Scarborough Borough Council

Cayton Bay Cliff Stability Assessment
Ground Investigation and Appraisal of
Engineering Stabilisation Options

April 2009

Halcrow Group Limited

Scarborough Borough Council

Cayton Bay Cliff Stability Assessment
Ground Investigation and Appraisal of
Engineering Stabilisation Options

April 2009

Halcrow Group Limited

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

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

Scarborough Borough Council

Cayton Bay Cliff Stability Assessment
Ground Investigation and Appraisal of Engineering Stabilisation Options

Contents Amendment Record

This report has been issued and amended as follows:

Issue	Revision	Description	Date	Signed
1	0	First Issue	17.4.09	JMC
1	1	Draft	30.4.09	JMC
1	2	Final	10.6.09	RM

Contents

Executive Summary **1**

1 Introduction **5**

1.1 Context *5*
1.2 Terms of reference *5*
1.3 Scope of work *6*
1.4 Ground investigation *6*

2 Site Description **10**

2.1 Site location *10*
2.2 Previous investigations *10*
2.3 Landslide event history *10*
2.4 Landslide geomorphology and ground behaviour *12*
2.5 Coastal erosion *12*

3 Ground Conditions **14**

3.1 Geology *14*
3.2 Groundwater regime *16*
3.3 Material properties *17*
3.4 Landslide ground model *18*

4 Slope Stability Assessment **20**

4.1 Slope stability model *20*
4.2 Model parameters *20*
4.3 Slope stability analysis results *22*
4.4 Conclusions of stability analysis *25*

5 Landslide Potential and Risk **27**

5.1 Landslide potential scenarios *27*
5.2 Revised landslide recession prediction *30*
5.3 Potential consequences *31*
5.4 Risk assessment *31*

6 Appraisal of Engineering Options **34**

6.1 Cliff management options *34*
6.2 Site-specific issues and constraints *34*
6.3 Engineering stabilisation measures *37*

6.4 Preferred stabilisation options *40*

7 Conclusions and Recommendations 42

7.1 Conclusions *42*

7.2 Recommendations and forward programme *44*

References 46

List of Tables

Table 1. Summary of borehole depths and instrumentation details

Table 2. Previous Cayton Bay studies currently in the public domain

Table 3. Summary of previous landslide events

Table 4. Summary of geological succession at Cayton Bay

Table 5. Landslide stratigraphy encountered at Cayton Bay

Table 6. Summary of soil strength characteristics

Table 7. Summary of rock strength characteristics

Table 8. Summary of geotechnical properties derived for slope stability modelling

Table 9. Slope stability sensitivity analysis varying the residual strength properties of the OCF

Table 10. Slope stability sensitivity analysis varying the residual strength properties of the FF

Table 11. Slope stability sensitivity analysis of potential elevated groundwater scenarios

Table 11. Slope stability sensitivity analysis of potential elevated groundwater scenarios

Table 12. Slope stability sensitivity analysis of landslide retrogression under potential elevated groundwater scenarios

Table 13. Updated qualitative risk assessment of the five future landslide scenarios at Cayton Cliff

Table 14. Updated headscarp landslide recession scenarios rationale

Table 15. Summary areas associated with SSSI status

Table 16. Summary of stabilisation measures

Table 17. Appraisal of conceptual landslide stabilisation measures

List of Figures

Figure 1. Land ownership and ground investigation plan

Figure 2. Site location plan

Figure 3. Geomorphological map

Figure 4. Groundwater monitoring

Figure 5. Soil plasticity characteristics

Figure 6. Cayton Bay landslide ground model

Figure 7. Slope stability modelling- shallow failure

Figure 8. Slope stability modelling- deep failure

Figure 9. Slope stability modelling of landsldie mechnisms

Figure 10. Landsldie recession scenarios for Cayton Cliff

Figure 11. Qualitative risk assessment based on the liklelihood and impact of each potential landslide behaviour scenario

Figure 12. Preferred stabilisation options

Figure 13. Preferred stabilisation options cross section

Figure 14.Cayton Cliff Stabilisaiton Scheme- forward programme of works

Executive Summary

This report presents the findings of the recent ground investigation at Knipe Point and Cayton Cliff completed in January 2009. The work was commissioned following large-scale remobilisation of a pre-existing coastal landslide at Cayton Cliff on 1st April 2008. The shoreline management strategy for the site is outlined in 'North East Shoreline Management Plan 2' which recommends a policy of 'managed realignment'; this policy precludes any hard coastal defences being introduced at the site. Future coastal instability risk at Cayton Cliff is likely to be perpetuated by shoreline erosion processes which will accelerate in time due to the effects of climate change and sea level rise.

The factual findings of the ground investigation are presented separately in the contractors report first issued in March 2009 (Norwest Holst 2009). The ground investigation has provided key data that facilitates interpretation and confirmation of the general 'ground model' of the coastal cliffs and specifically the subsurface landslide geometry and groundwater regime at Cayton Cliff.

The integrated interpretation has benefited from other data including surface geomorphological surveys, coastal erosion assessment, regular monitoring of ground movement marker pins installed across the site in May 2008, and subsurface groundwater and slip rod monitoring over the period December 2008 to March 2009. Key findings include:

- A significant thickness up to 39.8m of glacial till forming the headscarp at Knipe Point. The thickness of glacial till along the A165 headscarp attains a maximum thickness of 5.9m. The tills are susceptible to shallow slides in the form of rotational slumps, mudslides and mudflows.
- The sub-surface geometry of the Cayton Cliff landslide complex is controlled by the geological bedding and seaward dip of the underlying strata which has facilitated the development of gravity sliding upon a shear surface developed at the base of the Oxford Clay.
- The distinctive morphology and shape of Cayton Bay that exists today is the result of the unique geology of the site and the effects of rising sea level and coastal erosion over many thousands of years. Current rates of coastal erosion are reported to be of the order of 0.3-0.4m per year

although recession of the shoreline is counterbalanced by episodic seaward displacement and run-out of the landslide.

- The groundwater regime at Cayton Cliff is characterised by two independent water tables: an upper perched water table in the glacial tills and a deep water table confined within bedrock.

This report describes in detail the scope of the ground investigation, the nature of the ground conditions and geotechnical properties of materials encountered, and the instrumentation installed in the boreholes.

All of the above are used to develop a calibrated slope stability model for the site. The model was developed using an accurately surveyed topographic profile down the principal axis of the Cayton Cliff landslide complex guided by the surface geomorphology. The subsurface stratigraphy, material parameters and groundwater regime as encountered in the various boreholes has been added to the section. The model was then analysed to identify critical surfaces where slope failure is most likely. The model results correlate well with the field evidence. The model was then refined to back analyse the known landslide geometry and critical parameters required to mobilise failure of the cliffs; the model revealed two principal mechanisms both of which are controlled by distinct geology and groundwater regimes; they also represent varying degrees of hazard and risk at the site:

- Shallow failure mechanisms within the glacial till, comprising rotational slumps, mudslides and mudflows of varying extent on the headscarp and upper slopes of Cayton Cliff, and
- Deep translational failure mechanisms developed at the base of the Oxford Clay.

Sensitivity analysis of these models has demonstrated that the shallow failure mechanisms are most sensitive to relatively small increases in groundwater levels, with changes of only 1m or so reducing the factor of safety against landslides from above unity (i.e. marginally stable) to below unity (i.e. unstable). The deep failure mechanisms are also sensitive to groundwater changes but the magnitude of change required to bring about a similar reduction in stability is 2 to 3 times greater. The results demonstrate that a rise in groundwater level of around 3m from the condition recorded during the ground investigation (when no displacement of the landslide was recorded) would be sufficient to mobilise the entire Cayton Cliff landslide system.

Sensitivity analysis has also been performed to model the effects of coastal erosion on the stability of the deep failure mechanisms. The results demonstrate that the effects of coastal erosion over the next 50 to 100 years (i.e. toe erosion of 40m) will have an adverse effect on the stability of Cayton Cliffs. However, relative to other factors, the deep landslide mechanism is most sensitive to seasonal and short-term fluctuations in groundwater level.

Stability analysis of potential shallow and deep failure mechanisms of the headscarp at Knipe Point have also been performed. The results confirm that the most probable failure mechanism is from shallow rotational slumps, mudslides and flows within the glacial tills. Deep failure in bedrock, although feasible, is less likely based on the results of the ground investigation and stability analysis; this is also consistent with observations from site since early 2008.

The ground investigation and stability analysis has significantly improved confidence with the interpretation of the landslide ground model, mechanisms and causes of failure, which informs revised assessment of the landslide potential and risk. These are presented as a landslide recession potential map and risk matrix which supersede previous assessments presented in Halcrow's report to the National Trust in May 2008 and subsequent monitoring reports.

An outline of the cliff management options that might be considered for the site is provided along with brief consideration of key site-specific issues and constraints. The report identifies a range of engineering stabilisation measures and screens these to identify the most technically suitable options. The relative advantages and disadvantages of these options are described accounting for the site-specific issues and constraints including potential impact on environmental and other interests; outline 'ballpark' scheme costs are provided which are necessarily conservative at this stage as they are not based on any design or benefit cost analysis. The intention is to provide outline stabilisation options and potential costs to facilitate further discussion amongst stakeholders.

Preferred scheme options have been identified that will have the least impact on the SMP policy and environmental interests at the site whilst delivering the desired level of improvement in slope stability for a nominal design life of 50 years. The preferred options will respect the SMP policy whilst at the same time take into account the inter-relationship between landslide debris being deposited at foreshore level and being removed by coastal action. The principal objectives of the scheme are as follows:

- to prevent remobilisation of the deep failure mechanism and removal of support at the headscarp through lowering and control of the deep groundwater table through deep drainage (i.e. pumping wells).
- construction of a contiguous deep piled wall above the headscarp to prevent further recession and undermining of property and other assets.

Additional engineering stabilisation measures such as the construction of deep spaced piles (shear keys) set-back from the landslide toe, beach improvements across the Cayton Cliff frontage and improved surface water drainage could be considered to further improve the stability of the site. However, these measures may have a significant impact on the SSSI and other interests of the site and would increase scheme costs, as they do not provide alternatives to the preferred options described above.

The ground investigation and assessment clearly identifies the nature of the problem and has identified a preferred engineering solution hence complying with the terms of the grant by which the ground investigation and assessment was funded. Whilst coastal erosion has been a contributory factor in the long-term development of the problem, fluctuations in groundwater levels are attributed to triggering ground movement and episodic landslide events. A technically sound and environmentally achievable solution has been identified but this can only be delivered if further work is commissioned to progress the scheme design, including benefit cost analysis, to support project appraisal and funding applications under the coastal protection and land drainage acts.

The report recommends three key actions:

1. Maintain and continue monitoring of the surface and subsurface ground movement, groundwater and weather station network.
2. Stakeholder liaison to review the findings of this report and discuss the way forward for managing the cliff instability risk at the site in the short and longer term.
3. Review funding options for promotion of the preferred engineering scheme, conduct preliminary design and benefit cost analysis, and prepare a project appraisal report for application for funding.

Further details are provided in the main report.

1 Introduction

1.1 *Context*

A large reactivation of a coastal landslide complex occurred at Cayton Bay on the 1st and 2nd April 2008. The main features and impacts of the event included the retrogression of the cliff top and loss of property at Knipe Point, loss of slope support beneath the A165 Filey Road, major ground movements and opening of large cracks throughout the Cayton Cliffs, and uplift of the beach fronting Cayton Cliff. The remobilisation of the landslide and associated cliff top recession to date has led to the loss of private land, the demolition of three bungalows at Knipe Point and diversion of the Cleveland Way footpath inland from the Bay.

This large scale reactivation coupled with ongoing ground movement has raised concerns over the risk of potential further losses including a section of the A165 Filey Road and a further 56 bungalows at Knipe Point. To assist co-ordination of the community response and management of the cliff instability risk, the Cayton Bay Landslip Management Group was formed comprising representatives from the Scarborough Borough Council (SBC), landowners, local residents, agencies and stakeholders.

The issue of coastal erosion at Cayton Bay and associated landslide instability has been addressed previously in the Cayton Bay Coastal Management Strategy (2002) and the associated Shoreline Management Plan (SMP2) (*Section 2.5*). The site has been the subject of a number of previous investigations (*Section 2.2*) which have identified the extent and probable causes of landsliding. Despite these, a detailed interpretation of the landslide mechanisms, groundwater regime and hazard potential has not been possible due to lack of subsurface data. A recent report prepared by Halcrow Group Limited (HGL) on behalf of the National Trust (NT) recommended a detailed ground investigation be carried out to confirm the landslide geometry, mechanisms and groundwater regime, to determine the current and future potential landslide stability and associated risks, and to appraise the range of engineering stabilisation measures that could be considered to improve the stability of the site.

1.2 *Terms of reference*

HGL was commissioned by SBC to undertake a landslide stability assessment of the site including the procurement and management of a ground investigation. The commission has been performed by under a Professional Services Contract, supplemental to the Framework Agreement for Coastal Defence Services between HGL and SBC dated 19 April 2007. HGL was awarded the contract on 21st July 2008.

This commission was delivered by SBC with funding provided by the Environment Agency (EA) under the Coast Protection Act and the National Trust who have made a significant financial contribution to the investigation. Consultation with the Cayton Bay Landslip Management Group has taken place throughout the running of the commission.

1.3 *Scope of work*

The scope of work carried out by HGL includes:

- Design and specification of a ground investigation, tender assessment and procurement of a preferred Contractor.
- Management of a ground investigation comprising the drilling of six rotary boreholes drilled to a maximum depth of 110m, engineering and geophysical logging of boreholes, soil and rock sampling of core materials, laboratory testing, and the installation of standpipe piezometers and slip rod indicators in each borehole.
- Interpretation of a landslide ground model based on the findings of the ground investigation and previously published data; specifically, to determine the probable subsurface geometry of the landslide, the groundwater regime, geology and the associated geotechnical properties of the soils.
- Slope stability analysis using specialist Slope-W software to investigate the causes and mechanisms of ground movement,
- Review and update of the future potential landslide scenarios and associated landslide hazards and risk at the site.
- Appraisal of outline engineering stabilisation options and identification of preferred scheme options; including consideration of the relative environmental impacts of engineering measures and estimated costs.
- An outline programme to progress a preferred scheme to construction.

1.4 *Ground investigation*

As part of this commission a ground investigation was procured by SBC comprising the drilling of six boreholes using light cable percussion and rotary coring techniques. Halcrow (the Engineer) specified and supervised the ground investigation which was performed by Norwest Holst Ltd (NHL; the Contractor). The scope of the ground investigation comprised:

- 1 no. borehole (BH1) drilled on the headscarp at the A165
- 3 no. boreholes (BH2, BH3, BH4) drilled along the headscarp at Knipe Point
- 2 no. boreholes (BH5, BH6) drilled within the main landslide complex at Cayton Cliff
- Geophysical logging of the boreholes
- Installation of standpipe piezometers at each location to monitor groundwater levels
- Installation of slip rods to measure depth of subsurface ground movement
- Installation of an automatic weather station at Knipe Point
- Preparation of detailed engineering and geophysical logs of the boreholes
- Soil and rock sampling
- Laboratory testing to characterise the soils and rocks and provide parameters for use in slope stability analysis
- Topographical survey of borehole locations and section line through Cayton Cliff for use in slope stability analysis

The location of the boreholes is shown in *Figure 1*. The final position of each hole was designed to allow the development of a robust landslide ground model taking account of the access and environmental constraints at the site.

Access to the lower coastal slopes at Cayton Cliff was a significant constraint (see *Section 6.2.1*) to the investigation. The Cleveland Way footpath passes through the site but has limited height and width clearance; the path is not suitable for heavy plant and has been broken in several places by the recent land movement. Access to the path is possible through the Knipe Point residential development through several padlocked gates. The access constraints posed significant challenges in the planning, procurement and eventual cost of the ground investigation.

Cayton Cliff is a Site of Special Scientific Interest (SSSI) due to its important geological exposures and biological features (see *Section 6.2.2*). In planning the ground investigation works at the site, consultation and agreements with the NT and Natural England (NE) were reached regarding the locations of boreholes (BH5 and BH6) and the scope of drilling operations in order to minimise the impact on the SSSI; in support of this an environmental survey was carried out prior to the works and an Ecological Clerk of Works was appointed to advise on environmental issues during the ground investigation.

1.4.1 *Borehole instrumentation*

The boreholes were drilled to various depths as summarised in *Table 1* to confirm the nature and variability of the geology and landslide stratigraphy across the site. Each borehole was fitted with standpipe piezometers to monitor groundwater levels at specified depths tied to known stratigraphic units across the site. Selected standpipe piezometers were also installed with slip-rods to measure the depth of tube displacements deep in the ground. A summary of the borehole termination depth and depth of equipment installations is provided in *Table 1*.

Borehole	Termination depth (mbgl)	Piezometer reference	Standpipe piezometer installation	
			Slotted tubing zone (mbgl)	Response zone (m)
BH1	110	P1	45.0-11.0	45.0-10.0
BH2	97.4	P2a	97.4-81.0	97.4-80.0
		P2b	25.0-6.0	25.0-5.0
BH3	97	P3a	75.0-66.0	75.0-65.0
		P3b	38.0-16.0	38.0-15.0
BH4	90.2	P4a	90.2-69.0	90.2-68.0
		P4b	63.0-59.0	63.0-58.0
BH5	75.7	P5a	75-56	75-55
		P5b	32-21	32-20
BH6	56.25	P6	30-20	30-15

Note: mbgl – metres below ground level

Table 1. Summary of borehole depths and instrumentation details

1.4.2 *Logging procedures*

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 the European standards in accordance with BS5930:1999. The detailed borehole logs are presented in the ground investigation factual report (Norwest Holst, 2009).

