no account of the potential impact of climate change and sea-level rise, future average cliff recession rates in the range 0.1 to 0.2m/yr can be expected. However, the short-term data and site inspections indicate that episodic and localised events are likely and that losses of c. 1m or more are possible during a single event. The data for the different CBUs show conflicting spatial patterns of change, with historical maps suggesting greater erosion in the north of Flat Cliffs, while the historical aerial photos suggesting greater change in the south and central parts of the site.

Projection of these data therefore suggests that up to c. 20m of cliff recession can be expected at the site over the next 100 years. Given that this projection excludes any impacts of climate change, it is likely to be an underestimate. The NCERM project provides independent projections of coastal change for Flat Cliffs that comprise high, medium and low projections of erosion that account for the possible climate change impacts. The data for Flat Cliffs is summarised below.

Table 12. NCERM projections for Flat Cliffs under SMP2 no active intervention scenario

	20 yrs: low / medium / high erosion projection (m)	50 yrs: low / medium / high erosion projection (m)	100 yrs: low / medium / high erosion projection (m)
North (CBUs 21-24)	4.0 / 6.0 / 8.0	10.0 / 15.0 / 20.0	20.0 / 30.0 / 40.0
South (CBUs 25 to 29)	5.7 / 11.0 / 11.3	21.7 / 27.5 / 61.6	43.4 / 55.0 / 61.6

3.11 Landslide ground model

The geomorphological mapping is interpreted as an extensive landslide system comprising a series of blocks that have disconnected from the backscarp and moved downslope along a sub-horizontal basal shear surface. Certain blocks are back-rotated, which is interpreted to be caused by differential settlement. A rotational shear surface is not thought to be present because the block and headscarp morphology is linear and not curved, as would be expected in a rotational landslide.

The ground investigation data indicates that the entirety of the cliff is formed in glacial sediment, and consequently the landslide blocks must be formed from till and not bedrock. The landslides are likely to have been initiated as a consequence of sea-level rise and coastal erosion over the last few thousand years that will have steepened and destabilised the coastal slope. A period of wetter climate will have caused elevated groundwater levels that will have triggered ground movement and landslides. Subtle variations in the properties of the glacial sediments probably resulted in the formation of the distinctive undercliff block morphology seen to day, but these likely variations have not been confirmed by the ground investigation data collected to date.

Historical data on ground behaviour in the undercliff indicates that the landslide complex is marginally stable, with ground movement and landslip generally associated with occasional storms that act to erode the sea-cliff and remove support from the toe of the undercliff, and intense rainfall and surface water infiltration raising groundwater levels and porewater pressures that trigger movement.

4 Cliff stability analysis

This section presents the findings of a stability analyses for Flat Cliffs using data presented in the ground model (Section 3). Modelling has been undertaken along three cliff profiles (shown on Figure 1) to assess stability under current conditions and to test the sensitivity of the slopes to potential future scenarios of groundwater rise and toe erosion. The parameters used in the model are discussed below.

4.1 Soil parameters and groundwater

4.1.1 Groundwater

During the AEG 2011 ground investigation two exploratory holes were installed with 25mm vibrating wire piezometers; two in exploratory hole C3, at depths of 14.5m and 24.5m and one in C4A at a depth of 15.5m. Two historical boreholes (A3 and D1) contain 19mm vibrating wire piezometers, which were also monitored by AEG (Figure 1). Table 13 summarises the groundwater readings between September 2011 and April 2012.

Table 13. Groundwater summary

Borehole	Piezometer size	Installation depth (m AOD)	Groundwater reading (m AOD)		
			Low	Average	High
AEG 2011 Ground Investigation Installations					
C3	25mm	10.00	20.12	20.64	21.71
	25mm	20.00	26.37*	29.88*	32.74*
C4A	25mm	-3.70	-0.30	0.20	0.60
Historical Installations					
A3	19mm	6.30	24.48	25.08	25.28
D1	19mm	15.55	32.56	32.72	32.92

** the deep installation in C3 shows significant variation and AEG have commented that this installation may not be performing as intended, however it does seem to be stabilising out and the average value represents the general groundwater level well.*

It is worth noting that due to the composition of the glacial deposits (i.e. granular bands within a clay-rich unit), perched water tables are likely to exist. Therefore, some of the readings shown in Table 13 may represent perched water levels.

The groundwater levels modelled designed to reflect typical conditions. A sensitivity analyses has been undertaken to account for possible seasonal changes in groundwater due to wet winters or dry summers.

4.1.2 Geotechnical parameters

Glacial sediments are inherently variable and consequently there is extensive discussion in the literature relating to appropriate typical geotechnical parameters (Trenter, 1999). Typical peak effective stress parameters for tills vary between c'_P= 0 and 25kPa and ϕ'_P= 20°and 40°. It is possible that at very low confining pressures the Mohr failure envelope is curved so that c'_P becomes zero at zero effective stress. In general a trend in reducing ϕ'_P with increasing plasticity index has been identified for clay-rich tills, but this relationship does not necessarily follow for all tills that may have different particle size distributions. Plasticity indexes for tills at Flat Cliffs derived from the 2011 site investigation are in the range 12 to 24%.

Residual shear strength parameters have also been found to vary with material plasticity and typical values are c'_r= 0 and ϕ'_r= 10 to 30°. Effective stress (multistage) test results from tills sampled during a sewer diversion at Flat Cliffs indicate a range of shear strength with an average value of c'_p=0, ϕ'_p=31° and a lower bound value of c'_p=0, ϕ'_p=25°.

Laboratory test data shows moisture contents of the till ranged from 9.5% to 19.1% with an average of 13.8% (excluding one outlying value of 31.7%).

The bulk density results ranged from 1.75Mg/m^3 to 2.01Mg/m^3, with an average of 1.86Mg/m^3.

Plasticity test results of the till demonstrated a range of plasticity indexes (PI) from 12% to 24%, with an average of 16%; this average value equates to low plasticity material. Two of the 14 tests (14%) recorded an intermediate plasticity.

Using the relationship between PI and angle of shearing resistance presented in CIRIA 104, a conservative estimate of the effective friction can be determined. This correlation indicates an angle of friction in the range of 27° to 31°, with an average of 29°; these values conservative, but give a good indication of the likely friction angles of the tills.

Various drained and undrained shear strength (shear box and triaxial) tests were undertaken. Consolidated drained triaxial testing with porewater pressure measurements suggests average shear strength values of c'_p=12, ϕ'_p=28° and a lower bound value of c'_p=3, ϕ'_p=25°. Consolidated undrained triaxial testing with porewater pressure measurements suggests average shear strength values of c'_p=10, ϕ'_p=27° and a lower bound value of c'_p=0, ϕ'_p=22°.

Consolidated drained shear box test results suggest a range of shear strength results with an average value of c'_p=3, ϕ'_p=27° and a lower bound value of c'_p=0, ϕ'_p=26°. Residual shear strength results (from the consolidated drained shear box tests) suggest an average value of ϕ'_r=26° and a lower bound value of ϕ'_r=20. These results are not outside the range of values reported in the literature, however, compared to the peak strength results they appear a little high and may not represent the true residual values.

Undrained shear strength (c_u) in triaxial compression testing without the measurement of porewater pressure suggested a range of c_u of between 62kPa and 163kPa, with an average of 112kPa. The test data indicated a general trend of increasing shear strength with depth.

Undrained shear strength values were also derived from Standard Penetration Test (SPT) data based on CIRIA Report C143. This correlation suggested a range from 41kPa at 2m depth to 252kPa at 29.5m depth with a strong trend of increasing c_u with depth.

Table 14 presents a summary of the geotechnical parameters derived through both direct testing and well established correlations for the till deposits.

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Table 14. Geotechnical parameters for stability analyses

Strata	Unit Weight (kN/m3)	c' (kPa)	Φ'_p (°)
Till	19	0	25

A moderately conservative peak friction angle of 25° was adopted for the till. This value is slightly higher than the average of the lower bound values and was chosen in recognition of the known variability of tills and to ensure that stability modelling was based on credible parameters.

4.2 Model set up and results

The SLOPE/W cliff stability model was underpinned by a series of topographic cliff profiles that were extracted from a LiDAR digital terrain model, collected as part of the 2010 Cell 1 coastal monitoring programme (Figure 1). A detailed topographical survey was undertaken by Initial Land Surveys. This survey was used to further develop and refine the data extracted from the LiDAR digital terrain model.

Back analysis of the model was undertaken to improve confidence in the shear strength parameters adopted, the location of inferred shear surface(s) and the elevation of groundwater. Further analysis was then carried out to model the likely impact of future coastal erosion to slope stability.

It is likely that soil within the landslide mass will be largely intact and consequently have shear strength parameters close to peak values. However, the shear strength along the basal shear surface is more likely to be close to the residual value.

The long term stability of three cross sections were analysed; Flat Cliffs North, Centre and South (Figure 1). For the northern section only, which covers the only access route to Flat Cliffs, a sensitivity analysis was undertaken by changing the groundwater level by increments of 0.5m, whilst keeping the current slope profile constant and eroding the toe by increments of 10m, whilst maintaining a constant groundwater level.

All sections were modelled using a Morgenstern and Price block specified method with optimised critical slip surface. This method allows for translational slides to be identified. The use of the optimised function in SLOPE/W allows the slip surface to tend towards a fully specified model and therefore model the stability based on where the likely slip surfaces are located. The geomorphological mapping undertaken of the site has influenced the identification of the likely slip surfaces and therefore the stability methodology used.

