Scarborough Borough Council

Hundale Point to Scalby Ness
Scalby Ness Instability
Section One - Data Gathering & Analysis
October 2005

Halcrow Group Limited

Scarborough Borough Council

Hundale Point to Scalby Ness
Scalby Ness Instability
Section One – Data Gathering & Analysis
October 2005

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

Hundale Point to Scalby Ness

Scalby Ness Instability

Section One - Data Gathering & Analysis

Report No. R6641

Contents Amendment Record

This report has been issued and amended as follows:

Issue	Revision	Description	Date	Signed
1	0	Draft for SBC review	06.07.05	SKT
1	1	Final	21.10.05	SKT

Contents

Figures

Appendices

B. Field record sheet and response table

Executive Summary

The present stability and potential future stability of the cliffs at Scalby Ness have been investigated using a combination of new geomorphological mapping, new and previous ground investigation data, site monitoring and historic aerial photographs (1946, 1999-2000 and 2003) interpretation. This has been used to review the existing modelling and site interpretation and to develop the slope instability model using slope stability analysis. As a result, a number of key conclusions can be drawn from this study.

1. The previous ground model has been reviewed and revised in accordance with the results of the mapping and the stability analysis carried out for this study.

   a. The ground model has been revised for the north-east slopes. The shear surface at the base of the central back-tilted block is known to be at a greater depth than previously thought because further monitoring has revealed deeper movement in inclinometer SN1. Monitoring over the winter of 2002 to 2003 revealed the basal movement to be between 10.8 and 11.7mbgl, significantly deeper than the previous interpretation. This increased depth of movement changes the geometry of the sliding block and increases its factor of safety. Analysis of this deeper seated back-tilted block reveals it to be more stable than earlier analysis had shown.

      This change in interpretation is supported by the results of the geomorphological mapping. The location and morphology of the block suggests that this feature formed as a result of a much larger ancient deep-seated translation or rotational landslide, where the entire block moved as a single unit over a defined shear surface. The predominant mode of failure identified for these slopes is shallow failure of the upper oversteep glacial till slopes, with active toe erosion by the beck and subsequent localised failures of the lower slopes. The upper slopes are marginally stable. Increases in pore water pressure in the slopes reduce the factor of safety and could cause localised instability, especially where lenses of more permeable sands and gravels may be present. This can be anticipated in periods of intense rainfall.

b. The ground model for the north-west slopes has been refined, following further monitoring and the new geomorphological mapping, with two mudslide units identified within a shallow translational slide. Active toe erosion is taking place by the beck. The predominant failure mode identified from the analysis and the mapping is shallow translational failure, with localised block detachment processes at the head scarp also occurring. The north-west slopes are shown by analysis and the mapping to be marginally stable. Continued toe erosion or an increase in porewater pressure in the slopes reduces the factor of safety against instability.

c. The southern part of the north-east slopes has been partially regraded during the earthworks carried out to form the road to the Sea-Life Centre. This area is considered to be stable in current conditions, although localised shallow instability could occur in periods of heavy rainfall. The factors of safety for the slopes are less than would ideally be designed in accordance with BS6031.

2. A number of issues with the data provided by SBC have been highlighted in the report. In particular, some of the monitoring data is not correctly referenced and its source cannot be identified on site, for example, survey pin data and manual groundwater level monitoring in "SN3". Recommendations have been provided to improve the slope monitoring network and systematic recording of data and observation.
3. The data is sparse in some areas of the site, requiring interpretation of the ground conditions between widely spaced boreholes. It is noted there remain significant uncertainties with the past behaviour or development of the Scalby Ness slopes, most notably the frequency and magnitude of past slope failure events and historical rates of recession of the slope crest.
4. The interpretation of the predominant mechanisms acting on the slopes, and an assessment of the rates of retreat of the headscarps from aerial photography has allowed the identification of three landslide behaviour units:

- Behaviour Unit I (the north-west slopes) - an episodically active behaviour unit characterised by oversteep slopes that have been subjected to shallow translation movement and localised mudslide/ debris flow movements. The headscarp area has evidence of ongoing episodic block detachment and active toe unloading is evident at the base of the slope.

- Behaviour Unit II (the northern part of the north-east slopes) - an episodically active behaviour unit characterised by an oversteep rear headscarp, a mid-slope back-rotated block from a previous historic period of deeper instability, and localised active toe unloading in the lower slope.
- Behaviour Unit III (the southern part of the north-east slopes) - a currently stable behaviour unit that has undergone previous regrading and re-shaping as a result of the engineering works to form the access road to the Sea-Life Centre.

The behaviour units may be regarded independent of one another on account of their predominant mechanisms of slope failure, the historical rates change and past influences of engineering and development activities. The units have been used to define scenarios of slope development over the next hundred years (i.e. the strategy lifetime). The scenarios are not predictions, rather they are projections of what might happen given the occurrence of a particular set of environmental conditions over time, which are in themselves largely uncertain. The three scenarios consider a lower-bound, best-case and upper-bound projection of slope development at specified time steps over the next 100 years, for the three behaviour units. The scenarios are used to determine the possible future impacts of slope behaviour on built development at Scalby Ness. Probabilities have been assigned to each of the scenarios. The anticipated rates of recession with a "do nothing" approach have been considered for the three behaviour units to allow the impact of the retreat on property assets at Scalby Ness to be determined.

5. The results of this assessment indicate that assuming a "do nothing" option, the earliest anticipated date the crest of the slope will be approximately 1m from a property boundary is 2015. The probability of this occurring is considered low (0.15). Using the average retreat rates the estimated date by which the crest of the slope will be approximately 1m from a property boundary at Scalby Ness is 2025. The probability of this occurring is more likely (0.75). The most optimistic calculation shows that no property will be directly affected by 2105, although the crest of the north-east slope is likely to be format or close to the property boundary; the probability of this scenario is considered low (0.1).

6. Scalby Ness cliff management

    a. Given current limitations with data and monitoring records at the site, it is considered that provision of trigger levels for the site would not be meaningful.

    b. On the basis of the nature of the three behaviour units, it is considered that the preparation of a detailed action plan for implementation on the event of significant instability being detected is inappropriate and unnecessary at present, provided that a robust monitoring and field observation strategy is implemented.

    c. Recommendations are made for implementation of a robust monitoring and field observation strategy for Scalby Ness and details are provided to enable a short-term management strategy to be implemented, based on hazard status colours, using the results of the this study. Recommendations are also made for consideration of remedial measures at the site and further ground investigation. A longer-term management strategy is also presented. Full details are given in Section 9 of the report.

1 Introduction

1.1 *Terms of reference*

Halcrow Group Ltd. (Halcrow) was appointed by Scarborough Borough Council (SBC) in December 2004 to undertake the first phase of a two phase study which follows on from the draft Hundale Point to Scalby Ness Coastal Strategy completed in May 2003 by High-Point Rendel Ltd. (HPR).

During the course of preparation of the draft Coastal Strategy, DEFRA revised both the Flood and Coastal Defence Project Appraisal Guidelines and the prioritisation for funding of coastal defence schemes. The draft strategy identified slope instability to be an issue at Scalby Ness. DEFRA concluded in September 2003 that the strategy prioritisation score was not sufficient to enable works to proceed at Scalby Ness and that further studies and investigations were required to confirm the likelihood of asset loss. Further detailed investigations were designed and carried out by others and completed at Scalby Ness in 2004.

SBC commissioned a review of the Coastal Strategy in autumn 2004. The review would build upon the results of the further geotechnical monitoring. This review would include the following elements:

- A Section 1 geotechnical report examining modes and likelihoods of slope failure at Scalby Ness and based on monitoring data gathered in 2004, to provide an analysis of ground conditions at the site and to advise on appropriate monitoring and response actions in relation to the findings of ongoing monitoring.

- A second stage geotechnical report reviewing existing information and updating concept schemes for coastal protection and slope stabilisation identifying preferred options and likely scheme costs.

- A review of the scheme economics based on the updated likelihood of failure (and consequential loss of assets) and revised costs and scope of mitigating works.

- A final stage would revise and finalise the draft Strategy Report and prepare a revised Project Appraisal Report for agreement by Defra.

This report details the work undertaken by Halcrow in completing *Section One: Data Gathering and Analysis* of the study for Scalby Ness.

1.2 Scope of works

SBC's requirements for Section One are detailed in SBC's Employer's Requirements document (SBC, August 2004) as follows:

- geomorphological mapping of the whole of the Scalby Ness site area;
- comparison with previous mapping;
- analysis and interpretation of existing data and mapping to prepare a ground model;
- review of previous assumptions and use of new ground model to determine the validity of the previous assumptions;
- slope stability analysis to determine most likely mechanisms of failure, current stability of the slopes and the sensitivity of the slopes to changes in groundwater level;
- development of an event history of the slope through a review of available aerial photography to confirm cliff recession rates;
- use of recession rates to calculate probability of asset loss
- preparation of recommendations for appropriate monitoring and response actions by SBC for Scalby Ness.

1.3 Sources of information

The information made available to Halcrow in carrying out the Section One study is detailed in Table 1.

Report Title/ Data Type	Author / Source	Date	Format	Note
Hundale Point to Scalby Ness Draft Coastal Strategy	High-Point Rendel	May 2003	Hard Copy	
Factual Report on Supplementary Ground Investigation at Scalby Ness, Scarborough	Structural Soils	September 2004	Hard Copy	
Report on Ground Investigation at Scalby Ness, Scarborough.(Draft)	Structural Soils	November 2001	Hard Copy	
1:10,000 Landline	Ordnance Survey	Current	Digital	
Aerial photography	Scarborough Borough Council	1999-2000	Digital	CRV file (geo-rectified jpeg)
RAF aerial photography	Scarborough Borough Council	~1946	Digital	Geo-rectified jpeg
Aerial photography	Scarborough Borough Council	2003	Digital	Mr SID (geo-rectified jpeg)
Groundwater data	Scarborough Borough Council	29 June 2004 – 11 Oct 2004	Digital	4 readings per day
Movement peg data	Scarborough Borough Council	13.06.01 – 28.08.01, 16.01.02 – 25.06.02, 23.01.03 – 02.08.04	Digital	Peg coordinates inconsistent; unable to resolve final peg locations
Inclinometer data	Scarborough Borough Council	SN1 12.10.01 – 02.05.05; SNI1, SNP2I, SNI3 29.06.04 – 02.05.05; SN3 12.10.01 – 07.06.02 hard copy only	Digital and hard copy	GTILT format

Table 1 **Sources of information available for the Section One study**

2 Site description and history

2.1 Description and history

The site is located at Scalby Mills, approximately 3km north of Scarborough town centre at National Grid Reference TA 034909 and is a steeply incised coastal cliff formed in glacial till with a stream channel, Scalby Beck, at the cliff toe. The site location is shown in Figure 1.

The site includes north-west and north-east facing glacial till slopes above Scalby Beck (Figure 1).

The north-west facing slope consists of mainly shallow recent instability developed in oversteepened glacial till.

Historical development of the slopes may be assessed from the aerial photography. In the 1946 photograph, the north-west slopes are in heavy shadow (see Figure 11). In 1999/2000 there is evidence of relatively fresh movement on the slopes, where there are lighter areas, showing an absence of vegetation.

The north-east facing slope consists of a larger, deep embayment in glacial till with a back scar, approximately 100m in width, and a distinct reverse slope bench feature located mid-way up the slope. The southern part of the north-east facing slope comprises an arcuate headscarp, with vegetated glacial till slopes beneath. The central back-tilted block feature does not extend into this area.

Two arcuate headscarps with a central smaller headscarp are present at the crest of the north-east facing slope in the 1946 aerial photograph. The southernmost of these headscarps and the slopes beneath appear to have been regraded in part during construction of the road to the Sea-Life Centre (Figure 1). The effects of the regrading can be seen in the later photographs.

Scalby Beck is described on Ordnance Survey (OS) mapping as a ‘sea cut’ and it acts as an overflow to the River Derwent. The sea cut was developed in the early 19th Century to relieve extensive flooding problems in the Vale of Pickering. The beck flows from the River Derwent near Everley, some 8km west of Scalby Mills. In the west of the site, the beck flows north-east and then changes direction, flowing south-east to the sea. From the site inspection carried out during the geomorphological mapping and inspection of the 1:50 000 OS mapping of the area, it is considered that the beck valley within the site is naturally formed and not man-made. Localised areas of made ground encountered during the ground investigations and evidence of structures on the northern valley slopes reveal human influence in the valley.

The 1946 aerial photograph shows buildings on the crest of the cliffs in the same or similar location to the housing development constructed in the 1970s-1980s. These buildings are believed to be a former army camp. Houses visible west of the army camp are still present even on the most recent aerial photographs.
A housing development was constructed on the land above the cliffs during the 1970s and 1980s (HPR, 2002) and houses in Scholes Park Road are located within 10m of the cliffs in some cases.
The River Derwent is still prone to flooding and Scalby Beck acts as an overflow channel during flood periods. Scalby Beck is subject to tidal activity as far inland as the change in direction of flow from north-east to south-east (Pers. Comm., SBC, 26 January 2005). Toe erosion of the slopes is occurring on the site at a number of locations on the outside of meander bends, where erosion processes are more concentrated.

2.2 Cliff instability at Scalby Ness

In September 2000, SBC detected significant ground movement at the slope crests. An emergency coastal slope inspection and a rapid risk assessment were carried out by HPR in 2001 to 2002 (HPR, 2002). The Hundale Point to Scalby Ness coastal defence strategy was completed in draft in May 2003 (HPR, 2003).

Ground investigations were undertaken at the site by Structural Soils Ltd. in 2001 and 2004 (Structural Soils Ltd, 2001 and 2005) and inclinometers and piezometers installed.

Two earlier boreholes at the site had been carried out in 1995 for Yorkshire Water Services Ltd. by Exploration Associates.

3 Site reconnaissance

3.1 Geomorphological mapping

3.1.1 Methodology

Geomorphological site mapping of the north-west and north-east facing slopes was conducted to produce an accurate record of the slope morphology and salient geological and geomorphological features.

This information was used to produce a geomorphological interpretation of slope movement types, mechanisms and processes. Features were recorded on 1:1000 scale base maps using standard techniques using a compass to estimate slope direction, a clinometer to assess slope angles, and a 30 metre tape to measure the distances between features.

Data from field maps was digitised into an Arc View GIS system to provide a 'baseline' database of slope morphology, activity and any damage noted. This mapping may, if required, be updated following future re-surveys.

The GIS system was used to combine different data layers to enhance interpretation and construction of a detailed ground model.

3.1.2 Slope morphology

The slope morphology is illustrated in Figure 2. The slope morphology at the site can summarised as a series of distinct units.

The north-west facing slope consists of a vertical face approximately 1m in height at the summit of the slope. This feature extends approximately 70m along the slope face. Beneath this area, the slope angle decreases to approximately 25-28° before steepening in the centre of the slope to between 33-38°. This steep slope remains relatively constant until reaching the slope base where slope angle decreases to between 16-19° at Scalby Beck.

North-east facing slope consists of a steep upper slope unit with a potentially active arcuate head scarp. Beneath the head scarp slope angles are approximately 32° to 34°. Mid slope there is a 3°-5° reverse slope with evidence of surface water ponding toward the southern extent of the slope feature. The slopes then steepen to 31° after the reverse slope suggesting that the reverse slope is the upper surface of a large back rotated block. Below this slope angle vary between 12° and 29° where it meets Scalby Beck.

3.1.3 *Geomorphological interpretation*

Eight different geomorphological units were identified at the site, details of which are summarised below and shown on Figure 3.

(a) Upper slope plateaux in glacial deposits

An upper slope plateau is evident above the main scarp areas. This area is relatively flat with a slight dip 4° northwest and 3° southeast.

(b) Over-steep headscarp

Immediately beneath the plateau is the north-west and north-east facing oversteep headscarp. This extends approximately 100m from the sharp arête feature in the north-west to the solifluction deposits in the south east. In the north-east slopes the shape of the head-scarp is arcuate and has formed two head scarp sub units. The oversteep slopes show evident of cracking and localised shallow surface movement, and have evidence of block detachment processes at the head scarp summit. The lack of recent block detachment evidence suggests that this form of erosion is likely to be infrequent and related to extreme intensive rainfall events.

(c) Translational slide

The northwest slope is composed of a non-circular failure which involves translational motion on a non-planar slip surface. Movement is a result of weakness in the surface forming tills which are oversteep and subject to instability in heavy rainfall activity. The fresh headscarp and open cracking evident in the centre of the slope suggests that this translational slide is likely to be subject to periodic movement. However the size of the rear scarp and the geometry of the slope suggest that these movements are relatively small.

(d) Mudslide/ mudflows

Two mudslide/ mudflow units were identified within the translational slide area on the northwest facing slope. These have occurred within the area of previously translational sliding and consist of a source area at the rear headscarp with a track and debris accumulation lobe at the base of the slope. The scarcity of vegetation and the activity noted toward the headscarp suggests that these features are still seasonally active and further localised shallow movement may be expected.

(e) Back rotated block

A large back rotated block is evident immediately below the steep north-east headscarp. This block extends the entire length of the headscarp and has a surface reverse slope of approximately 4° and a front edge slope of 31°. The surface water ponding to the south west of the block suggests the potential for water pressures to build up behind the block. The location and morphology of the block suggests that this feature formed as a result of a much larger ancient deep-seated translation or rotational landslide where the entire block would have slid as a single unit over a defined shear surface.

(f) Lower slope glacial deposits

A series of lower slope glacial deposits are located toward the base of both the north-west and north-east facing slopes. Here slope angles are much lower than above, typically 5-20°, and often subject to a series of undulations. This subdued nature suggests that although this area has been subject to periods of previous movement these slopes are currently inactive.

(g) Dormant toe unloading

At the base of the north-east facing slope is an area where toe unloading has previously occurred. This area had a distinct steep arcuate scarp which shallows toward the beck to form a distinct depression. A series of eroded arcuate scars were identified within the depression, which have been subdued by other slope processes. This suggests that this unit is not currently active but may be a dormant feature prone to reactivation in certain conditions.

(h) Active toe unloading

At the base of both the north-west and north-east facing slopes are two areas of active toe unloading. In both instances these features have a distinct semi-circular scarp with an initial steep slope which shallows towards the beck. Both locations have notable saturated ground with evident arcuate tension cracking within the zone of active instability.

3.2 Comparison with earlier mapping

Geomorphological mapping of the site was carried by HPR (2002) during a previous ground investigation. Although this mapping has only limited interpretation of the landslide units there is a good record of the position of breaks of slope, cracking and morphology.

Both maps illustrate the same zones of active toe unloading at the base of both the north-west and the north-east facing slopes and depict an oversteep headscarp with back rotated block on the north-east facing slope. Notably the extent of back rotation of the block is different with the angle being 2° in the 2000 map and approximately 5° in the current mapping. This may suggest that movement of the block has occurred as suggested by the inclinometer data, although no evidence of recent activity of the block was identified.

4 Ground conditions and ground model

4.1 *Site geology*

The geology of the site is shown on British Geological Survey 1:50 000 England and Wales geological map sheet 34 & 44 to be glacial till underlain by the Long Nab Member of the Scalby Formation. The glacial till is described as clay with pebbles and lenses of gravel. The Long Nab Member comprises mudstones and sandstones of the Middle Jurassic system.

4.2 *Strata encountered*

Ground investigation at the site (Structural Soils, 2002 and 2005; Exploration Associates, 1995) has revealed varying glacial till strata, typically described as:

- Firm/stiff/very stiff dark brown and dark grey, occasionally brown and reddish brown slightly sandy, slightly gravelly CLAY. Gravel is fine to coarse, angular to rounded, of varying lithologies including sandstone, mudstone, chert and coal. Local partings and pockets of silt and sand.

- Firm to stiff, grey and dark brown thinly to thickly laminated CLAY, often interlaminated with silty fine to medium sand.

- Loose to dense light orange brown, yellow brown and brown slightly gravelly slightly silty fine to medium SAND. Occasional thin interlaminations of dark brown clay/silt.

Occasional fissures within the glacial till have been described variously as irregular, blocky and slickensided. Orientations vary from sub-vertical to sub-horizontal.

The solid strata are exposed in the banks of Scalby Beck where sub-vertical faces have been cut through the sandstones of the Scalby Formation Long Nab Member. The exposed faces show cross-bedding and sets of medium to widely spaced discontinuities.

Ground investigation at the site (Structural Soils, 2002 and 2005; Exploration Associates, 1995) has encountered sandstone, siltstone and mudstone, typically described as:

- Weak/moderately weak/ moderately strong/ locally strong, dark grey, grey and light grey, moderately weathered, fine and fine to medium grained SANDSTONE. Occasional thin laminae of black coal and siltstone are noted. The sandstone is also occasionally described as cream, mottled yellow, stained dark red and orange brown. Occasionally micaceous. Discontinuities described as sub-horizontal to sub-vertical, extremely closely to widely spaced, incipient, tight to open, rough, planar regular and irregular, stained orange, occasionally with clay infilling.

- Very weak to weak dark grey moderately weathered silty fine-grained SANDSTONE/ sandy SILTSTONE. Very weak friable indistinctly laminated orange brown and blue-grey sandy SILTSTONE. Highly to moderately weathered.

- Very weak/ weak/ moderately weak dark brown and grey highly weathered MUDSTONE. Occasionally thinly laminated. Occasionally completely weathered mudstone, described as a stiff or hard clay with angular lithorelicts of mudstone. Locally yellow or stained orange. Discontinuities described as extremely closely to closely spaced, randomly orientated, incipient, planar regular, stained orange.

Figure 4 shows the layout of the surveyed exploratory holes on the site.

4.3 *Site monitoring*

Groundwater, inclinometer and movement peg monitoring has been carried out at Scalby from June 2001. Rainfall data has been made available to Halcrow by SBC, from a local weather station.

4.3.1 *Groundwater monitoring*

Groundwater monitoring has been undertaken since 2004 using automated piezometers. These have been installed at various locations and depths across the site. The results show that perched groundwater is present in the glacial tills at the site, above a lower groundwater table. The minimum and maximum groundwater level (GWL) readings in metres below ground level (mbgl) from each automated piezometer are summarised in Table 2 below.

Groundwater monitoring has also been carried out manually at Scalby Ness. Data has been recorded from six instruments installed in dynamic probe holes (DP1, DP2, DP3, DP6, DP9, DP10 and DP11) and two instruments constructed during the 2002 ground investigation.

Three readings are available from each of the dynamic probe instruments, over a period from 2 September 2004 to 8 October 2004. This period of readings is not long enough to get a true picture of groundwater levels within the slope. As with all manual monitoring systems, there is no guarantee that peaks in groundwater level will be monitored, in fact, this is most unlikely. The results of the monitoring are summarised in Table 2 below.

Groundwater monitoring in one of the two earlier holes is recorded as data from SN3. SN3 is in fact an inclinometer. The depth recorded to the base of the hole from 18 December 2001 to 29 October 2002 is approximately 3.45m. This corresponds with the response zone installed for borehole SN4 upper piezometer at 2 to 3.5mbgl. Therefore this data is interpreted as being from SN4 upper piezometer. The tape is reported as sticking on 23 January and 4 February 2003. Data thereafter from 11 April 2003 to 8 October 2004 has a depth to the base of the hole as 19.8 to 20.1mbgl. SBC note on the monitoring data that they are not sure if this is the correct borehole. It is possible that the instrument being read from 11 April 2003 onwards is inclinometer SN1. This was installed to a depth of 19.5m. It cannot be SN3 which was terminated at 12.1mbgl or SN4, terminated at 15mbgl. SN2 data is recorded on a separate sheet. Due to the uncertainties as to which instrument has been monitored, this data has not been used in analysis.