Downhole geophysical logging was carried out in selected boreholes. The geophysical logging involved:

- Gamma formation porosity (natural gamma logging)

- Neutron formation porosity to assess moisture content and porosity variability in the ground
- Verticality logging to assess tilt and tile azimuth
- Induction logging to assess permeable zones in the ground and the porosity characteristics in dry or fluid filled holes
- Formation density (gamma gamma logging)

The downhole geophysical logs provide valuable data to assist interpretation of the ground conditions and, specifically, to cross correlate strata between boreholes across the site.

1.4.3 *Laboratory testing*

Laboratory testing of rock and soil samples was scheduled by HGL on core samples selected for testing by the HGL Assistant Engineer's Representative. Detailed laboratory results are presented in the Ground Investigation Factual Report (Norwest Holst, 2009).

1.4.4 *Site monitoring*

Monitoring of groundwater levels was undertaken daily by the Contractor during the period of the site works. Following this period both groundwater monitoring and slip rod measurements have been undertaken weekly by trained representatives from the NT. The data recorded by the automatic weather station is recovered by the NT on a monthly basis.

2 Site Description

2.1 *Site location*

Cayton Bay is located on the North Yorkshire coast approximately 3.5km south-east of Scarborough and 7.5km north-west of Filey. The bay forms a large Undercliff comprising Cayton Cliff and Tenants' Cliff which form a North West arc around the bay. The northern limit of the cliffs comprises the prominent headland of Knipe Point which delimits the current rear-scarp of the landslide to the north of the site. This rear-scarp continues south to form a large cliff parallel to the A165 Filey Road *(Figure 2)*.

2.2 *Previous investigations*

The Cayton Bay landslide has been the subject of a number of previous studies. These are summarised in *Table 2*.

Date	Author	Report	Client
2001	Halcrow	Cayton Bay Coastal Strategy Study	SBC
2002	Halcrow	Coastal monitoring programme 2001-02. Filey and Cayton Bay cliff inspection and condition assessment.	SBC
2006	Fish, Carey & Moore	Landslide geomorphology at Cayton Bay, North Yorkshire. *Proceedings of the Yorkshire Geological Society,* 56 (1) 5-14	-
2008	Halcrow	Cayton Cliff, Cayton Bay, North Yorkshire, Stability Report and Cliff Management Plan	National Trust

Table 2. Previous Cayton Bay studies currently in the public domain

2.3 *Landslide event history*

The site has been subject to seasonal ground movement and episodic landslide events. This has included historical instability of the Cayton Cliffs, landslide runout onto the beach fronting Cayton Cliffs, and retreat of rear headscarp particularly in the area of Knipe Point. The potential for further ground movement and episodic landslide events at Cayton Cliff poses a significant risk to people who access the unstable area and key assets located adjacent to the headscarp. These assets include a number of properties at Knipe Point and along the Filey Road, the A165 Filey Road, and services infrastructure including gas and water pipelines, and electrical services.

Ground movement and landslide events have been recorded at the site for a number of years these are summarised in *Table 2*. Further details of the landslide events that have occurred at the site are published in a number of previous technical reports and papers (e.g. Halcrow 2008; Fish *et al*., 2006).

Date	**Landslide event description**
1850-1890	Headscarp subsidence near Osgodby village occurred.
1926-1938	Headscarp subsidence by approximately 2m over length of 50m at Osgodby village.
1946	Ministry of Health Coast Protection Survey notes presence of huge slip a short distance north of pumping station leaving "vast crater a quarter of mile wide."
May 1969	Large failure occurred from flank of Knipe Point ridge in the area now occupied by bungalows.
1974-1975	Ground movement affected area of Knipe Point.
1981	Surveys by Mills (1981) observed 2m of settlement for 20m of footpath along A165; Minor tension cracking on steep slopes of Cayton Cliffs and numerous translational slides identified beneath A165 and Knipe Point.
2000-2001	Investigations by Halcrow (2001) identified localised failures from Knipe Point Ridge and at Cayton Cliffs resulting in damage to access footpath.
2002	Investigations by Halcrow (2002) identified numerous tension cracks and minor elongate mudslides within Cayton Cliff resulting in localised damage and disturbance to footpaths.
2003	Approximately 1m of recession of the Knipe Point cliff was reported by local residents and resulted in the relocation of the boundary fence inland.
February 2008	Headscarp reactivation and mudslide development at Knipe Point leading to cliff top recession and the evacuation of two cliff top properties at Knipe Point.
1st April 20008	A major reactivation of the Cayton Cliff landslide involving an estimated 5m seaward displacement of the entire complex. Evidence of fresh tension cracking along lateral margins and within headscarps and disruption and damage to footpaths including the Cleveland Way. The reactivation resulted in the demolition of two cliff top properties at Knipe Point.
April 2008- onwards	Continued ground movement with Cayton Cliffs causing further damage to and closure of the Cleveland Way footpath. Continued localised recession of the cliff top at Knipe Point and along the A165.

Table 3. Summary of previous landslide events

2.4 *Landslide geomorphology and ground behaviour*

2.4.1 *Mapping and interpretation*

Geomorphological mapping of the Cayton Cliff landslide complex was undertaken by Fish *et al.* in 2003 and in 2008 by Halcrow Group Ltd on behalf of the National Trust (NT). The mapping was undertaken to detail the surface morphology at the site and to record any change in ground conditions associated with ground movement and landslide activity.

2.4.2 *Slope morphology*

The Cayton Cliff morphology consists of steep to moderately steep scarps with slope angles between 20° and 30°, separated by flat or back-rotated bench features with ponds or marshy ground indicative of poor natural surface drainage. The margins of the bench and scarp topography are characterised by a series of elongated ridges and the shoreline fronting Cayton Cliff comprises a steep sea cliff formed by uplifted debris from deep landslide movement. A number of lower lying coastal areas are located at the toe of large mudslides which have run-out across the beach forming characteristic lobate features.

2.4.3 *Geomorphological interpretation*

A geomorphological interpretation is presented in *Figure 3* based on the surface morphology and limited published geological information. Results suggest that an ancient deep-seated translational failure has developed at Cayton Cliffs as depicted by the steep distinct 'block and scarp' morphology which is apparent throughout the site. This morphology has subsequently been degraded by glacial till deposits which have led to the development of large mudslides which are active in the shallow soils.

2.5 *Coastal erosion*

The issue of coastal erosion at Cayton Bay and associated landslide instability was addressed by the Cayton Bay Coastal Management Strategy (2002) and the adopted Shoreline Management Plan - North East SMP2 (SBC 2007).

The distinctive morphology and shape of Cayton Bay that exists today is the result of the unique geology of the site and the effects of marine transgression and coastal erosion over many thousands of years since the cessation of the last glaciation, around 20,000 years before present (BP). At the termination of the last glaciation, sea level was much lower than present with sea levels rising rapidly in the early to mid Holocene period between 11,000-3,000 years BP. The coastal cliffs and shape of the bay as observed today will have been largely formed over this period as a result of rapid coastal erosion and large-scale episodic landsliding. Present-day sea levels in the region are thought to have been broadly reached by around 3,000 years BP since which the rate of sea level rise, coastal erosion and landsliding activity is likely to have been much less than compared to the early and mid-Holocene period.

The North East SMP2 reports an erosion rate of c. 0.3-0.4 m/yr is likely for the cliffs forming of Cayton Bay; however, it is noted that no distinction is made for the various geology and materials exposed at the shoreline which are likely to have quite marked variation in resistance to marine erosion.

A more detailed assessment of cliff behaviour and recession potential was presented in the Cayton Bay Coastal Management Strategy (2002). The assessment comprised observation and mapping of cliff morphology, landslides, geology, materials, current cliff activity and recession potential, all of which have a significant influence on coastal erosion rates and the sediment budget for Cayton Bay. In respect of future cliff behaviour and erosion potential at Cayton Cliff, the following cliff failure scenarios were summarised in the coastal strategy report:

- "Small-scale failure of the rear scarp causing localised settlement of cliff top land (up to 50m). Over the next 50 years the likelihood of this scenario is considered high.

- Major reactivation within the current boundaries of the landslide complex resulting in the run-out of debris onto the beach. Evidence of eroded debris lobes and boulders arcs on the beach attest the relative frequency of events of this nature and it is considered that similar events are likely over the next 50 years.

- Initiation of major landsliding involving rapid loss of cliff top land. Continued degradation of the landslide complex has historically caused steepening of the rear and edge scarps. The stability of these has decreased in time and there is increasing potential for first time failure of these scarps in the future."

A key point to note is that whilst Cayton Cliff is subject to ongoing toe erosion, land movement and episodic run-out of debris lobes onto the beach have the effect of temporarily advancing the shoreline and protecting the cliff base, counteracting the effects of marine erosion and recession of the shoreline.

3 Ground Conditions

3.1 *Geology*

The regional geology is available in a number of publications (e.g. Fox-Strangways & Barrow, 1882; Fish *et al.*, 2006) and is illustrated in the geological map of the area (BGS, 1998). A summary of the key geological units and their estimated thicknesses at Cayton is provided in *Table 4*.

Chronostratigraphy	Lithostratigraphy		Rock types	Estimated thickness (m)*
	Formation	Member		
Quaternary	Filey		Tills, sands and gravels and laminated clays	30
Upper Jurassic	Lower Calcareous Grit	Tennant's Cliff	Sandstone and oolitic limestone	50
	Oxford Clay	Weymouth	Mudstone	37
Middle Jurassic	Osgodby	Hackness Rock Langdale Reddcliff rock	Friable sandstones, limestones and chaemosite	20
	Cayton Clay Cornbrash	Fleet	Limestone and mudstone	3
	Scalby	Long Nab Moor Grit	Mudstone and sandstone	60
	Scarborough		Limestone and mudstone	30
	Cloughton	Gristhorpe Lebberston Sycarham	Sandstone, mudstone and coals	<85

Table 4. Summary of geological succession at Cayton Bay, after Fish et al. (2006)
**after Rawson and Wright (2000) and Mills (1981)*

The solid geology at Cayton comprises a sequence of Middle and Upper Jurassic rocks that are affected by faulting associated with the Peak Trough which lies some distance offshore to the north of the site (Fish *et al.*, 2006). The oldest rocks present at the site comprise Gristhorpe and Lebberston Members of the Cloughton Formation and are exposed at the tip of the Knipe Point headland. A series of faults extends to the south of Peak Trough and passes through Cayton in a NNW to SSE direction. These faults down-throw to the west and juxtapose younger rocks of the Oxford Clay formations against the Gristhorpe and Lebberston members (Fish *et al.*, 2006). The Oxford Clays form the Cayton sea cliffs and are exposed at sea level. Toward Tenants' Cliff the Oxford Clay is overlain by Lower Calcareous Grit comprising calcareous sandstones and oolites and characteristic cherts. The sea cliffs in this area are formed from massive displaced blocks of Lower Calcareous Grit.

3.1.1 *Quaternary deposits*

The quaternary geology of the coastline consists of a variety of glacial sediments incorporating glacial tills, outwash sands and gravels reported to have be deposited in the Late Devensian approximately 26,000 to 13,000 years BP (Evans et al., 1995).

The site of Cayton is believed to have been the site of a large moraine stretching over Cayton and Flamborough and associated with the development of Glacial Lake Pickering which formed inland. Eyles *et al.*, 1994 have proposed that the moraine was formed by a surging glacier moving episodically across the North Sea basin over the soft deformable sediments. These surges would lead to the rapid fluctuation of the ice sheet position and the subsequent deposition of separate tills with intervening meltwater sands and gravels. Interbedded sediments such as these can lead to the formation of discontinuities and lenses of porous sediment can act as perched water tables within the till. In such instances excess pore water pressures may act to destabilise the tills which is believed to be a major cause of landsliding in till cliffs (e.g. Clark and Guest, 1994).

3.1.2 *Landslide stratigraphy*

The stratigraphy and the relative thickness of the different geological units have been established from the engineering logs of the boreholes. A summary of the main materials encountered is provided in *Table 5*.

Of particular importance is the sequence of glacial tills distributed around the headscarp of Cayton Cliff. The ground investigation has confirmed a relatively thin sequence of glacial tills along the A165 section and a considerably thicker sequence of glacial tills at Knipe Point. The significance of this relates to the relative incompetence of the glacial tills and their vulnerability to mass movement processes. This is corroborated by the landslide geomorphology which indicates the principal axis of headscarp recession is aligned to the maximum thickness of the glacial till sequence at Knipe Point.

A further observation of significance confirmed in 3 boreholes was the prevalence of polished slickensided surfaces towards the base of the Oxford Clay. This provides compelling evidence that the basal shear surface of the Cayton Cliff landslide complex is developed at this interface and is for the most part deep-seated ranging between 40m and 60m below ground level (bgl).

Material encountered	**Summary description**	**Thicknesses encountered (m)**					
		BH1	BH2	BH3	BH4	BH5	BH6
Filey Formation glacial tills (FF)	Glacial tills generally ranging from stiff orange brown gravelly sandy clays to soft brown slightly sandy gravelly silty sandy clays. Sand/silt lenses also observed at varying depths.	5.9	32.7	39.8	37.6	18.87	30.10
Lower Clacareous Grit Formation (LCGF)	Strong to moderately strong orange brown fine to medium grained sandstones and siltstones with some rough fracturing and discontinuities.	73.65	40.1	18.2	9.56	11.93	-
Oxford Clay Formation (OCF)	Brownish grey to blue grey moderately weak to weak mudstone with often closely space thick laminations and thin siltstone bands. Distinct fissuring and polished surfaces are evident at varying depths.	30.45	19.6	27.15	27.09	36.7	22.2
Osgodby Formations (OF)	Very strong to strong blue-green fine grained sandstone with bands of grey brown siltstone. Distinct fissuring and polished surfaces are evident within the siltstone bands	-	5	11.85	15.95	18.2	3.95

Table 5. Landslide stratigraphy encountered at Cayton Bay

3.2 *Groundwater regime*

The site investigation has confirmed that interbedded strata of contrasting permeability are present at the site.

The borehole piezometers (see *Section 2.5.1*) were monitored between 01.12.2008 to 31.03.2009 which identify two separate water tables acting independently at the site (*Figure 4*). These comprise:

- A perched water table (WT1) in the glacial till (FF) forming the Knipe Point headscarp; the groundwater response indicates rest water levels at about 70m above Ordnance Datum (AOD) or approximately 10m bgl and relatively high in the glacial till sequence. The perched water table (WT1) is at or close to ground level within Cayton Cliff. This gives rise to the presence of ponds and waterlogged soils in areas of poor surface drainage.
- A deeper groundwater table (WT2) at approximately 17mAOD recorded in piezometers (P2a, P3a and P5) which is likely to be in hydraulic continuity with the bedrock strata LCGF, OCF and OF.

3.3 *Material properties*

The material properties have been established for each of the key strata across the site *(Table 5)* from laboratory based testing. Details of all laboratory testing are provided in the Contractor's Final Factual Report (Norwest Holst, 2009).

3.3.1 *Plasticity*

Plasticity characteristics have been evaluated from Atterberg Limit tests conducted on soil samples from the FF, LCGF and OCF strata encountered in all six boreholes. The results have been plotted on a plasticity chart (*Figure 5*) and demonstrate that all three materials plot above the 'A line' as either high or intermediate plasticity clays (CL to CI).

The greatest variability in plasticity was observed in the glacial till samples resulting from the locally variable percentages of sand, silt and clay sized particles. Three tests undertaken on the OCF show that 2 samples were intermediate plasticity clays and the third samples to be low plasticity clay. Only one sample from the OF was suitable for atterberg limit testing. This sample was an intermediate plasticity clay although is unlikely to be representative of the behaviour of the full geological unit.

3.3.2 *Soils and rock strength characteristics*

Soils strength characteristics have been assessed for samples from the FF and OCF. The peak and residual strength testing for the FF was undertaken using both undrained triaxial cell tests and standard shear box tests. Additional residual strength tests were conducted on remoulded samples using ring shear tests.

Strength testing on samples of the OCF was conducted using a standard direct shear box. A summary of the testing results is provided in *Table 6* below.

Rock strength characteristics have been assessed for rock core samples from the LCGF, OCF and OF using direct shear, point load and unconfined compressive strength tests. A summary of testing results is provided in *Table 7* below.

Material	Peak strength		Residual strength		Test type
	c' (kN/m²)	Ø' (°)	c' (kN/m²)	Ø' (°)	
FF	13-19	24.5-33.5	3.8-12	19.5-33.5	Direct shear box
FF			0	20-29	Ring shear
FF	5-101	3-34.5			Triaxial testing
OCF	23-130	15-34.5	3-29	8-31	Direct shear box

Table 6. Summary of soil strength characteristics

Material	Direct Rock Shear		Point load		UCS
	Peak (MPa)	Residual (MPa)	Is	IS50	
LCGF	0.489	0.474	0.04-1.04	0.06-1.25	
OCF	0.359-0.736	0.304-0.893	0.05-1.0	0.04-1.36	9.48-24.6
OF	2.412	2.229	0.03-0.69	0.05-0.87	

Table 7. Summary of rock strength characteristics

3.4 *Landslide ground model*

The geology, material properties and groundwater characteristics have been combined with surface geomorphological mapping and ground movement monitoring to develop a conceptual landslide ground model for the site (*Figure 6*); combining these independent lines of evidence provides a robust basis for verifying the ground model and mechanisms of failure which significantly improves confidence with the model. A systematic and integrated assessment of these data confirms two principal mechanisms of landslide movement:

- A deep-seated translational landslide.
- A shallow mudslide mechanism.