Three standard inclinometers and one acoustic inclinometer were installed. Exploratory holes C1, C2 and C5 were installed with standard inclinometers and C1A with an acoustic inclinometer.

No significant movement had been observed in these installations between the date of installation (August and September 2011) and the date that the latest monitoring had been received when writing this report of April 2012. This is not unexpected as it is usual for such installations to take a period of time, 6 months or so, to equilibrate with the stress state of the surrounding soil.

4.2.1 Northern section results

The exploratory holes relevant to the northern section are: C1 and C1A (AEG 2011 investigation) and D1 and D2 (Norwest Holst 2001 investigation) (Figure 1).

The long term global factor of stability was computed as 0.94 and is presented in Figure 8. Despite this model showing a value less than unity and therefore a failed state, in reality it shows that the slope has marginal instability. The stability of the toe is shown on Figure 9 and this shows that with a FoS of 0.86 the toe is in the process of failing or has a low margin of stability.

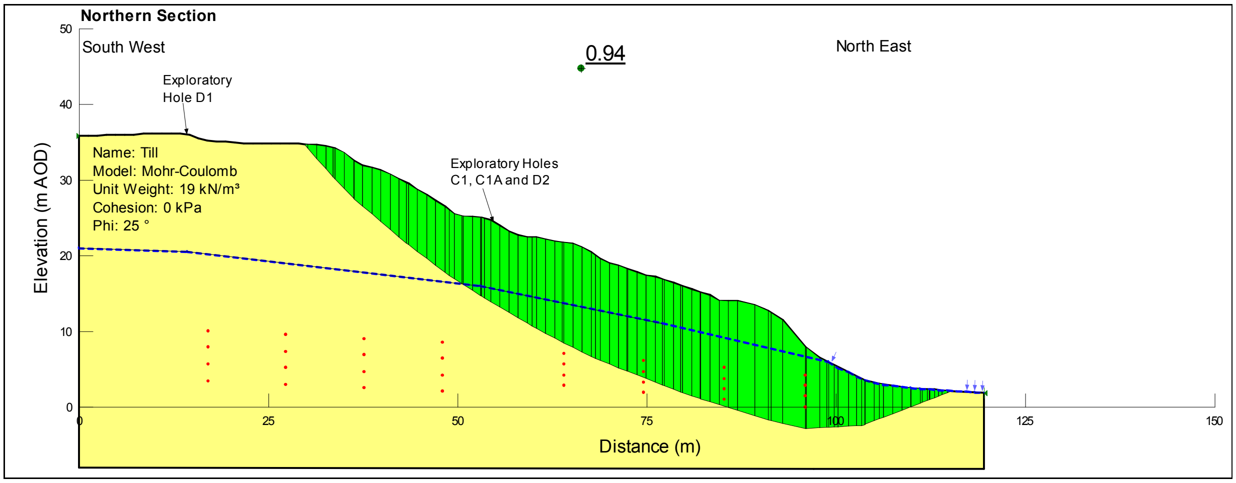

Figure 8. Northern Section; Long term stability of the existing slope profile

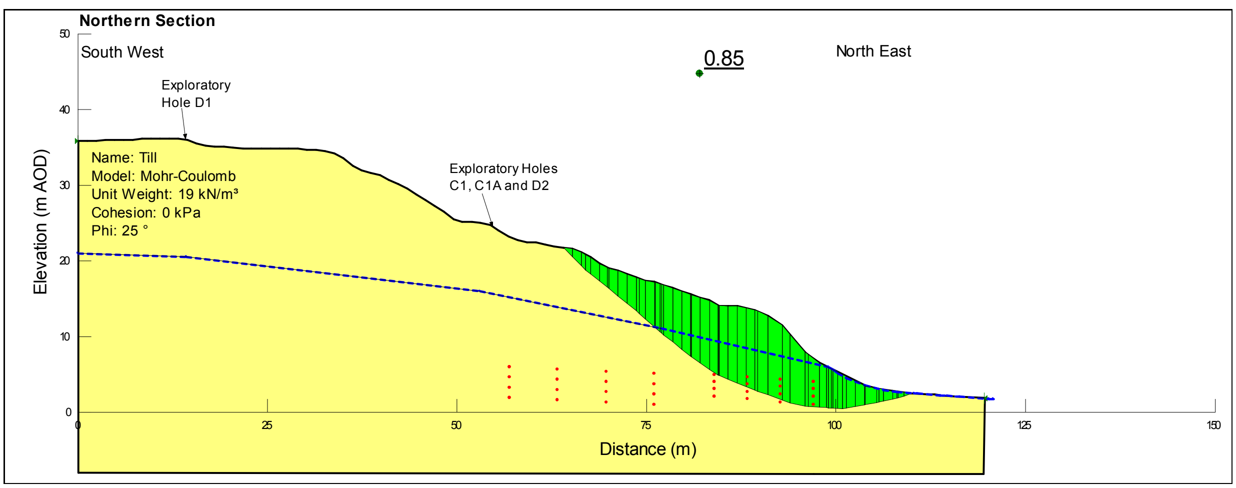

Figure 9. Northern Section; Long term stability of the existing slope toe

Increasing the internal friction value to 31° for the global stability condition has the effect of increasing the overall FoS to 1.22 demonstrating that the frictional properties of materials along this section are a critical factor in determining FoS.

The existing groundwater conditions of the Northern Section were used as a baseline condition and the groundwater levels were increased in increments of 0.5m. Although the initial condition shows marginal instability (FoS = 0.94), this sensitivity analyses was undertaken to demonstrate how the stability of the slope reduces when the groundwater level is increased.

Table 15 shows the sensitivity of groundwater rise on the global stability of the slope, for example, with a 6m rise in groundwater there is a 33% reduction in the stability of the slope. The data shows that the long term stability of the slope is sensitive to the rise in groundwater level

Table 15 . Long term global stability reduction due to groundwater rise

Groundwater level (m above existing 'average' levels)	Factor of Safety (FoS)	Percentage change in FoS from existing (%)
0	0.94	0
0.5	0.93	1
1.0	0.91	3
1.5	0.89	5
2.0	0.86	9
3.0	0.82	13
4.0	0.76	19
5.0	0.71	25
6.0	0.63	33

The section was also modelled following increments of 5m toe erosion from the baseline shown in Figures 8 and 9 and results are summarised in Table 15. The FoS for each erosion increment recorded. Figure 10, 11 and 12 show the FoS as a result of 10m, 20m and 30m of toe erosion.

Table 16 shows that the stability of the slope is very sensitive to the erosion of the slope toe and that any change will cause a reduction in the stability of the slope. These figures demonstrate very low FoS and demonstrate how toe erosion affects the stability of the slope. Table 16 presents the results of this sensitivity analyses.

Table 16. Long term stability reduction due to toe erosion

Figure reference	Toe erosion (m from baseline)	Factor of Safety	Change in FoS from baseline (%)
1	0	0.94	0
-	5	0.84	11
7	10	0.75	20
-	15	0.69	27
8	20	0.36	62
-	25	0.35	63
9	30	0.26	72