A comprehensive data set of groundwater monitoring is available for the manually monitored piezometers installed in SN2. Data is available from 18 December 2001 to 8 October 2004. Maximum and minimum groundwater level readings for SN2 are summarised in Table 2 below.

The groundwater levels used in the slope stability analysis are shown on the various cross-sections (see Appendix A) and described in Section 5.4 below.

Table 2 Minimum and maximum piezometer readings

Piezometer	Maximum GWL		Minimum GWL	
	Reading (mbgl)	Date	Reading (mbgl)	Date
BH P1 lower	7.32	25/08/2004	8.01	29/06/2004
BH P1 upper	15.3	29/06/2004	17.07	11/10/2004
BH P2A lower	33.45	14/10/2004	33.57	30/07/2004
BH P2A upper	6.05	25/08/2004	6.82	29/06/2004
BH P3	15.97	10/09/2004	16.24	15/09/2004
BH P4 lower	4.08	28/08/2004	4.81	09/08/2004
BH P4 upper	4.07	29/08/2004	4.81	29/08/2004
DP1	Dry	2&23/09/2004 8/10/2004	Dry	2&23/09/2004 8/10/2004
DP2	7.01	02/09/2004	7.24	08/10/2004
DP3	4.81	08/10/2004	5.28	02/09/2004
DP6	7.50	2&23/09/2004	7.53	08/10/2004
DP9	1.51	02/09/2004	2.18	23/09/2004
DP10	1.41	02/09/2004	2.00	08/10/2004
DP11	2.09	02/09/2004	2.83	08/10/2004
SN4 upper	2.80	13/08/2002	3.27	17/07/2002
SN2 lower (A-left)	2.80	6/05/2004	7.94	18/11/2003
SN2 upper (B-right)	1.18	10/02/2003	>3.20	28/10/2003 to 30/12/2003

4.3.2 *Movement data*

(a) Inclinometer data

Inclinometers have been installed in the north-east slope and monitored from October 2001. The inclinometer locations and depths are summarised below in Table 3. Copies of the latest inclinometer data are presented as Figures 5 to 9.

Table 3 Inclinometer locations and depths

Inclinometer reference	Easting	Northing	Installation depth (mbgl)
SN1	E 503479.6	N 490951.7	19.50
SN3	E 503499.5	N 490966.7	12.10

Inclinometer reference	Easting	Northing	Installation depth (mbgl)
I1 (SNI1)	E 503387.93	N 490958.36	30.50
P2(I) (SNP2I)	E 503405.94	N 490927.89	34.90
I3 (SNI3)	E 503467.09	N 490863.77	17.20

Table 3 (cont). Inclinometer locations and depths

Two inclinometers were installed in the north-east slope in 2001: SN1 and SN3.

Data from SN1 has been recorded from 12 October 2001 to present (2 May 2005 is the latest available data). This inclinometer is located on the back-tilted central block in the north-east slope. 50mm of movement has been recorded at a depth of between 10.8 and 11.7mbgl. An initial 10mm of movement occurred between 27 September 2002 and 28 November 2002. The remaining 40mm occurred by 23 January 2003. No significant movement has since been recorded in this inclinometer.

The data held by Halcrow for inclinometer SN3 is from 12 October 2001 to 7 June 2002. This inclinometer is located in the lower slopes of the north-east slope, below the central back-tilted plateau. Only a hard copy of movement data is available for this inclinometer; no digital data were available. Two zones of movement have been recorded in the inclinometer: at 5.8 to 6.5mbgl and from ground level to approximately 1.5mbgl. 10mm of movement had occurred at the lower level between 23 November 2001 and 31 January 2002. A further 20mm of movement has been recorded from 31 January to 25 March 2002, giving a total recorded movement of approximately 30mm. The next and final reading of 7 June showed a slight continued movement at depth. Inspection on site during the geomorphological mapping revealed that the inclinometer had failed at approximately 1 to 1.5m depth, apparently due to shallow surface movement. A recommendation has been made to SBC by Halcrow (26 January 2005) that this inclinometer installation be repaired and used again for monitoring.

Inclinometers SNI1, SNP2I and SNI3 were installed during the second ground investigation in 2004. Digital monitoring data is available for these installations from 29 June 2004 to present (latest available data is 2 May 2005).

SNI1 is located behind the crest of the north-west facing slope. SNP2I is located above the crest of the north-east slope, towards the western end of the slope. SNI3 is located at a lower level, adjacent to the road to the Sea-Life Centre. No significant movement has been detected in these inclinometers. Towards the base of both SNI1 and SNI2, small spikes of movement of less than 5mm in cumulative deflection have been interpreted as slight movement at the joints in the inclinometer casing.

The results of the inclinometer monitoring show that movement has occurred at depth in SNI1 and SNI3. The depth of movement is consistent with the movement of the back rotated block along a pre-existing shear surface within the tills and close to the underlying bedrock. These depths have been used in the ground model for this slope.

(b) Movement peg monitoring data

Pins to monitor movement were installed in pairs along the headscarp of both the north-east and north-west facing slopes. One pin of each pair was located on the crest of the slope, one just below the crest in the till slopes beneath. The pins have been subject to regular repeat surveys. The data available from the pin surveys is from June 2001 to August 2004. Interpretation of the data has been inconclusive because it was not possible to determine exactly which pins were located where on the slopes.

4.3.3 *Rainfall data*

A paper copy of daily rainfall totals from a local weather station was provided to Halcrow by SBC for the Scalby Ness study. The data cover the period from 1 January 2000 to 30 September 2004 and are presented graphically in Figure 10.

An interpretation of the data using a 50 day moving average reveals that previous activity at the site, both in September 2000 and from late September 2002 to January 2003 (SN1), has been linked to periods of intense or sustained rainfall events where groundwater levels would be significantly higher than usually expected. The movement in SN3 from November 2001 to March 2002 does not coincide with a period of a high 50 day moving average, which would suggest that activity at this location was triggered by a source other than rainfall. SN3 is located in a wet area of the slope subject to surface movement. It is possible that drainage onto the slope in this location (pipes were identified during the geomorphological mapping discharging onto the slope in this area) locally increased the water level in the slope, causing movement to be recorded in the inclinometer.

4.4 ***Ground model***

4.4.1 *Description*

The ground model for each cross-section analysed in the slope stability analysis has been built up from the existing information. The geology as revealed by the ground investigations has been interpreted for each section. Where inclinometer data is applicable, this has been used to fix the position of the shear surface. Groundwater levels recorded during monitoring have been used to estimate the current range of water levels in the slopes. The models chosen for analysis have been derived from the geomorphological mapping. Shallow translational slides have been analysed for the north-west slopes. The north-east slopes have been modelled considering a deeper-seated slip for the central back-tilted block, with shallower rotational slips analysed in both the upper and lower part of the slope, modelling the activity recorded by the mapping. Further details of the model for each slope are given below.

Six cross-sections have been analysed for Scalby Ness. Three are through the north-east slopes (Sections 1, 2 and 3), two through the north-west slopes (Sections 4 and 5), and one through the road to the Sea-Life Centre (Section 6). The locations of the cross-sections are shown on Figure 4.

(a) Ground model for the north-east slopes (Sections 1, 2 and 3)

These cross-sections are illustrated in Appendix A. The simple model used for many of the analyses has glacial till (undifferentiated) overlying bedrock (sandstones and mudstones) of the Scalby Formation. A more detailed model of the till including sandy/gravelly layers was used with a perched water table to investigate the sensitivity of the upper parts of the slope to increases in perched water level. The location of the shear surface of the central block was modelled using results form the inclinometer monitoring. A variety of failure mechanisms was studied: the stability of the central block, the stability of materials at the toe, the effect on the central block of erosion at the toe of the slope, the stability of the upper slopes and the overall stability of the whole slope, should large-scale failure of the central block occur.

(b) Ground model for the north-west slopes (Sections 4 and 5)

These cross-sections are illustrated in Appendix A. As for the north-east slopes, the model used for the analysis comprised an upper undifferentiated glacial till layer, overlying bedrock (sandstones and mudstones) of the Scalby Formation. Failure surfaces modelled for this slope were generally parallel to the slope surface, modelling the shallow translational failures identified in the geomorphological mapping, or shallow rotational failures. The effect of erosion of the toe on the overall stability of the slope was investigated. The sensitivity of the slope to changes in groundwater level was modelled.

(c) Ground model for the southern part of the north-east slope, through the road to the Sea-Life Centre (Section 6)

This cross-section is illustrated in Appendix A. The ground model used in analysis comprised an upper undifferentiated glacial till layer, overlying bedrock (sandstones and mudstones) of the Scalby Formation. The appropriate depths of the materials were derived from logs of nearby exploratory holes. No shear surfaces have been identified in this area from study of the results of inclinometer I3. Therefore the modelling used a grid of centres and radii to determine the lowest factor of safety for the slope under differing conditions.

4.4.2 *Comparison with previous ground model*

The significant difference between the current and previous ground models is the depth of the shear surface beneath the central back-tilted block in the north-eastern slopes. At the time of writing the Hundale Point to Scalby Ness Coastal Strategy Study (HPR, 2003) in 2002, evidence of movement in inclinometer SN1 was inconclusive. No more than 6mm of movement had been recorded. HPR interpreted the shear movement at the base of the back-tilted block to be at approximately 6m depth. Further monitoring over the winter of 2002 to 2003 revealed the basal movement to be between 10.8 and 11.7mbgl, significantly deeper than the previous interpretation. This increased depth of movement changes the geometry of the sliding block and increases its factor of safety.

5 Slope stability analysis

5.1 *Stability model*

Factors of safety may be calculated which allow the stability of a slope to be quantified. Simply, the factor of safety of the slope (FOS) is the ratio of the forces resisting failure to the forces promoting failure. A factor of safety less than 1.0 would indicate the slope is unstable and failure is likely. A factor of safety of between 1.3 and 1.4 would normally be considered adequate to prevent failure as stated in BS 6031 (1981) although a higher factor of safety may be required by Scarborough Borough Council.

Slope stability analysis is a useful technique which can be used to indicate likely mechanisms acting at a site. The analysis allows causes of the various mechanisms to be investigated and the sensitivity of the slopes to variations in soil strength parameters and groundwater level to be studied.

Slope stability analysis has been carried out for six cross-sections prepared from SBC topographical survey data. The computer program used is Slope/W Version 5.19. The method of analysis used for Scalby Ness is the Morgernstern-Price limit equilibrium method. Groundwater was modelled using piezometric lines and soil strength was modelled using the Mohr-Coulomb soil strength model. Potential slip surfaces were defined either using a grid of centres and radius lines or fully specified shapes.

5.2 *Soil parameters*

The soil parameters used in analysis have been derived from the ground investigation information provided by SBC and are presented in Table 4 below. The high and low values given in the table are the highest and lowest values of the range of results from the laboratory testing.

During the analysis a range of parameters has been used, to determine the likely parameters applicable for each stability model. This is discussed in more detail in Section 5.4 below.

Glacial Till	Unit Weight	Effective Stress Parameters		Undrained shear strength	Residual Shear Strength (c'r=0)
	(kN/m3)	c' (kPa)	phi' (degrees)	Cu (kPa)	(degrees)
Low	17.8	0	26	75	22.5
High	21.0	5	32	150	27.0

Sandstone/Mudstone	Unit Weight	Effective Stress Parameters		Unconfined Compressive Strength	Residual Shear Strength (c'r=0)
	(kN/m3)	c' (kPa)	phi' (degrees)	(MPa)	(degrees)
Low	17.8	0	30	0.04	-
High	21	10	38	50	-

Table 4 Slope Stability Soil Parameters

5.3 *Groundwater levels*

Groundwater levels used in the models for the stability analysis have been derived from the range of data recorded by SBC for the piezometers at the site. Modelling has also been undertaken using groundwater levels 2m, 4m and 6m higher than this, to allow for an increase in groundwater level, either due to extreme rainfall events or possible climate change.

5.4 *Slope stability analysis results*

The results of the stability analysis are summarised in Tables 5 to 8 below. The soil parameters used are described as "peak" – these are parameters that will apply for a first time failure at that shear surface, "post peak" – reduced shear strength, not as low as "residual", applicable because strength of clay slopes is known to decrease with time, and "residual" – lowest strength parameters on a shear surface where failure has already occurred. The groundwater level (GWL) used in analysis is described briefly. The level used in the analysis can be seen in the extracts from the Slope-W program in Appendix A for each of the sections. The model number given in each of the results tables below refers to the models shown in Appendix A.

5.4.1 *North-east slopes*

(a) Section 1

Section 1 is located on the generally flatter slopes at the south-eastern end of the slope, towards the road. Details and results of the analysis are given in Table 5 below.

Table 5 Stability analysis results – Section 1

Ø'	GWL	Model	FOS
Peak 30°	Low beneath slip	Model 1/1. Looking at instability of lowest part of slope near beck. Note - this basal slope is slightly oversteepened so there will be localised shallow movements. Rotational.	1.15
Peak 30°	Low gwl, within lower part of slip.	Model 1/2. Looking at stability of lower back- tilted block. Block is much flatter here due to geometry. Rotational.	2.53

Ø'	GWL	Model	FOS
Peak 30°	Low gwl	Model 1/3. Modelling failure and removal of back-rotated block – considering failure of upper slope. Rotational.	1.54
Peak 30°	Low gwl	Model 1/4. Modelling failure and removal of back-tilted block – considering failure of overall slope after toe loss (large scale) Rotational.	1.94

Table 5 (cont) Stability analysis results – Section 1

(b) Section 2

Section 2 is located towards the northern end of the north-east slope and is the closest section to inclinometers SN1 and SN3. This section has been analysed in more detail than the other sections for the north-east slope because the most data is available to build up the ground model. Details and results of the analysis are given in Table 6 below. Notes on the implications of the results in terms of mitigation measures where appropriate are given in italics.

Table 6 Stability analysis results – Section 2

Ø'	GWL	Model	FOS
Peak 30°	High gwl to top of block	Model 2/1. Using specified shear surfaces through planes identified by inclinometers. Looking at overall stability of back-tilted block.	1.32
Residual 22.5°	High gwl to top of block	Model 2/2. Looking at stability of lower back-tilted block, as above except lower Ø' *Block is marginally stable with high gwl and residual parameters.*	1.00
Residual 22.5°	High gwl to top of block	Model 2/3. Looking at stability of lower back-tilted block, lower Ø', toe loss due to erosion modelled. *Results imply instability will occur if these conditions arise.*	0.96

Ø'	GWL	Model	FOS
Residual 22.5°	Lower gwl	Model 2/4. Looking at stability of lower back-tilted block, lower Ø', lower gwl. *Results show drainage will improve factor of safety.*	1.42
Residual 22.5°	Lower gwl	Model 2/5. Looking at stability of lower back-tilted block, lower Ø', lower gwl and toe loss due to erosion modelled. *Toe erosion reduces FOS, therefore toe protection will prevent this.*	1.29
Peak 30°	Gwl below slip	Model 2/6a and b. Looking at upper slope, modelling 1st time failures. Rotational. Relatively shallow slip. Recession of approx. 2m in one event. *Marginally stable against such slips*	1.00
Post peak 28. 5°	Gwl below slip	Model 2/7. Infinite slope analysis of upper slope to determine Ø' which gives FOS of about 1 i.e. natural angle of repose. *Regrading of crest and establishment of vegetation could increase FOS.*	1.00
Post peak 28. 5°	Lower gwl	Model 2/8. Modelling loss of whole lower back rotated block. Looking at rotational failure of overall slope after such a loss. 5m recession. *Results show this is unlikely in the circumstances modelled.*	1.16
Peak 32°(upper-bound)	Perched gwl in till at 27mAOD	Model 2/9. Modelling perched groundwater in sand and gravel layer in upper till deposits from BHP2. Slip surface modelled in upper slope.	1.10

Ø'	GWL	Model	FOS
Peak 32º(upper-bound)	Perched gwl in till at 29mAOD	Model 2/10. Modelling perched groundwater in sand and gravel layer in upper till deposits for +2m gwl. Slip surface modelled in upper slope.	1.05
Peak 32º(upper-bound)	Perched gwl in till at 31mAOD	Model 2/11. Modelling perched groundwater in sand and gravel layer in upper till deposits for +4m gwl. Slip surface modelled in upper slope. *Regrading and drainage at the crest and in the upper slopes would increase FOS.*	0.95

Table 6 (cont) Stability analysis results – Section 2

(c) Section 3

Section 3 is the most northerly of the cross-sections analysed for the north-east slope. Details and results of the analysis are given in Table 7 below.

Table 7 Stability analysis results – Section 3

Ø'	GWL	Model	FOS
Residual 22.5°	High gwl to top of block	Model 3/1. Modelling specified shear surface at base of lower back rotated block. Looking at overall stability of back-tilted block.	1.02
Residual 22.5°	Lower gwl	Model 3/2. Looking at stability of lower back-tilted block, as above except lower gwl	1.55
Peak 30°	Gwl below slip	Model 3/3. Rotational failure of upper slopes, gives shallow failure with 2m recession	1.03
Peak 30°	Lower gwl	Model 3/4. Looking at stability of overall slope, modelling removal of lower back-tilted block. Lowest FOS found	1.05

(d) Section 6

Cross-section 6 is a cross-section through the north-east slopes and the road to the Sea-Life Centre. This is a 27° slope, cut and formed in the area of a former backscar, as shown in the 1946 aerial photograph. Modelling this slope showed the most likely mode of failure (i.e the mode with the lowest factor of safety) was a slab failure or shallow rotational failure 1 or 1.5m thick. This was a localised failure above the road, not a failure of the whole slope. For Ø' of 30°, the factor of safety was 1.17 (Model 6/1 in Appendix A), for Ø' of 32°, the factor of safety was 1.27 (Model 6/2). Considering the stability of the overall slope, the factor of safety was greater than 1.3 (Model 6/4). The groundwater level modelled was below the slip surface. If the groundwater rises, the factor of safety will decrease.

5.4.2 *North-west slopes*

(a) Section 4

Section 4 is the more northerly of the two sections analysed for the north-west slope. Details and results of the analysis are given in Table 8 below. Notes on the implications of the results in terms of mitigation measures where appropriate are given in italics.

Table 8 Stability analysis results – Section 4

Ø'	GWL	Model	FOS
Peak 30°	Low beneath slip	Model 4/1. Looking at the extent of a potential slip towards top of slope for a FOS of approx. 1.0. This gave approx. 2.5 or 3m recession. A lower phi value of say 27 or 28 degrees gave deeper slips, however these are not evident on site. Shallow rotational	1.03
Peak 30°	Low gwl, within lower part of slip.	Model 4/2. Looking at extent of potential slip with FOS around 1 – recession about 5m. Rotational. *Results show this slope is marginally stable.*	1.02

Ø'	GWL	Model	FOS
Peak 30°	Low gwl	Model 4/3. Extent of potential slip towards top of slope with a FOS around 1.0 with toe erosion modelled. Recession closer to houses, say 7 to 8m recession. Rotational. *Results show loss of toe due to erosion increases proximity of slip towards houses. Toe protection would reduce the likelihood of this occurring.*	1.01
Peak 30°	High gwl	Model 4/4. Looking at extent of a potential slip in lower slope with FOS<1 following gw rise – result is toe unloading with failure of lower slope. Rotational. *Toe protection and/or drainage if practical would help guard against such an event.*	0.79
Peak 30°	Low gwl	Model 4/5. Infinite slope analysis, shallow slip, say 2m deep. Result is FOS about 1.0. Slope currently marginally stable. Toe unloading/erosion and/or gw rise means the potential failure surface would deepen or enlarge. *This reflects what is occurring on the slopes ie slopes are currently marginally stable.*	1.00
Peak 30°	Low gwl	Model 4/6. Analysis to determine the FOS of a potential shear surface that could directly influence properties at the top of the slope. . Toe unloading/erosion and/or gw rise means the potential failure surface would deepen or enlarge. Rotational. *Results imply that one event occurring affecting the houses is less likely than a series of smaller events.*	1.11

Ø'	GWL	Model	FOS
Peak 30°	Gwl at 16mAOD below housing	Model 4/7. Model to determine groundwater sensitivity. GWL at low level. Sample shear surface chosen.	1.03
Peak 30°	Gwl at 18mAOD below housing	Model 4/8. Model to determine groundwater sensitivity. GWL at low level + 2m (within range of currently recorded levels)	0.97
Peak 30°	Gwl at 20mAOD below housing	Model 4/9. Model to determine groundwater sensitivity. GWL at low level + 4m.	0.88
Peak 30°	Gwl at 22mAOD below housing	Model 4/10. Model to determine groundwater sensitivity. GWL at low level + 6m.	0.79

Table 8 (cont) Stability analysis results – Section 4

(b) Section 5

The analysis of cross-section 5 gave similar results to cross-section 4. This part of the north-west slope is slightly more stable as the sub-vertical scarp is not present. The models analysed are presented in Appendix 1 (ground model and models 5/1 to 5/3).

5.5 Summary of stability analysis results

5.5.1 North-east slopes

From the inclinometer data available and the results of the stability analysis, the central back-tilted block is currently stable. Analysis showed movement to occur only when high groundwater conditions coincide with significant erosion at the toe and low soil strength parameters.

Localised instability has been observed in the upper slope area. Analysis suggests this area is marginally stable with post-peak parameters. Localised instability may be anticipated in conditions of high or extreme rainfall.

In order to determine the effect of changes in groundwater levels within the glacial till, the Section 2 model was amended (based on BH P2) to determine the effect of a permeable sand and gravel bed within the cohesive glacial till deposits (generally clay and occasional interbedded with sand and gravel layers).

Assuming a phi' of 32 degrees for the Glacial Till soils (an upper bound soil parameter) the factor of safety of the upper slope was about 1.10 for the condition when the sand and gravel bed was fully saturated.

The model was amended to allow for a 2m and 4m increase in pressure head within the sand and gravel layer only (i.e. as a short term response to increase in groundwater level due to high rainfall). For an increase of 2m head of water pressure the factor of safety of the face of the slope reduced to 1.05 and for an increase of 4m head of water pressure the factor of safety of the face of the slope reduced further to 0.95.

This sensitivity analysis shows that there is a risk of localised failure of the upper slopes should the groundwater pressure within discrete permeable bands rise significantly. The potential for such failure could further increase if these permeable bands are not able to drain freely due to a slip of soil from a higher level.

The ground investigations undertaken to date are not sufficient to enable to determine which parts of the site could be susceptible to instability due to the presence of saturated sand and gravel pockets. Based on the walkover survey no significant spring lines where encountered in the upper slopes, however, seepages may only be apparent following wet weather. Localised areas of seepages and wet ground were identified in the lower slopes and these have been recorded in the mapping process.

Large scale instability of the whole slope was analysed by considering failure of the lower block (due to significant toe erosion and high groundwater levels combined with residual shear strength parameters), together with a lower groundwater level and post-peak parameters. Even with this situation, the factor of safety was still 1.16.Given that failure of the lower block itself has been shown to occur only with significant toe erosion, high groundwater levels and residual shear strength parameters, it is considered unlikely that large scale instability of the whole slope will occur during the lifetime of the study (100 years).