3.4.1 *Mechanisms 1- deep-seated translational landslide*

Interpretation suggests a deep translational landslide shear surface is present toward the base of the OCF where observations of fissures, fractures and slicken-sides were recorded in BH2, BH5 and BH6. The surface geomorphology reveals the translational landslide has developed in a series of large landslide blocks with clear bench and scarp topography which in some instances are characterised by reverse slopes. This has allowed ponding to develop and there is also poor drainage of water from the ground surface. The deep landslide complex currently terminates at the existing landslide headscarp of Knipe Point. Movement along this shear surface is controlled by groundwater pressures acting on the basal shear surface and the long term effects of coastal erosion removing toe support from the sea cliffs and lower landslide blocks.

3.4.2 *Mechanism 2- shallow mudslide*

A second upper shear surface is proposed within the softer till deposits which extend over the deeper landslide blocks. This shallow mudslide complex is affected by a higher perched water table recorded in the tills (see *Section 3.2*). Geomorphological evidence suggests that the mudslide complex is draped over the translational landslide blocks and extends landward towards the headscarp at Knipe Point where the most recent mudslide activity has occurred.

4 Slope Stability Assessment

4.1 *Slope stability model*

4.1.1 *Introduction*

Slope stability modelling was undertaken using the Morgenstern and Price method, which provides a Factor of Safety (FoS) for a slope under given conditions; the method is appropriate for translational failure surfaces of the type confirmed at Cayton Cliff. A slope with a FoS of 1.0 is at marginal stability and for an existing landslide would be the known field conditions at the point of mobilisation. A FoS of >1 is a theoretically stable slope, while a FoS <1 is a theoretically unstable slope. A factor of safety of 1.3 is deemed an appropriate level of stability for design as it allows for some natural variation in shear strength, slope characteristics and material properties (ref BS 8031).

4.1.2 *Location of cross section and alignment with boreholes*

To develop a slope stability analysis model a representative cross section line was selected along the central axis of the Cayton Bay landslide as revealed by the geomorphology (*see Figure 1*). The section line was surveyed by the Contractor using standard survey methods (*see Section 2.5*). The location of boreholes is offset by various distances from the section line. These have been projected onto the section line accounting for the local dip and strike of key strata marker horizons.

The section line is not necessarily orthogonal to the coastline and in certain locations is not perpendicular to the slope morphology. Whilst care has been taken when reconciling subsurface interpretation, landslide mechanisms and topography it should be noted that a small change in the orientation of the section line has a negligible impact on the stability of deep shear surfaces.

4.2 *Model parameters*

4.2.1 *Model stratigraphy*

The slope stability analysis model is based on information collected from BH2, BH5, and BH6. The stratigraphy has been simplified from the landslide ground model presented in *Figure 6*. These simplifications include a thinning of the LCGF through the site and removal of local topographic effects as these cannot be modelled with any certainty. Sensitivity analysis of the simplified model showed that these changes have negligible impact on the performance of the model.

The geological dip and strike has been calculated from the borehole records using the base of the OCF as the marker horizon. The calculations suggest a dip of 3.6 degrees SE with a calculated dip bearing of 157.9 and a strike of 67.9 degrees. These results appear consistent with an apparent seaward dip which illustrated in the landslide ground model (*Figure 6*).

4.2.2 *Material properties*

The material properties adopted for the landslide ground model were derived from the laboratory testing data and previously published data on the geotechnical properties of mudrocks (Cripps & Taylor, 1981) and glacial tills (Clark & Guest, 1991). Following analysis of these data sources the geotechnical parameters selected for the preliminary stability modelling are summarised in *Table 8* below.

Stratigraphic unit	**Unit weight**	**Residual shear strength**	
	γ (kN/m³)	**c' (kN/m²)**	**Ø' (°)**
FF	18	0	25
LCGF	18	0	45
OCF	18	0	14
OF	20	0	45

Table 8. Summary of geotechnical properties derived for slope stability modelling

4.2.3 *Groundwater*

Two groundwater tables were incorporated in the slope stability model to account for the findings of the site investigation (*see Section 3.2 and Figure 4*). These comprise:

- a deep water table with hydraulic continuity through the LCGF, OCF and OF, and
- an upper perched water table within the glacial tills (FF).

The elevations of the water tables used in the stability analysis were based on the monitoring records obtained in the period December 2008 to March 2009 when no major displacement of the Cayton landslide complex was observed or recorded. It is noted that the elevation of water tables will fluctuate depending on antecedent effective rainfall and complex hydrogeological responses, and are likely to have been higher at the time of landslide re-mobilisation in April 2008. By definition, higher groundwater tables translate to greater excess porewater pressures which ultimately trigger landslides and ground movement (see *Section 4.3.3*).

4.3 Slope stability analysis results

4.3.1 *Analyses of existing ground conditions- undefined shear surface*

Initial modelling was undertaken to investigate the proposed landslide mechanisms of deep failure in the OCF and shallow failures within the FF. The models assessed the optimum shear surface within the landslide cross section but without predefining the depth or shape of shear surface. The initial stability analysis was conducted using the parameters as outlined in *Table 8 (Section 4.2.2)*.

The model confirmed the landslide mechanisms anticipated from the knowledge of movement in the boreholes and from the geomorphological mapping, as explained in *Section 3.4*. In summary this comprises:

- a shallow mudslide seated in the till from Knipe Point had the lowest FoS in the shallow slope analysis *(Figure 7), and*
- a deep translational failure of the whole slope from Knipe Point seated along the base of the Oxford Clay and toeing out beneath the current beach had the lowest FoS in the deep slope failure analysis *(Figure 8)*.

4.3.2 *Analyses of existing ground conditions- pre-defined shear surface*

Three basal shear surfaces were then predefined within the stability model based on the initial modelling results described above in *Section 4.3.1*, as well as observations and monitoring records from the ground investigation.

These three surfaces were designed to allow analysis of the following landslide mechanisms (Figure 9):

- ***Mechanism 1*** – a deep translational failure along the base of the OCF extending from the headscarp of Knipe Point to beneath Cayton beach.
- ***Mechanism 2*** – a deep translational failure along the base of the OCF extending from the centre of the existing landslide complex in Cayton Cliffs to Cayton beach.
- ***Mechanism 3*** – a shallow mudslide within the superficial glacial deposits extending from the headscarp at Knipe Point to the base of the existing sea cliff at Cayton Bay.

Sensitivity analyses were undertaken on the material properties of both the OCF and FF to assess the potential shear strength parameters at failure for all three mechanisms. The results of this sensitivity analysis are summarised in *Tables 9 and 10*.

Sensitivity analysis of the three potential landslide mechanisms demonstrates that minor alterations in the residual phi' value may cause a significant reduction in the FoS for both deep translational landslide mechanism and shallow mudslide failure mechanism. Site records from the ground investigation, site monitoring and previous mapping studies confirm that the existing landslide complex is only marginally stable in its current condition. Back analysis of the current condition would therefore suggest an operational residual phi' value of 12.5 degrees for the OCF and an operational residual phi' value of 20 for the FF.

OCF Residual strength		**Factor of Safety**		
Ø' (°)	**c' (kN/m²)**	**Mechanism 1**	**Mechanism 2**	**Mechanism 3**
15	0	1.23	1.27	1.33
14	0	1.15	1.18	1.33
13	0	1.08	1.10	1.33
12.5	0	1.04	1.06	1.33
12	0	1.00	1.02	1.33

Table 9. Slope stability sensitivity analysis varying the residual strength properties of the OCF

FF Residual strength		**Factor of Safety**		
Ø' (°)	**c' (kN/m²)**	**Shear surface 1**	**Shear surface 2**	**Shear surface 3**
25	0	1.23	1.27	1.33
22	0	1.22	1.26	1.15
20	0	1.21	1.26	1.03
18	0	1.21	1.25	0.92

Table 10. Slope stability sensitivity analysis varying the residual strength properties of the FF

4.3.3 *The effect of groundwater variation on the landslide system*

The stability model, with pre-defined shear surfaces and operational residual phi' values (as described above), has been used to assess the potential implications of increased groundwater levels on the stability of Cayton Cliff landslide complex; the analysis provides an indication of the sensitivity of the various mechanisms to seasonal and episodic increases in groundwater level, and the potential impact of increased winter rainfall on groundwater levels due to predicted climate change.

Sensitivity analysis was undertaken varying both the upper water table (WT1) and the deeper water table (WT2). The analysis considered groundwater levels from 1m to 5m above the measured levels for WT1 and from 1m to 3m above measured levels for WT2. A summary of the impacts on the factor of safety is provided in *Table 11*.

The sensitivity analysis demonstrates that only marginal rise in the groundwater level in WT1 was required to reduce the FoS of shallow failure mechanisms to below 1. A rise of 3m in the groundwater level in WT2 was required to reduce the FoS of deep failure mechanism to below 1.

		Modelled groundwater level				
Mechanism 3	**WT1**	**measured**	**+1m**	**+2m**	**+3m**	**+5m**
	FoS	1.035	0.998	0.961	0.927	0.862
Mechanism 1	**WT2**	**measured**	**+1m**	**+2m**	**+3m**	**+5m**
	FoS	1.04	1.03	1.01	0.99	

Table 11. Slope stability sensitivity analysis of potential elevated groundwater scenarios

4.3.4 *The effect of coastal erosion on the landslide system*

The stability model was analysed to simulate the effect of a 1m, 5m and 10m recession of the toe of the landslide due to the effects of coastal erosion. The results demonstrate that the deep landslide mechanism 1 is relatively insensitive to the effects of coastal erosion and toe undercutting of the magnitude indicated. Further modelling indicated that at least 40m of toe erosion and recession would be needed to reduce the current factor of safety of the deep failure mechanism from 1.04 to unity.

4.3.5 *Retrogression of the landslide headscarp*

Slope stability analysis was also conducted of the potential retrogression of landslide mechanisms 1 and 2 using the operational residual phi' values described in *Section 4.3.2* and pre-defined shear surfaces which extend 40m behind the existing landslide headscarp (see Figure 9). The analysis considered both the measured and potential groundwater levels as described in *Section 4.3.3* and the results are summarised in *Table 12*.

Modelling results also demonstrate that a retrogressive shallow mudslide failure (mechanism 3) is only marginally stable under the measured groundwater conditions and therefore only a modest rise of 2m in the water table is required to reduce the FoS below 1.

		Modelled groundwater level						
Mechanism 3	**WT1**	**measured**	**+1m**	**+2m**	**+3m**	**+5m**		
	FoS	1.052	1.01	0.98	0.94	0.87		
Mechanism 1	**WT2**	**measured**	**+1m**	**+2m**	**+3m**	**+5m**	**+6m**	**+10m**
	FoS	1.12	1.11	1.10	1.09	1.07	1.06	1.02

Table 12. Slope stability sensitivity analysis of landslide retrogression under potential elevated groundwater scenarios

Retrogression of a deep-seated translational landslide (mechanism 1), however, is currently marginally stable under the measured groundwater conditions (FoS = 1.12). Elevated groundwater level scenarios are less effective in reducing the FoS to a critical point of failure. The potential for a deep-seated retrogressive failure at the landslide headscarp could therefore be considered to be relatively low compared with the shallow mudslide mechanism; this is supported by observations since early 2008 of relatively small localised collapses, mudslides and mudflows on the headscarp.

4.4 Conclusions of stability analysis

The results of the stability analysis verify the landslide ground model and failure mechanisms presented in *Section 3.4*. The integration of the various independent observations and data presented in Sections 2-4 has significantly improved understanding and confidence about the landslide mechanisms and causes of failure at Cayton Cliff. The stability analysis has confirmed the relative importance and sensitivity of various controlling parameters governing the stability of the landslide complex, as follows:

- The deep failure mechanism is governed by the subsurface geometry of the sliding mass and the residual friction angle and groundwater pressures acting on the basal shear surface (12.5°); fluctuations in groundwater levels of the order of several metres reduce the factor of safety to unity and have been identified as the principal cause of failure and displacement of the recent landslide remobilisation; the deep landslide mechanism is less sensitive to the short-term effects of marine erosion and recession at the toe of the landslide although in the long-term toe erosion is clearly significant.
- The shallow mudslide mechanism is governed by the steeper surface slope geometry and shear strength acting on the relatively shallow failure surfaces and is sensitive to relatively small fluctuations in seasonal groundwater levels.

Since the mobilisation of the Cayton Cliff landslide in April 2008 a number of alternative hypotheses of the cause of the landslide have been pursued by stakeholders and the media. These include possible leakages from existing drainage infrastructure i.e. Osgodby reservoir, mains and foul water supply to Knipe Point, McCain's effluent discharge pipeline to the north of Knipe Point, and the impacts of the A165 bypass construction through Osgodby some distance landward of the site. We are aware through the Cayton Bay Landslip Management Group that investigations carried out by others have not revealed any source of leakage or impact on the natural groundwater regime.

Based on the findings of the ground investigation and stability analysis presented herein it is unlikely that these human-induced effects are a significant contributing factor to the large-scale remobilisation and potential ongoing instability at Cayton Cliff which can be fully explained as a natural consequence of the unique ground conditions, groundwater regime and episodic nature of deep-seated coastal landsliding which is a principal characteristic of the long-term evolution of the site.

It is noted, however, that groundwater seepage from the Knipe Point headscarp may give rise to localised erosion and failures of the headscarp and that should uncontrolled drainage occur, such as from soakaways, instability of the headscarp will be exacerbated; this particular issue was first reported in the coastal strategy study (HGL, 2002).

5 Landslide Potential and Risk

5.1 Landslide potential scenarios

A report undertaken by HGL on behalf of the National Trust (Halcrow 2008) identified future scenarios which could impact the site in the future and pose significant levels of hazard and associated risks. The risks posed by each scenario were assessed using a risk matrix approach which combined qualitative levels of impact and their associated likelihood of occurring over the next 5 years.

The scenarios comprised:

- Scenario 1 - Natural degradation of oversteepened headscarp to a more stable profile, assumed to be 28º
- Scenario 2 - Seasonal winter displacement of the landslide system leading to headscarp failure and recession
- Scenario 3 - Continuous displacement of the landslide system leading to headscarp failure and recession
- Scenario 4 - Rapid failure and recession of the headscarp due to the presence of weak soils and excess groundwater pressures
- Scenario 5 - Runout of the landslide toe

Whilst this initial assessment provided a baseline risk assessment of the causes and effects of landslide behaviour, the mechanisms and principal causes of landsliding could only be inferred from the surface geomorphological evidence, expert judgement and previously published geological data.

Based on the findings of the recent ground investigation and monitoring records obtained from the site since May 2008, a review and update of the landslide potential risk scenarios is presented below. A particular point of note is that the surface monitoring results do not provide evidence of ongoing continuous displacement of the main Cayton Cliff landslide assumed in Scenario 3 above, therefore, this scenario is no longer considered credible. Further, the detailed knowledge of the ground conditions, mechanisms and causes of landsliding presented herein provides new evidence and improved confidence for refining the landslide potential scenarios, as follows:

- Scenario 1 - Natural degradation of oversteepened headscarp to a more stable profile, assumed to be 28º
- Scenario 2 - Seasonal displacement of the Cayton Cliff deep-seated landslide removing support to the headscarp
- Scenario 3 - Deep-seated failure and recession of the headscarp fronting the A165
- Scenario 4 - Rapid failure and recession of the headscarp at Knipe Point
- Scenario 5 - Runout of the landslide toe

The following sub-sections provide further description of the revised scenarios.

5.1.1 *Natural degradation of the oversteepened headscarp at Knipe Point (Scenario1)*

The widespread landslide movements which occurred in April 2008 have led to the unloading (loss of support) and oversteepening of the headscarp at Knipe Point which is presently near vertical. As a consequence the angle of the headscarp is greater than the angle of internal friction for the FF. It is therefore anticipated that the headscarp will continue to degrade through localised failures and headscarp recession until the angle of repose is reduced to a more stable position. The process of degradation may occur over many tens of years following the initial oversteepening event.

5.1.2 *Seasonal displacement of Cayton Cliff deep-seated landslide (Scenario 2)*

Seasonal increases in groundwater levels are the most likely cause of ground movement and less frequent landslide events. At a number of coastal landslide sites across the UK, studies have established significant relationships between ground movement rates, groundwater levels and rainfall events. Where these involve ground displacement and associated groundwater tables at significant depth (greater than 30 mbgl) relatively long antecedent rainfall conditions are often required to significantly raise groundwater levels Moore *et al*., 2007.

At present there are insufficient data from the site to assess the relationship between rainfall, groundwater and ground movement which should be established to inform revised hazard and risk assessment and early warning of landslides. However, slope stability modelling has shown that the deep-seated translational landslide mechanism is sensitive to relatively small changes in groundwater levels. Such increases are likely to be episodic, linked to extreme climatic events, but the effects of climate change and other factors could result in increased frequency of higher groundwater levels and remobilisation events in the future.