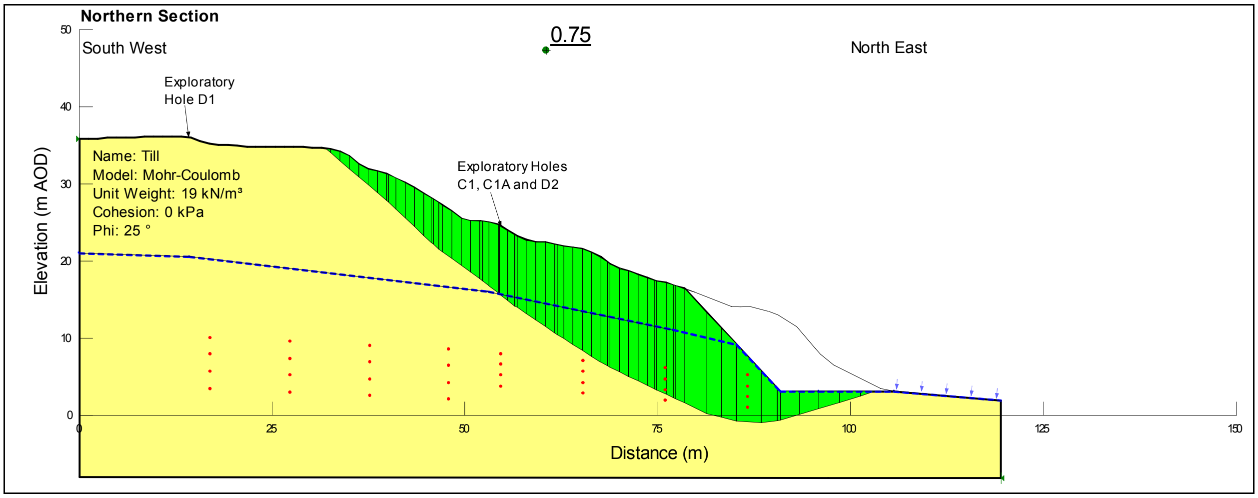

Figure 10. Northern Section; Long term stability with 10m toe erosion

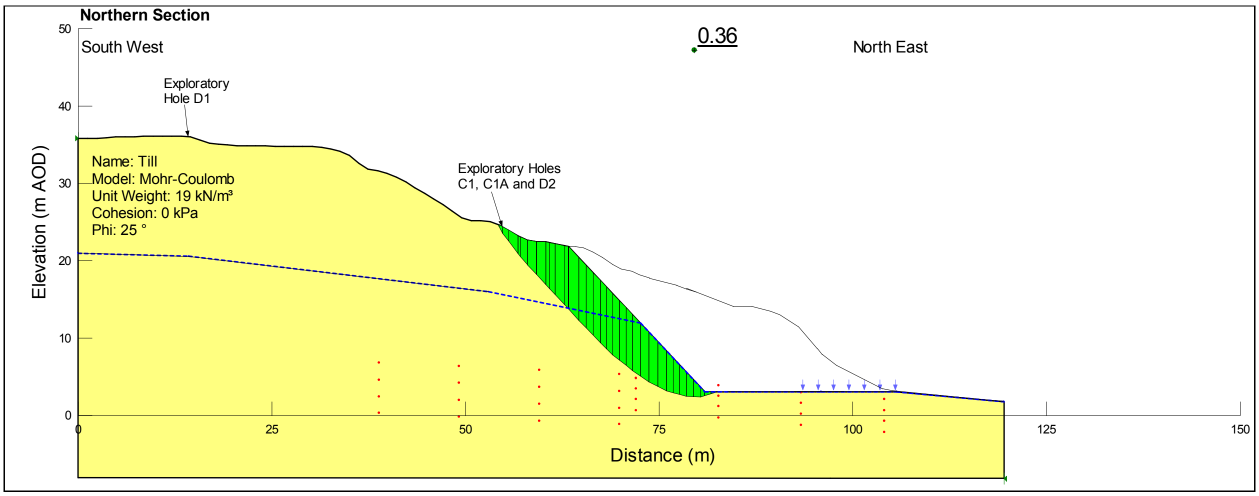

Figure 11. Northern Section; Long term stability with 20m toe erosion

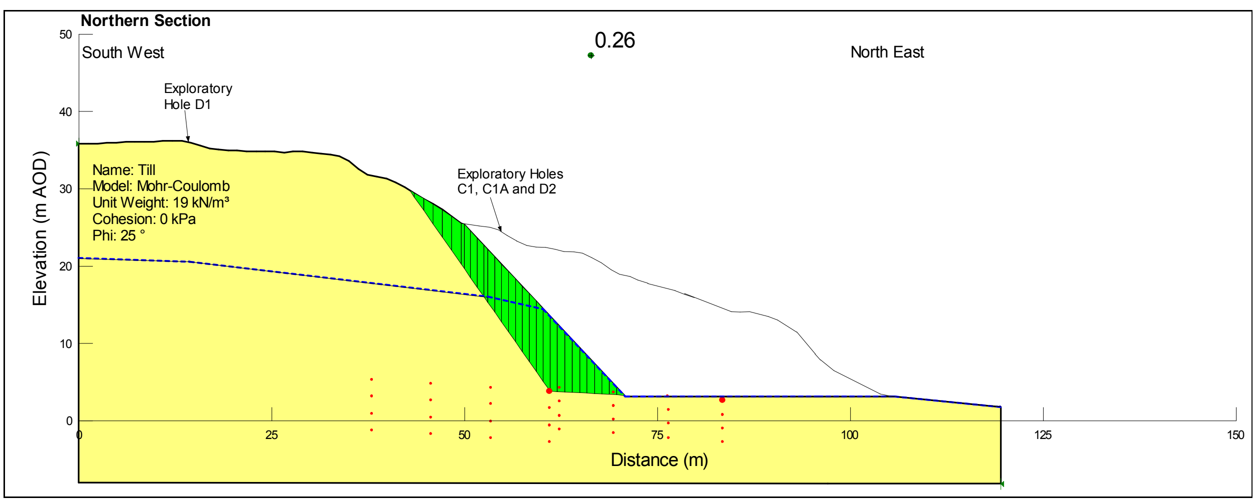

Figure 12. Northern Section; Long term stability with 30m toe erosion

4.2.2 Central section results

The exploratory holes relevant to the central section are: C2 (AEG 2011 investigation) and A2, A3 and B1 (Figure 1). The long term global stability of this section shows a FoS of 1.96 (Figure 13) and the stability of the toe shown on Figure 14 has a FoS of 1.12. Both of these conditions are shown to be stable in the long term with their current ground surface and 'average' groundwater profile modelled.

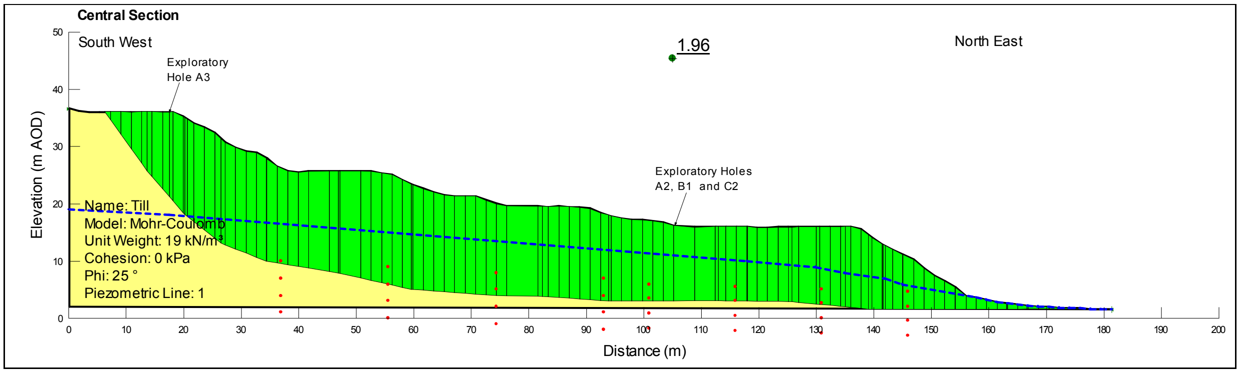

Figure 13. Central Section; Long term stability of the existing slope profile

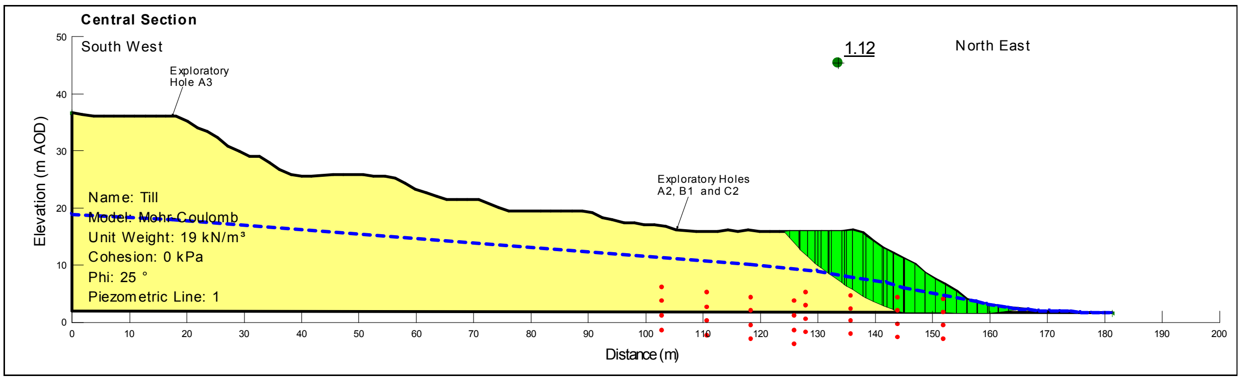

Figure 14. Central Section; Long term stability of the existing slope toe

4.2.3 Southern Section results

The exploratory holes relevant to the southern section are: C3, C4, C4A and C5 (Figure 1). As with the central section, the southern section also exhibits stability in the long term, with the global FoS shown on Figure 15 of 1.84 and the toe stability shown on Figure 16 of 1.14.