The southern end of the north-east slope and the road to the Sea-Life Centre have been shown to be stable in the modelling carried out for the Stage One Study.

There is no triggering factor of toe erosion that affects this section of the north-east slope. The slopes are also well vegetated at present. Much of the slopes was graded to 27 degrees during the works to build the road to the Sea-Life Centre. It is not anticipated that large scale instability of these slopes will occur during the lifetime of the study (c100 years).

There is only one inclinometer currently working within the back-tilted block of the north-east slopes. In order to confirm the model, or provide further data to amend the model, inclinometer SN3 should be brought back into good repair and monitored as well, if this is possible. The inclinometers installed around the edge of the north-east slopes will provide evidence of movement should a deeper-seated event occur.

5.5.2 *North-west slopes*

These slopes are steeper than the north-east slopes and hence less stable. Higher soil strengths have been used in the slope stability analysis. Lower strengths showed instability occurring in the model which had not been observed on site. Modelling suggests that instability could occur in both the lower and upper parts of the slopes.

Lower slope instability has been shown to arise as a result of groundwater rise and erosion of the toe of the slope. Upper slope instability is a result of over-steepened slopes. Localised instability of the upper slopes may be expected in high or extreme rainfall events.

Overall, from observations and mapping, instability is likely to be relatively shallow and translational. Analysis has shown that with toe unloading due to erosion or failure, the potential failure surface may deepen.

Analysis was carried out to determine the factor of safety of a potential shear surface, under current groundwater conditions, that could directly affect the properties at the top of the slope. The current factor of safety against such a slip occurring is 1.11.

The sensitivity of the slopes to changes in groundwater level has been modelled. A shear surface giving approximately 4m of retreat at the head of the slope was chosen to use for comparison between the different groundwater levels. Using a peak parameter of phi' of 30 degrees as the strength of the glacial till, the factor of safety of the overall slope was about 1.03.

The model was amended to allow increases of 2m, 4m and 6m in groundwater level above current conditions, modelling a short term increase in groundwater level as a response to high rainfall. For an increase of 2m head of water pressure, the factor of the slope reduced to 0.97, for an increase of 4m head of water pressure the factor of safety reduced further to 0.88 and for a 6m increase in head, the factor of safety was calculated at 0.79.

This sensitivity analysis shows that there is a risk of failure of the north-west slopes should the groundwater pressure within the overall slope rise significantly. As with the north-east slopes, there is also the potential for localised failure in the north-west slopes due to the presence of more permeable bands of sand and gravel within the glacial till. The potential for such failure could further increase if these permeable bands are not able to drain freely due to a slip of soil from a higher level. The ground investigations undertaken to date are not sufficient to enable to determine which parts of the site could be susceptible to instability due to the presence of saturated sand and gravel pockets.

6 Calculation of rates of retreat of the coastal cliffs

6.1 *Introduction*

An assessment of the historical and current level of activity at the site is required to:

- Assess the potential for future activity;
- Assess the likely future scenarios of retreat;
- Assess the integrity of the properties at the top of the slope.

This requires knowledge of the mechanisms of slope movement at the site, the response of the slopes to rainfall events and interpretation of historical records of movement.

6.2 *Aerial photograph interpretation*

One source of information giving a historical record of movement is aerial photography. Photography from three separate epochs was studied; the details of the photographs are summarised in Table 9. The aerial photographs were geo-rectified and used in GIS to map and delimit the position of the river, headscarp areas and any further main features on the site that could be identified.

Table 9 Aerial photographs used in cliff top recession analysis

Year	Source	Format	GIS
1946	SBC	Scanned jpeg	Geo-rectified jpeg
1999 - 2000	SBC	Scanned CRV	Geo-rectified jpeg
2003	SBC	Scanned SID	Geo-rectified jpeg

Figures 11, 12 and 13 show the three epochs of aerial photos. The retreat lines for the three epochs have been shown on each photograph, together with the landline mapping. Errors in the geo-rectification of the photographs have been assessed using root mean square errors (RMSE) of known points in relation to the 2000 landline survey as shown in Table 10 below.

Table 10 Errors in geo-rectification of aerial photography

Year of photograph	RMSE	Landline error	Total error
1946	10.98m	1.10m	12.08m
1999 - 2000		1.10m	
2003	1.56m	1.10m	2.66m

By measuring the maximum and minimum crest recession directly from the photographs and applying the errors appropriately, maximum, minimum and average recession rates can be calculated for the different slopes.

For the north-east facing slopes, the maximum crest recession measured from aerial photographs from 1946 to 2003 was 6.0m and the minimum crest recession was 2.0m. Therefore the maximum possible recession over this period is 6.0 + 12.08 + 2.66m i.e. 20.74m. The minimum possible recession is 2.0 – 12.08 – 2.66m; in practical terms, 0.0m.

For the north-west facing slopes, the maximum crest recession measured from the aerial photographs from 1946 to 2003 was 3.2m and the minimum crest recession was 2.8m. Therefore the maximum possible recession over this period is 3.2 + 12.08 + 2.66m i.e. 17.94m. The minimum possible recession is 2.8 – 12.08 – 2.66m; in practical terms, 0.0m.

This data allows near-minimum, maximum and average annual rates of retreat of the headscarp to be calculated for the north-west and north-east facing slopes from the aerial photographs. The rates are given in Table 11 below. The near-minimum rates are calculated from the crest recession recorded from the photographs without correcting for geo-rectification errors.

Table 11 Calculation of cliff retreat rates from 1946 to 2003 from aerial photography

Slope	Rate of retreat (m/year)		
	Near-Minimum	Maximum	Average
North-east	0.035	0.36	0.20
North-west	0.049	0.31	0.18

6.3 *Retreat rates from block movement evidence*

From the walkover survey and geomorphological mapping carried out for this study, it was evident on site that recession of the headscarp is taking place through localised failure of blocks, typically 0.75 to 1m wide, falling from the headscarps onto the slopes beneath. The state of weathering of the blocks on site suggests that such a failure is not a frequent event. Degraded blocks could be seen on the slopes below the headscarp. It has been estimated that the winter of 2000-2001 was approximately a 1 in 20 year event in the north-east of England (Pers.Comm. R Moore). This data can be used to give a recession rate for both the north-east and north-west slopes of 0.05m/year. Over 100 years, this will mean a headscarp retreat of 5m.

The effects of climate change giving an increased frequency of intense rainfall events may be accounted for by increasing the frequency of block failure in this model. Assuming a 1 in 20 year event currently will become a 1 in 10 year event in the future, different rates of recession can be calculated for the varying assumptions as to when the change in frequency will occur. Assuming conditions remain unaltered until 50 years from now and then the effects of climate change are felt, an average recession rate of 0.75m per year over 100 years and a headscarp retreat of 7.5m can be expected. If the effects of climate change start now, then an annual rate of retreat of 0.1m/year can be calculated, leading to a headscarp retreat of 10m over the next century.

6.4 *Previously estimated rates of retreat*

Previous retreat rates were calculated for a 71 year period between 1928 and 1999 from Ordnance Survey mapping and aerial photography by High-Point Rendel (HPR, 2002). The average annual cliff top recession rate was calculated at 0.3m/year. The error quoted was 3% giving a range from 0.291 to 0.309m/year.

Published data is also available for coastal recession along the north Yorkshire coast. A previous study of coastal recession in Yorkshire has recorded a retreat rate of 0.26m/year occurring along the Whitby to Sandsend coast and a figure of 0.32m/year was calculated in studies of the northeast Yorkshire coast (HPR, 2002).

6.5 Present best estimated rates of retreat

A best estimate of rates of retreat of the headscarps is required to carry out the economic analysis, in terms of property loss. There are uncertainties in the above data which are outlined below:

- Uncertainties in aerial photography interpretation. The RMSE method has been used to give upper and lower bound rates of retreat from interpretation of the aerial photography, which is the appropriate way of dealing with ortho-rectificational errors. The average rate of retreat calculated by HPR using the 1999 aerial photograph does not state positively that a geo-referenced photograph was used. As such, there may be errors in the calculation which are not included in HPR's quoted rate of retreat. The current error quoted by Ordnance Survey for their Landline mapping is +/- 1.1m. An error of at least this magnitude should be used when dealing with the 1928 mapping. Again, this does not appear to be included in HPR's rate of recession.

- Use of coastal data "inland". While there is no doubt that flow in Scalby Beck is influenced by tidal movements and water may be impounded in the beck during particularly high tides, the banks of the beck are not subject to the same erosive forces as a cliff toe subject to constant wave erosion. The beck slopes are formed of over-steepened glacial till, but it is not anticipated that these would retreat at the same rate as unprotected coastal slopes.

A range of rates of retreat is therefore recommended for use in the economic analysis. The rates predicted using the analysis from failed blocks on site falls within the rates calculated from aerial photography. The near-minimum and average aerial photography recession rates are less than the published "coastal" rates of 0.26 and 0.32m/year, which is appropriate from the above discussion about use of "coastal" rates "inland". The rates used in the analysis should be those in Table 11 above.

These retreat rates have been used to prepare Figures 14 to 16 which show headscarp loss scenarios for the north-east and north-west slopes.

7 Cliff behaviour

7.1 *Behaviour units*

Bringing together the geomorphological mapping, the results of the stability analysis, the historical data and the slope monitoring records allows a number of behaviour units to be defined for Scalby Ness. These behaviour units may be regarded independent of one another on account of their predominant mechanisms of slope failure, the historical rates change and past influences of engineering and development activities. The behaviour units identified for Scalby Ness are described below and shown on Figure 3.

7.1.1 *North-west slopes– Behaviour Unit I*

This behaviour unit is characterised by a non-circular failure involving translational motion on a non-planar slip surface in glacial till deposits, which has resulted in the creation of an oversteep headscarp at the crest of the slope. There is evidence of block detachment processes operating at the crest of the slope. Two mudslide/ debris slide units were identified within the translational failure on this slope. This unit is likely to be subject to periodic movement, as evidenced by a fresh headscarp and open cracking in the centre of the slope. This evidence and the results of the slope stability analysis suggest that movements are relatively small. Erosion of the toe of the slope is actively occurring, reducing support to the materials above. Recession rates calculated for this unit over the period from 1946 to 2003 from aerial photography range from zero to 0.31 m/year. There is no instrumentation to monitor movements within the slope. The inclinometer at the crest of the slope, I1, is showing no significant movement. This is as anticipated; it is not located within the area where active movement would be expected and deep-seated failures are not considered likely in this unit. Groundwater levels monitored in piezometer P1 Upper from 29 June 2004 to 11 October 2004 show a variation in groundwater level corresponding to peaks in rainfall over this period. A rise of approximately 0.5m in groundwater level from 7.8 to 7.3mbgl was recorded. P1 Lower at approximately 17mbgl showed no corresponding rise in groundwater level over the same period.

7.1.2 *North-east slopes (northern part) – Behaviour Unit II*

Behaviour Unit II is characterised by an oversteep headscarp, above oversteep glacial till slopes showing evidence of cracking and localised shallow surface movement. There is evidence of block detachment processes operating at the crest of the slope. A large back-tilted block is present across the unit. The location and morphology of this block suggests that this is the result of a large ancient deep-seated rotational or translational landslide. The subdued nature of the lower slopes with lower slope angles suggests that this area has been subject to periods of previous movement. Part of these lower slopes is currently inactive. Part is currently active, with notable saturated ground and evidence of arcuate tension cracks. Erosion of the toe of the slope is actively occurring, reducing support to the materials above. Recession rates calculated for this unit over the period from 1946 to 2003 from aerial photography range from zero to 0.36 m/year. Monitoring of inclinometers SN1 and SN3 has revealed movement of the central back-tilted block occurring at depth and for SN1 correlating with periods of high rainfall. Monitoring in inclinometer P2(I) at the crest of the slope is showing no significant movement. As for inclinometer I1 above the north-west slope, this is as anticipated; it is not located within the area where active movement would be expected and deep-seated failures of the whole of the slope are not considered likely in this unit. Groundwater levels monitored in piezometer P2A Upper (located at the rear of the upper plateau) from 29 June 2004 to 11 October 2004 show a variation in groundwater level corresponding to peaks in rainfall over this period. A rise of approximately 0.55m in groundwater level from 6.6 to 6.05mbgl was recorded. P2A Lower at approximately 33.5mbgl showed no corresponding rise in groundwater level over the same period. Monitoring of borehole P4 in the central block shows the upper and lower instruments to be in hydraulic conductivity. Groundwater levels monitored from 29 June 2004 to 11 October 2004 show a variation in groundwater level corresponding to peaks in rainfall over this period. A rise of approximately 0.7m in groundwater level from 4.8 to 4.1mbgl was recorded.

7.1.3 *North-east slopes (southern part) – Behaviour Unit III*

The aerial photograph of 1946, before the construction of the road to the Sea-Life Centre, shows an arcuate headscarp above a feature which is considered to be the relic backscar of an ancient rotational slip. The slopes have been regraded during the recent road construction and are currently well vegetated and showing no signs of recent instability. Inclinometer I3 is located above the road to the Sea-Life Centre and is showing no significant movement. Results of the slope stability analysis also confirmed that this unit is reasonably stable with factors of safety of between 1.1 and 1.2 calculated in the analysis. The toe of the unit is protected from erosion by the rock outcrops at Scalby beck and the toe protection put in place around the Sea-Life Centre carpark. From the evidence of mapping, inclinometer monitoring and analysis, this behaviour unit is considered to be stable under current conditions. Groundwater levels monitored in piezometer P3 (located in the centre of the upper plateau) from 29 June 2004 to 11 October 2004 show little variation in groundwater level corresponding to peaks in rainfall over this period. A variation in level of approximately 0.2m from 16.0 to 16.2mbgl was recorded.

7.2 *Current and potential hazards associated with ground movement*

The behaviour units described above are used below in section 7.3 to consider the current and potential hazards associated with ground movement. The near-minimum, maximum and average recession rates of the headscarps derived from the aerial photography are used to assess the risk to property behind the slope crests. The nature of potential landslide events has been discussed in sections 5.5.1 and 5.5.2 above. The likely scenarios of failure or development of the slopes are drawn together in section 7.3 below. The probability of failure is covered later in Table 12 in section 7.3.

7.3 *Scenarios of slope development*

Figure 3 shows the three discrete slope behaviour units (I, II and III). A description of each behaviour unit is given in Section 7.1 based on a full assessment of historical data, geomorphological site mapping, slope monitoring records and stability analysis. The behaviour units may be regarded independent of one another on account of their predominant mechanisms of slope failure, the historical rate of change and past influences of engineering and development activities. These important factors will to a large extent, govern future slope behaviour assuming a 'no-intervention or do-nothing' management policy. Therefore, they provide the spatial framework for modelling future scenarios of slope development and their potential economic impacts.

It is noted there remain significant uncertainties with the past behaviour or development of the Scalby Ness slopes, most notably the frequency and magnitude of past slope failure events and historical rates of recession of the slope crest.

Taking full account of these uncertainties, the behaviour units can be used to define scenarios of slope development over the next hundred years (i.e. the strategy lifetime). It is important to note that these scenarios are not predictions, rather they are projections of what might happen given the occurrence of a particular set of environmental conditions over time, which are in themselves largely uncertain.

The scenarios consider a lower-bound, best-case and upper-bound projection of slope development and associated cliff top recession at specified time steps over the next 100 years, for the three behaviour units. The uncertainties with the available data and analysis are accounted for in the range of projections for each scenario and time step. The scenarios are to be used to determine the possible future impacts of slope behaviour on built development at Scalby Ness.

The predictions of slope behaviour assume a 'Do Nothing' policy and provide an indication of the location and timing of the potential economic losses that may occur over the strategy lifetime (c100 years). This approach informs the choice of coastal defence policy options and where coastal protection measures may be most needed.

The anticipated rates of recession with a "do nothing" scenario for the three behaviour units have been combined into Table 12 below, to allow the potential impact of cliff retreat on property assets at Scalby Ness to be determined.

Table 12 Anticipated cliff retreat and consequential property losses

Behaviour Unit	Time (years)	Cliff recession in metres (no. of buildings affected)		
		Lower-bound [Probability=0.1]	Average-case [Probability=0.75]	Upper-bound [Probability=0.15]
I (north-west slope)	10	0.5 (0)	1.8 (0)	3.1 (0)
	20	1 (0)	3.6 (0)	6.2 (0)
	30	1.5 (0)	5.4 (0)	9.3 (1)
	40	2 (0)	7.2 (0)	12.4 (2)
	50	2.5 (0)	9 (1)	15.5 (3)
	100	5 (0)	18 (5)	31 (8)

Behaviour Unit	Time (years)	Cliff recession in metres (no. of buildings affected)		
		Lower-bound [Probability=0.1]	Average-case [Probability=0.75]	Upper-bound [Probability=0.15]
II (north-east slope – northern part)	10	0.35(0)	2 (0)	3.6 (0)
	20	0.7 (0)	4 (0)	7.2 (2)
	30	1.1 (0)	6 (0)	10.8 (3)
	40	1.4 (0)	8 (2)	14.4 (4)
	50	1.75 (0)	10 (3)	18 (6)
	100	3.5 (0)	20 (9)	36 (14)
III (north-east slope – southern part)	10 - 100	Only localised recession is anticipated for this area, which should not affect properties (see recession lines on Figures 14 to 16)		

Table 12 (cont) Anticipated cliff retreat and consequential property losses

The number of buildings affected by the different recession rates is indicated in brackets in Table 12 above. It should be noted that several buildings are affected by behaviour units I and II and these should not be duplicated in calculation of cumulative present value costs. Note a building may be a block housing two properties or a garage unit. The buildings considered have been individually labelled on Figures 14 to 16.

The anticipated probability for the different retreat scenarios is given in Table 12; these probabilities are applicable to Behaviour Units I and II.

8 Causal factors, warning signs, trigger levels and emergency plan

8.1 *Causes of slope instability*

From the review of data and analysis detailed in the earlier sections of the report, it is possible to list a variety of factors that may cause or promote the onset of instability at Scalby Ness.

The causes of slope instability are well documented by others (e.g. Jones and Lee 1994; Moore, Lee and Clark 1995). Such studies separate the causes of slope instability into two categories, namely:

- Preparatory factors that work to make the slope increasingly susceptible to failure without actually initiating it;
- Trigger factors that initiate movement.

In broad terms, however, the great diversity of causal factors may be divided into internal causes that lead to a reduction in shear strength and external causes that lead to an increase in shear stress.

The potential causal factors for Scalby Ness are detailed below in Table13, together with appropriate early warning signs for SBC to relate to findings of their ongoing monitoring of piezometers, inclinometers and visual inspections.

Table 13 Causal factors and warning signs

Causal factor	Description	Warning sign
Increase in pore water pressure in the slopes (internal cause)	Analysis has shown that increase in pore water pressures in the slopes leads to a decrease in the stability of the slopes by causing a reduction in shear strength. Such effects are most severe during wet periods of intense rainstorms. Intense rainfall after long dry spell can cause a sudden increase in pore water pressures in the slopes, with tension or shrinkage cracks in the slopes aiding rapid ingress of water. Existing drainage discharges onto both the north-west and north-east slopes (as at January 2005). This feeds water directly into the slopes, increasing pore water pressure	Higher levels of groundwater recorded in piezometers. Results of rainfall show increased levels after dry period. Drainage onto the slopes is evident during walk-over inspections.
Weathering (internal cause)	Weathering of soil leads to reduction in shear strength. Cohesive soils may be subject to strength loss due to weathering. Weathering effects may be heightened on un-vegetated slopes. Physical or chemical weathering may cause loss of cohesive or frictional strength.	Exposed soil surfaces Desiccation and cracking of surface soils Evidence of localised soil creep
Low shear strength of materials (internal cause)	Soils with discontinuities characterised by low shear strength such as bedding planes, faults, joints etc.	Not evident at the surface.
Over-steep headscarps (external cause)	The physical slope angle of the headscarps at Scalby Ness encourages spalling and block failure at the crest of the slopes.	Evidence of tension cracks immediately above the headscarp Fresh face and fresh deposits of soil beneath headscarp. Damage to vegetation. Localised slumping and slope readjustment

Causal factor	Description	Warning sign
		Presence of detached block from the upper headscarp Change in results of pin monitoring
Oversteep slopes (external cause)	The north-west slope is oversteep and marginally stable. Increase in porewater pressure or toe erosion has been shown in analysis to trigger instability. The upper slopes of the north-east (northern) slope (Behaviour unit II) are also over-steep.	Localised signs of activity e.g. tension cracks and bulging mid-slope Movement evident in results of pin survey
Removal of lateral support - undercutting of toe (external cause)	Undercutting of toe due to erosion or incision by Scalby beck at the toe of the slope, leading to loss of support to lower slopes (NE) or whole slope (NW).	Exposed eroding river banks Large bank slumps Overhanging river banks Erosion evident in results of pin survey
Removal of lateral support - removal of material from the toe of the slope due to instability (external cause)	Continued localised failure and movement of active areas identified in the mapping in the NE slope leads to loss of support to slope above, increase in slope angle, reduction in weight of material comprising the lower block.	Change in river bank condition Localised mudsliding above river bank Removal of material evident in results of pin survey
Increased loading (external cause)	Natural accumulations of water, snow, talus (accumulations of fragments of weathered material at the toe of slopes) and man-made pressures (e.g. fill, tips, and buildings) can all contribute to increased loading on the slopes. At Scalby Ness rubbish has occasionally in the past been tipped onto the slopes.	Presence of water, snow, talus or rubbish on the slopes.
Occurrence of deep-seated instability		Movement at depth in inclinometers. Possibly tension cracks in upper plateau above headscarps

Table 13 (cont) **Causal factors and warning signs**

8.2 *Trigger Levels*

The slope stability analysis has illustrated the variety of factors which influence the stability of the slopes at Scalby Ness, such as water levels within the slopes, the influence of sand and gravel lenses and the effect of toe erosion. The monitoring installed to date has been based on the earlier ground model, which considered that deep-seated failure of the slopes was probable. The current ground model considers shallower movements to be more likely.

The inclinometers installed in 2004 around the crest of the slopes provide a way of monitoring for deep-seated slips, should these occur. Automated piezometers have also been installed around the crest of the slopes. These record water levels at the rear of the slopes and not within the potentially active parts of the slopes.

There is only one correctly-functioning inclinometer currently installed in an area where activity is anticipated on the slopes (inclinometer SN1 in the north-east slope). Although manual groundwater data is available from the time when movement was recorded in inclinometer SN1, there is no guarantee that a maximum groundwater level was recorded, therefore trigger levels for the groundwater level to produce this instability are unknown and could only be derived from analysis. There is no inclinometer and no automated groundwater monitoring installed within the active north-west slopes.

Given the lack of automated monitoring data within the slopes where movement is anticipated and the sensitivity of the slopes to the various factors, it is not currently meaningful to give trigger levels for the monitoring. For example, if a trigger level were provided for a piezometer, to maintain a certain factor of safety in the slopes, the trigger level would only be applicable to one set of circumstances for that slope such as assumed groundwater levels within the slope and no toe erosion occurring. Once toe erosion had occurred, then the level is not appropriate. Without monitoring within the slope, then the applicability of the trigger level for that slope cannot be determined. It is not realistic with the current array of monitoring to provide trigger levels for the slopes. Should mitigation measures such as toe protection, regrading or drainage be carried out to provide a more stable system, this increased stability, coupled with monitoring in more appropriate locations, would allow trigger levels to be determined and used.