Under this scenario it is assumed that seasonal displacement of the Cayton Cliff landslide system will continue to remove support from the headscarp, thereby, promoting ongoing failure and recession of the headscarp. A significant finding of the ground investigation is the relatively thin unit (5.9m) of glacial till (FF) along the A165 section compared with the much greater thickness (39.8m) present at Knipe Point. The potential failure of FF along the A165 section is consequently limited by the reduced thickness of till and is significantly different from the Knipe Point section.

At Knipe Point, the slope stability assessment assumed that the upper shallow mudslides developed in glacial till (FF) are currently marginally stable. Stability analysis based on a present day FoS of 1.03 for the shallow mudslide mechanism has demonstrated that groundwater levels of the order of 1m above those measured at the site between December 2008 to March 2009 would be sufficient to reduce the FoS below 1. Analysis of the retrogression potential of the mudslide headscarp indicates that groundwater levels of the order of 2m above December 08 to March 09 conditions would result in significant headscarp failure and recession and almost certain loss of further bungalows at Knipe Point in the future. The results therefore suggest that continued mudslide activity and recession along the Knipe Point headscarp is likely during above average and/or prolonged wet winter periods.

5.1.3 Deep-seated failure and recession of the headscarp fronting the A165 (Scenario 3)

Along the A165 section, there has not been any obvious headscarp retreat since the remobilisation of the Cayton Cliff landslide; however, observation of a tension crack and settlement of the road carriageway above the headscarp at its highest point could represent early signs of pre-failure.

Analysis of a potential 40m retrogression of the deep landslide, seated at the base of the OCF, provides a FoS of 1.12 under present groundwater conditions. Sensitivity analysis conducted of increased groundwater levels demonstrates that even with an unrealistic 10m rise in groundwater level from the currently measured water table still remains marginally stable with FoS of 1.02. Deep-seated failure of the A165 headscarp is therefore considered to be unlikely.

The rate and extent of future cliff failure and recession along the A165 section is likely to be less than that experienced recently at Knipe Point (this is confirmed by site monitoring data since May 2008). However, we would note that the risk remains significant due to the close proximity and potential consequences of headscarp recession and collapse of the A165.

5.1.4 *Rapid failure and retrogression of the headscarp at Knipe Point (Scenario 4)*

The recent ground investigation did not reveal any significant variability in the till (FF) sequence between boreholes that might indicate the presence of buried channel sequences or confined pockets of sand where excess groundwater pressures may develop. However, given the limited number of boreholes all located adjacent to the headscarp it is not possible to entirely rule this scenario out although it would appear less credible.

As described above for Scenario 3, deep-seated failure of the headscarp at the base of the OCF is considered less likely than shallow failures within the till.

5.1.5 *Runout of the landslide toe (Scenario 5)*

Scenario 5 considers the potential for landslide run-out events, i.e. the breakdown of landslide blocks, being mobilised into mudslides and flows downslope and running-out over the lower cliffs and beach. This scenario requires a reduction in slope stability by:

- Continued or increased marine erosion of the sea cliff;
- Elevation of groundwater to critical threshold, or
- High intensity rainfall mobilising disturbed surface sediments.

The nature of the surface materials and the field evidence for previous landslide runout events would suggests that these events are likely to occur in the future.

5.2 Revised landslide recession prediction

Predictions of potential headscarp recession distances for the next 5 years have been reassessed for the updated Scenarios 1-4 (*Figure 10*). The mapped recession distances represent worst-case scenarios and indicate what could happen at the site in the future. *Table 13* provides an explanation of the input data used and the rationale behind the recession projections as presented on the map.

5.3 *Potential consequences*

From *Figure 10*, notable impacts are predicted for all scenarios and the potential consequences associated with each are outlined in *Table 14*. The consequences vary depending on the type of failure described, the area of the site potentially affected, and their anticipated impact on vulnerable assets at and adjoining the site.

The key assets at risk are:

- Further loss of land and properties at Knipe Point and the associated risks to residents;
- Structural damage or loss of the A165 road and associated risks to buried services, traffic and the public footpath;
- Structural damage or loss of properties along the A165/ Osgodby and associated risk to residents;
- Severing or loss of major services including water supply, gas mains, electricity supply, a telecom cable and broadband\telephone lines;
- Inundation of the beach and associated risk to the public;
- Loss of the Cleveland Way National Trail and local access to the beach;
- Damage and disturbance of habitat within the Cayton Bay SSSI.

5.4 *Risk assessment*

A revised assessment of the risk of each of the scenarios has been undertaken using a qualitative risk matrix. The risk matrix is used to consider the likelihood of each scenario and the associated impact that a given scenario would have on the site to determine whether the risk of a given scenario is Very High, High, Medium or Low. The risk matrix used in this assessment is included in *Figure 11* and the results of the risk assessment are summarised in *Table 14*.

Landslide Recession Scenario	Headscarp Behaviour Unit	Recession Distance	Input Data and Rationale for Worst Cases
1: Natural degradation of oversteepened headscarp to a more stable profile	Knipe Point	1. 8.4 m	• 1: Largest recession distance required to attain a stable 28° slope profile at Knipe Point from the current active headscarp. 28° is the lowest friction angle for cohesionless loose sand of uniform grain size (Selby, 1993). This calculation makes no account of the effects of vegetation, seepage erosion or development. • 2: The ground investigation has revealed FF thicknesses of only 5.9m along the A165 headscarp (BH1). The FF is underlain by a 73.65m of LCGF which forms the cliff face. Therefore, natural degradation is likely to occur as a result of oversteepening.
	A165	2. 1-2 m	
2: Seasonal displacement of the landslide system leading to headscarp recession	Knipe Point	3. 40.8 m	• 3: The largest, post 1st April 08, mean daily headscarp recession rate (0.27 m d^{-1}) at Knipe Point (monitoring location H10), multiplied by the number of days in the winter season when ground movement could be anticipated (151 days- December to April inclusive, in a non-leap year). • 4: No measured erosion has occurred along the A165 where the thickness of the FF is significantly reduced therefore only limited headscarp recession is anticipated along the A165 section
	A165	4. 5 m	
3: Deep-seated failure and recession of the A165 headscarp	A165	5. 40 m	• 5: Based on analysis of a 40m retrogressive deep-seated failure of the headscarp at the base of the OCF. Analysis suggests that such an event is unlikely under current and modelled elevated groundwater scenarios.
4: Rapid failure and recession of the Knipe Point headscarp	Knipe Point	6. 100 m	• 6: Based on the recession distance experienced at Holbeck Hall 4-8th June 1993, where over 60m of the cliff top was lost overnight, and a further 35m collapsed over the next three days (Moore, 1996). Such a failure may not encompass the entire area mapped, but is more likely to be localised in spatial extent. Results of the ground investigation indicate this scenario is rare and probably not credible at Knipe Point. However, slope stability analysis of the headscarp has shown that failures of up to 40m may be anticipated with relatively small (c 3m) increases in the groundwater level.

Table 13. Landslide recession scenarios

Landslide Scenario	Description	Causes	Likelihood	Impact	Risk Rating	Consequences
1	Natural degradation of oversteepened headscarp to a more stable profile	• Reduction in elevated groundwater levels during the anticipated drier summer conditions • Landslide achieving new equilibrium following recent reactivations	5	4	Very High	• Loss of properties along the Knipe Point headscarp
2	Seasonal displacement of the deep-seated landslide leading to failure headscarp	• A critical groundwater threshold is the key cause of ground acceleration and likely to be associated with high antecedent rainfall conditions following periods of intense or prolonged rainfall.	4	4	Very High	• Loss of properties at Knipe Point • Risk to property owners • Potential loss of sections of the A165, associated traffic disruption and management requirements • Loss of critical services
3	Deep-seated failure and recession of the A165 headscarp	• Recent landslide activity has lead to loss of support to the headscarp fronting the A165. Loss of support may lead to the propagation of a shear surface at the base of the OCF causing retrogressive failure of the headscarp through a deep-seated failure mechanism.	3	4	Very High	• Loss of properties along the A165 • Loss of critical services serving the region • Loss of A165 road and associated traffic disruption and management
4	Rapid failure and recession of the Knipe Point headscarp	• Recent landslide activity has lead to loss of support to the headscarp fronting Knipe Point. Loss of support coupled with excess pore pressures within weak tills could lead to the rapid failure and retrogression of the headscarp.	2	5	High	• Loss of properties along Knipe Point • Potential loss of critical services • Damage to A165 road and associated traffic disruption and management
5	Runout of the landslide toe	• Marine erosion acting on the sea cliff and recently uplifted beach toe may act to remove toe support. This loss of support coupled with periods of heavy rainfall may act to mobilise mudslides which could runout across the beach.	4	3	High	• Loss of beach access • Loss of SSSI habitats • Risk to beach users • Risk to footpath users within Cayton Bay

Table 14. Qualitative risk assessment of future landslide scenarios at Cayton Cliff

6 Appraisal of Engineering Options

6.1 *Cliff management options*

Cliff management options for the site were previously outlined to the National Trust (Halcrow, 2008). In summary these included:

- ***Option 1: Do nothing;*** involving no future works at the site including cessation of the existing monitoring.
- ***Option 2: Managed retreat;*** requiring a continuation of monitoring and investigation activities to improve understanding of the landslide causes and mechanisms to inform stakeholders of potential future landslide hazards, their associated risks, and deal with their consequences as and when they arise.
- ***Option 3: Landslide stabilisation;*** comprising the design and construction of engineering stabilisation measures to control or prevent further ground movement and headscarp recession at the site.

It is not our brief to review the full range of cliff management options as detailed in the bullets above, however, further comment is provided below regarding specific stakeholder interests at the site which will need to be taken into account in decision-making and promoting engineering stabilisation works at Cayton Cliff.

Our brief is to outline the range of engineering measures that could be considered for Option 3, landslide stabilisation. The following identifies in outline the engineering stabilisation measures that could be employed to improve the stability of the Cayton Cliff landslide complex and headscarp; these measures are assessed in terms of their technical, environmental and economic criteria.

6.2 *Site-specific issues and constraints*

Whilst the consequences and risk associated with the potential landslide scenarios outlined in *Section 5* are significant, there are a number of site-specific issues and potential constraints that will require careful consideration during design and construction stages, these include:

- Site access
- SSSI designation of Cayton Cliff
- Shoreline management plan policy for north Cayton Bay

- Landowner interests: Knipe Point and Osgodby Residents, and the National Trust
- Filey Road (A165)

6.2.1 *Site access*

Access to lower Cayton Cliff is restricted to a steep unsurfaced track of limited width, height and load capacity. Access of heavy plant onto the lower slopes will be severely constrained through lack of access by public roads. Consideration could be given to accessing the site from the beach, sea or air. The lower slopes of Cayton Cliff are uneven, ponded, soft and densely vegetated and are not suitable for heavy plant without some form of temporary road construction. The site is of special scientific interest (see below) and permissions for any form of construction and enabling works will be required.

Access above the headscarp is feasible via the A165 and private roads with reasonable width, height and load capacity, however, at Knipe Point, the presence of densely spaced bungalows and landscaped gardens severely restricts access to the headscarp; in order to carry out any major works above the headscarp, bungalows may need to be temporarily demolished and rebuilt.

Access to the headscarp along the A165 is restricted along a short section by the road carriageway which abuts the headscarp and would require traffic management or road closures to allow any significant civil engineering works.

Biological Features	Geological features
Grassland and woodland with pools (Tenant's Cliff)	Cross bedded sandstones above the Millepore Bed (north side of Knipe Point at beach level)
Cliffs and foreshore with invertebrate interest (Osgodby to Cayton Bay)	Cornbrash exposures (beach level south Knipe Point)
Cornelian Bay	Oxfordian Stratotype of 1990

Table 15. Summary areas associated with SSSI status

6.2.2 *SSSI designation*

The area known as Cayton Cliff is designated a Site of Specific Scientific Interest (SSSI) due to its important geological exposures and biological features. Therefore, any measures considered for the site should specifically avoid damage to the key areas and interests summarised in *Table 15*. Of these, the invertebrate interest on the cliffs and foreshore at Cayton Cliff is the main environmental issue at the site.

6.2.3 *Shoreline Management Plan*

The coastal management strategy at the site is outlined in 'North East Shoreline Management Plan 2' published by SBC (2007). This plan recommends a policy of 'managed realignment', as follows:

"by working with natural processes to reduce risks, whilst allowing natural coastal change. This may range from measures which attempt to slow down rather than stop coastal erosion and cliff recession to measures that address public safety issues e.g. promoting the build-up of beach material in front of unstable cliffs, or improving drainage of unstable coastal slopes."

Recognising that the principal mechanism is a deep-seated landslide sensitive to fluctuations in groundwater, the future instability of Cayton Cliff is likely to be perpetuated by coastal erosion processes at the toe. This is likely to accelerate in time due to the effects of climate change and sea level rise. The policy of 'managed realignment' precludes any hard coastal defences being introduced at the site. However, engineering stabilisation of the cliffs will respect this policy whilst at the same time take into account the inter-relationship between landslide debris being deposited at foreshore level and being removed by coastal action.

In connection with shoreline management at Cayton Cliff, we would note the Final Preliminary Report published by Defra in July 2006 on '*Adapting to changing coastlines and rivers*'. The report was commissioned by Defra under the Making Space for Water: Strand SD2 taking forward a new Government strategy for flood and coastal erosion risk management. In this report a preliminary framework highlighting potential key adaptation approaches and tools for implementation is presented along with a shortlist of 'crunch sites'; we would note that Cayton Cliff was not included in the shortlist. It is beyond the scope of our brief to consider the specific merits of adaptation at Cayton and would note this is a matter to be considered in parallel with engineering intervention options. The particular circumstances and challenges at Cayton Cliff to identify an appropriate and sustainable way forward that balances the interests of all stakeholders would provide a good test case for the adaptation toolkit and should be recommended to the Environment Agency.

6.2.4 *Landowner Interests: Knipe Point and Osgodby Residents, and the National Trust*

The residents at Knipe Point have been severely affected by the remobilisation of the Cayton Cliff landslide and ongoing failure and recession of the headscarp. Three bungalows have been demolished to date and further properties are threatened. Understandably, the owners and residents seek to mitigate the effects of further headscarp failure and recession and thereby secure their homes and investments. It is noted that the threat of losing homes due to landslip may also have a significant impact on the health and well being of residents many of whom are elderly.

As landowner of Cayton Cliff, the National Trust's policy for the sustainable management of its coastal sites, known as 'shifting shores – living with a changing coastline' is summarised as follows:

"The next task is to understand the detailed changes at each of our sites and plan ahead with local communities and other partners. Broadly, our options are to 'holding the line' or to adapt to change, either immediately or through 'buying time' with interim measures.

'The Trust realises that sometimes this choice will be hard because there may be adverse consequences whatever the decision. Our policy is to take a long-term view, working with natural coastal change wherever possible. Therefore, we favour adaptation because this will give us the time and space to adjust with the coast."

6.2.5 *Filey Road (A165)*

North Yorkshire County Council is the responsible Highways Authority for the Filey Road which is located above the headscarp at Osgodby. Local and strategic services are located beneath the road carriageway. The road and services are threatened by the ongoing failure and recession of the headscarp which could lead to disruption of services and damage to assets in the future.

6.3 Engineering stabilisation measures

The range of engineering slope stabilisation measures that could be considered to stabilise Cayton Cliff is presented in *Table 16*; the specific objectives of the various measures are provided.

Based on the confirmed ground model and stability assessment, the range of technically feasible engineering measures has been screened to identify those options that are likely to deliver the required improvement in stability of the Cayton Cliff landslide and headscarp. Only those engineering measures considered to be suitable and effective at delivering the required improvement in stability are presented in *Table 17*; a ballpark estimate of the likely construction costs is provided along with the relative advantages and disadvantages of each option with respect to the site-specific issues identified in *Section 6.2*.

The ballpark construction costs are intended for high-level discussion amongst stakeholders; more accurate estimates will need to be provided during design. The ballpark estimates are considered to be relatively 'conservative'; they make allowance for contractor costs, design and supervision fees, and contingency for dealing with access and other potential constraints which have the potential to significantly increase costs. The costs have been estimated from a variety of sources, including construction guidance documents, SPONS database, and from analogue schemes that are presently at feasibility and design stages.

Category	Examples	Objectives
Surface water drainage	• Crest drains • Hydraulic cut-off walls • Trench drains	Designed to collect surface water and prevent percolation to the landslide shear surface where ground movement may be initiated
Groundwater drainage	• Horizontal drains • Vertical drains • Subsurface drains • Pumping wells • Siphon drains	Designed to control and lower groundwater levels where high groundwater levels are associated with ground movement at depth. Drains are designed to prevent the build up of excess porewater pressures at the shear surface.
Earthworks	• Slope regrading • Cliff top excavations	Designed to either reduce the angle of the slope to a position below the friction angle of the failing material or alternatively remove active ground from the site through excavation of the failing soils to a more stable surface.
Slope reinforcement works	• Soil nailing • Rock bolting • Slope anchoring • Wire meshing	Designed to support the existing ground conditions to increase the stability of the slope and anchor or pin the weaker materials to intact bedrock or soils at depth.
Structural solutions at landslide toe	• Retaining walls • Toe protection works • Shear keys	Designed to prevent continued ground movement and loss of slope support by increasing the weight at the toe of the landslide, reduce erosion or undercutting by marine or fluvial processes, prevent further landslide runout or prevent future movement along the landslide shear surface.