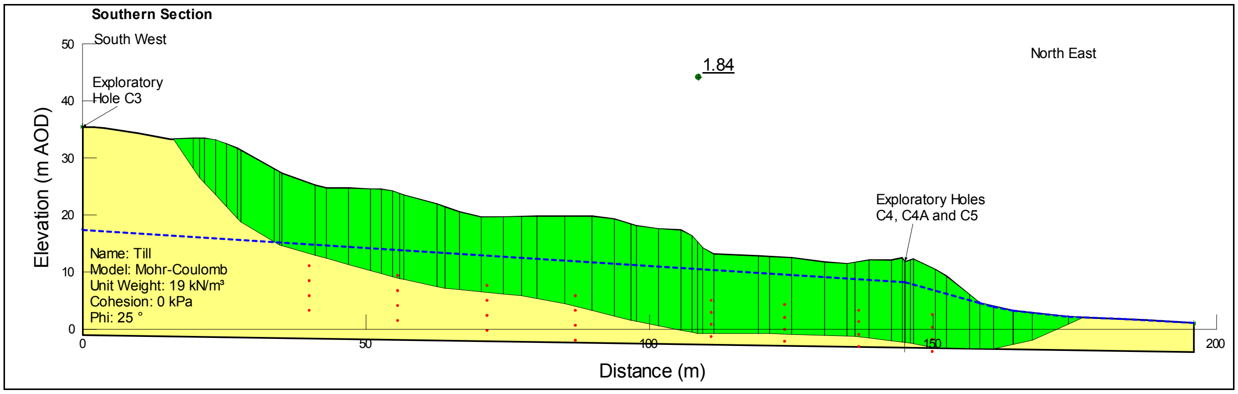

Figure 15. Southern Section; Long term stability of the existing slope profile

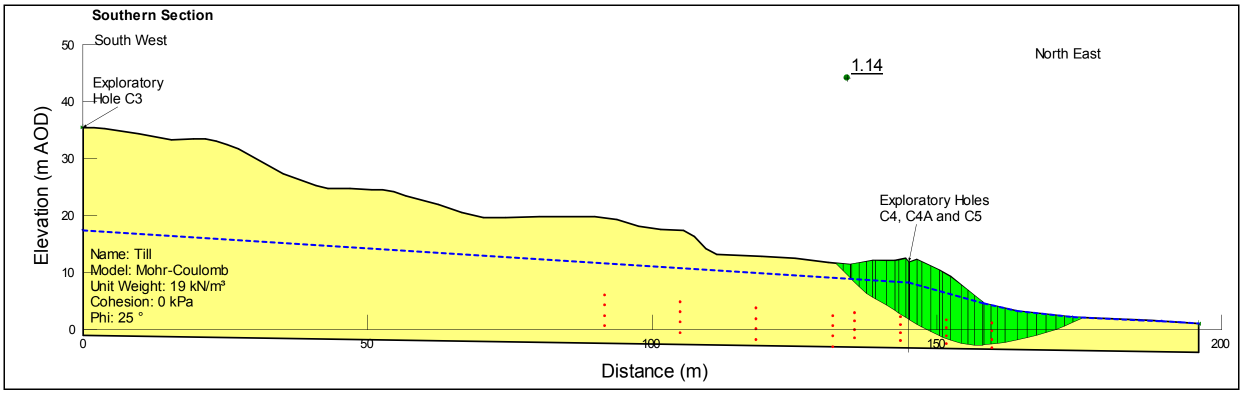

Figure 16. Southern Section; Long term stability of the existing slope toe

4.3 Summary and implications

Due to the nature and variability of the till deposits encountered (i.e. both granular and cohesive) the ground model for the stability analyses was best represented by a single soil unit. The geotechnical parameters associated with this deposit are also likely to be variable and the values used in the analyses are conservative.

The existing conditions modelled (Northern, Central and Southern Sections; Figures 10 to 16) show that Flat Cliffs is marginally unstable in the northern section, and marginally stable in the central and southern sections. Sensitivity analysis undertaken for the northern section shows the slopes are very sensitive to groundwater rise and toe erosion.

The numerical modelling, mapped geomorphology and evidence for past ground movements indicates that the northern part of the site – and in particular the access road – is the area most at risk. The most likely scenario for ground movement at this area is for the pre-existing mudslide at this location to reactivate, most likely in association with a period of sustained and intense rainfall and/or a storm coincident with high tides that causes significant cliff erosion.

Initiation of landsliding is likely to be indicated by movement recorded by inclinometers installed adjacent to the road and/or by the appearance of tension cracks. Exact timescales for activity are hard to predict, but early indicators of activity are likely to occur over a period of months to weeks. Landsliding may then occur rapidly, leading to partial or total collapse of the road and adjacent slopes over a period of hours to days. Instruments have not been installed for sufficient time to determine the relationship between rainfall, groundwater levels and ground movement, and therefore a programme of visual inspection is recommended. This is described in Section 5.3 below

5 Management strategy and response plan

5.1 Context

Flat Cliffs is formed of an 'undercliff' subject to cliff instability and coastal erosion. The area was developed in the 1920s and now comprises approximately 50 residential homes. In addition, Yorkshire Water maintains a wastewater pumping station and associated infrastructure at Flat Cliffs. The pumping station and residential homes are accessed via a single private road from the Primrose Valley Holiday Park.

The Undercliff has been affected by cliff instability and ground movement in the past that has resulted in moderate to serious damage to property, buildings, the access road and utility services. Historical records and geotechnical monitoring conducted over the past 10 years or so provide compelling evidence of the impact of ground instability on the community at Flat Cliffs. Cliff instability takes the form of progressive 'seasonal' ground movement and occasional more rapid landslip. Rates of ground movement are typically highest following prolonged and excessive rainfall periods during the winter months and as a result of rapid coastal erosion.

The historical cliff behaviour and impact on the community is likely to be made worse in future due to the effects of climate change and sea level rise. Changes in the frequency and intensity of rainfall are anticipated to result in wetter winters, raising groundwater levels and accelerating ground movement. Higher sea levels and more frequent storms are anticipated to result in higher rates of coastal erosion, removing slope support from the Undercliff, and promoting more widespread landslip.

The consequences of ongoing cliff instability and ground movement include damage to property, buildings, the access road and services. There is real concern that the access road could collapse at any time, which would prevent vehicular access into and out of Flat Cliffs. The decline in stability of the Undercliff due to progressive coastal erosion and loss of slope support, coupled with accelerated ground movement rates, are likely to cause more widespread and serious damage to property, buildings and services, requiring an increasing level of investment to maintain serviceability. In the long-term, occupation of Flat Cliffs is unlikely to be sustainable due to the risk of cliff instability and coastal erosion.

5.2 Management strategy

Given the context provided above, it is recommended that a management strategy is developed for Flat Cliffs to mitigate the risk and impacts of ground instability and coastal erosion for the well-being and safety of residents. A framework for the management strategy is presented in Figure 17 and might include a range of measures to mitigate the impacts of cliff instability and ground movement.

The successful management of coastal instability issues at Flat Cliffs will require buy-in, participation and agreement of roles and responsibilities between residents, the council and emergency services. The following issues will need to be addressed and taken forward by stakeholders in developing the management strategy:

- Formation of a residents' landslide committee to coordinate risk communication, manage potential future landslip events, and plan possible private coastal defences, drainage schemes or alternative access routes to and from Flat Cliffs (NB due to the shoreline management plan policy and the private-ownership of the site, such schemes are unlikely to receive central government funding through Scarborough Borough Council).

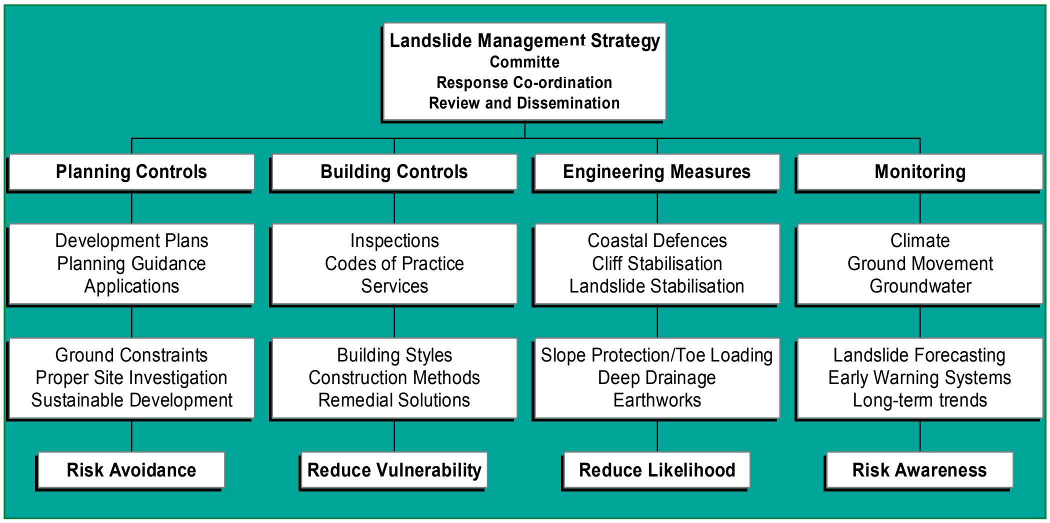

Figure 17. Framework for a Landslide Management Strategy at Flat Cliffs

- Implementation of appropriate planning and building controls to ensure new development is not at risk of land instability nor exacerbates instability on neighbouring property.
- A commitment to regular maintenance and monitoring of geotechnical instruments installed at Flat Cliffs to provide an accurate and continuous record of ground conditions and associated weather patterns and events. SBC are currently collecting and analysing monitoring data for the site from instruments installed in 2011. However, monitoring in future years is conditional on funding being available.
- Repeat site inspection and analysis of monitoring data to determine thresholds and associated hazard warning levels.
- Agreed frequency of reporting and communication protocols for defined hazard warning levels to ensure all relevant parties are kept informed.
- Agreed responsibilities and responses of individuals and organisations which must be acted upon for defined hazard conditions and warning levels.
- Informing local residents and land owners of best practice for slope management (e.g. prevent waste accumulation on slopes and reducing drainage discharge by ensuring all properties' drains are functioning correctly).
- Periodic review and update of the management strategy to ensure each party is aware of the roles and responsibilities of individuals and organisations.

5.3 Inspection and monitoring

The identification and notification of potentially hazardous ground movements will come via two main channels including:

- Local residents and members of the public
- Landslide monitoring programme

The role of local residents in the day-to-day observation and reporting of cliff instability and ground movement at Flat Cliffs is an essential part of the management strategy and response. Communication amongst the residents of Flat Cliffs is therefore essential as they are best placed to alert of potential ground instability issues. It is recommended that observations be coordinated through a residents' landslide committee. Significant observations should be reported to the council by the committee, with further advice sought if necessary.

Although automatic recording of weather and groundwater, and periodic measurement of sub-surface movement data will be ongoing, these will only be interpreted on an infrequent basis and cannot be relied upon as forewarning of potential hazards or events. Until such times as reliable relationships and thresholds between rainfall, groundwater and ground movement can be established, it is not possible or advisable to implement a warning system based on automatic monitoring of rainfall and groundwater levels at this stage.

Therefore, the recommended strategy is to conduct regular site inspections and expert review of the monitoring data, and using Table 17, determine the current hazard warning level for the site based on the observations and results. Each hazard warning level includes a description of the ground stability conditions and proposed actions. Any change in hazard warning level should be communicated through the appropriate channels to all affected stakeholders. A sign board notifying of the current hazard warning status on the access road would be an effective means of informing residents.