In the meantime, with a robust monitoring strategy and by seeking expert advice at the appropriate time, it will be possible to manage the situation at Scalby Ness appropriately. Details of a recommended monitoring strategy are given in Section 9, Recommendations, below.

8.3 Emergency Action Plan

The requirement for an emergency action plan needs to be put into context with the scenarios for instability presented in this report. On the basis of the nature of the three behaviour units, it is considered that the preparation of a detailed action plan for implementation in the event of significant instability being detected is inappropriate and unnecessary at present, provided that a robust monitoring and field observation strategy is implemented (see Section 9 below).

9 Recommendations

Following this detailed review and analysis of the instability issues at Scalby Ness a number of recommendations have been identified. These are:

1. Implementation of a robust monitoring and field observation strategy for Scalby Ness.

2. Implementation of a short-term management strategy, using the results of the monitoring

3. Consideration of remedial measures at the site, further ground investigation and longer-term management strategy

9.1 Monitoring and Field observation strategy

The results of the analysis and mapping carried out for the study suggest the likelihood of a large scale failure immediately affecting property is less than previously thought. However, the condition of the cliffs and coastal slopes at Scalby Ness are assessed to have only a small margin of stability and are subject to localised erosion at the slope toe and crest. Local erosion and surface instability are expected to continue over the strategy lifetime and, therefore, the following Site Management Strategy is recommended.

- Continued monitoring of existing inclinometers at monthly intervals from November to March and two-monthly intervals from April to October, with additional monitoring during or shortly after periods of intense rainfall.

- Repair of inclinometer SN3 and monitoring as above.

- Consideration of installation of inclinometers within the north-west slopes and possibly the upper north-east slopes.

- Continued monitoring of automated piezometers

- Consideration of installation of automated monitoring in piezometers in active zone of north-west slopes (this may be possible in existing piezometers) and in upper slopes of the north-east slope. Until this is carried out, manual monitoring of existing piezometers should be continued.

- Clear labelling of piezometer and inclinometer numbers on site – this would avoid confusion on site, for example data received labelled BH SN3 implies that an inclinometer is being read as a piezometer. It would be good practice to continue to measure and record the depth to the base of the piezometer which is being read – this provides a way of checking exactly which instrument has been read.

- Installation and surveying of a series of movement pins across the slopes to Ordnance Survey co-ordinates – this avoids problems with local co-ordinate sets such as the data received to date from SBC. Clear labelling of the survey pins. Pairs of survey pins should be set back a known distance from the crest of the slopes and measurements made along the line of the pins to the crest using a steel tape so a quantitative record of crest recession is obtained.

- Regular checks of the state of the banks of the beck, identifying any areas where active erosion is taking place (monthly with walk-over). Pairs of survey pins should be set back a known distance from the bank and measurements made along the line of the pins to the bank using a steel tape so a quantitative record of erosion is obtained. A good photographic record should be maintained.

- Regular monthly walk-over surveys should be conducted to check the condition of the slopes and to observe and record indicators of activity such as opening up of tension cracks or block detachment processes. Observations and non-automated monitoring results should be recorded on a Field Record Sheet such as the example provided in Appendix B. This sheet would provide a helpful reminder during walkover surveys of the items to be recorded, and would be a straightforward and consistent way of monitoring the slopes. Any features such as tension cracks, areas of movement and ponding should be sketched on a plan (sheet 3 of the Field Record).

In connection with the two bullet points above, a good photographic record should also be maintained.

- Taking the appropriate action in response to results of the monitoring in accordance with section 9.2 below.

The site walk-overs and monitoring should be undertaken by a competent person (e.g. chartered geologist or engineer) with suitable experience of landslide investigation.

9.2 *Implementation of the short-term management strategy*

Management of the slopes at Scalby Ness will require a combination of actions brought together in one effective strategy. We recommend that SBC should consider implementing a scheme with stages similar to those outlined below and described in more detail in Sections 9.2.1 to 9.2.5:

- Stage 1 - Dealing with immediate slope management issues, e.g. rubbish and waste accumulating on the slopes, drainage discharging onto the slopes, vegetation management.

- Stage 2 - Regular monitoring of instruments, survey pins and the physical state of the slopes, as detailed in Section 9.1above.

- Stage 3 - Using the results of the monitoring to determine which indicators of change are present in the slopes and hence determining a cliff behaviour scenario and hazard warning status from Table 14 and/or the flowchart on sheet 4 of the Field Record Sheet.

- Stage 4 – Taking action in response to the hazard warning status in accordance with Table 15 and/or the flowchart on sheet 4 of the Field Record Sheet

- Stage 5 - Continued communication with residents to keep them informed of the way the slopes are being managed

9.2.1 *Stage 1 - Dealing with immediate slope management issues*

SBC staff should be vigilant in dealing with matters in relation to maintenance of the slopes. For example, drainage pipes discharging onto a slope face should be intercepted and the water discharged safely elsewhere and not allowed to continue feeding into areas of potential instability. It is understood that accumulations of rubbish have occurred on the slopes of Scalby Ness in the past. However, this appears to have been effectively dealt with by Council staff. Any future accumulations of debris or rubbish should be cleared up as soon as possible.

9.2.2 *Stage 2 – Regular monitoring*

Regular monitoring of instruments, survey pins and the physical state of the slopes, as detailed in Section 9.1 above should be carried out.

9.2.3 *Stage 3 - Using the results of the monitoring to determine a cliff behaviour scenario and hazard warning status*

After each walk-over and monitoring survey an assessment should be made by a competent person (see section 9.1) for each of the behaviour units using the Flow chart (Appendix B). For each slope, the results of the monitoring should be analysed to see which indicators of change are present. "Indicator of change" is a general term and covers four broad categories of movement or pre-cursors to movement that can be determined by monitoring and visual inspection. These are toe erosion, high groundwater level, tension crack development in upper plateau(x) more than 1m from the cliff crest and slope activity. Signs which could be observed on site and classified as "indicators of change" are described in more detail in Table B1 in Appendix B.

For example, if toe erosion and a high groundwater level had been monitored in the north-west slope, but no tension cracks in the upper plateau or slope activity had been observed, Flow chart (appendix B) shows that the hazard warning status is Amber for the north-west slope.

After each round of monitoring or walkover survey, the status of the slopes should be determined. A determination should be made for each of the three Behaviour Units.

9.2.4 *Stage 4 – Taking action in response to the hazard warning status*

Once the hazard warning status has been determined for each Behaviour Unit, action should be taken by SBC in accordance with Table 14 below. This table gives the overall response required for each hazard warning status. SBC should also refer to Table B2 in Appendix B, which gives further details of the response to individual indicators of change.

The responses given in the tables are not necessarily exhaustive and appropriate action should be taken by SBC in response to the circumstances observed on site and in accordance with the recommendations of any expert appointed to review the results, if applicable.

Table 14 Response to hazard warning status at Scalby Ness

Hazard warning status	Description	Response
Green	The slope has been subject to engineering works and is showing no signs of instability.	Continued monitoring as recommended in Section 9.1, reducing with time. Regular walk-over surveys. Annual inspection of defences to assess potential maintenance requirements.
Yellow	The slope has not been subject to engineering works and is currently showing no signs of major instability.	Continued monitoring as recommended in Section 9.1. Any significant changes to be highlighted and relayed to SBC site manager for appropriate action. Provide monitoring results to consultant as appropriate.
Amber	The slope has not been subject to engineering works. Localised evidence of instability, toe erosion occurring, leading to possible future wider scale slope activity.	Review requirement for localised engineering works and mitigation measures. Increase frequency of monitoring. Provide monitoring results to consultant as appropriate. Seek expert advice.

Hazard warning status	Description	Response
Red	High activity indicating potential for large scale instability. Tension cracks >1m from crest on upper plateau indicate potential for deep-seated movement.	Seek expert advice immediately. Monitor daily or more frequently if necessary. Evacuate residents if property is put at risk by proximity of tension cracks. Monitor inclinometers – check for evidence of deep-seated movement. Consider implementation of major engineering works?

Table 14 (cont) Response to hazard warning status at Scalby Ness

The key to the above response table is for SBC to seek expert advice immediately in interpreting the results of the monitoring, if there are results which give cause for concern. SBC should consider engaging a consultant to provide advice on the monitoring results.

9.2.5 *Stage 5 - Communication with residents*

Continued communication with residents is most important in allaying concerns about the state of the slopes. Two-way communication should be encouraged, so that any concerns the residents may be made known to the Council. It is appreciated that SBC hold regular meetings with the residents of Scalby Ness and this good practice should continue. A regular newsletter and progress reports to residents may be an effective method of disseminating information between the meetings.

9.3 *Remedial measures, further ground investigation and longer-term management strategy*

Section Two of SBC's Hundale Point to Scalby Ness Coastal Strategy Employer's Requirements (SBC, 2004) requires the consultant to consider identification and development of options for the site, including remedial measures. We recommend that Section Two of the strategy is carried out, to allow identification of appropriate and cost-effective mitigation measures for the site. It is anticipated that some relatively low-cost measures, such as installation of toe protection and regrading of the crests of the slopes, would ensure or improve the factor of safety of the slopes.

Further ground investigation would allow some of the gaps in the ground models to be filled in with more certainty. For example the location of sand and gravel lenses may be further characterised to allow appropriate design of mitigation measures and drainage. Additionally, further investigation would provide the opportunity for the installation of instrumentation in more appropriate locations, such as inclinometers and automatic piezometers in the north-west slopes and possibly in the upper slopes of the north-east slopes.

A longer-term management strategy should be developed once the choice of remedial measures has been made. The strategy may also include for regular ortho-rectified aerial photography of the slopes, to monitor toe erosion, crest retreat and slope behaviour.

10 Conclusions

This Section 1 geotechnical report examines modes and likelihoods of cliff failure at Scalby Ness. The report reviews the site history and development. It describes the geomorphological mapping carried out for the study. Based on monitoring data gathered by SBC, supplemented with the new geomorphological mapping, it provides an analysis of ground conditions at the site, reviews the previous ground model and presents a revised ground model for the slopes. Scenarios and probabilities for slope development are presented. These probabilities allow the effect of the slope development scenarios on the properties at the crest of the slopes to be assessed. Recommendations are made on appropriate monitoring and response actions in relation to the findings of ongoing monitoring. A short-term management strategy is proposed based on hazard status determination for the slopes. Recommendations are also made for further ground investigation, consideration of remedial measures and a longer term management strategy.

References

British Standards Institution (1981). *BS 6031: 1981. Code of practice for Earthworks.*

High-Point Rendel Ltd. *Scalby Ness Coast Protection and Cliff Stabilisation: Rapid Risk assessment.* Draft report, Issue 3. March 2002.

High Point Rendel. (May 2003). (Draft) Coastal strategy,

Jones, D and Lee, EM. (1994). *Landsliding in Great Britain, Department of Environment*. London: HMSO.

Moore, R; Lee, EM and Clark, AR. (1995). *The Undercliff of the Isle of Wight: a Review of Ground Behaviour.* Cross Publishing: Newport, Isle of Wight,

Scarborough Borough Council, August 2004. *Employer's Requirements for Hundale Pint to Scalby Ness Coastal Strategy for Scarborough Borough Council.*

Structural Soils. (September 2004). *Factual Report on Supplementary Ground Investigation at Scalby Ness, Sacrborough*, Final report No: 40548.

Structural Soils, (November 2001). *Report on Ground Investigation at Scalby Ness, Scarborough, North Yorkshire*, Draft report No: 16902

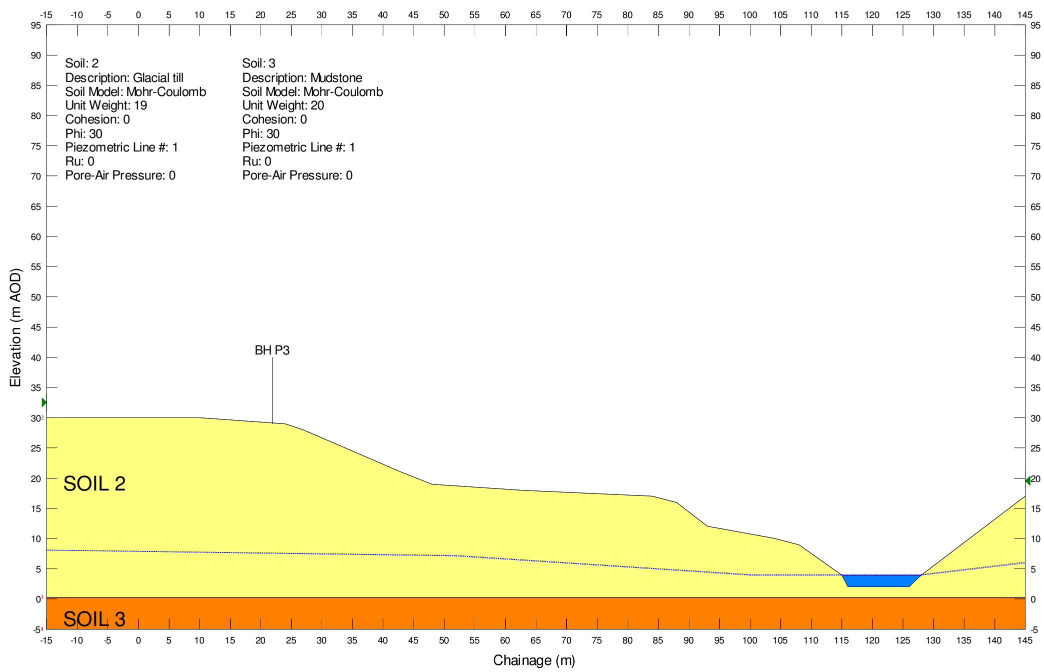
FIGURES

APPENDICES

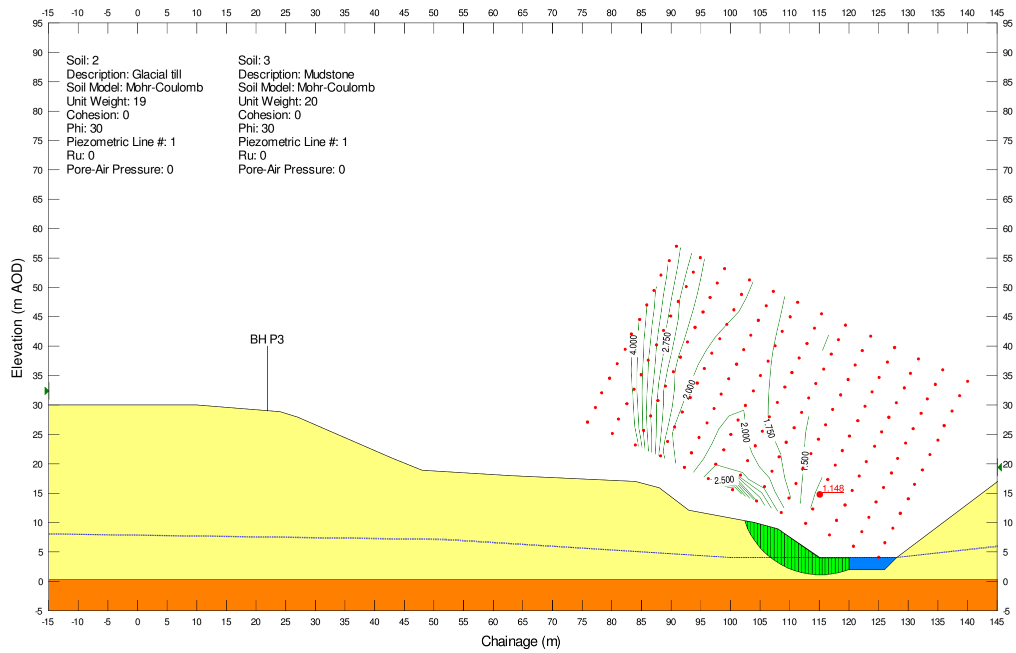
A Slope stability analysis

A.1 North-east slope

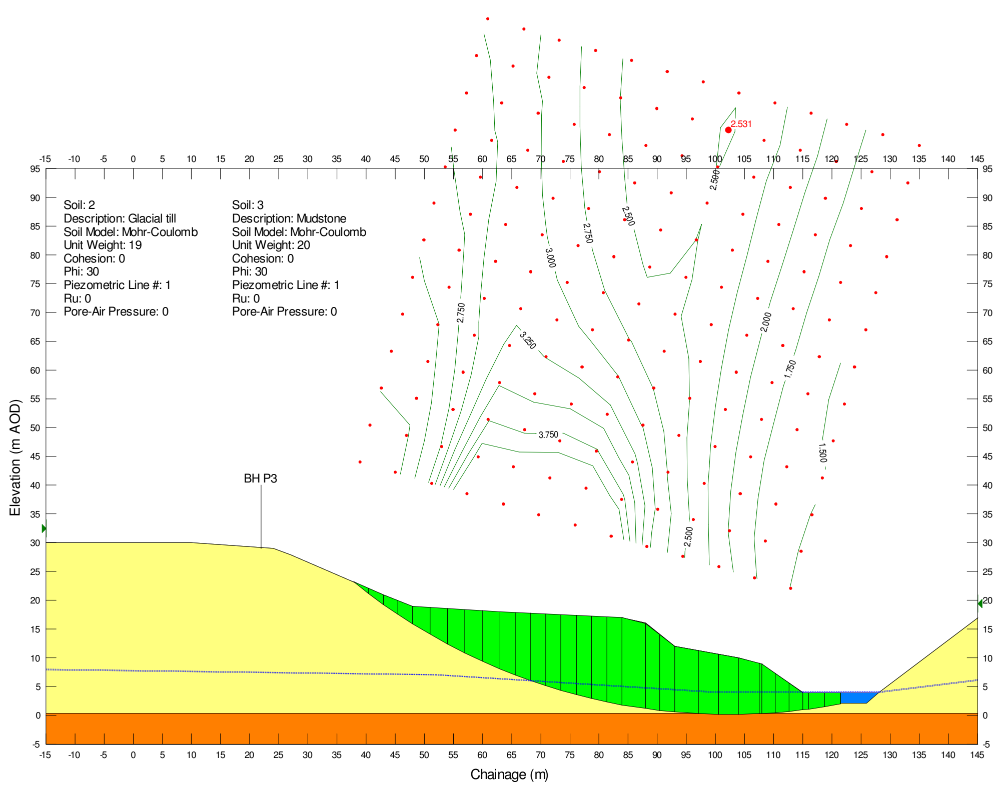
A.1.1 Section 1



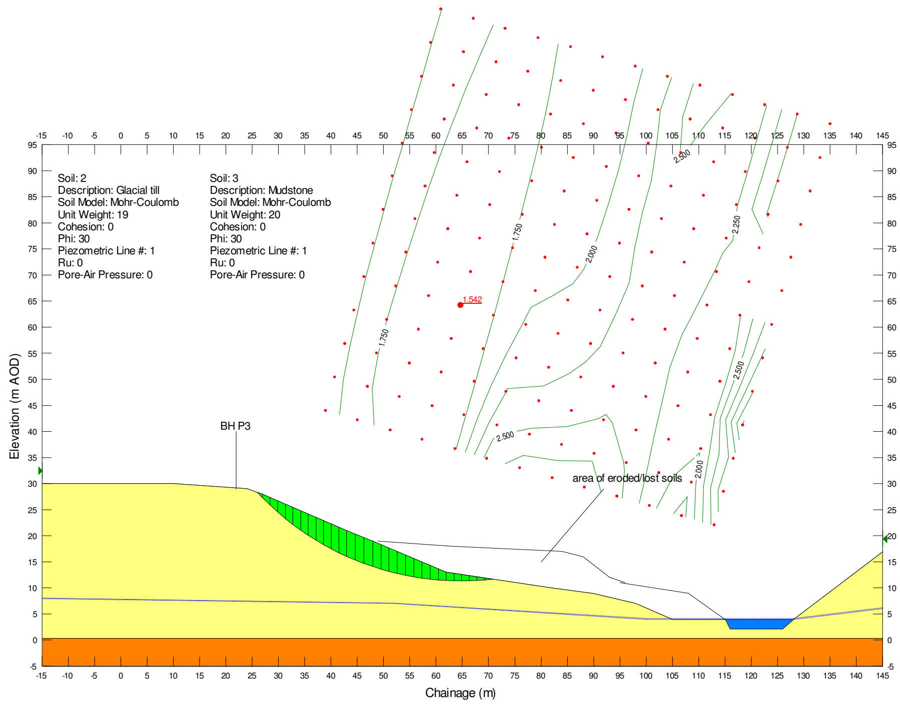
Section 1. Ground Model



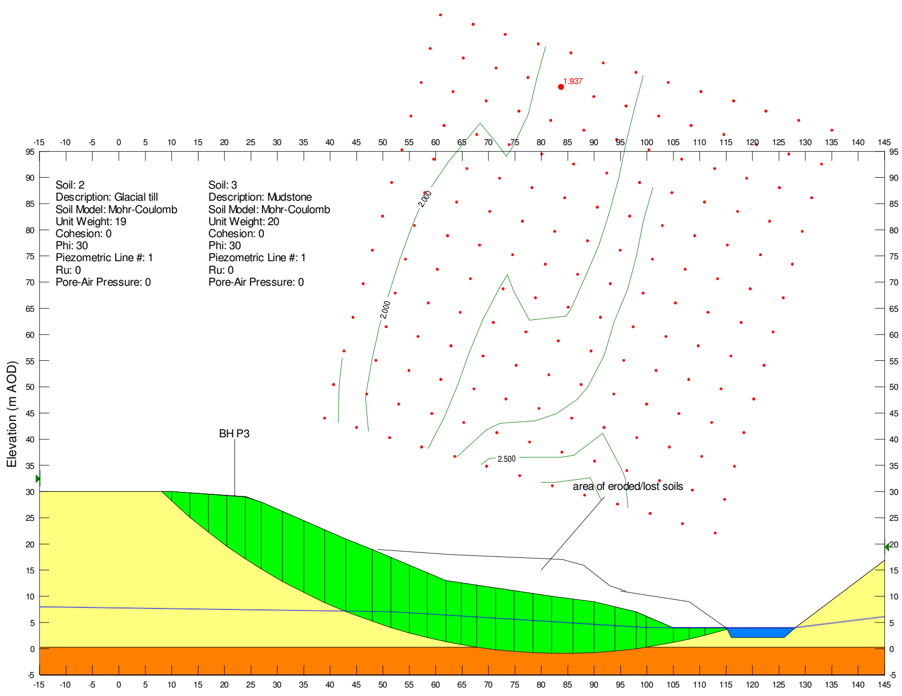
Section 1. Model 1/1. FOS=1.15 (phi'=30º, peak parameters, reduced GWL)



Section 1. Model 1/2. FOS=2.53 (phi'=30 º, peak parameters, overall slope)