Table 16. Summary of Summary stabilisation measures

Table 17. Appraisal of conceptual landslide stabilisation measure

Purpose	Solution	Advantages	Limitations	Estimated cost (£)
1. Lower and control deep groundwater levels within Cayton Cliff and thereby prevent further seasonal and episodic deep remobilisation of Cayton Cliff	Installation of deep drainage wells around or within Cayton Cliff landslide (various options could be considered from gravity drains, pumping or siphon wells)	• Depending on design, potential limited impact on the SSSI both visually and during construction works • Does not impact the surface water table which is critical to SSSI value of site • Prevents loss of support to headscarp • Depending on design access for construction could be from beach level or above headscarp mitigating need to access lower slopes • Most effective measure for achieving desired increase in stability or factor of safety of Cayton Cliff	• Operational costs for pumping and siphon systems although use of gravity drains will reduce this requirement • Maintenance cost to ensure drains are functioning correctly • Uncertainty in the groundwater regime and response to deep drainage due to limited data, and therefore further ground investigation and pumping tests will be required to progress design. • If design requires access to lower Cayton Cliff, temporary works could have adverse impact on SSSI; mitigation measures will reduce adverse impacts • Wells constructed through landslide mass vulnerable to ground movement and shear. • Cost of scheme and sources of funding could be prohibitive	2.5-4M (120 no. 60m deep drainage wells) additional £20,000 (estimated annual maintenance running costs)
2. Stabilisation of the Knipe Point headscarp and prevention of cliff recession	Contiguous concrete bored piles through FF into LCGF beneath	• Prevents further recession (all mechanisms) of the headscarp providing a secure future for cliff top homes • Works would be conducted outside of the Cayton Cliffs SSSI on private land • Engineering works localised to Knipe Point with minimal impact on the Filey Road • Standard design and limited lead time to construction (subject to planning approval)	• Restricted access may require further demolition of properties close to the existing headscarp. These could be rebuilt following works. • Costly construction due to required depth of piles • Works may trigger collapse and recession of the headscarp due to vibration and loading; mitigation measures will reduce this likelihood • Cost of scheme and sources of funding could be prohibitive • Contractor capability for depth of piles could be limited • Technical feasibility of achieving pile depths	4.1M (10m deep CFA piles) 12M (50m deep cored piles)
3. Control of surface water drainage in Cayton Cliff to prevent shallow mudslides	Construction of surface drainage network in Cayton Cliff	• Reduction in surface water runoff causing erosion • Reduction of potential for shallow surface mudslides • Relatively low cost solution • Design relatively straightforward • Will reduce likelihood of major run-out across beach	• Access of plant onto site • Would require ongoing maintenance to ensure correct functioning • Some disruption to protected species within SSSI may be expected, mitigation required to maintain ponded areas • Recent ground disturbance may have fractured natural drainage network and therefore detailed drain survey required to ensure drainage measures would not exacerbate ground movement • Drainage network could be damaged by deep-seated ground movement	50,000-150,000
4. Reduce marine erosion of the sea cliffs preventing long-term unloading of Cayton Cliff	Construction of rock toe revetment – other methods such as beach feeding and control structures might also be considered in line with SMP policy	• Prevents further unloading and decline in stability of Cayton Cliff • Mitigates possible effects of sea level rise increasing toe erosion • Limited excavation works required • Relatively easy access from beach	• Prevention of coastal erosion may impact exposure of geological interest (SSSI) • Negative aesthetic impact for beach users • Health and safety issues concerning public access to open rock structures • Hard structures may contravene SMP policy of managed realignment • Long-term sustainability questionable	4.5M-6.7M

6.4 *Preferred stabilisation options*

Given the complexity of the landslide mechanisms and site constraints associated with working within the Cayton Cliff SSSI the preferred engineering stabilisation options would aim to:

- prevent deep-seated ground movement of Cayton Cliff and re-establish support to the headscarp at Knipe Point and along the Filey Road, and

- prevent shallow failures and recession of the Knipe Point headscarp and stabilise the cliff-top and assets located above the headscarp.

To achieve these objectives with minimal environmental impact at the site the preferred stabilisation options would comprise (*Figure 12*):

- Installation of deep drainage to reduce and control groundwater levels in the deeper water table (WT2).

- Construction of spaced or contiguous concrete bored piles at Knipe Point to isolate the lower Cayton Cliff landslide system from the land above the headscarp.

These measures would act to stabilise the site with the minimal long-term impact on the SSSI and SMP policy and will not involve hard coastal defences or surface drainage measures. Therefore the impacts on the SSSI should be limited to localised and short-term impacts associated with the additional investigation and drainage trials for design, and construction of deep drainage wells. Slope stability analysis has confirmed that these measures will improve the stability of the site by up to 20% (FoS=1.2) which provides a sufficient level of stability for a designed slope (*Figure 13*).

Additional investigation and design of the suitability of deep drainage measures is needed; specifically whether deep drainage wells within the Cayton Cliff landslide or interceptor drainage wells around the headscarp are equally effective at achieving the desired improvement in FoS. The latter option potentially benefits from easier access above the headscarp and would have minimal impact on the SSSI interests at Cayton Cliff. Should engineering stabilisation be taken forward as an viable option, allowance will need to be made for commissioning a hydrogeological investigation and drainage trials to support detailed design – this has been allowed for in the estimation of costs provided in *Table 17*.

The design of spaced or contiguous concrete bored piles to stabilise the Knipe Point and A165 headscarp will also require further design. The principal would be to construct piles through the weak unsupported glacial tills into the underlying more competent Lower Calcareous Grits and Oxford Clay. In order to achieve that the length of piles may need to exceed 50m at Knipe Point significantly increasing costs. Shallower piles may be considered but there is a risk that these could be undermined by failure at the base of the tills and promote a large-scale and potentially sudden collapse of Knipe Point. Alternative options such as soil pinning, slope reprofiling and surface protection measures will also be vulnerable to failure at the base of the glacial tills, potentially undermining the stabilisation measures and causing an larger scale failure of the headscarp than would have occurred in its natural condition. Consequently these measures are not a preferred option.

Additional engineering stabilisation measures such as the construction of deep spaced piles (shear keys) set-back from the landslide toe, beach improvements across the Cayton Cliff frontage and improved surface water drainage could be considered to further improve the stability of the site. However, these measures may have a significant impact on the SSSI and other interests of the site and would increase scheme costs, as they do not provide alternatives to the preferred options described above.

Further work is required to progress preliminary design and evaluate the benefit costs and viability of scheme options which is beyond the scope of this report

7 Conclusions and Recommendations

7.1 *Conclusions*

Halcrow was commissioned by Scarborough Borough Council to undertake a landslide stability assessment at Cayton Cliff including the commissioning and supervision of a ground investigation to determine the subsurface geometry of the Cayton Cliff landslide, groundwater regime, ground conditions and associated geotechnical properties of the soils. The results have been used to construct a conceptual landslide ground model for the site which has been verified by independent sources of data and modelling. The ground model has confirmed with a high degree of confidence that Cayton Cliffs comprises a deep-seated translational landslide system. The origin of the landslide complex is not known but believed to be many thousands of years old dating back to the early to mid Holocene; the evolution of the coastal cliffs forming Cayton Bay is characterised by episodic reactivation of large-scale landslide complexes through time although there are no known historical records of any previous major reactivation of the entire Cayton Cliff landslide complex.

The key landslide mechanisms affecting the site are:

- A deep-seated translational landslide mechanism seated at the base of the Oxford Clay (OCF). Stability analysis confirms ground movement is controlled by the residual strength of OCF and a deep confined groundwater table which generates excess porewater pressures at the basal shear surface; in the long term, loss of toe support through coastal erosion also acts to reduce the stability of the landslide complex.

- A shallow mudslide mechanism seated in the glacial tills (FF) which mantle the solid geology at the site. Stability analysis has demonstrated that ground movement is controlled by an upper groundwater table identified within the glacial tills (FF). Analysis of potential groundwater scenarios has indicated that only a modest rise in the upper water table is required to destabilise the shallow mudslide mechanisms of failure which are responsible for the ongoing failure and recession of the headscarp at Knipe Point.

A review and updated qualitative risk assessment is presented which considers the likelihood and consequences of five potential landslide recession scenarios. These are credible scenarios which may impact the site in the future.

The risk assessment has demonstrated that the potential risk of these events impacting the site is 'high' to 'very high'. The area most at risk is the Knipe Point headscarp and residential development where a number of landslide scenarios have been considered in *Table 14*. Scenarios 1 and 2 involve the continued landward recession of the Knipe Point headscarp which are likely to lead to the loss of further properties. Failure and recession of the headscarp fronting the A165 is considered to be less at risk due to the much reduced thickness of glacial till (FF).

Slope stability analysis has demonstrated that deep-seated failure at the base of the OCF beneath the headscarp fronting the A165 (Scenario 3) is unlikely.

Scenario 4 considers the potential for rapid failure of the headscarp at Knipe Point due to excess pore pressures in the upper groundwater table (WT1). Whilst this event is considered to be very unlikely (rare) such a failure could result in the rapid recession of the headscarp up to 100m inland (similar to that experienced at Holbeck Hall) which would result in significant impact on property and homes above the headscarp, endangering residents, and potential impact on the A165 coastal road and buried services.

This stability assessment has appraised a range of engineering stabilisation measures that could be considered to provide improvement and long-term stability of the site. The appraisal has considered the relative effectiveness of measures to achieve the required improvement in factor of safety and their potential impacts on the site; a key consideration is the potential environmental impact that engineering measures may have on the Cayton Cliffs SSSI.

The primary objectives of engineering stabilisation include:

- reducing the potential for seasonal and episodic deep-seated ground movement of Cayton Cliff, and
- preventing the ongoing failure and recession of the headscarp at Knipe Point.

The preferred stabilisation options to achieve these objectives include:

- the installation of deep drainage to reduce and control groundwater levels in the deeper water table (WT2), and

- the construction of contiguous concrete bored piles along the Knipe Point headscarp to prevent further collapse and headscarp recession.

These measures would improve the factor of safety to an acceptable level of stability for a pre-failed slope of 1.2 and would have minimum impact on the SSSI and other stakeholer interests at the site. However, the costs of promoting such a scheme relative to the benefits could be prohibitive and will depend on identifying sources of funding and successful demonstration of any required benefit: cost assessment processes.

Potential sources of funding for coastal landslide stabilisation may be sought from:

- coast protection act (1972)
- land drainage act (1991)
- private sources e.g. landowners
- highways act (1980)

An application for funding under the coastal protection or land drainage act is likely to be the most appropriate way forward. However, funding contributions from the other potential sources identified above should also be considered.

7.2 Recommendations and forward programme

Key recommendations arising from this report include:

1. a need to maintain and continue monitoring of the surface and subsurface ground movement, groundwater and weather station network which is currently undertaken by the National Trust. The observations and data collected serve a number of purposes:

    - they provide observation and early warning of potential hazards such as signs of pre-failure of the headscarp at Knipe Point and along the A165. Regular updates or site monitoring reports at appropriate intervals throughout the year should be shared with all stakeholders and individuals at risk of cliff instability at Cayton Cliff so that they may take appropriate action and mitigate the risk.

- The ground movement, groundwater and weather data should be analysed to establish any trends in data and the relationships between antecedent rainfall, groundwater, ground movement and landslide event frequency. We would recommend that analysis of such data is undertaken at least once a year.

2. Stakeholder liaison to review the findings of this report and discuss the way forward for managing the cliff instability risk at the site in the near future and longer term. Balancing the needs of all stakeholders is clearly important and a fuller assessment of the range of viable management options for the site should be carried out, including consideration of the Adaptation framework commissioned by the EA (see *Section 6.2.3*)

3. Review funding options for promotion of the preferred engineering stabilisation options and prepare an application for funding under the land drainage act 1991. An outline programme for progressing the design of the preferred scheme is provide in *Figure 14*. Key elements and the critical path of this programme include:

   - Stakeholder liaison

   - Preparation of a project appraisal report and funding application

   - Commissioning of environmental studies early to support additional site investigation and drainage trials

   - Commissioning of additional site investigation and drainage trials early to support preliminary design

   - Preliminary design of stabilisation works

   - Environmental impact assessment of preferred scheme

   - Planning submission

   - Detailed design and construction

References

Clark, A.R. & Guest, S. (1991). 'The Whitby cliff stabilisation and coast protection scheme.' In: Slope Stability Engineering: developments and applications, 283-290.

Clark, A.R. & Guest, S. (1994). 'The design and construction of the Holbeck Hall landslide coast protection and cliff stabilisation emergency works.' Proceedings of the MAFF Conference for River and Coastal Engineers.

Cripps, J.C. & Taylor, R.K. (1981). 'The engineering properties of mudrocks.' The Quarterly Journal of Engineering Geology. 14, (4) 291-309.

Defra (2006). Adapting to Changing Coastlines and Rivers, Making Space for Water: Strand SD2, Taking forward a new government strategy for flood and coastal erosion risk management. Preliminary Report for Defra.

Evans, D.J.A., Owen, L.A. & Robert, D. (1995). 'Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England.' Journal of Quaternary Science, 10, 241-265.

Eyles, N., McCabe, A.M. & Bowen, D.Q. (1994). 'The stratigraphic and sedimentological significance of Late Devensian ice sheet surging in Holderness, Yorkshire, UK'. Quaternary Science Reviews, 13, 727-759.

Fish, P.R, Moore, R., & Carey, J.M. (2006). 'Landslide geomorphology at Cayton By, North Yorkshire.' Proceedings of the Yorkshire Geological Society, 56, (1)

Norwest Holst Soil Engineering (2009). 'Report on Ground Investigation at Cayton Bay Landslip.' Scarborough, Final Factual Report.

Halcrow Group Limited (2001). Cayton Bay Coastal Strategy Study. Report to Scarborough Borough Council.

Halcrow Group Limited (2002). Coastal monitoring programmes 2001/02. Filey and Cayton Bay cliff inspection and condition assessment. Final Report to Scarborough Borough Council.

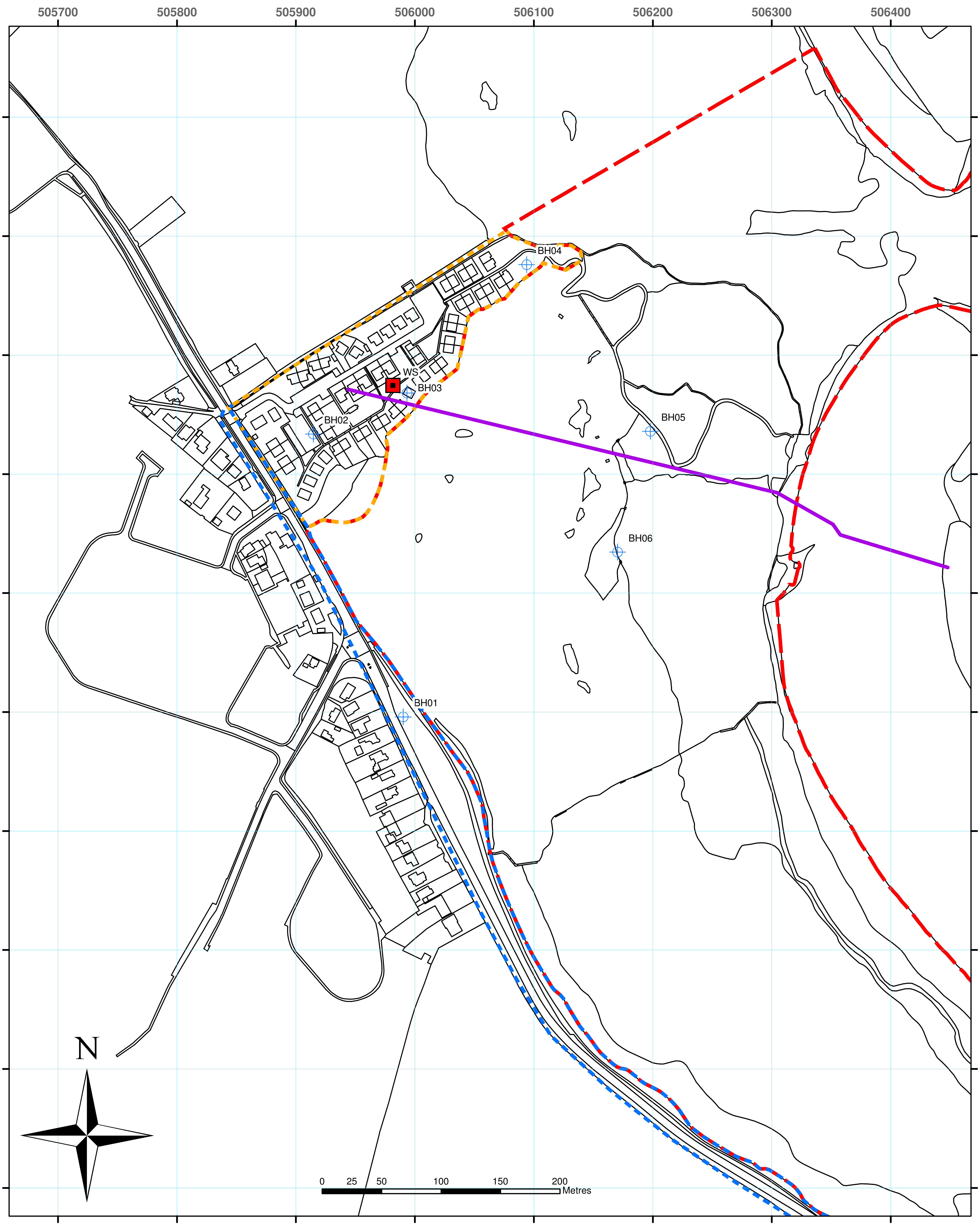
Halcrow Group Limited. (2008). Cayton Cliff, Cayton Bay, North Yorkshire Stability Report and Cliff Management Plan. Final Report to The National Trust

Mills, D.R. (1981). Feasibility study into the possible development of a coastal site at Knipe Point, Cayton Bay, northeast Yorkshire. Unpublished MSc thesis, Department of Geology, University of Leeds.