Table 17. Proposed actions for different hazard warning levels

Hazard Warning Level	Ground stability conditions	Proposed action
1	Ground stability conditions are stable. Rainfall and / or coastal erosion over the preceding month has been low or below average.	Residents to be vigilant and regularly inspect known areas and features of instability, and report any new observations to the council through the landslide committee. Continue monitoring of automated instruments and bi-annual review of inclinometers. Conduct annual inspection and damage survey of the site, and re-survey the permanent ground markers. Analyse all data and identify trends and relationships between key parameters. Publish findings and inform stakeholders.
2	Ground stability conditions are stable. Rainfall and / or coastal erosion over the preceding month has been high or above average.	In addition to the above, increase the frequency of inspections and review of monitoring data to monthly. If two or more consecutive months of above average rainfall or erosion occur, inspection of the site by a council officer is recommended. They should assess the hazard warning level based on site observations and analysis of the monitoring data and recommend further inspection and follow-up as appropriate.
3	Ground stability conditions are unstable. Localised evidence of instability may include cliff failure and erosion, groundwater seepage, new and open tension cracks, settlement of the road and / or property.	In addition to the above, increase the frequency of site inspection and review of monitoring data to weekly. Seek expert advice as appropriate. Undertake monitoring of inclinometers, a damage survey, and re-survey of permanent ground markers. Define the areas most at risk and consider evacuation of any elderly or infirm residents from the area at risk.

Hazard Warning Level	Ground stability conditions	Proposed action
4	Ground stability conditions are actively unstable and developing. The scale and rate of ground movement is serious and threatens property, buildings, the access road and services.	Alert the emergency services. Evacuate residents from properties and buildings affected by landslip. If there is danger of losing the access road evacuate the entire community provided it is safe to do so. Otherwise seek refuge in the designated refuge area (Fig 18) and await evacuation by the emergency services. Seek expert advice; conduct daily site inspection and review of monitoring data. Assess the risks of re-occupation of the area and individual properties.

5.4 Emergency response planning

It is recommended that an emergency response plan is developed for Flat Cliffs, similar to the one prepared for Cayton Cliffs by Scarborough Borough Council (2010) by North Yorkshire County Council (NYCC) emergency planning department. The aim of the plan is to provide comprehensive guidance to the emergency planning department and aid commanders, chief officers and other responders in the decision making, implementation and co-ordination processes required in response to the potential for, and or the catastrophic failure of, an area of identified cliff instability at Flat Cliffs. The plan will include:

- Site description
- Plan activation – thresholds and triggers
- Command and control
- Actions, roles and responsibilities
- Stand down of response
- Recovery

This section of the report outlines the initial step in the development of an emergency plan. It is strongly recommended that the relevant emergency planning body (NYCC) be appraised of the situation and that they take forward this outline to develop a fully functioning emergency plan for Flat Cliffs. Information presented in this report can be used to inform development of the emergency response plan. The full extent, timing and nature of potential cliff instability and ground movements at Flat Cliffs is difficult to quantify and predict, and as a consequence a degree of flexibility is required regarding an ‘appropriate’ response which should be proportionate to the situation. Therefore, individuals tasked with making such judgements should be familiar with the site and the available information and reports addressing cliff stability conditions at Flat Cliffs.

The emergency response plan will assume that an appropriate monitoring strategy is continued at the site and that responsible organisations and individuals have the resources in place to respond and act quickly to changing circumstances so that appropriate warning is issued to residents for their safety. SBC will undertake monitoring subject to available funding, if not, the landslide committee will need to make alternative arrangements for collection and analysing monitoring data.

The hazard warning levels and proposed actions outlined in Table 17 provide a clear description of the anticipated pre-cursor conditions and consequences of cliff instability and ground movement. Only hazard warning level 4 is expected to require the support of emergency services. The potential for persons to be lost or become trapped in landslide debris is a distinct possibility, particularly if the access road and properties collapse or vehicles and people were to be caught up in any significant land movements. The potential for missing persons and casualties and fatalities is therefore a possibility given the uncertainties about the slope failure and trigger mechanisms at Flat Cliffs.

Given these circumstances rescue from the site may be particularly difficult in the event of a collapse / landslide and hindered by: poor access; land instability and subsequent landslides, collapsed buildings and debris, exposed services presenting hazards such as gas and electricity. Operations to rescue residents from the site may be severely hampered in the event the single access road into Flat Cliffs is severed by landslip (see Figure 18 for egress routes). In this situation, safe access would only be possible via the foreshore and beach at low tide, or by air. Access down the steep cliff (by rope or ladder) or across an active landslide will be impractical given the relatively elderly population and safety considerations. Therefore, it is recommended that a refuge area is designated for the evacuation of residents near to the beach access, which is also the more stable part of the Undercliff (Figure 18).

The Police will be responsible for contacting the following Category 1 responders and establishing multi-agency command centre(s) as appropriate:

- North Yorkshire Police
- Fire & Rescue Service
- Yorkshire Ambulance Service
- Maritime & Coastguard Agency
- Scarborough Borough Council
  North Yorkshire County Council
- North Yorkshire & York Primary Care Trust

Some of these Category 1 responders are responsible for alerting other agencies such as voluntary organisations.

Category 2 responders can be requested as appropriate by any of the attending agencies, but the request for them to attend command centre(s) should be made via the Police. They include:

- Yorkshire water
- CE-Electric
- Untied Utilities (Gas)
- BT

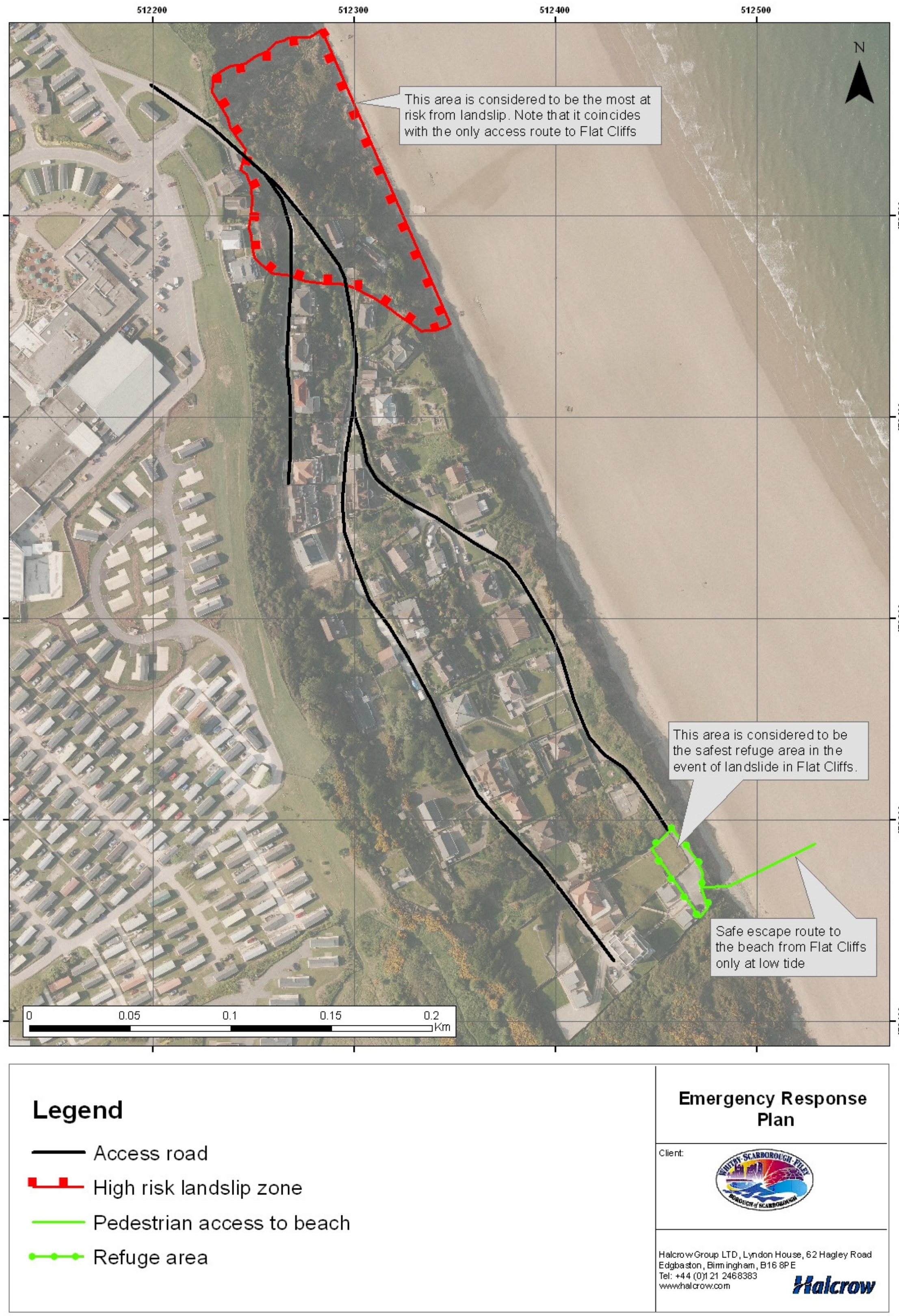

Figure 18. Flat Cliffs emergency response plan

6 Conclusions

This report details the results of a ground investigation and review of *in situ* monitoring data for the purpose of assessing current and future stability of potentially unstable coastal slopes at Flat Cliffs. A desk-study review of existing council records, technical reports, maps and other data reveal the community at Flat Cliffs, comprising about 50 homes, has been affected by cliff instability and ground movement resulting in moderate to serious damage to property, buildings, the access road and services.