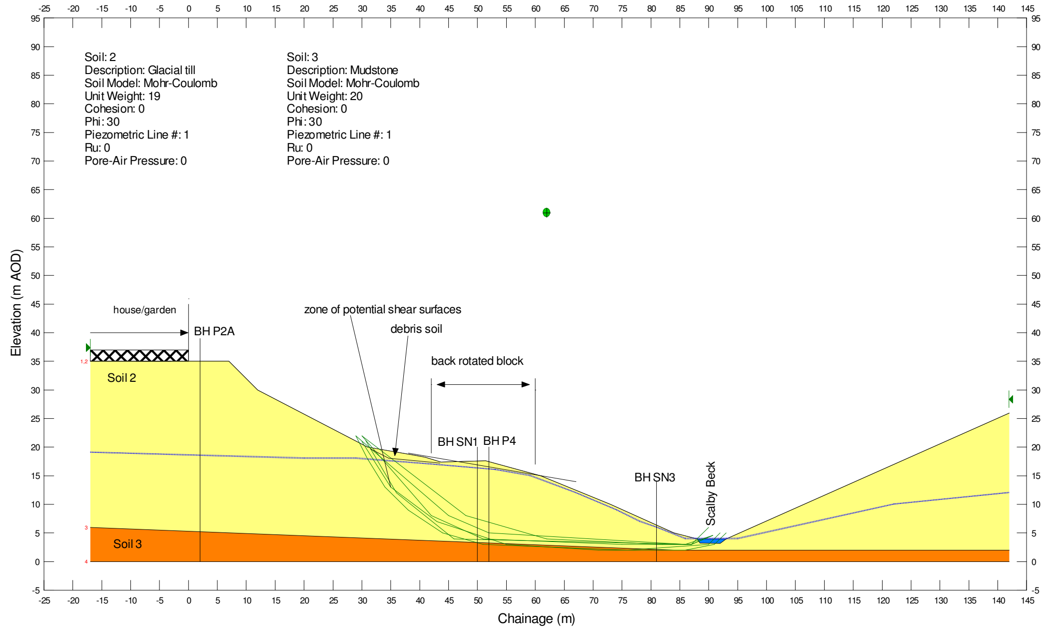


Section 1. Model 1/3. FOS=1.54 (phi'=30 º, peak parameters, overall slope and lowest FOS)

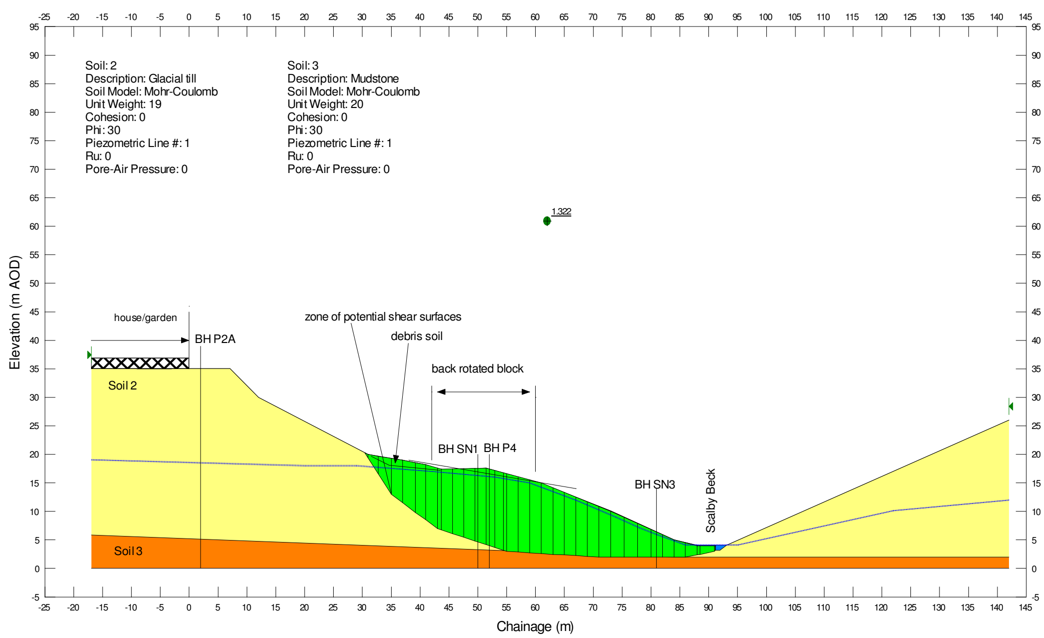


Section 1. Model 1/4. FOS=1.94 (phi'=30 º, peak parameter, FOS for overall slope following toe loss)

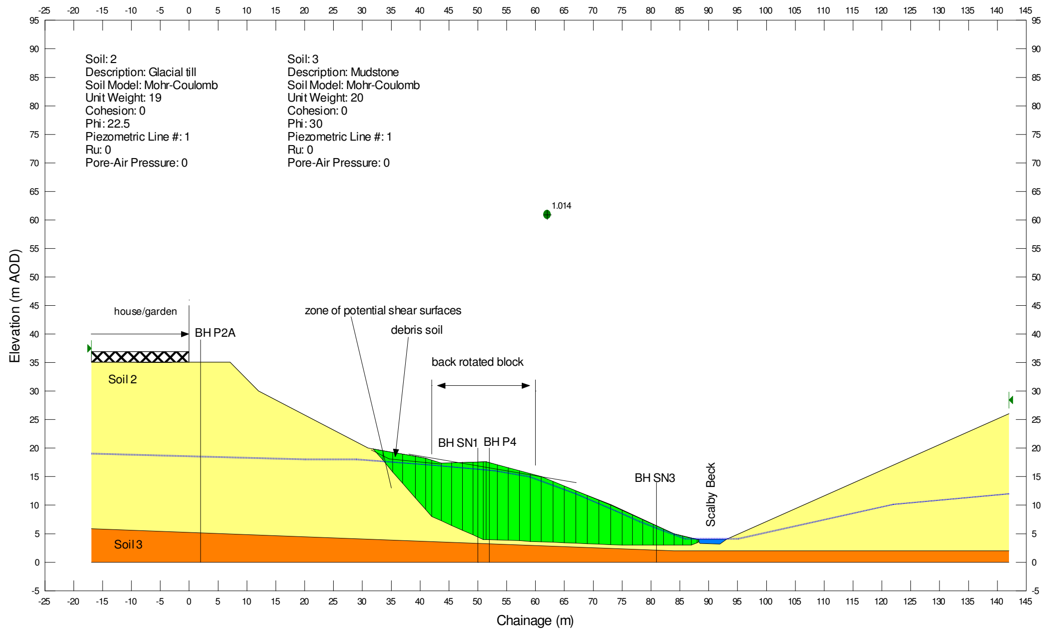
A1.2 *Section 2*



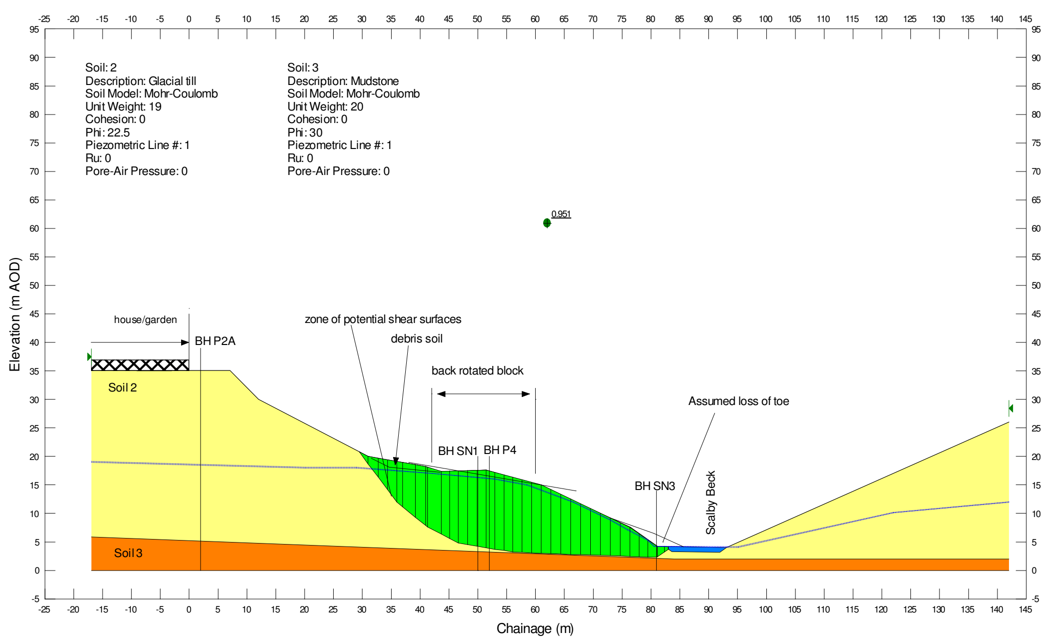
Section 2. Ground Model with full pore water pressure (pwp) in lower block



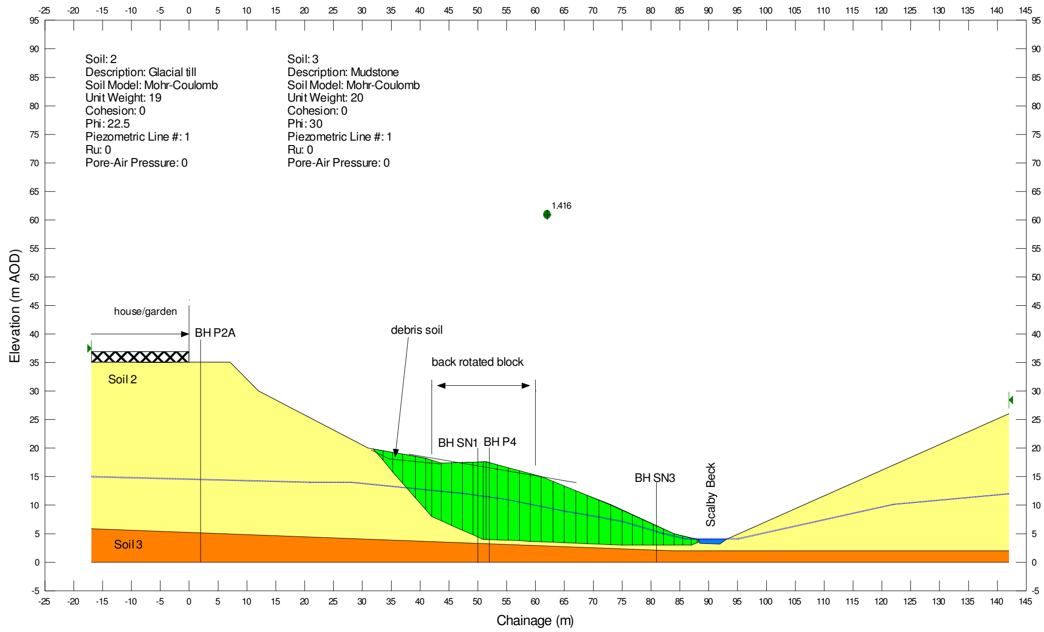
Section 2. Model 2/1. Block FOS>1.30 (phi'=30 º, peak parameters, full pwp)



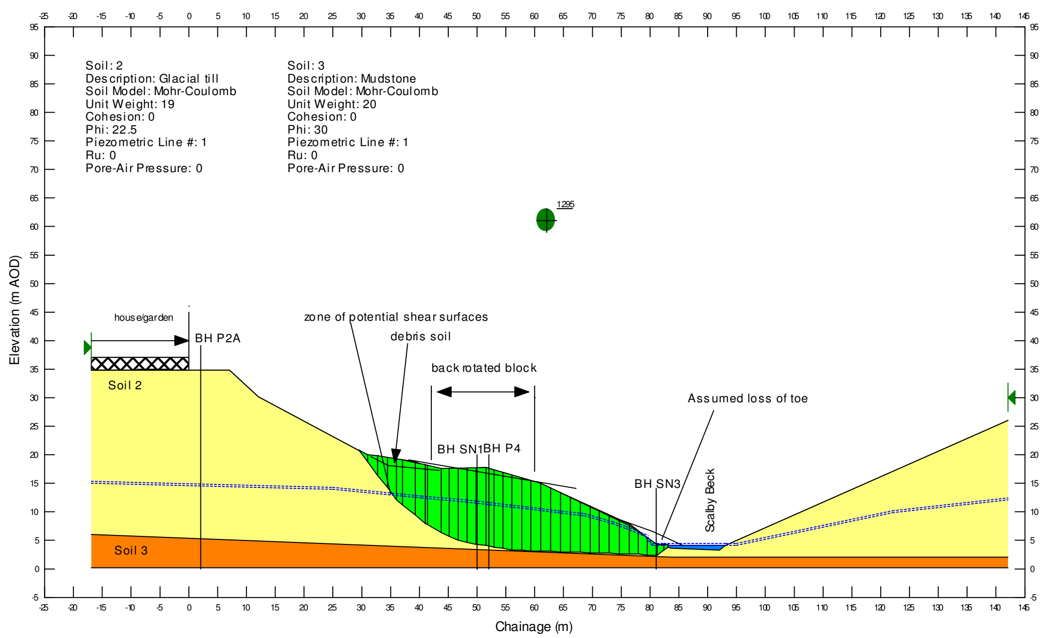
Section 2. Model 2/2. Block FOS=1.00 (phi'=22.5 °, post-peak/residual parameters, full pwp)



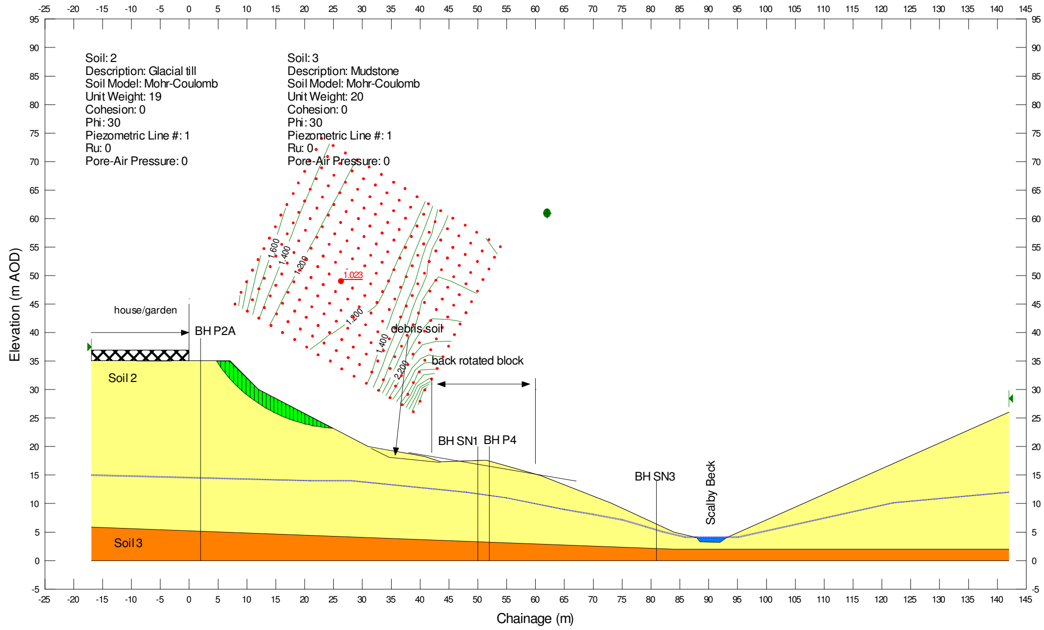
Section 2. Model 2/3. Block FOS<1.00 (phi'=22.5 °, post-peak/residual parameters, full pwp, toe loss)



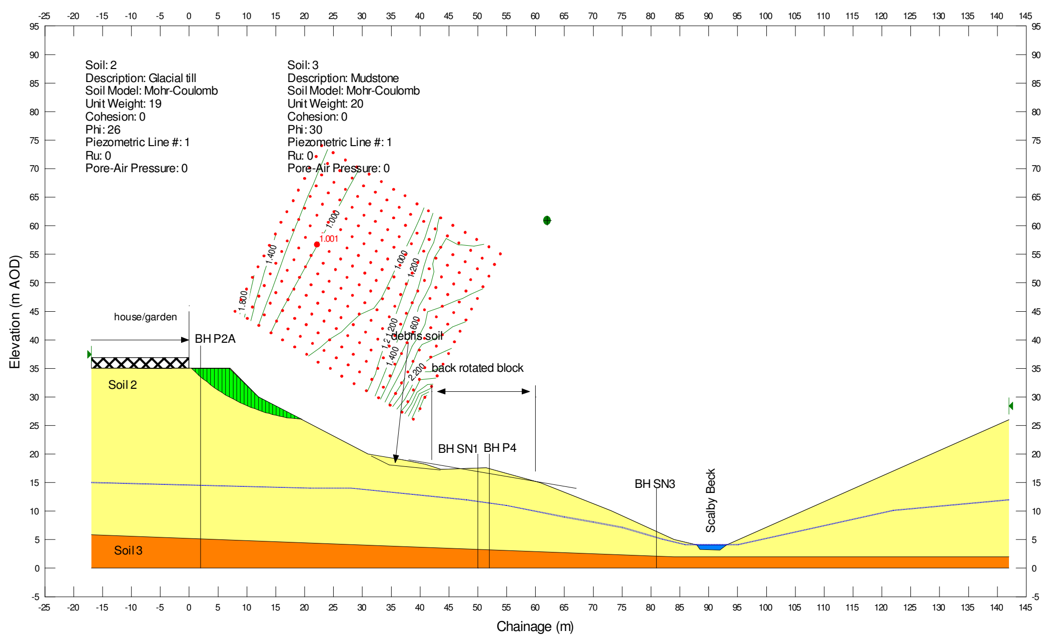
Section 2. Model 2/4. Block FOS>1.30 (phi'=22.5 °, post-peak/residual parameters, reduced pwp, toe loss)



Section 2. Model 2/5. Block FOS>1.00 (phi'=22.5 °, post-peak/residual parameters, reduced pwp, toe loss)

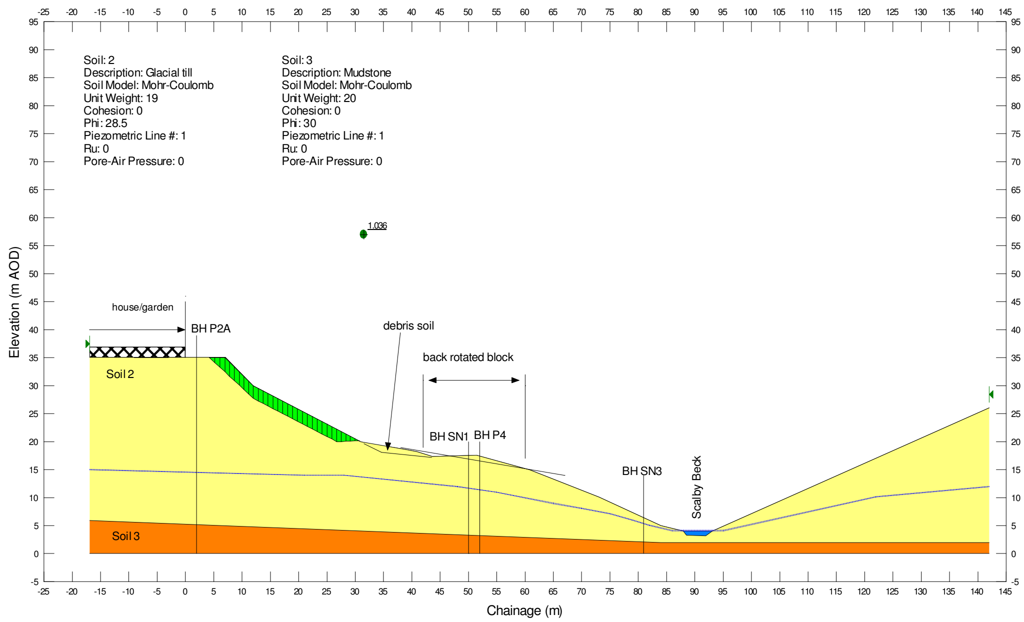


Section 2. Model 2/6a. FOS=1.02 (phi'=30 º, peak parameters, top of slope)

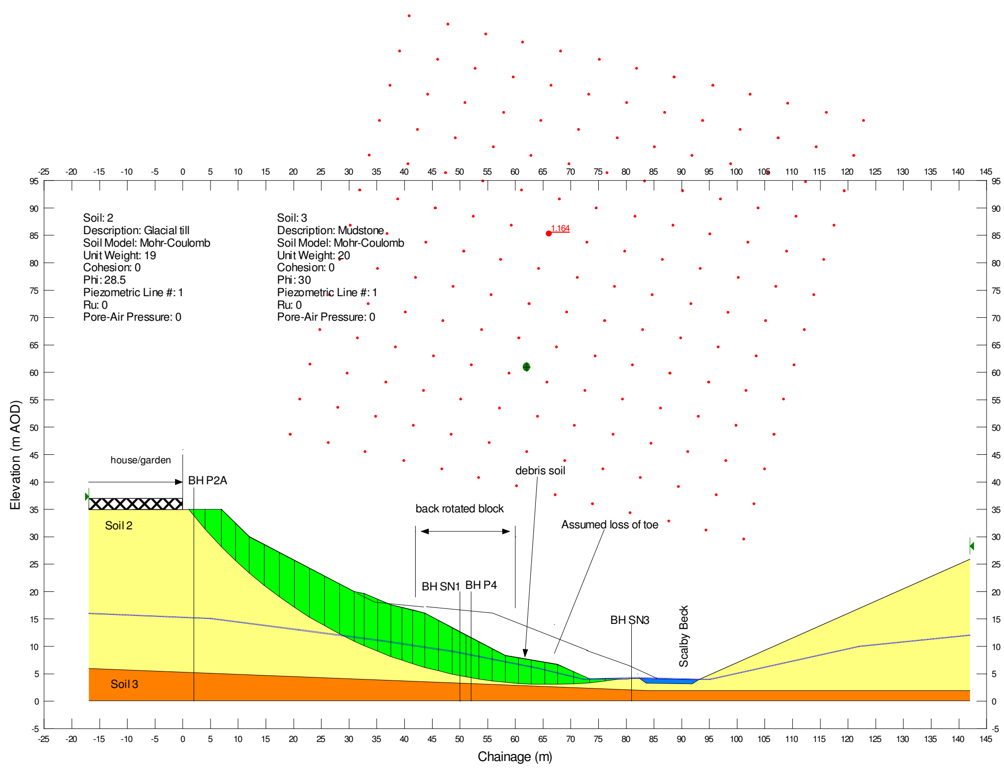


Section 2. Model 2/6b. FOS=1.00 (phi'=26 º, lower bound peak parameters, top of slope)