Moore, R.M., Carey, J.M., McInnes, R.G. & Houghton, J. (2007). 'Climate change so what? Implications for ground movement and landslide frequency.' Landslide and Climate Change, E.d. McInnes, R.G., Jakeways, J., Fairbank. H. & Mathie, E.

Rawson, P.F. & Wright, J.K. (2000). 'The Yorkshire Coast'. Geologists' Association Guide No. 34. Geologists' Association, London. 3rd Edition.)

Scarborough Borough Council (2007) North East SMP2. Report prepared by Haskoning.



Legend

Topographic survey line

Land owner boundaries

Knipe Point Freeholders Ltd

National Trust

North Yorkshire County Council

Borehole

Weather station

Halcrow Group Limited

Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 4562345 Fax +44(0)121 4561569
www.halcrow.com

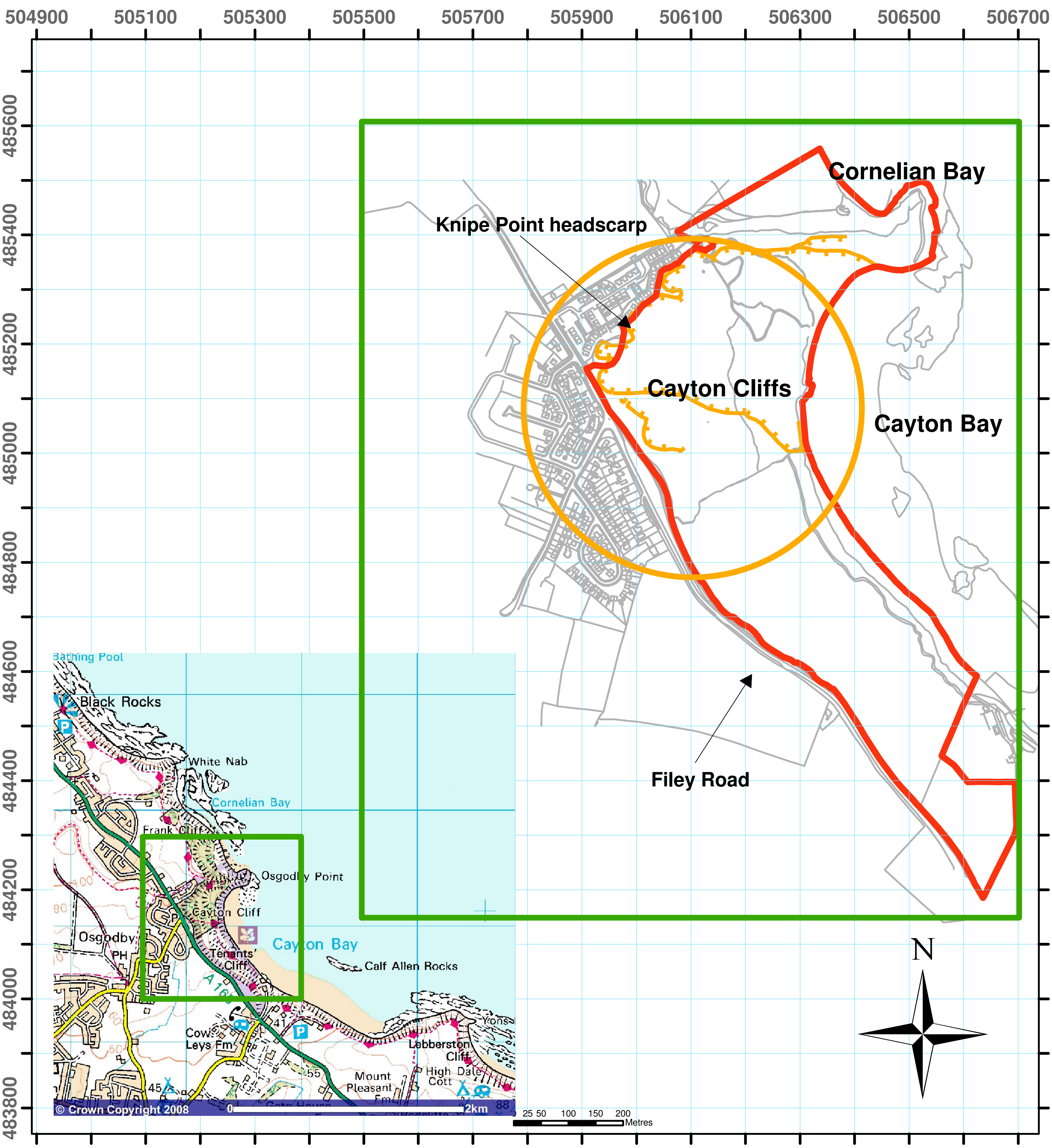
Client

Scarborough Borough Council

Licence info

Figure 1. Land ownership and ground investigation plan

Halcrow



Legend

- National Trust
- Active Landslide Mapped on 3.4.08-9.4.08
- Ground investigation site

Figure 2.
Site Location Plan

Halcrow Group Limited
Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 4562345 Fax +44(0)121 4561569
www.halcrow.com

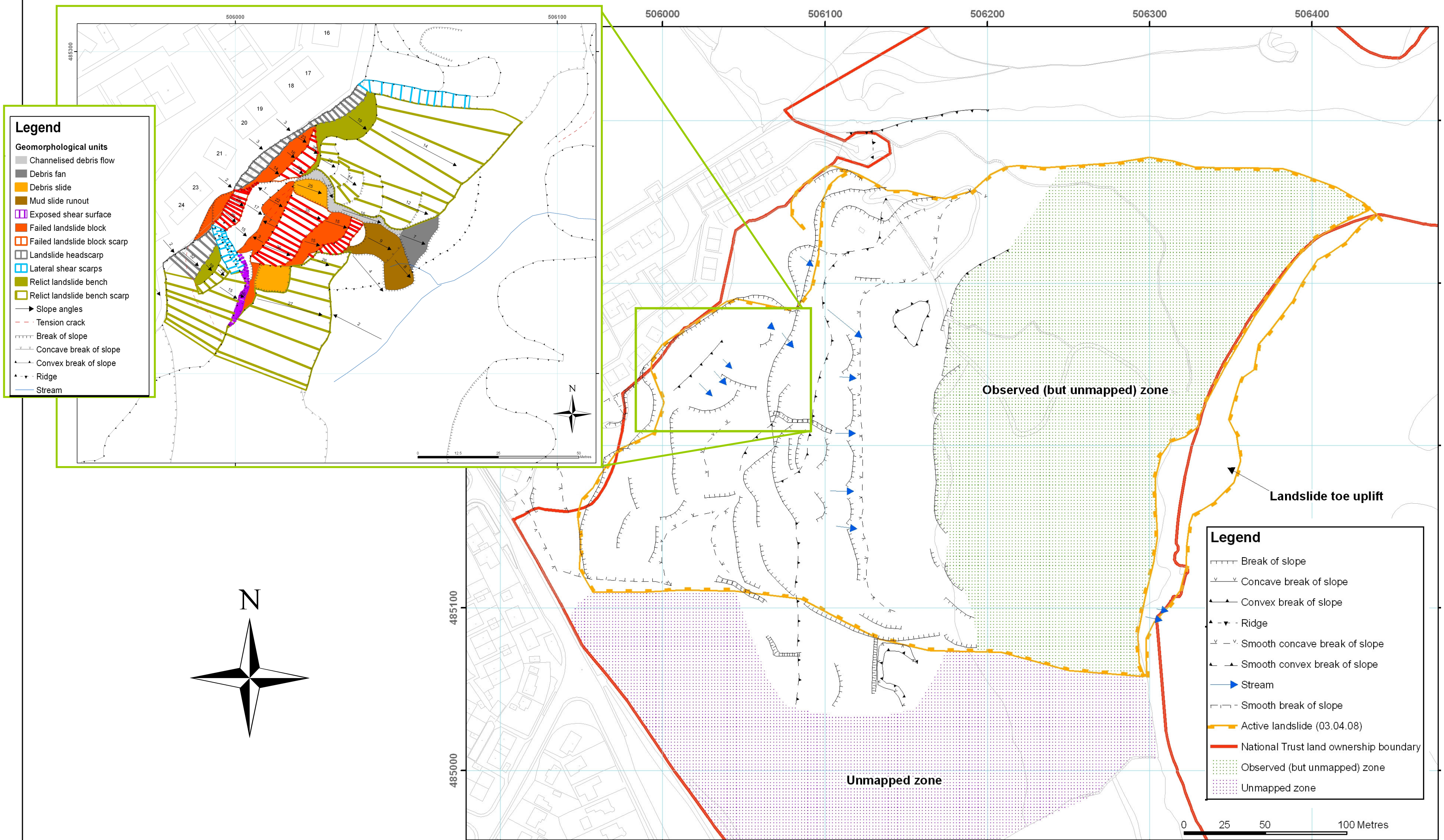
Halcrow

Client

Scarborough Borough Council

Licence info

Figure 3. Geomorphological map



Halcrow

Figure 4. Groundwater monitoring

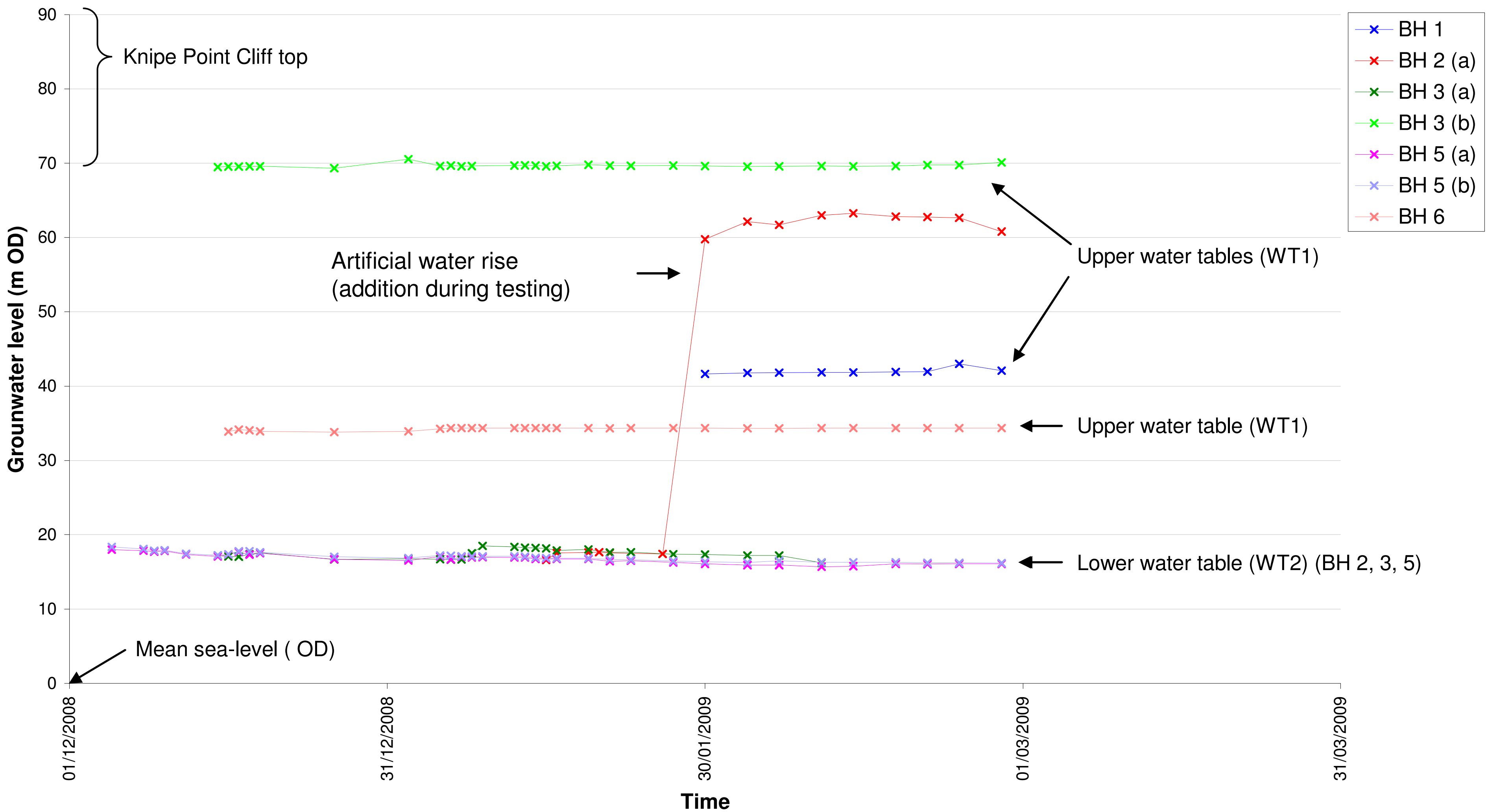


Figure 5. Soil plasticity characteristics

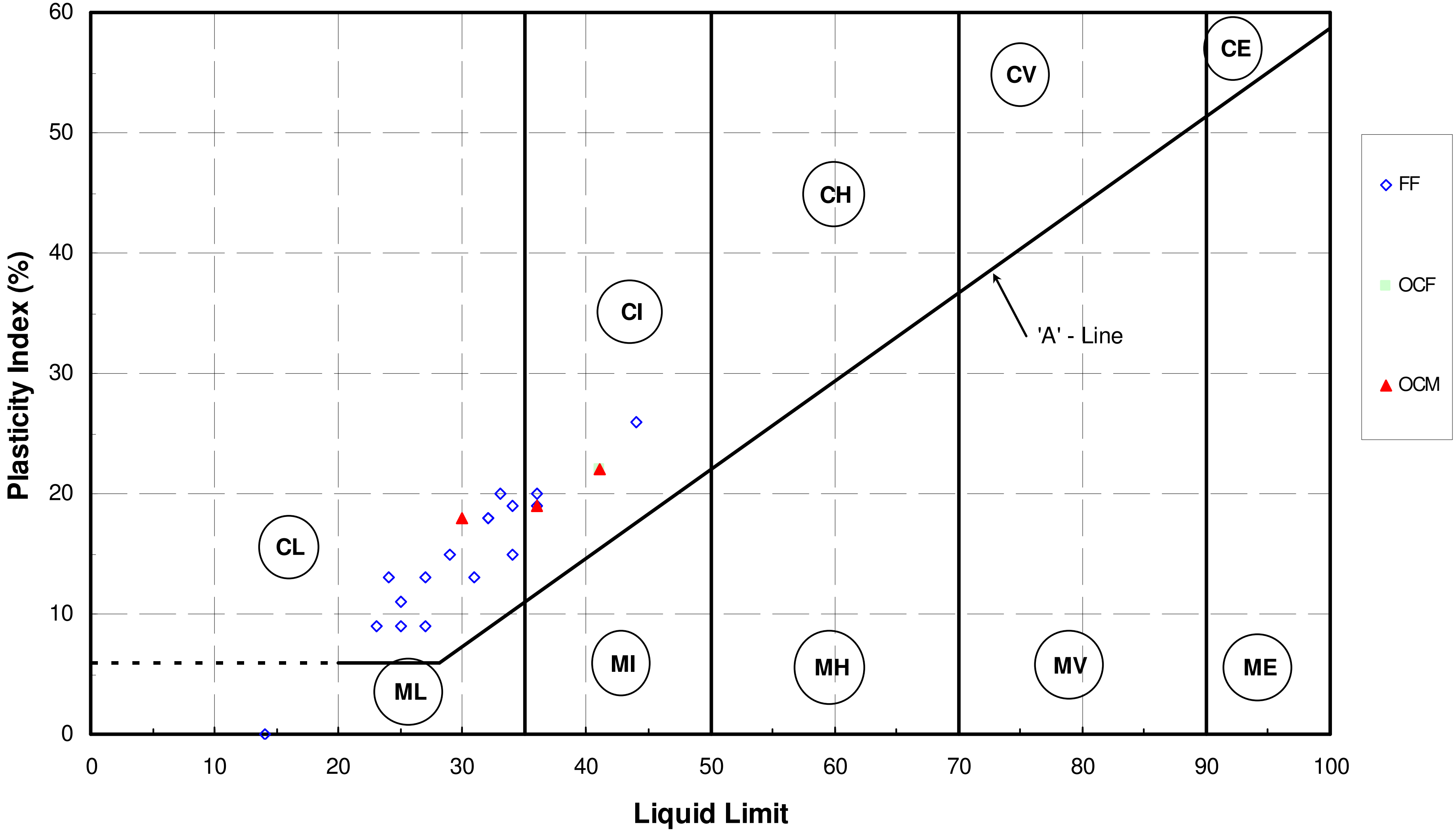


Figure 6. Conceptual landslide ground model

Key- Site materials

		Formation	Description
	FF	Filey Formation	Various sediments of glacial origin
	LCGF	Lower Calcareous Grit Formation	Sandstones and Siltstones
	OCF	Oxford Clay Formation	Mudstones and Siltstones
	OF	Osgodby Formation	Sandstones and Siltstones