A previous ground investigation commissioned in 2001 provided critical information on ground conditions and *in situ* monitoring which the current assessment has benefited. Further subsurface information and in situ monitoring has been installed as part of the current investigation. The investigation comprised drilling of 6 boreholes up to 35m deep, engineering logs of the soils encountered, sampling of materials for geotechnical testing, installation of a ground marker network, and the installation of piezometers and inclinometers to monitor groundwater and subsurface ground movement, respectively. Detailed topographic, geomorphological and damage surveys have also been carried out to provide information on the nature and extent of current instability.

The information and data obtained from the site investigation has been used to develop detailed 'ground models' of the site that characterise the nature and likely mechanisms of cliff instability and landslides. Slope stability analysis (using Slope/W software) of pre-determined slope cross sections has been completed to establish the current stability of the slope. A sensitivity analysis has been conducted to account for inherent uncertainty of parameters related to the variability of the glacial sediments and groundwater conditions. The stability analysis has also been used to demonstrate the future impact of increases in groundwater level and removal of slope support through coastal erosion.

A management strategy is proposed for Flat Cliffs to mitigate the risk and impacts of cliff instability, ground movement and coastal erosion. Critical components of the strategy include:

- Involvement of residents for inspection and reporting of site conditions
- Maintenance and expert review of *in situ* slope monitoring
- Implementation and review of a hazard warning system to alert residents of prevailing site conditions and the risk of cliff instability and ground movement

Guidance is provided on the frequency and scope of future monitoring linked to defined hazard warning levels. The default requirement is for monthly maintenance and review of continuous instrumentation, bi-annual measurement of inclinometers and an annual expert review to analyse trends and key parameter relationships. The frequency of inspection and review of monitoring data should be increased in line with the prevailing hazard warning level and guidance provided herein.

It is recommended that an emergency response plan is developed for Flat Cliffs given concerns about the current stability and vulnerability of the northern part of the site and single access road. Information is provided on emergency access and egress routes, and evacuation procedures, including designation of a refuge area for residents that may become trapped as a result of failure of the single access road.

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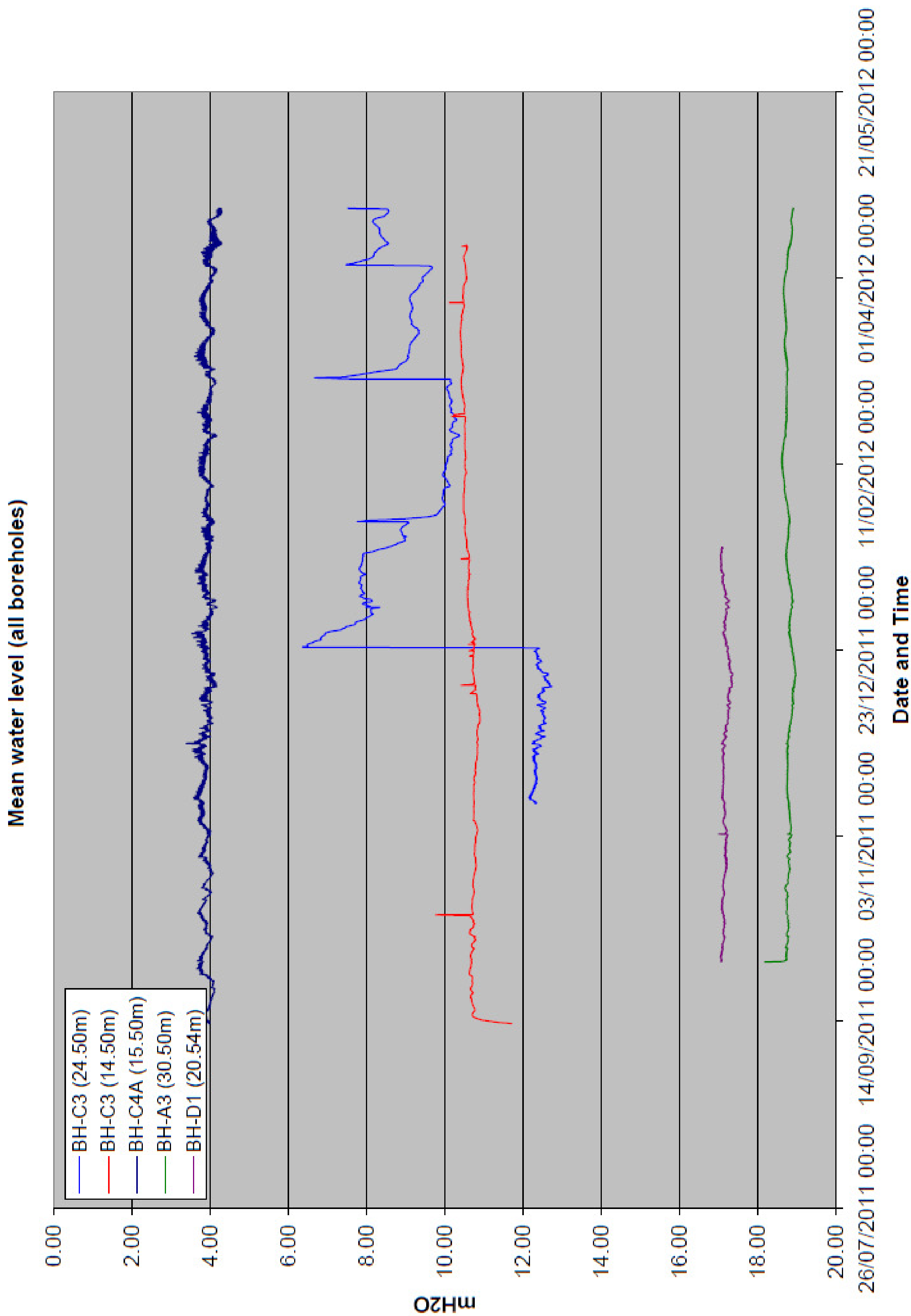
Appendix A Records of groundwater monitoring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BH-C3 (24.50m)
BH-C3 (14.50m)
BH-C4A (15.50m)
BH-A3 (30.50m)
BH-D1 (20.54m)
mH20
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
26/07/2011 00:00
14/09/2011 00:00
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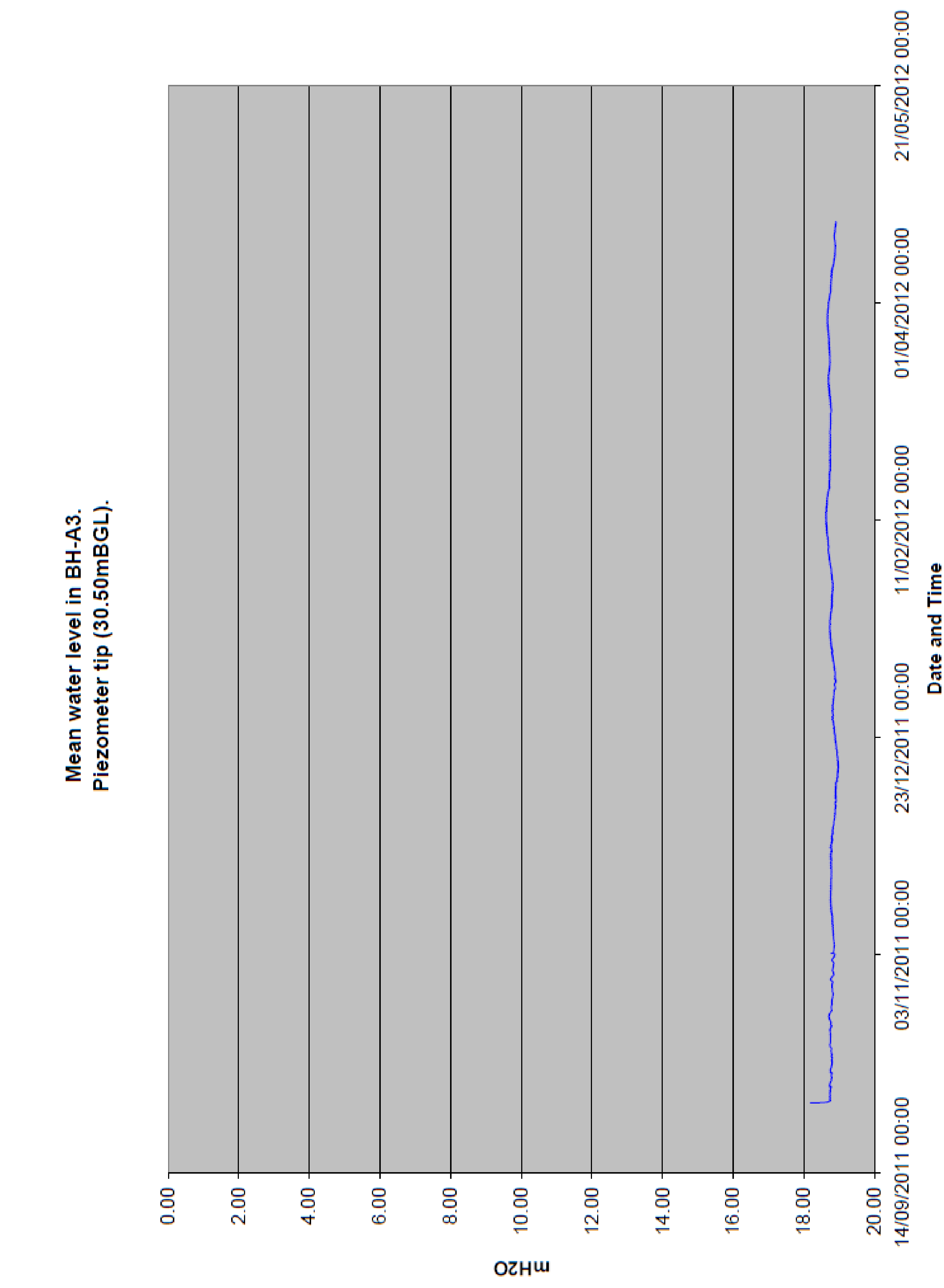
01/04/2012 00:00
21/05/2012 00:00
Date and Time