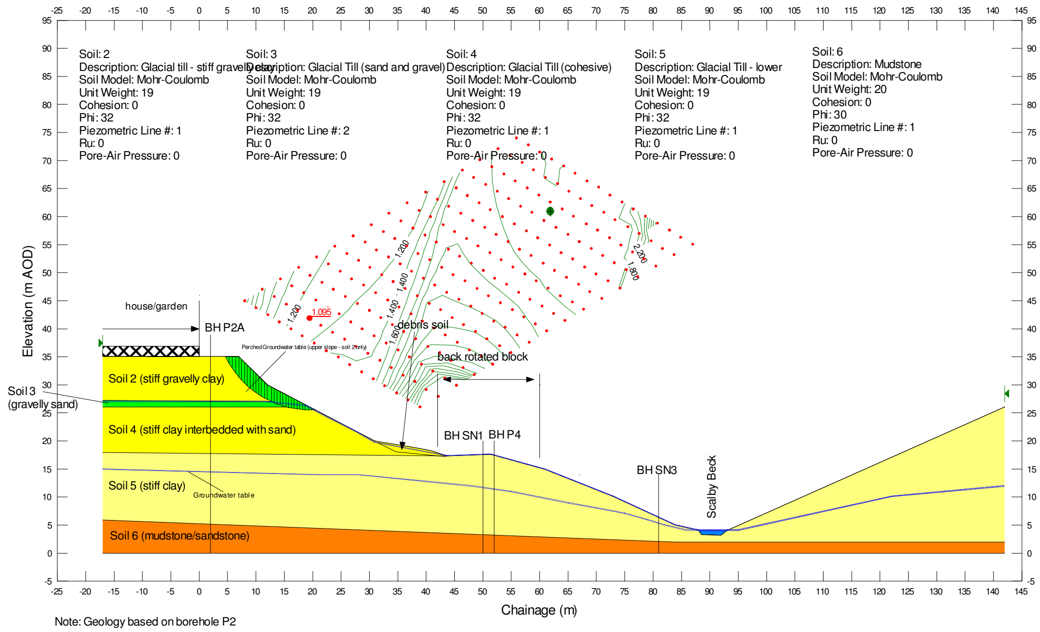
(Note: variation in glacial till could give rise to localised areas of instability, no pwp allowed at top of the slope)



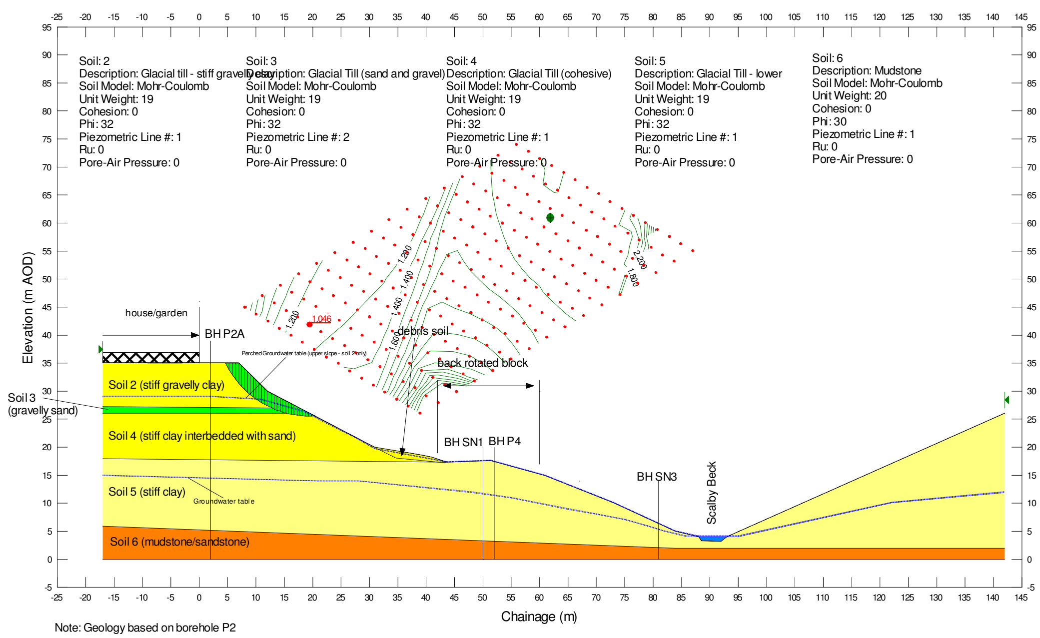
Section 2. Model 2/7. Infinite Slope FOS=1.00 (phi'=28.5 º, top of slope)
(analysis to determine phi' for a FOS of about 1.00, i.e. natural angle of repose)



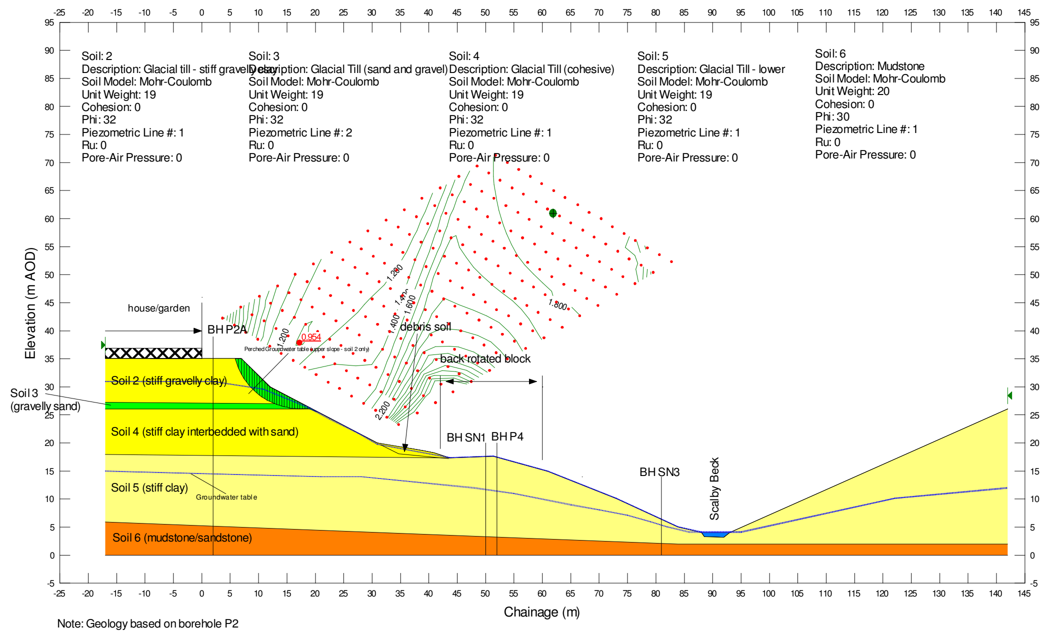
Section 2. Model 2/8. FOS=1.16 (phi'=28.5 º, peak parameters, reduced pwp, complete toe loss)



Section 2. Model 2/9. Perched Groundwater within the Upper Glacial Till Deposits.

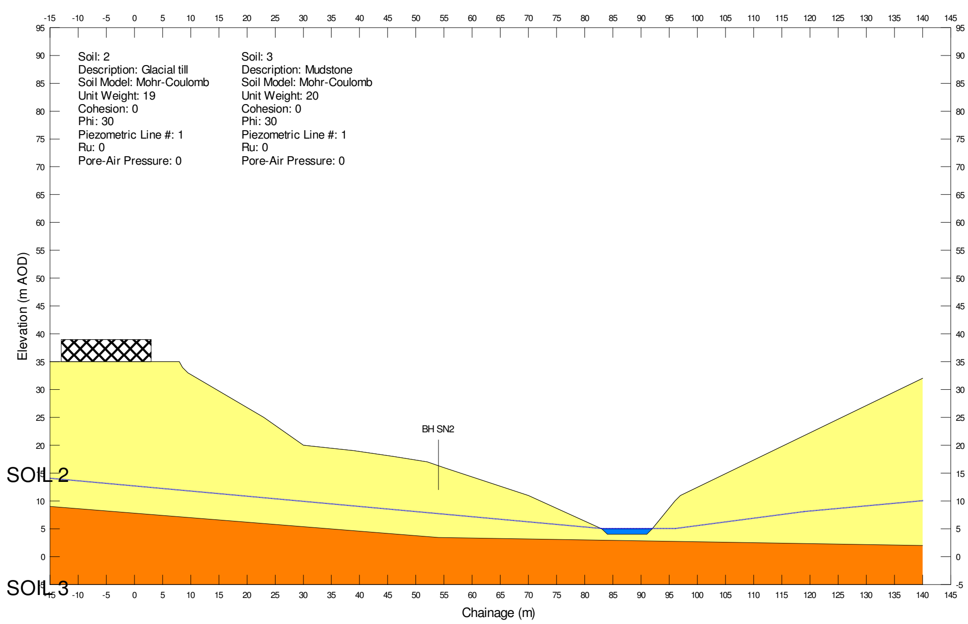


Section 2. Model 2/10. Perched Groundwater within the Upper Glacial Till Deposits for a +2m Groundwater Level. (FOS=1.05)

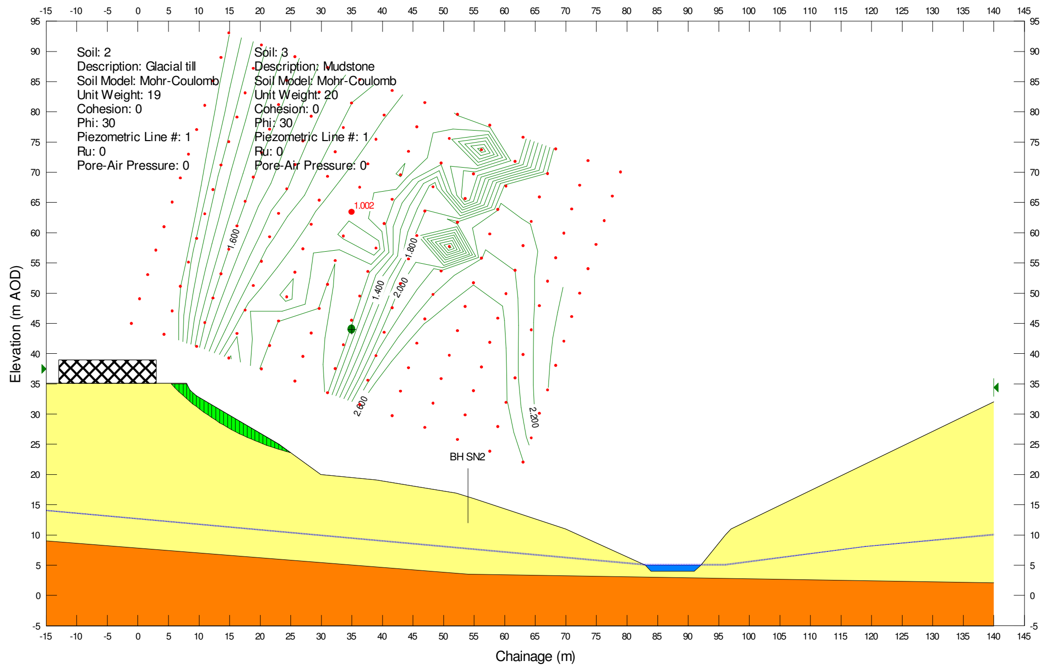


Section 2. Model 2/11. Perched Groundwater within the Upper Glacial Till Deposits for a +4m Groundwater Level. (FOS=0.95)

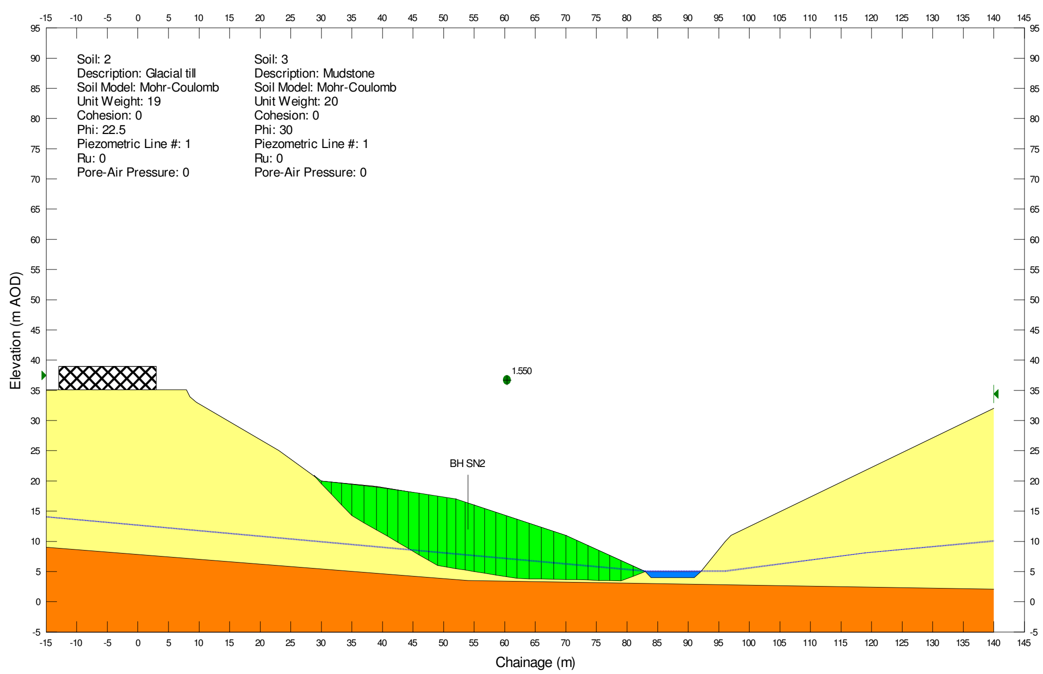
A1.3 *Section 3*



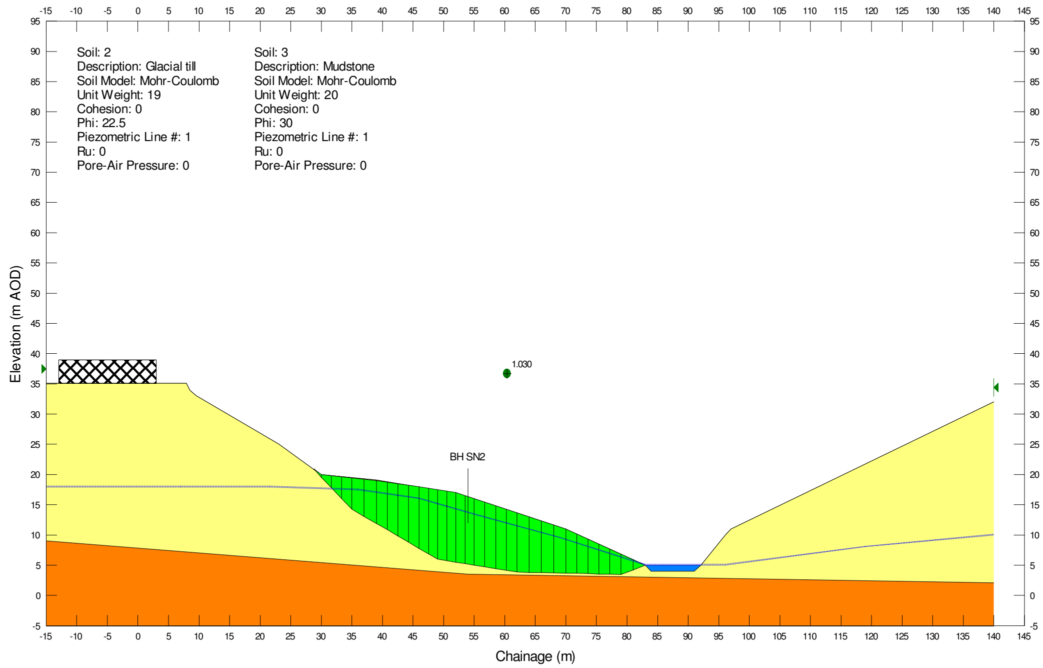
Section 3. Ground Model



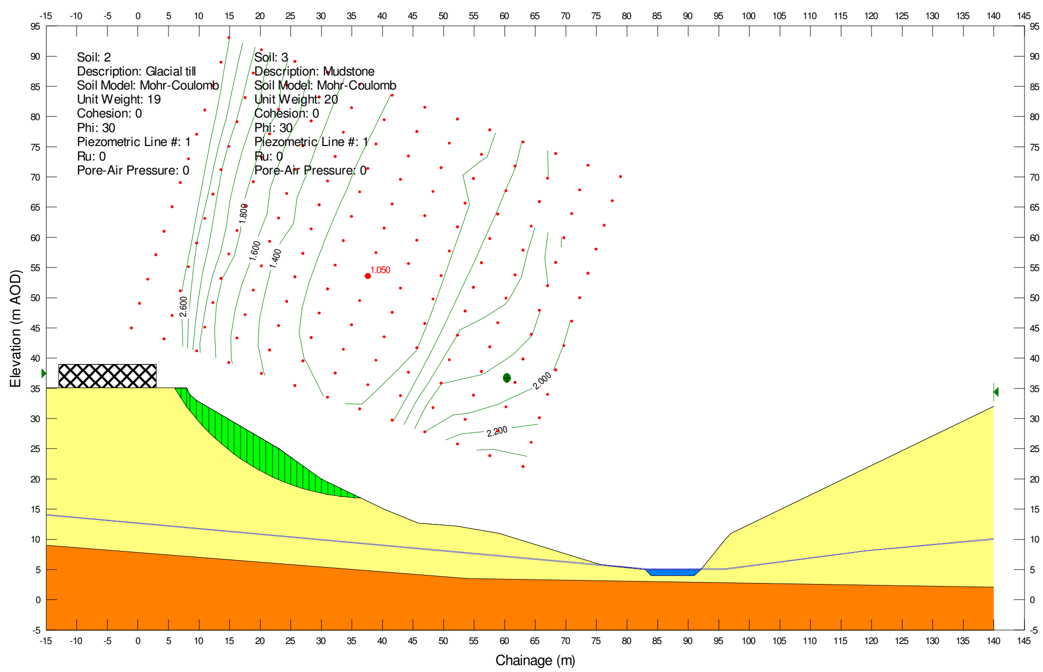
Section 3. Model 3/1. FOS=1.02 (phi'=30 º, peak parameters, FOS for upper slope)



Section 3. Model 3/2. FOS=1.55 (phi'=22.5 º, post-peak/residual parameter, FOS for block)

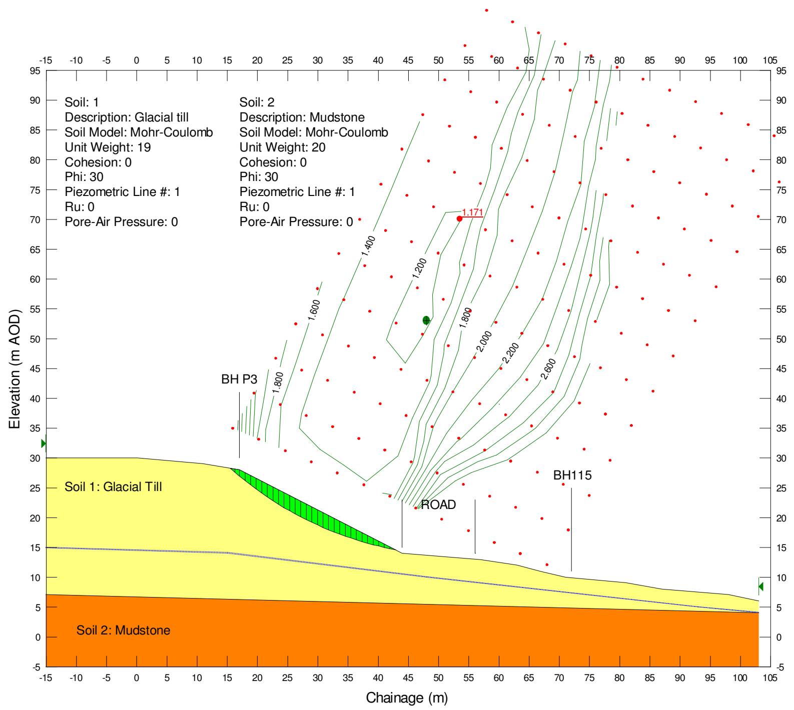


Section 3. Model 3/3. FOS=1.03 (phi'=22.5 º, post-peak/residual parameters, FOS for block, with raised GWL)

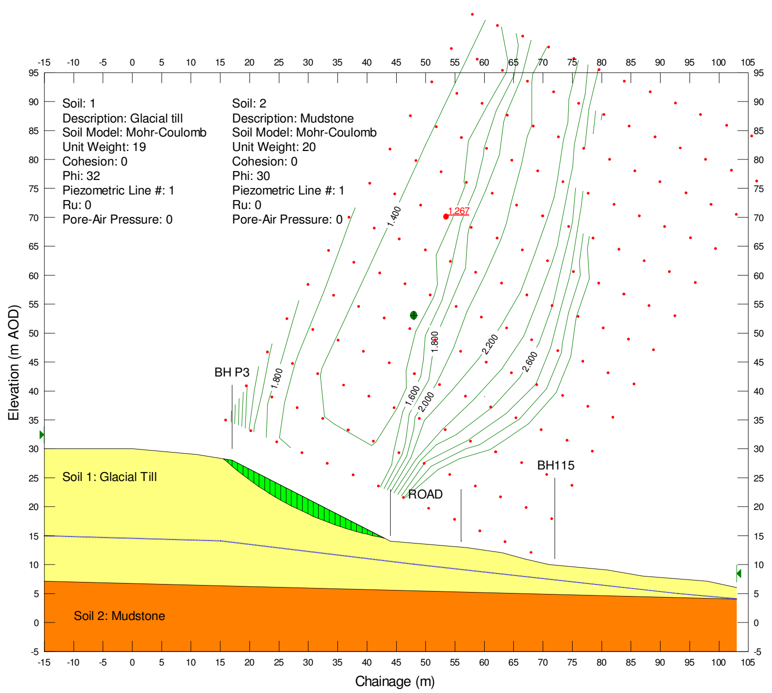


Section 3. Model 3/4. FOS=1.03 (phi'=30 º, peak parameters, with toe erosion) Lowest FOS shown