Key- Groundwater monitoring and shear surfaces

	Standpipe piezometers
WT	Measured groundwater table
	Proposed landslide shear surface

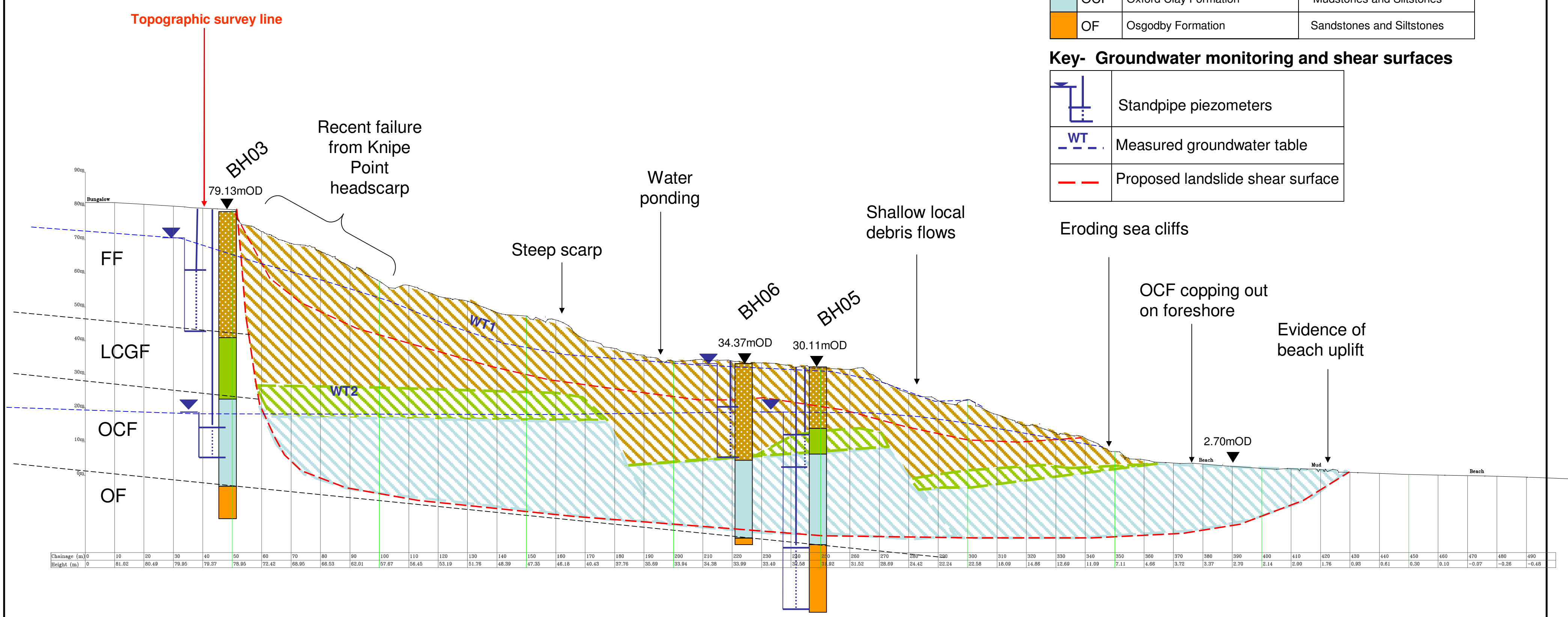
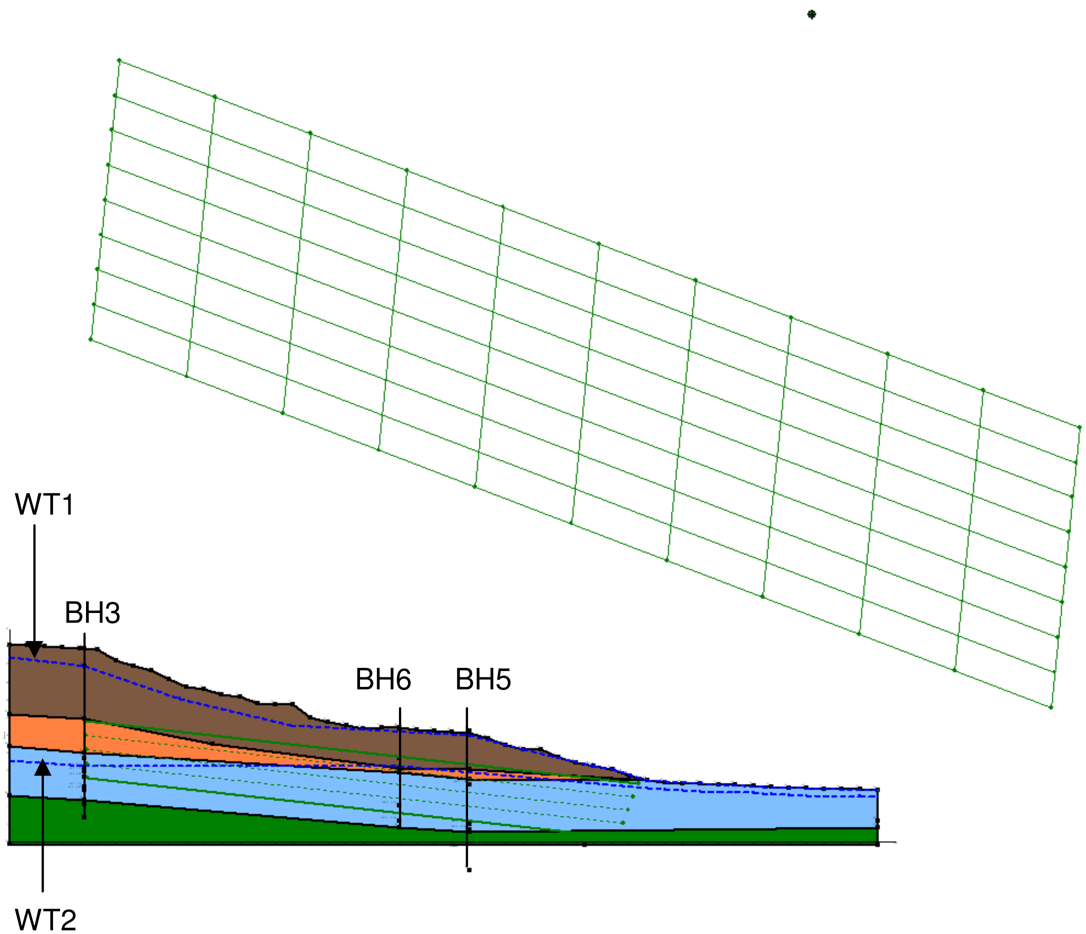


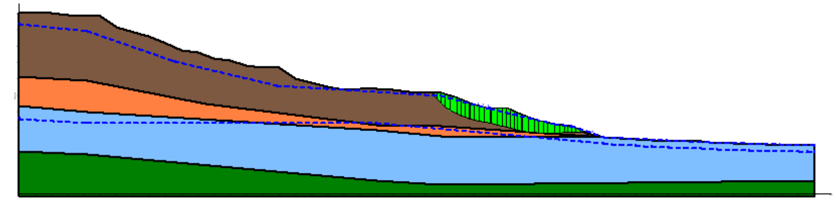
Figure 7. Slope stability modelling, shallow failure

Model set up	Example shear surfaces

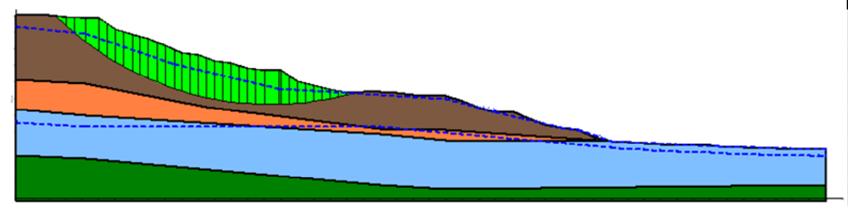
Model set up



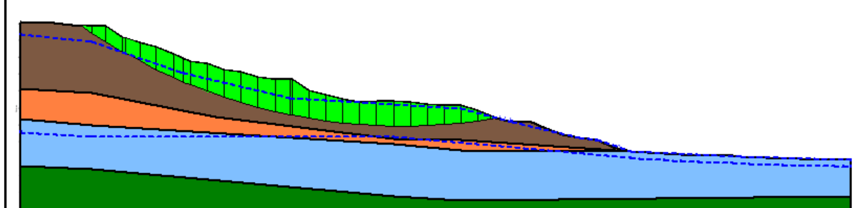
Example shear surfaces



Cliff erosion, Cayton Bay



Mudslide and headscarp retreat, Knipe Point



Shallow mudslide Cayton Cliff

Figure 8. Slope stability modelling, Deep failure

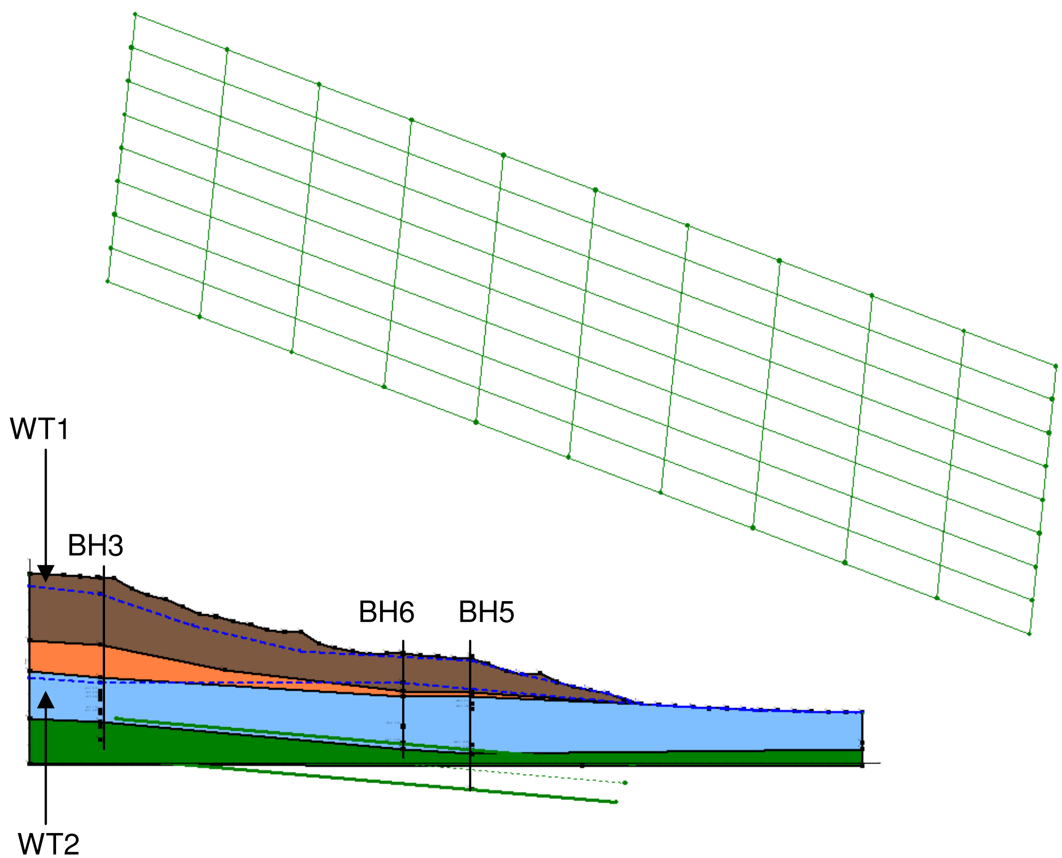
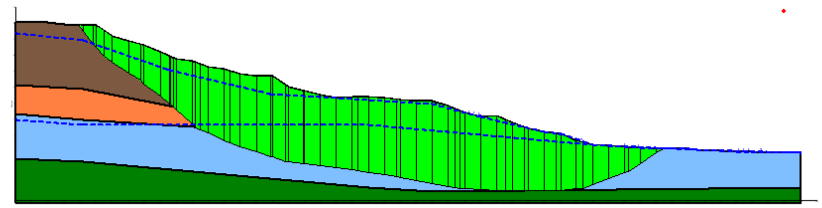
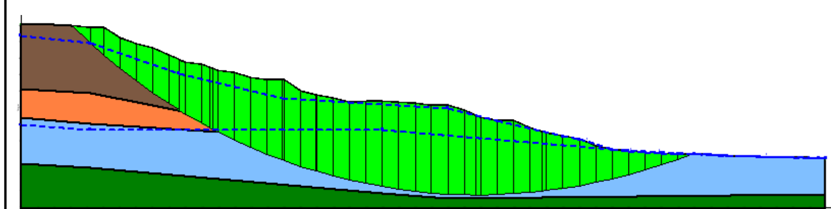
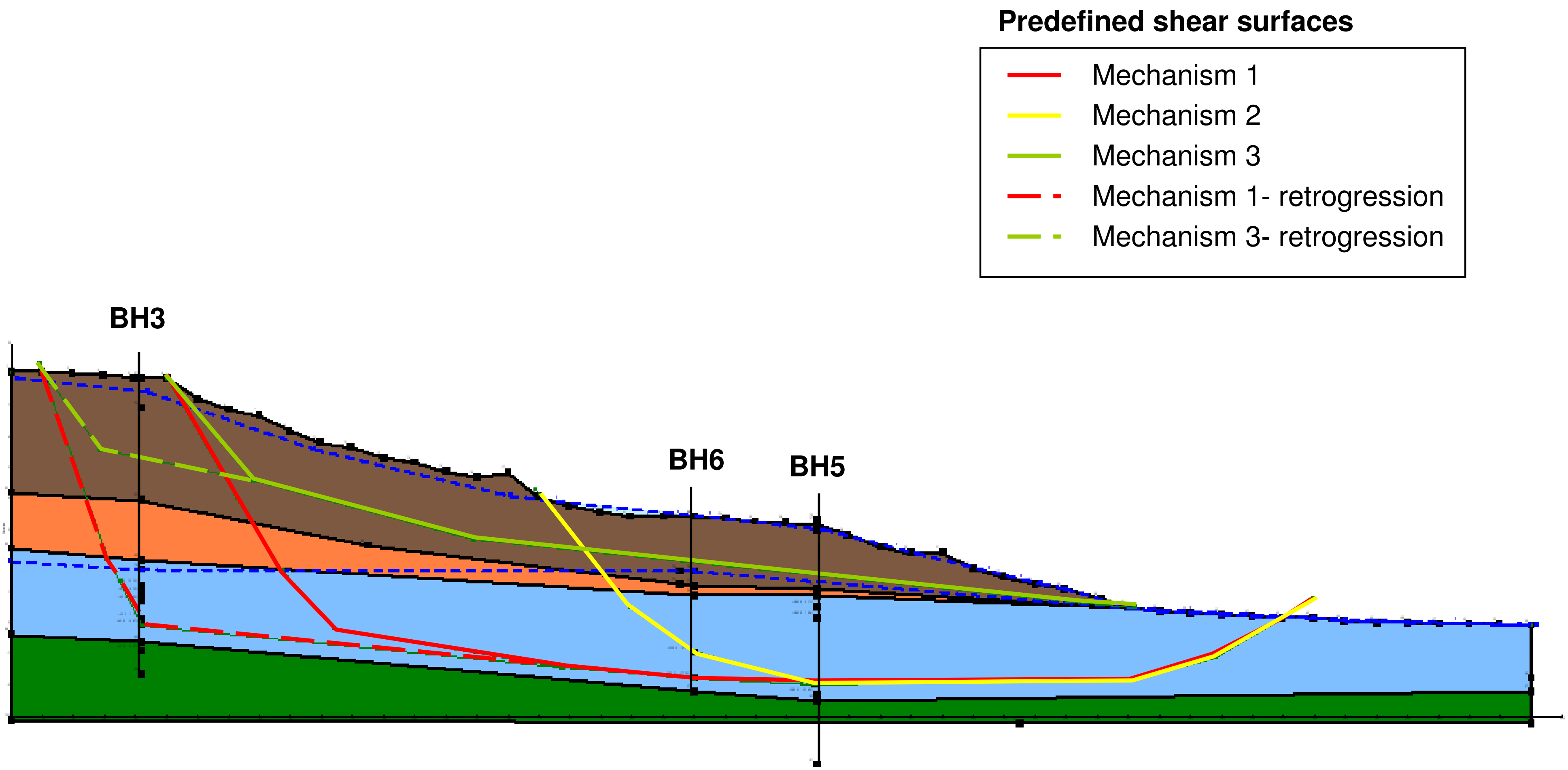
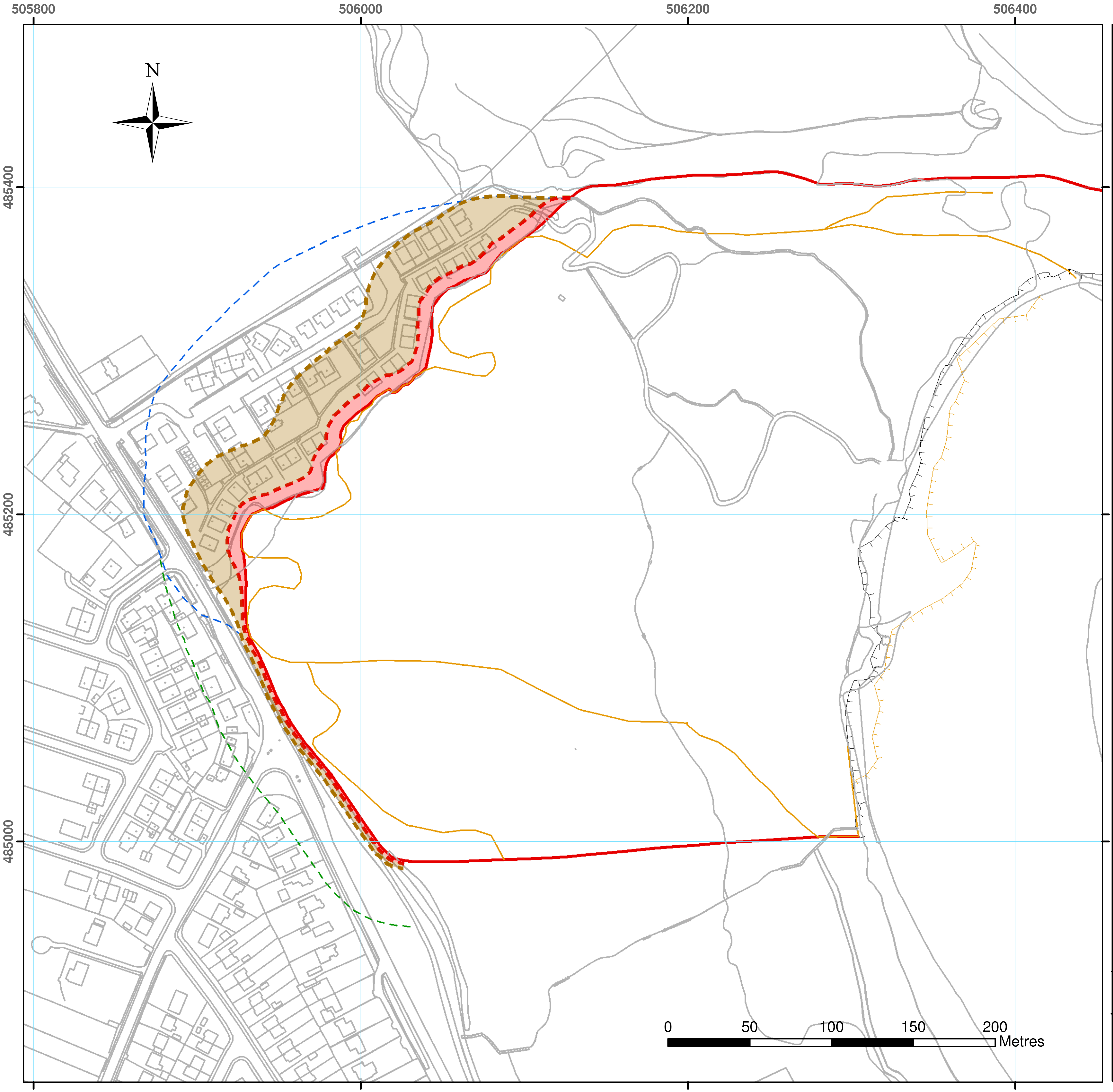
Model set up	Example shear surfaces
	 Deep translational failure seated in the OCF  Deep rotational failure seated in the OCF