Mean water level in BH-A3.
Piezometer tip (30.50mBGL).
mH2O
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2.00
4.00
6.00
8.00
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12.00
14.00
16.00
18.00
20.00
14/09/2011 00:00
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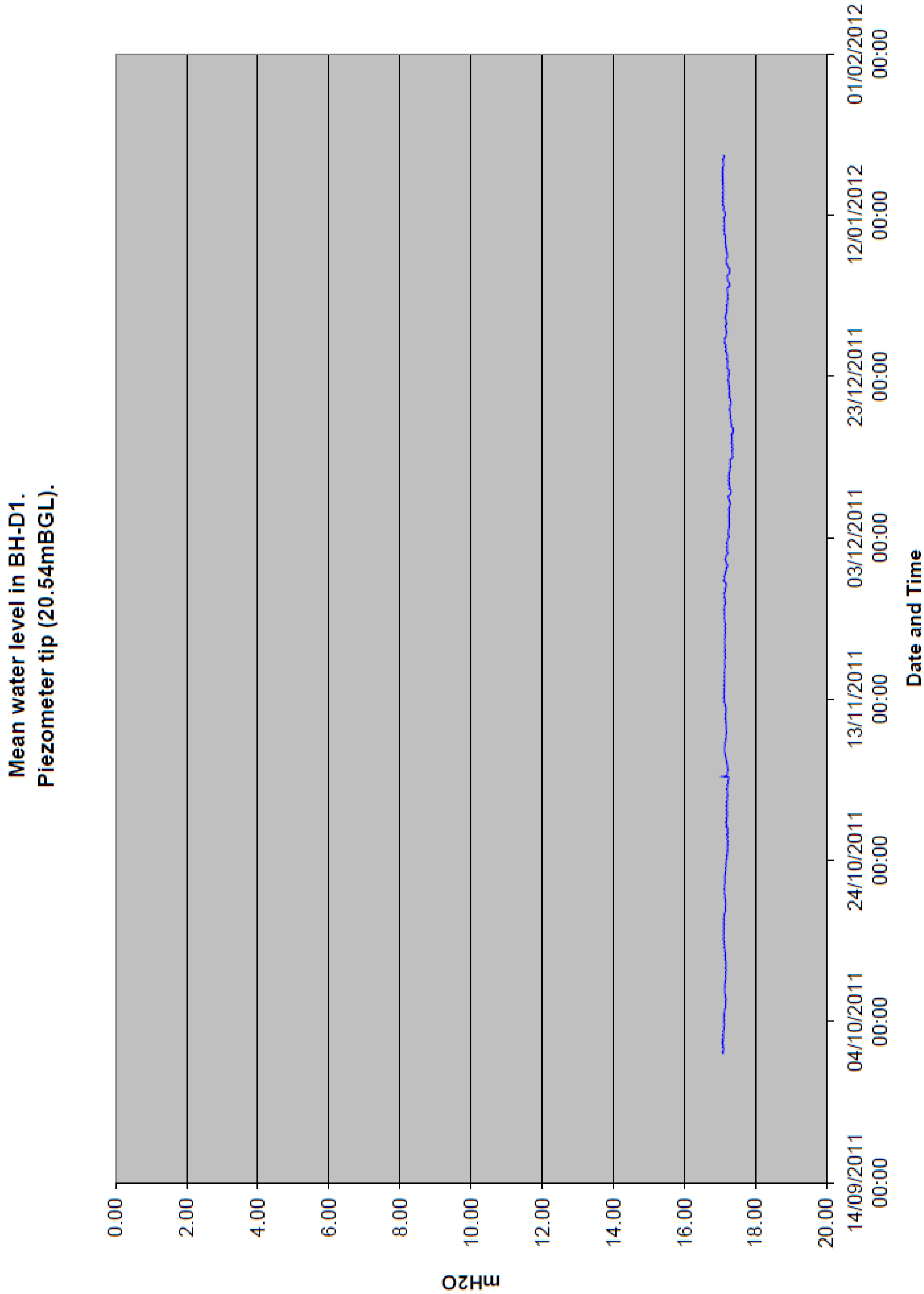
21/05/2012 00:00
Date and Time



Mean water level in BH-D1.
Piezometer tip (20.54mBGL).
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0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
20.00
14/09/2011 00:00
04/10/2011 00:00
24/10/2011 00:00
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23/12/2011 00:00
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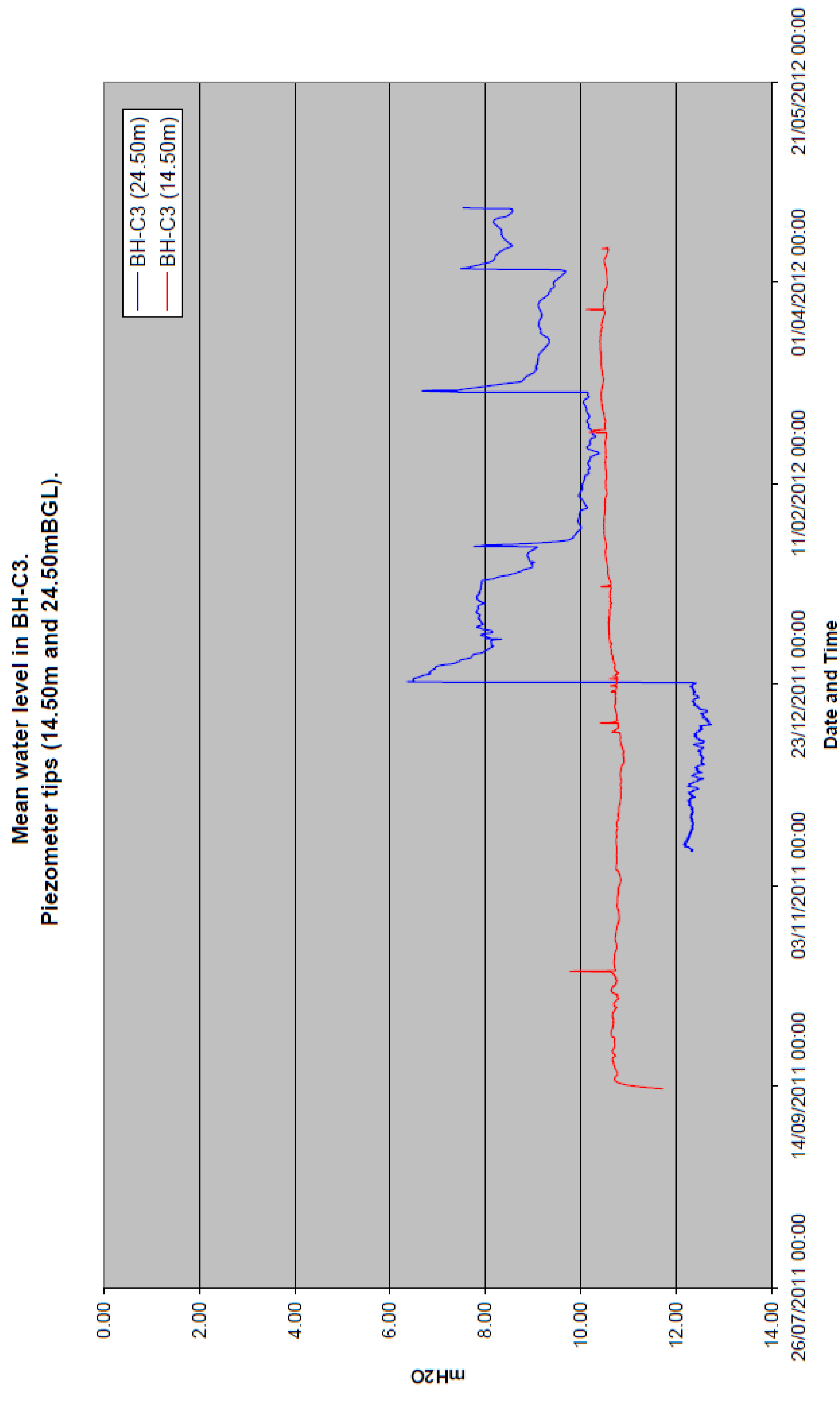
01/02/2012 00:00
Date and Time