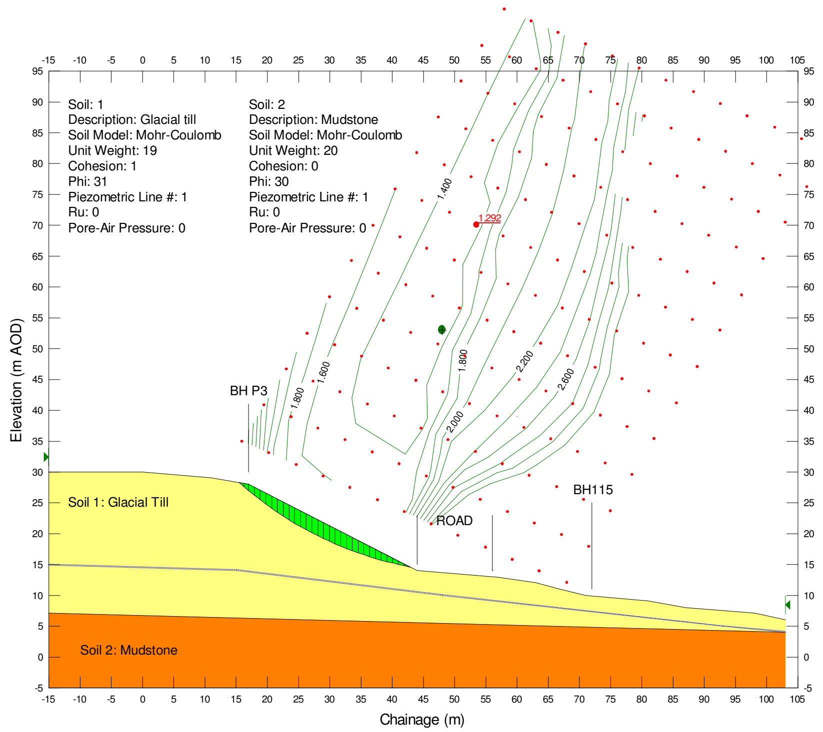
A1.4 *Section 6*



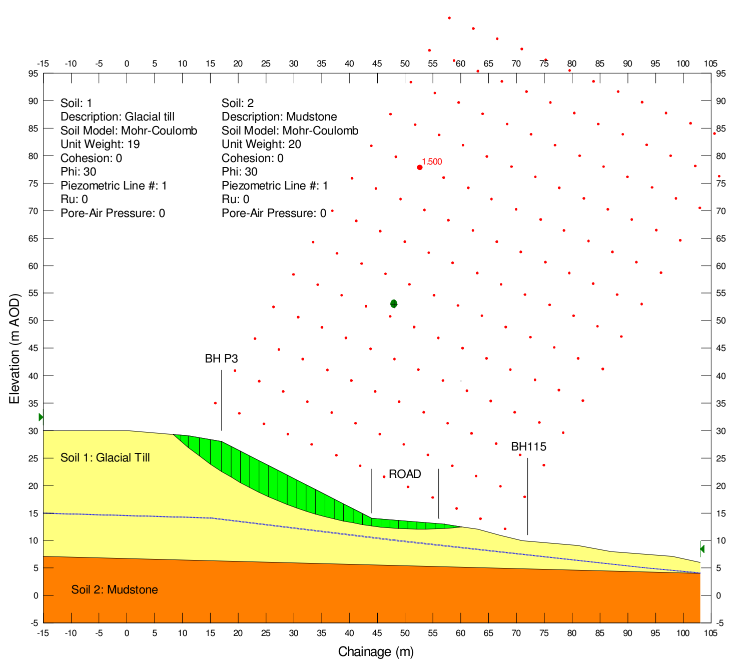
Section 6. Model 6/1. FOS 1.17 for Ø’ of 30°



Section 6. Model 6/2. FOS 1.27 for Ø’ of 32° (peak parameters)



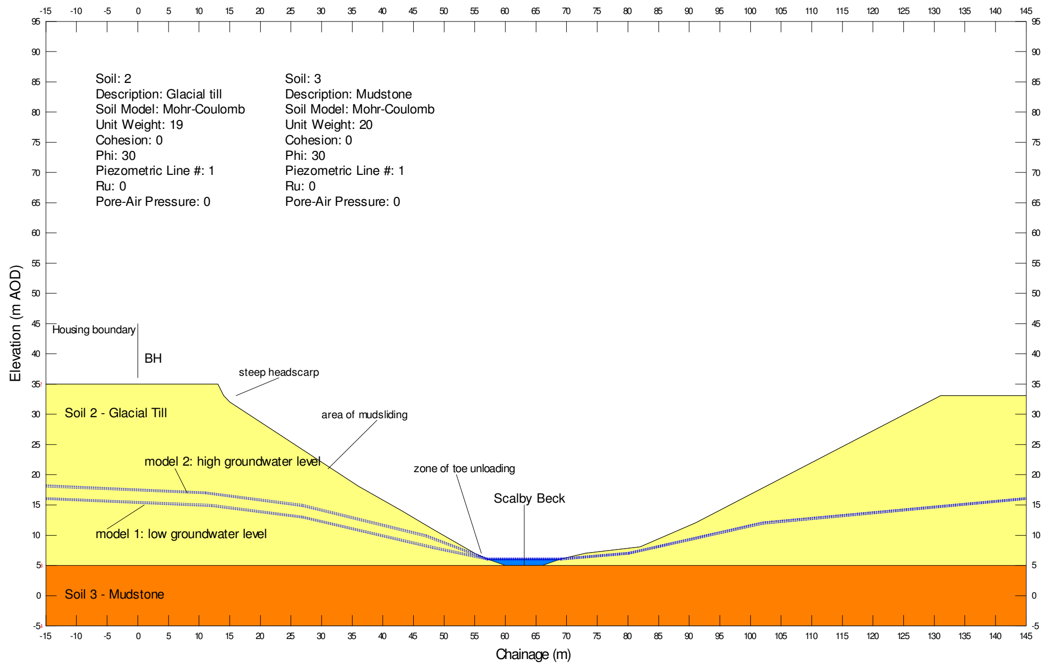
Section 6. Model 6/3. Determination of parameters which would provide a FOS of about 1.30 (c'=1kPa and ϕ'=31 degrees)



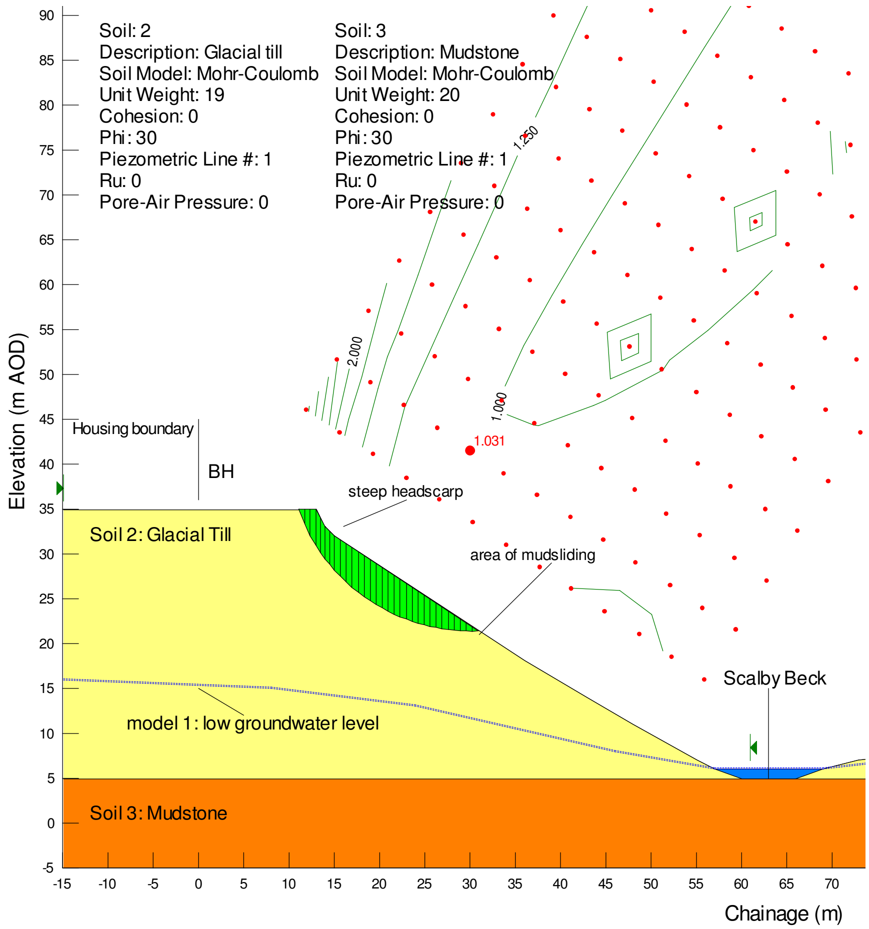
Section 6. Model 6/4. Considering failure of the whole slope. FOS 1.5 for ϕ'=30 degrees.

A.2 North-west slopes

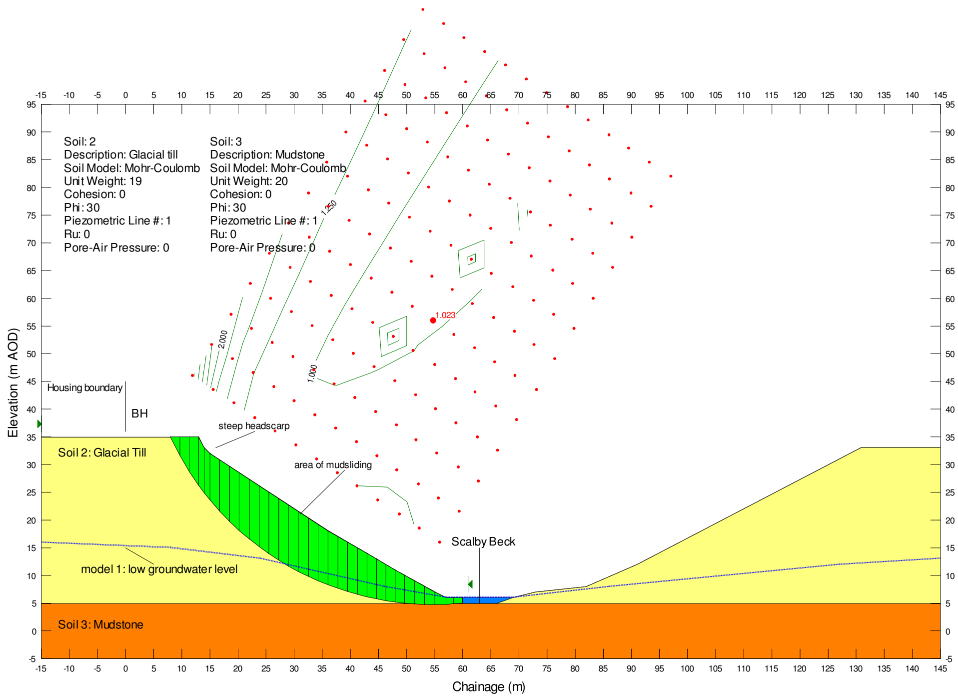
A2.1 Section 4



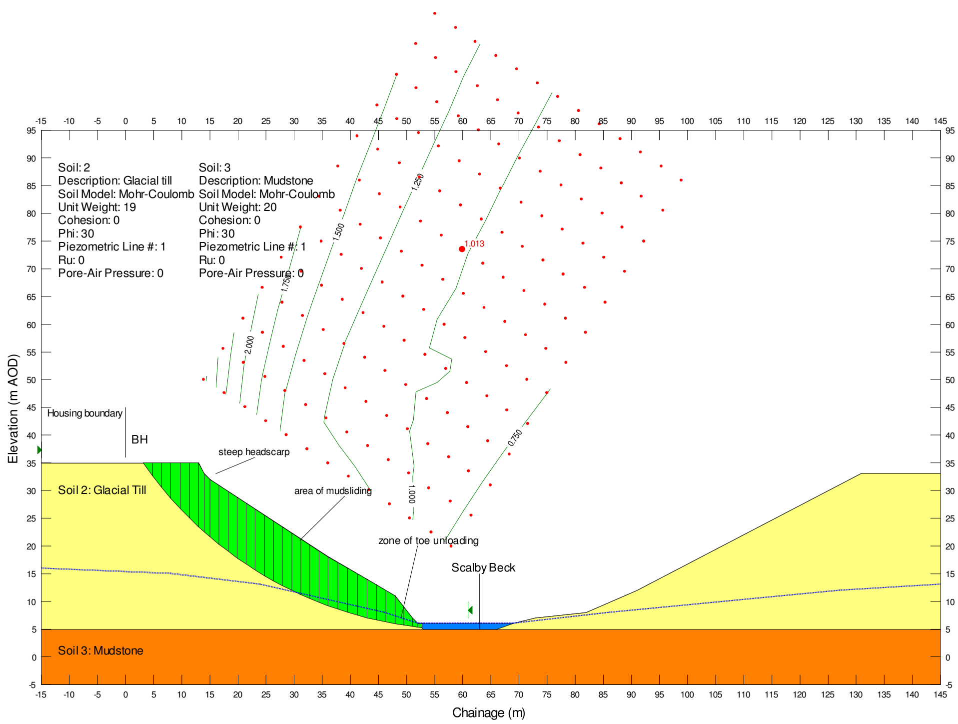
Section 4. Ground Model



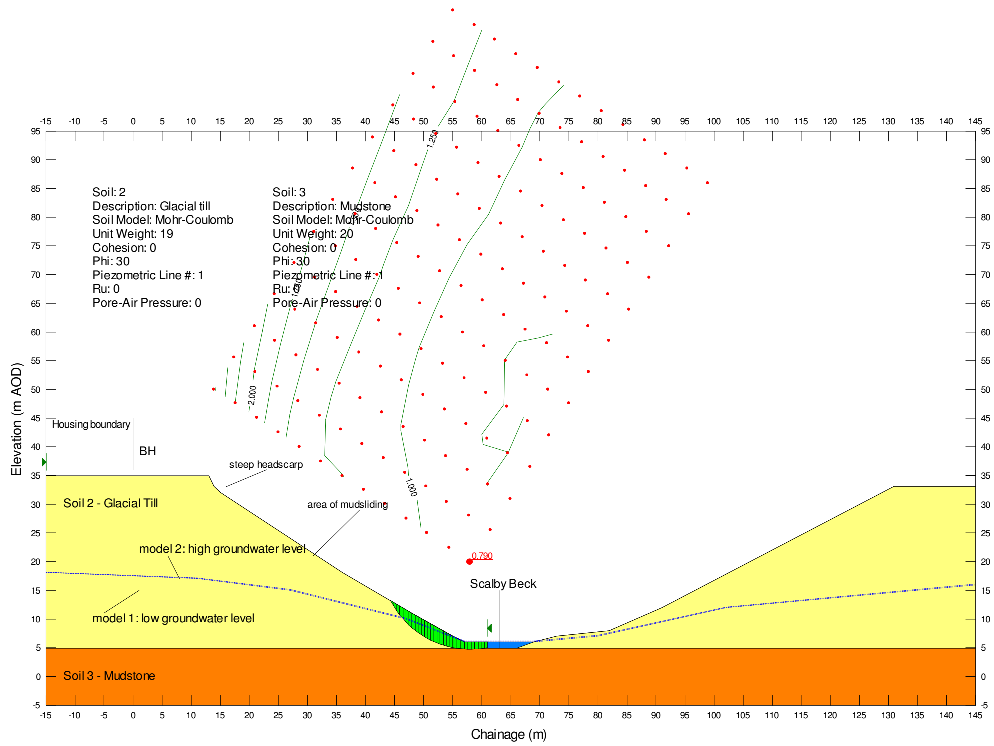
Section 4. Model 4/1. Extent of a potential slip surface at the top of the slope with a factor of safety of about 1.00



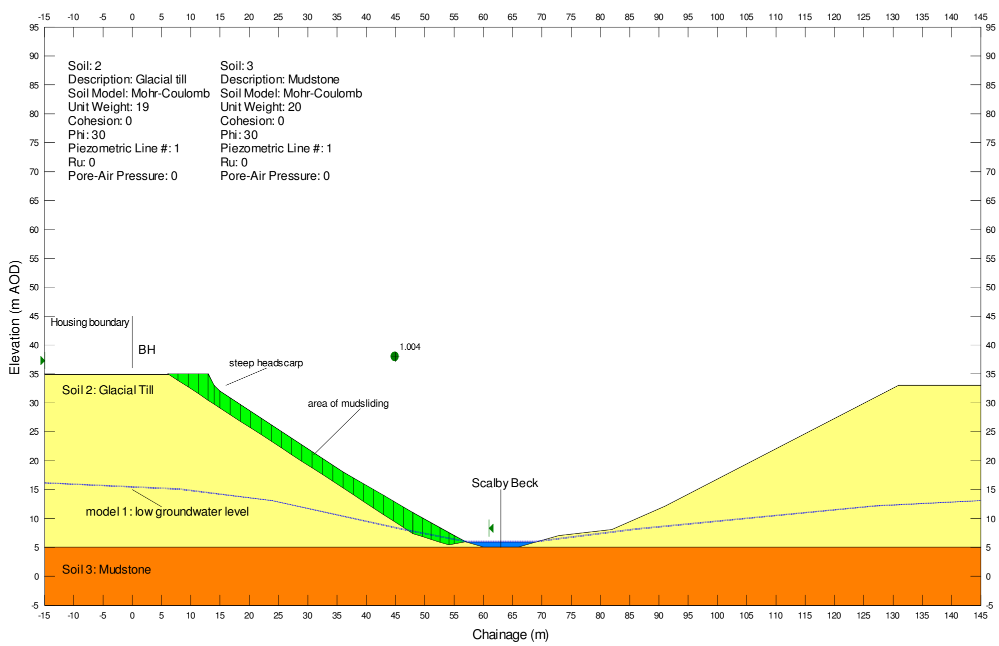
Section 4. Model 4/2. Extent of a potential slip surface (whole slope) with a factor of safety of about 1.00



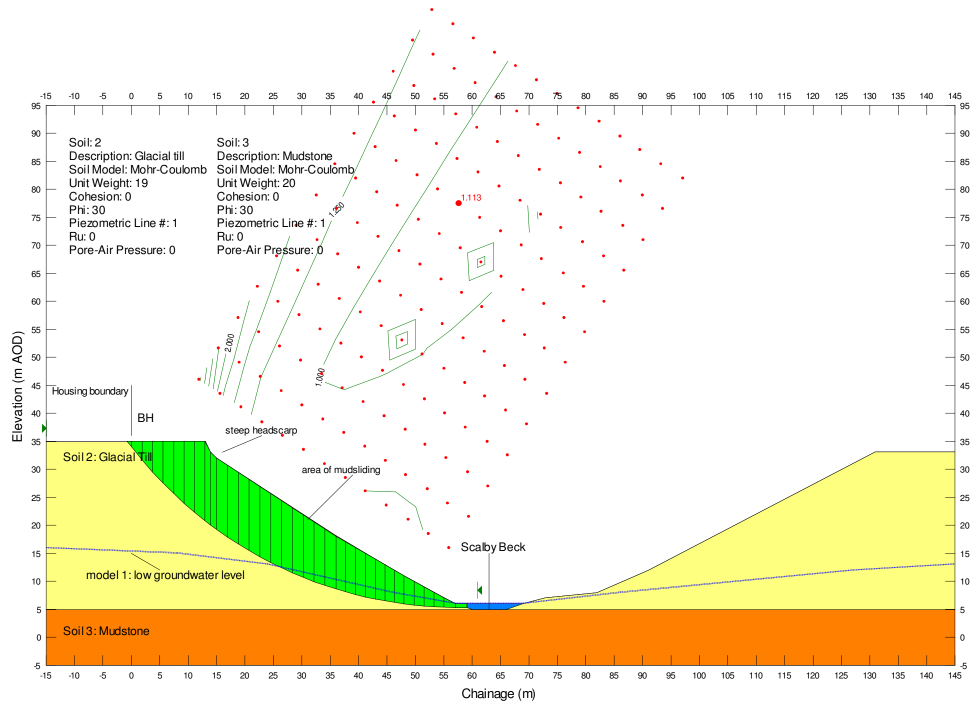
Section 4. Model 4/3. Extent of a potential slip surface (whole slope) with a factor of safety of about 1.00 following some toe unloading. Note the proximity of the potential shear surface to the housing boundary compared to the slope without additional toe unloading(above).



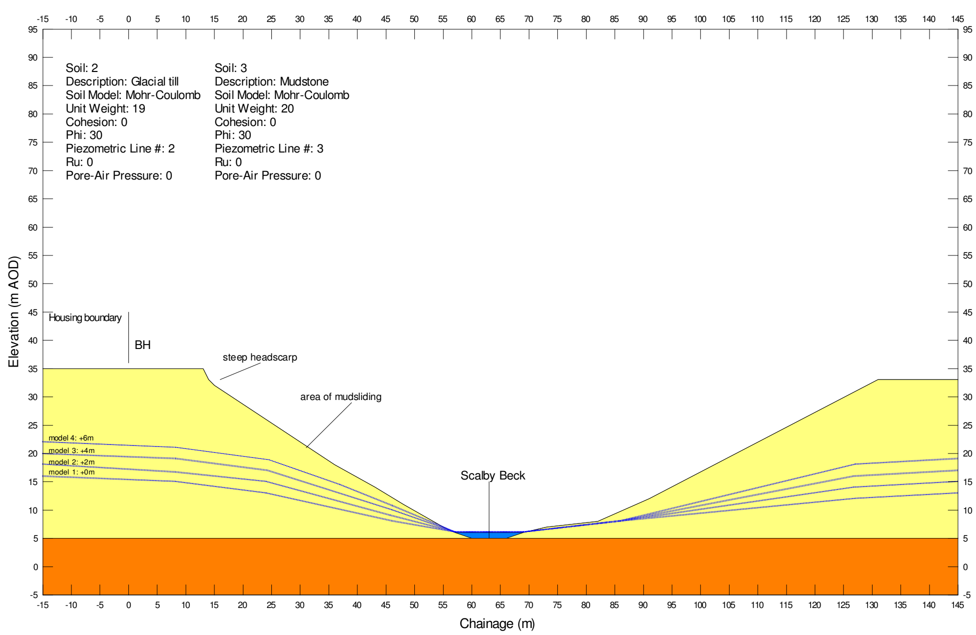
Section 4. Model 4/4. Extent of a potential slip surface (lower slope) with a factor of safety of less than 1.0 following groundwater rise (this would result in toe unloading – see above section)



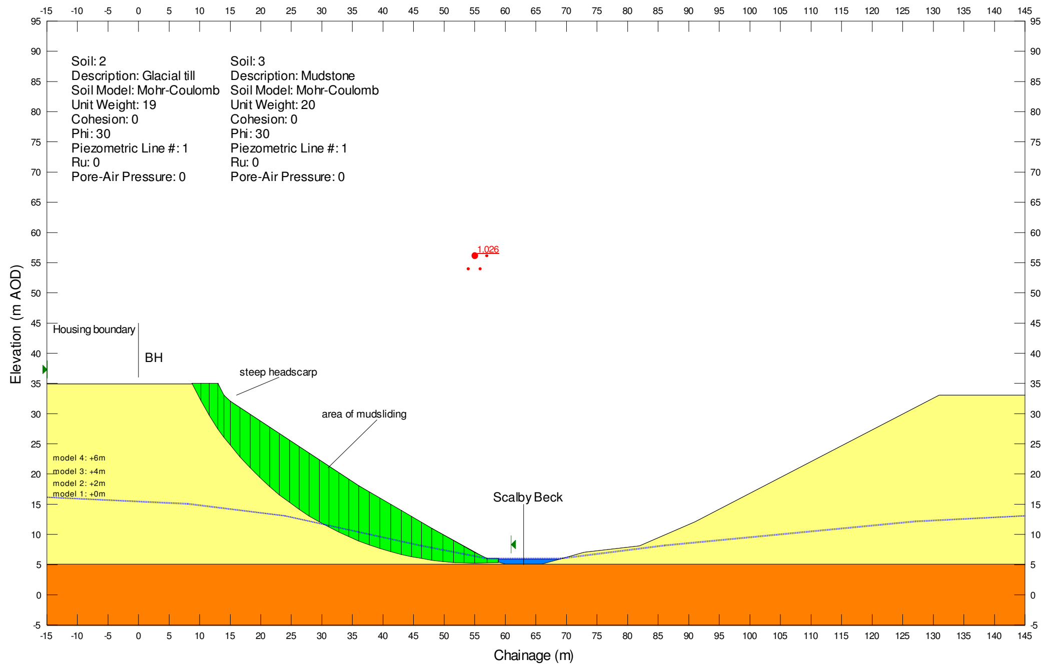
Section 4. Model 4/5. Infinite Slope FOS about 1.00, i.e. the slope is currently at its natural angle of repose. Should there be toe unloading and/or groundwater rise then the potential failure surface would deepen/enlarge.