Figure 9. Slope stability modelling of landslide mechanisms



Halcrow



Legend

- Active landslide
- Active headscarp & lateral margins
- Toe of beach uplift
- Toe of sea cliff

Landslide scenarios (see table below)

- Scenario 1 potential extent
- Scenario 2 potential extent
- Scenario 3 potential extent
- Scenario 4 potential extent
- Scenario 1 recession zone
- Scenario 2 recession zone

Landslide Scenario	1	2	3	4
Description	Natural degradation of oversteepened headscarp to more stable profile, assumed to be 28 degrees	Seasonal movement of the deep landslide leading to headscarp failure and recession	Deep-seated failure and recession of the A165 headscarp	Rapid failure and recession of the Knipe Point headscarp
Cliff Top Recession Potential	2 to 9m	Up to 40m along Knipe Point headscarp Up to 5m along A165 headscarp	Up to 40m based on slope stability assessment	Up to 100m based on Holbeck Hall landslide analogue
Impact	Significant losses of properties at Knipe Point and the A165	Significant losses of property at Knipe Point potential undermining of A165, damage to strategicand local services	As for Scenario 2	Catastrophic losses of property at Knipe Point. damage to A165, Loss of strategic and local services, local access and risk to life and residents, pedestrians and vehicle occupants
Likelihood	Probable	Possible	Unlikely	Rare
Timing	0 - 5 years (uncertain)	0 - 1 year	0 - 1 year	0 - 5 years (uncertain)

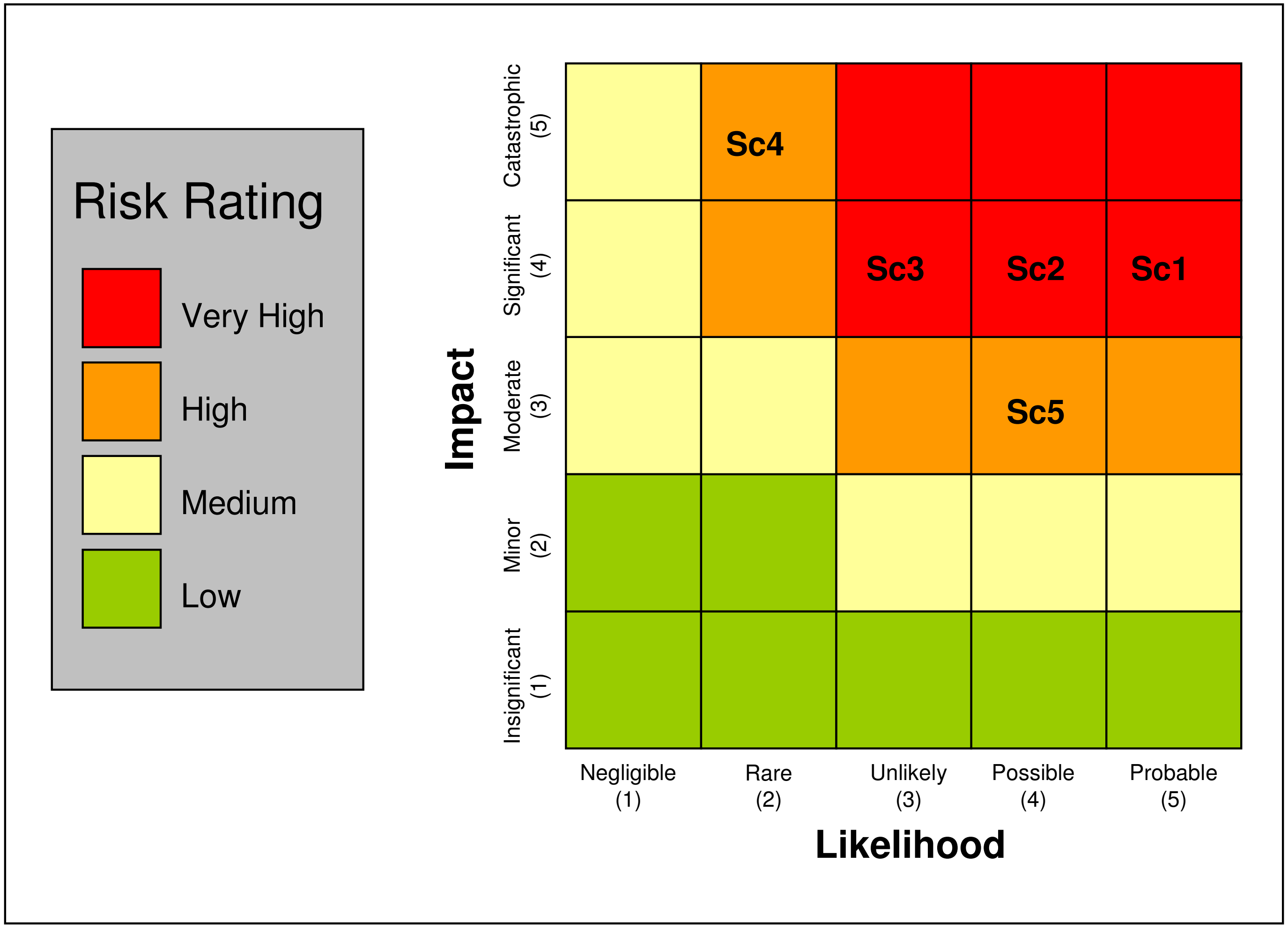
Figure 10
Landslide Recession Scenarios
for Cayton Cliff (April 2009)

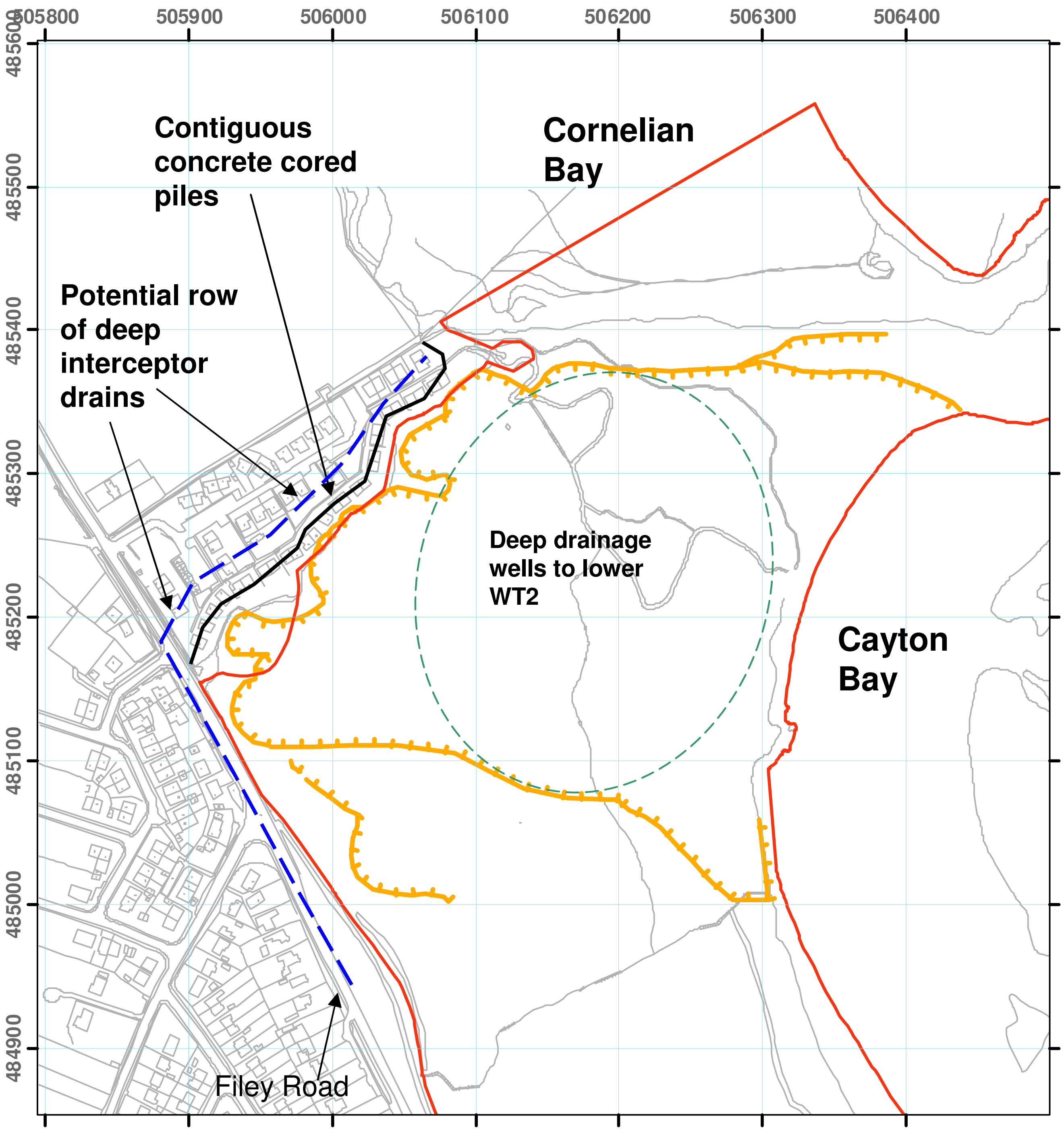
Halcrow Group Limited
Lyndon House, 62 Hagley Road, Edgbaston, Birmingham, B16 8PE
Tel: +44 (0)121 4562345 Fax +44(0)121 4561569
www.halcrow.com

Halcrow

Client
Scarborough Borough Council

Figure 11. Qualitative risk assessment based on the likelihood and impact of landslide potential scenarios





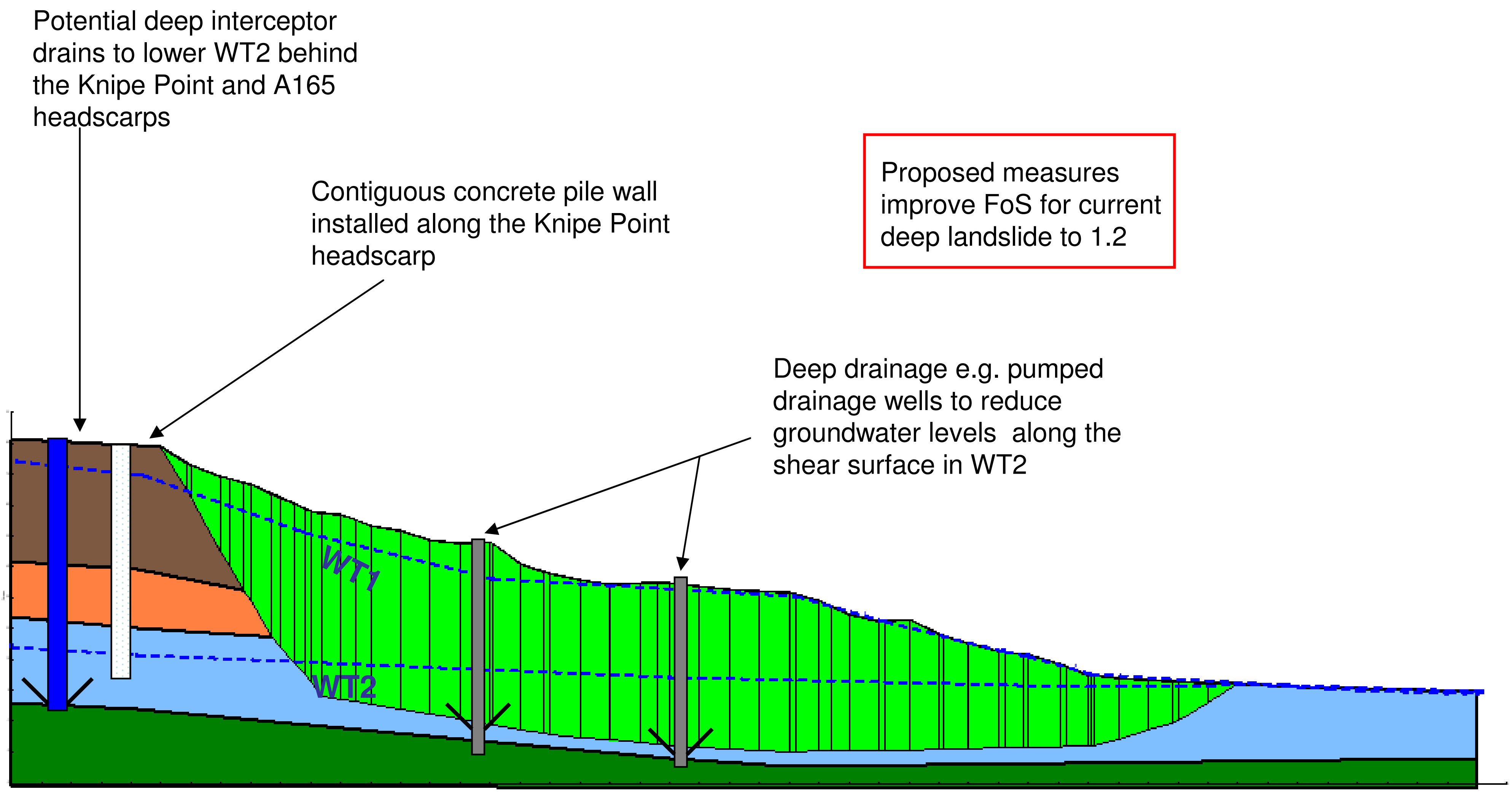
Legend

- cored piles
- deep drainage wells
- deep interceptor drains
- NT ownership boundary
- area of 2008 landslide activity

Figure 12.

Preferred stabilisation options

Figure 13. Preferred stabilisation options cross section



Halcrow

Figure 14. Cayton Cliff Stabilisation Scheme- forward programme of works