Mean water level in BH-C3.
Piezometer tips (14.50m and 24.50mBGL).
BH-C3 (24.50m)
BH-C3 (14.50m)
mH2O
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
26/07/2011 00:00
14/09/2011 00:00
03/11/2011 00:00
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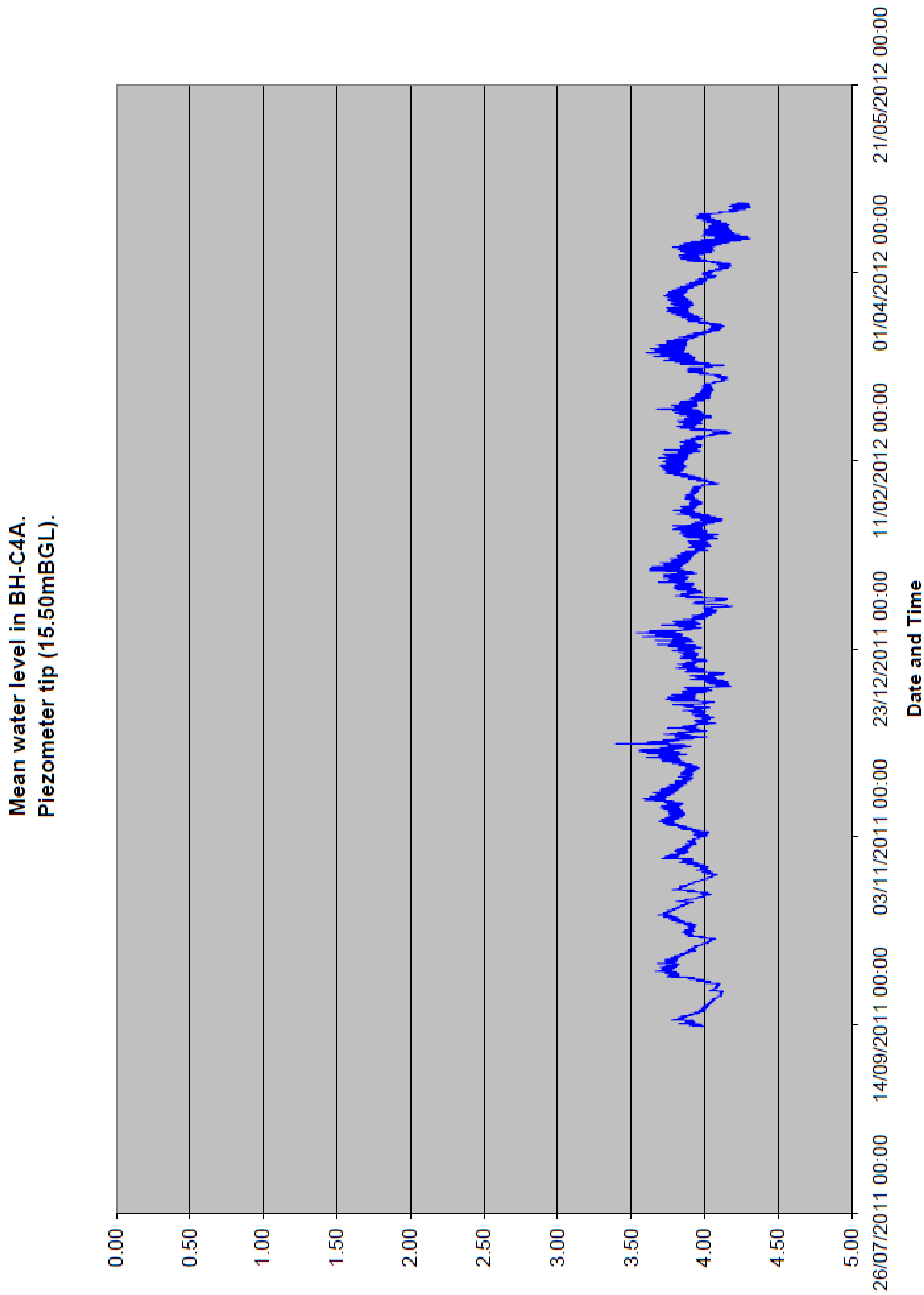
11/02/2012 00:00
01/04/2012 00:00
21/05/2012 00:00
Date and Time


Mean water level in BH-C4A.
Piezometer tip (15.50mBGL).
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1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
26/07/2011 00:00
14/09/2011 00:00
03/11/2011 00:00
23/12/2011 00:00
11/02/2012 00:00
01/04/2012 00:00
21/05/2012 00:00
Date and Time

Appendix B Records of ground movement

Location / photo	Description	Severity
1	Broken and disturbed paving slabs, resulting form shallow ground movement on oversteep slope	Slight
2	Leaning lamp post unlikely associated with landslide movement	Negligible
3	Local crack to garden wall	Negligible
4	Settlement in access road and signs of repeat repairs of over landslide shear	Serious
5	Distortion and cracking of paving slabs	Negligible
6	Damage to retaining wall	Slight/Moderate
7	Open crack and distortion to wall	Moderate
8	Disturbed and damaged garden slabs	Slight
9	Heavily fractured/ distorted retaining wall	Serious
10	Heavily fractured/ distorted retaining wall	Serious
11	Cracking and localised creep a cliff crest	Slight
12	Cracking and localised creep a cliff crest	Slight
13	Heavily fractured/ distorted retaining wall	Serious
14	Heavily fractured/ distorted retaining wall	Serious
15	Heavily fractured/ distorted retaining wall	Serious
16	Open crack in pavement with evidence of previous repair	Moderate
17	Open crack and settlement in parking bay. Evidence of previous repair	Moderate
18	Open crack and settlement in parking bay. Evidence of previous repair	Moderate
19	Cracking within brick retaining wall	Moderate
20	Cracking and displacement of brick retaining wall	Serious
21	Cracking along property access path	Slight
22	Tilting of garage	Serious
23	Active scarp suggesting retrogression of sea cliff within garden	Moderate
24	Settlement and rotation of property	Serious
25	Cracking and heave within the road	Slight
26	Cracking and heave within the road	Slight
27	Cracking in path	Slight
28	Tilting shed	Moderate
29	Cracking at corner of building	Slight
30	Collapsed fencing due to localised ground movement within the cliff scarp	Moderate
31	Localised damage to retaining wall	Slight
32	Crack to side of property	Slight/Moderate
33	Localised damage to garden wall	Slight
34	Cracking and warping of property wall	Moderate
35	Damage to concrete garden path	Slight
36	Bulging and rotation of retaining wall	Moderate
37	Large open crack in retaining wall	Serious

38	Crack in concrete path	Negligible
39	Crack in garden wall	Slight
40	Back rotated garage	Moderate
41	Cracking within retaining wall	Slight
42	Cracking within property	Negligible
43	Cracking within retaining wall	Slight
44	Cracking within retaining wall	Slight
45	Cracking in concrete wall	Negligible
46	Cracking within retaining wall	Slight
47	Cracking within retaining wall	Slight
48	Localised slip behind retaining wall	Moderate
49	Crack within retaining wall	Slight
50	Crack damage to property	Negligible
51	Crack damage to property wall and above archway	Slight
52	Crack damage to garden wall	Slight
53	Crack damage to garden wall	Slight
54	Crack damage to garden wall	Moderate
55	Crack to wall archway and wall rotation	Moderate
56	Settlement within paved driveway	Negligible
57	Cracking in concrete pavement	Negligible
58	Cracking in concrete pathway	Slight
59	Cracking and settlement of concrete pathway	Serious
60	Cracking across concrete pathway and property	Serious
61	Cracking within wall	Slight
62	Cracking and warping within wall	Moderate
63	Property tilting	Serious
64	Local damage to property	Negligible
65	Local cracking to concrete pathway	Slight
66	Local cracking to property	Slight
67	Damage to concrete pathway	Negligible
68	Cracking and warping of wall	Moderate
69	Warping of wall	Slight
70	Cracking to retaining wall	Negligible
71	Cracking to retaining wall	Negligible
72	Cracking within concrete	Slight
73	Cracking within concrete pavement	Slight
74	Cracking within concrete pavement	Slight
75	Cracking within property wall	Slight
76	Cracking within concrete pathway	Negligible
77	Cracking within retaining wall	Slight
78	Cracking to concrete pavement	Slight

79	Cracking in wall	Negligible
80	Cracking in wall	Moderate
81	Cracking and rotation of wall	Moderate
82	Cracking in concrete pathway	Negligible
83	Cracking in wall	Negligible
84	Cracking in wall	Negligible
85	Cracking in wall	Negligible
86	Cracking in wall	Moderate
87	Cracking in garden terrace	Slight
88	Cracking in property wall	Moderate
89	Cracking to corner of building	Slight
90	Cracking to garden wall	Slight
91	Crack in building	Moderate
92	Cracks in building	Moderate
93	Cracking and distortion of driveway	Serious
94	Cracking in driveway	Negligible
95	Cracking in concrete parking bay	Serious
96	Cracking in property wall	Negligible
97	Damage and repair to concrete path	Negligible
98	Cracking in property wall	Negligible
99	Uneven terrace- crack opening	Moderate
100	Cracking along path	Negligible
101	Cracking in concrete car park	Moderate
102	Cracking in wall	Slight
103	Cracking in wall	Slight
104	Cracking in wall	Slight
105	Cracking in wall rendering – possible frost damage	Negligible

Appendix C Historical aerial photographs

1940

1967

1980

512100
512200
512300
512400
512500
478600
478500
478400
478300
478200
478100
478000
N
Historical aerial imagery
1940
Client:
Halcrow Group LTD, Lyndon House, 62 Hagley Road
Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 2468383
www.halcrow.com
Halcrow
Legend
Extent of study area
2012 Ordnance Survey Mastermap
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Km


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478600
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478200
478100
478000
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Historical aerial imagery
1967
Client:
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Tel: +44 (0)121 2468383
www.halcrow.com
Halcrow
Legend
Extent of study area
2012 Ordnance Survey Mastermap
0
0.05
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512100
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478000
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Historical aerial imagery
1980
Client:
Halcrow Group LTD, Lyndon House, 62 Hagley Road
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Tel: +44 (0)121 2468383
www.halcrow.com
Halcrow
Legend
Extent of study area
2012 Ordnance Survey Mastermap
0
0.05
0.1
0.15
0.2
Km

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