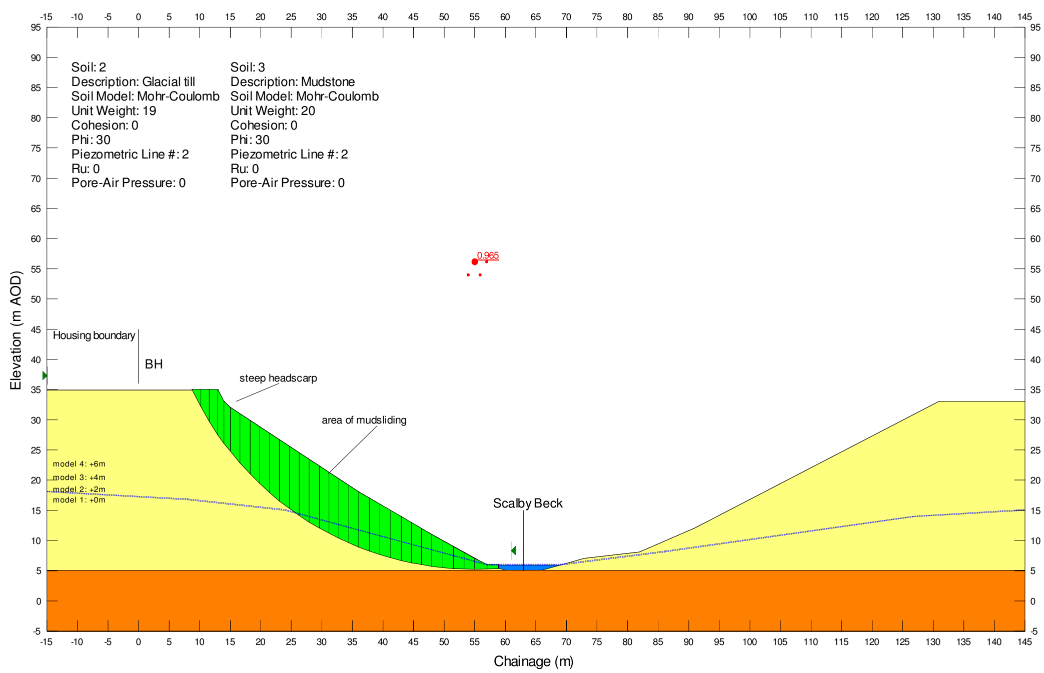
Section 4. Model 4/6. Stability Analysis to determine the FOS of a potential shear surface that could directly influence the properties at the top of the slope. (FOS=1.11). Should there be long term toe unloading and/or groundwater rise then the potential failure surface would deepen/enlarge.



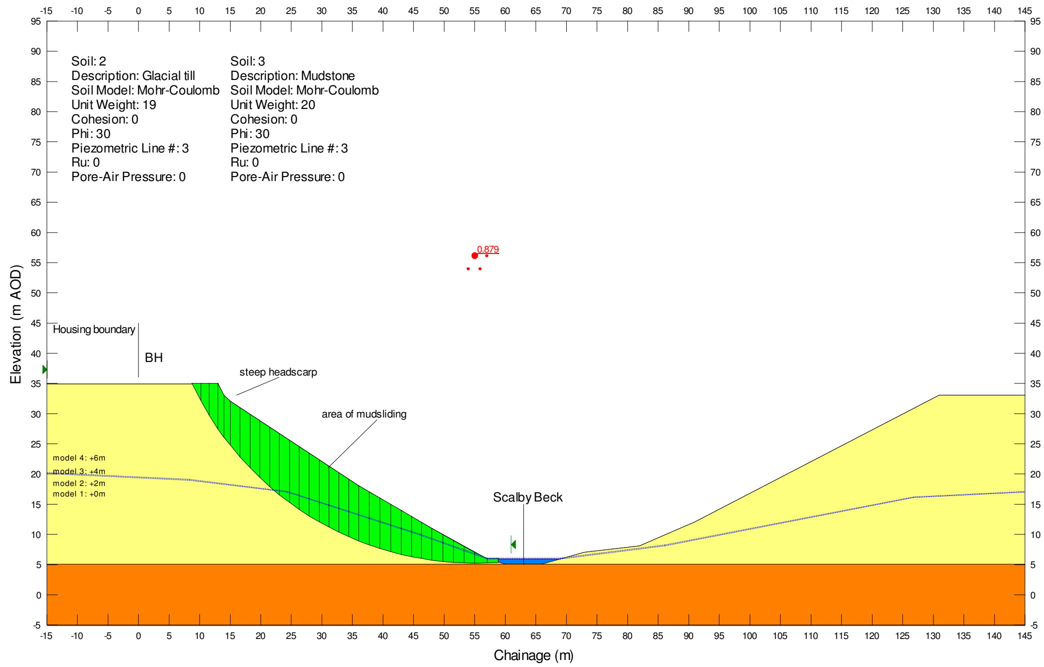
Section 4: Groundwater Sensitivity Review: Presumed GWL profiles. Note: an example potential shear surface has been selected to determine the effect of GWL on FOS and not the size of the shear surface/failure block.



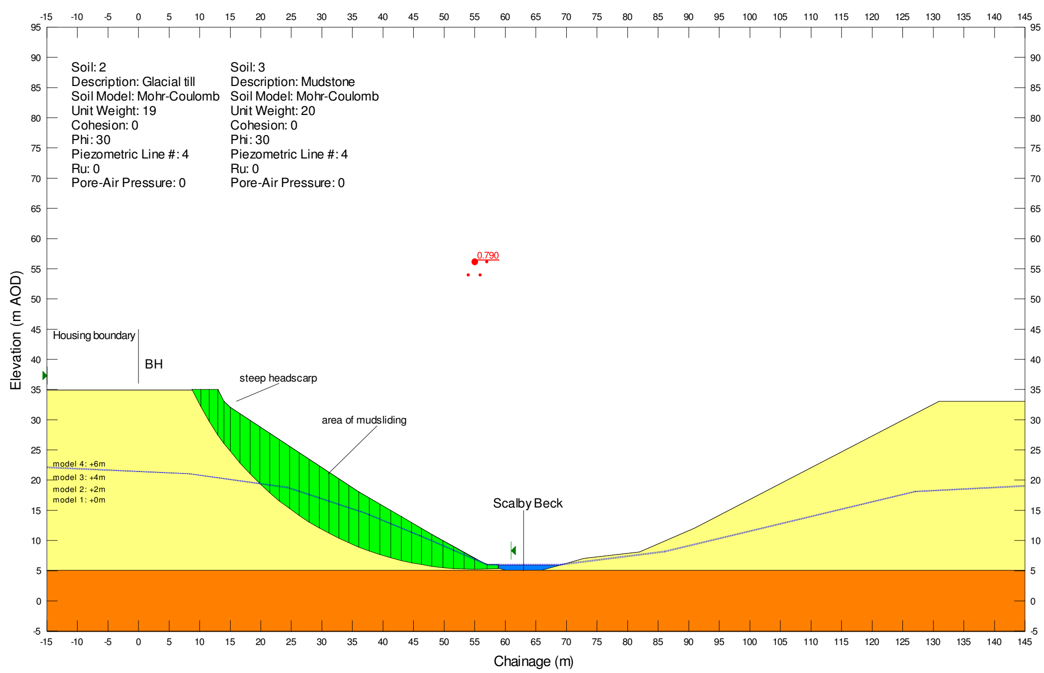
Section 4. Model 4/7. Groundwater Sensitivity Review: Model +0m



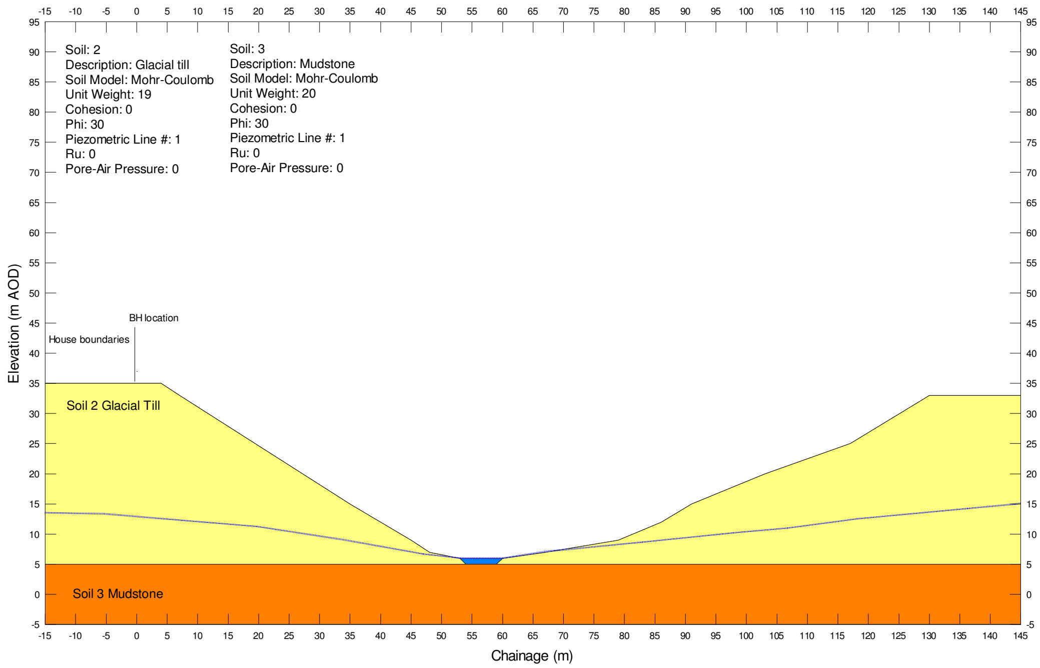
Section 4. Model 4/8. Groundwater Sensitivity Review: Model +2m



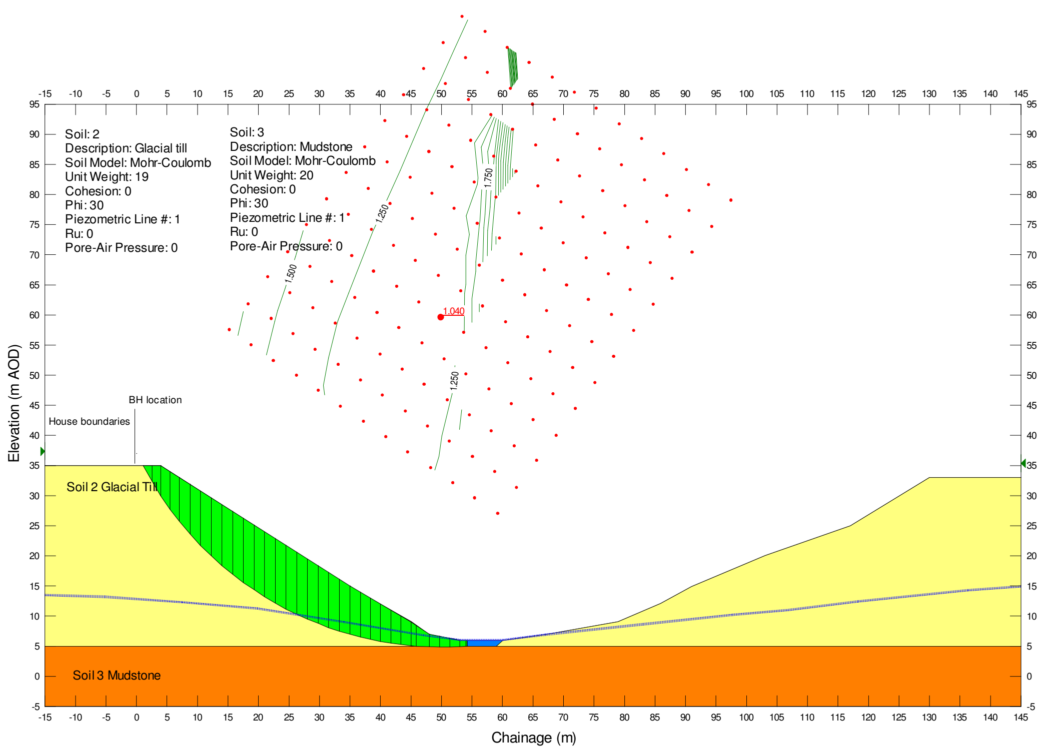
Section 4. Model 4/9. Groundwater Sensitivity Review: Model +4m



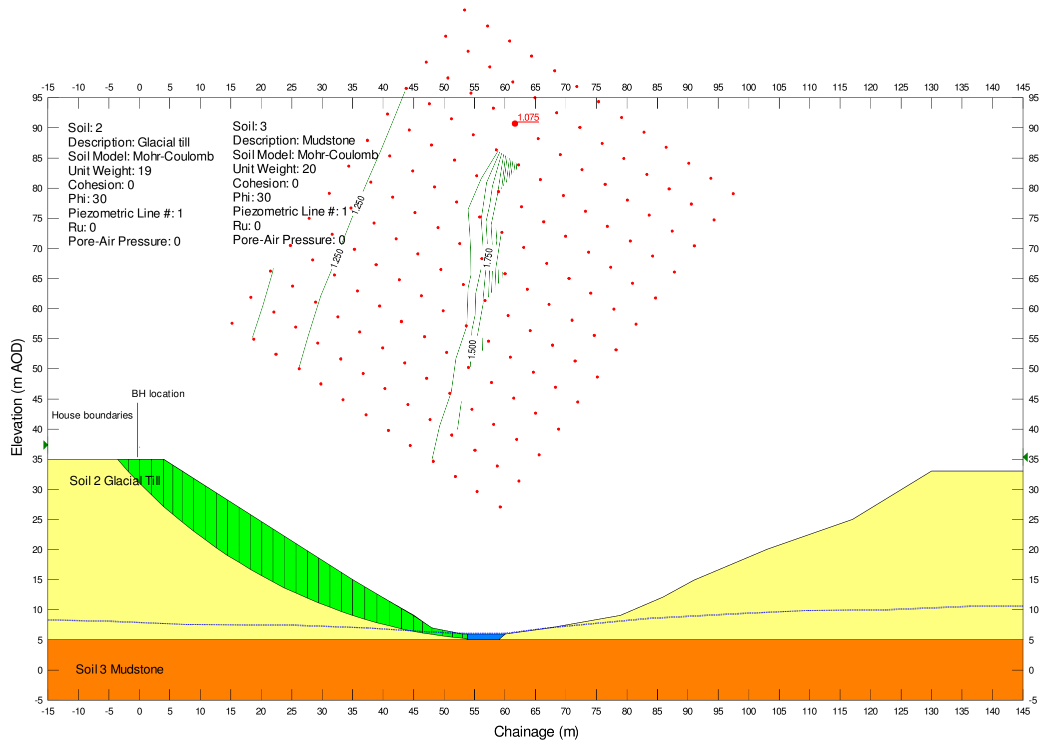
Section 4. Model 4/10. Groundwater Sensitivity Review: Model +6m



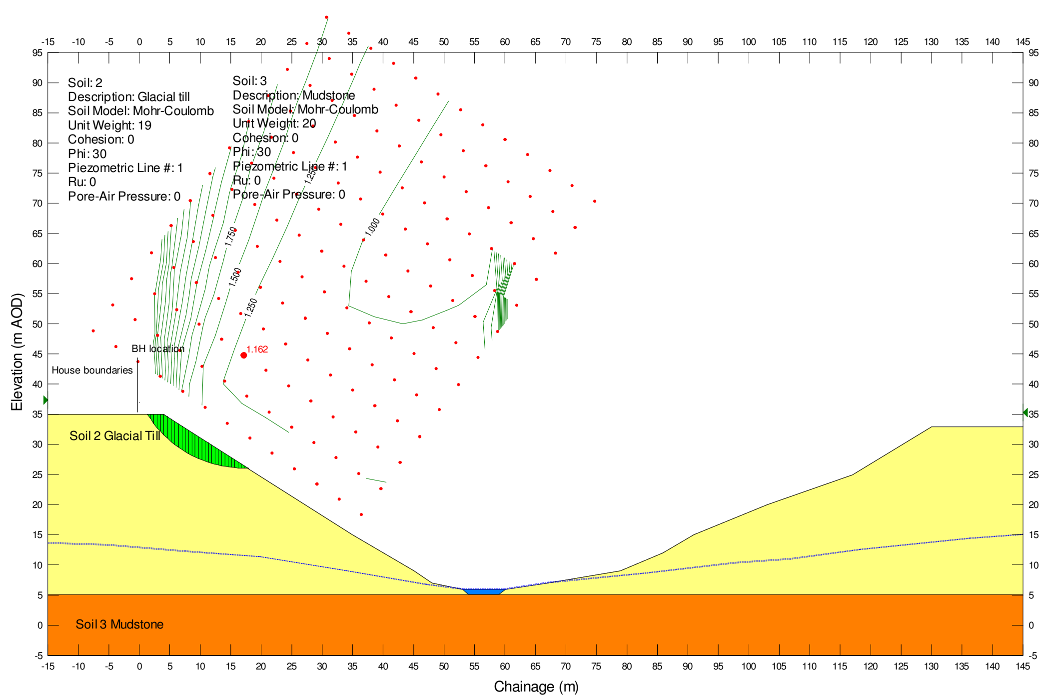
Section 5. Ground Model



Section 5. Model 5/1. FOS=1.00 (phi'=30 °, peak parameters)



Section 5. Model 5/2. FOS=1.00 (phi'=30 º, peak parameters, reduced GW)



Section 5. Model 5/3. FOS=1.16 (phi'=30 º, peak parameters, top of slope)

B Field record sheet and response table

B.1 ***Field record sheet***

A suggested Field Record Sheet for Scalby Ness is given at the end of this appendix.

B.2 ***Responses to site and instrumentation observations identified at Scalby Ness.***

In addition to the use of Tables B1 and B2 below, reference should also be made to Section 9.2 and Tables 14 and 15 of the report.

Signs which could be observed on site and classified as "indicators of change" in Table 14 are described in more detail in Table B1 below.

Table B1 Indicators of change

Indicator of change	Observation
Toe erosion	Exposed banks of Scalby Beck, devoid of vegetation (not rock) Obvious areas of erosion Mass slumping and detachment of soil Detached blocks within the beck Oversteep and overhanging banks
High groundwater level	Heavy and prolonged rainfall Seepages Damaged water pipes Ponded water Saturated ground Piezometer reading

Indicator of change	Observation
Cracked ground	New cracking on the upper plateaux (NB cracks >1m from crest could indicate deep-seated movement – seek expert advice immediately) Cracking and exposed soils on the steeper slopes Extension of existing cracks Closing of cracks in the lower slopes Cracking immediately behind the river bank
Slope activity	General area of recently disturbed ground Back-tilted or fallen trees and hedges Bulging in the lower slopes Cracked ground in the upper or lower slopes Damage to monitoring installations Damage to drains, sewers and other underground pipes

Table B1 (cont)   Indicators of change

Response actions to the indicators of change observed on site are given in general terms in Table 15 of the report. More detail is given in Table B2 below.

Table B2 Response actions to indicators of change

Causal factor	Description	Warning sign	Response
Increase in pore water pressure in the slopes (internal cause)	Analysis has shown that increase in pore water pressures in the slopes leads to a decrease in the stability of the slopes by causing a reduction in shear strength. Such effects are most severe during wet periods of intense rainstorms. Intense rainfall after long dry spell can cause a sudden increase in pore water pressures in the slopes, with tension or shrinkage cracks in the slopes aiding rapid ingress of water. Existing drainage discharges onto both the north-west and north-east slopes (as at January 2005). This feeds water directly into the slopes, increasing pore water pressure	Higher levels of groundwater recorded in piezometers. Results of rainfall show increased levels after dry period. Drainage onto the slopes is evident during walk-over inspections.	Continue monitoring, possibly at an increased frequency or with more regular downloads of automated data. Additional walk-over to identify any flooding or ponding of water on site. If inclinometer movement occurs at the same time, **seek expert advice**.
Weathering (internal cause)	Weathering of soil leads to reduction in shear strength. Cohesive soils may be subject to strength loss due to weathering. Weathering effects may be heightened on un-vegetated slopes. Physical or chemical weathering may cause loss of cohesive or frictional strength.	Exposed soil surfaces Desiccation and cracking of surface soils Evidence of localised soil creep	Monitor change via the field record sheet. If significant change is identified, **seek expert advice**.

Causal factor	Description	Warning sign	Response
Low shear strength of materials (internal cause)	Soils with discontinuities characterised by low shear strength such as bedding planes, faults, joints etc.	Not evident at the surface. Inclinometer movement would indicate where movement is occurring in a zone of low shear strength.	Regular transmittal of digital inclinometer data to consultant, if appropriate. If any significant change in inclinometer data occurs, especially at depth, **seek expert advice immediately.**
Over-steep headscarps (external cause)	The physical slope angle of the headscarps at Scalby Ness encourages spalling and block failure at the crest of the slopes.	Evidence of tension cracks immediately above the headscarp Fresh face and fresh deposits of soil beneath headscarp. Damage to vegetation. Localised slumping and slope readjustment Presence of detached block from the upper headscarp Change in results of pin monitoring	Monitor change via the field record sheet. If significant change is identified, **seek expert advice**.
Oversteep slopes (external cause)	The north-west slope is oversteep and marginally stable. Increase in porewater pressure or toe erosion has been shown in analysis to trigger instability. The upper slopes of the north-east (northern) slope (Behaviour unit II) are also over-steep.	Localised signs of activity e.g. tension cracks and bulging mid-slope Movement evident in results of pin survey	Monitor change via the field record sheet. If significant change is identified, **seek expert advice**.

Causal factor	Description	Warning sign	Response
Removal of lateral support - undercutting of toe (external cause)	Undercutting of toe due to erosion or incision by Scalby beck at the toe of the slope, leading to loss of support to lower slopes (NE) or whole slope (NW).	Exposed eroding river banks Large bank slumps Overhanging river banks Erosion evident in results of pin survey	Monitor change via the field record sheet. If significant change is identified, **seek expert advice**. Consider remedial measures to protect toe of slopes.
Removal of lateral support - removal of material from the toe of the slope due to instability (external cause)	Continued localised failure and movement of active areas identified in the mapping in the NE slope leads to loss of support to slope above, increase in slope angle, reduction in weight of material comprising the lower block.	Change in river bank condition Localised mudsliding above river bank Removal of material evident in results of pin survey	Monitor change via the field record sheet. **Seek expert advice**. Consider remedial measures including drainage. If significant change is noted e.g.>1m loss, **seek expert advice immediately.**
Increased loading (external cause)	Natural accumulations of water, snow, talus (accumulations of fragments of weathered material at the toe of slopes) and man-made pressures (e.g. fill, tips, and buildings) can all contribute to increased loading on the slopes. At Scalby Ness rubbish has occasionally in the past been tipped onto the slopes.	Presence of water, snow, talus or rubbish on the slopes.	Remove material if rubbish dumped on upper slopes. Seek advice if instability or weathering results in an accumulation of material. Depending on its location, it could be beneficial to slope stability. Continued vigilance and slope inspections to prevent further accumulations of material.

Causal factor	Description	Warning sign	Response
Occurrence of deep-seated instability		Movement at depth in inclinometers. Possibly tension cracks in upper plateau above headscarps	**Seek expert advice immediately.**

Table B2 (cont) **Response actions to indicators of change**