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Scoping study for coastal instability hazard susceptibility – Filey Bay, Beachy Head and Lyme Bay

Information Products Programme

Internal Report IR/05/018

BRITISH GEOLOGICAL SURVEY

INFORMATION PRODUCTS PROGRAMME

INTERNAL REPORT IR/05/018

Scoping study for coastal instability hazard susceptibility – Filey Bay, Beachy Head and Lyme Bay

G. Wildman and P.R.N. Hobbs

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View westward of Black Ven landslide complex.

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 0131-667 1000 Fax 0131-668 2683
e-mail: scotsales@bgs.ac.uk

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☎ 020-7589 4090 Fax 020-7584 8270
☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast, BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ

☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

This report is the published product of an initial scoping study by the British Geological Survey (BGS) into the potential for coastal landslides to occur. It attempts to model the causative factors to produce a coastal landslide hazard map.

Acknowledgements

In essence, this report has been an extension to the GeoSure Landslide Hazard Assessment. It borrows techniques and reasoning from this study and, as such, owes much to the work of Alan Forster.

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Summary

This report describes the factors that may lead to coastal landslides. It assesses these on a national scale and suggests ways in which they can be incorporated into a landslide potential hazard map for Great Britain. It then details how these factors can be combined in a GIS to produce a digital hazard map in three areas of the country. The results from these test areas are discussed and improvements suggested that might increase the validation of the model.

1 Introduction

As part of the Geoscience National Information (GENI) project, ***susceptibility to coastal instability hazard*** has been selected as a topic for evaluation. Coastal instability hazards manifest themselves in a variety of ways around the British coast. Being part of a very dynamic system these should be viewed in 4 dimensions in order to appreciate their impact; i.e. not only the current situation but changes with time. As an example, a large coastal landslide in a high cliff consisting of soft lithologies may cause massive loss of land locally within a short time-scale (hours or days), but with little risk of injury. A high / steep cliff in very strong lithologies may result in occasional minor rock falls, which though contributing little to coastal erosion, could (depending on location) represent a major hazard to the public due to the suddenness and unpredictability of the event. Lithologies intermediate between 'soft' and 'strong', for example chalk, tend to produce high, near-vertical cliffs. Whilst these materials usually give some warning of failure, they nevertheless ultimately fail catastrophically. These latter probably represent the most dangerous of cliff types, though such events are widely spaced in time at any particular location. However, consideration of the implications of slope failure is not within the remit of this study, as it forms part of risk, rather than hazard, assessment.

Coastal landsliding plays a key role in coastal instability, particularly in the case of 'soft rock' lithologies forming substantial cliffs and platforms. This is true both in terms of the overall cliff recession processes and in the assessment of *risk* to life and property. The other key factor in 'soft' cliff coastal erosion is direct mechanical erosion or scour; that is, impact by waves resulting in removal of material on a more or less continuous basis. The combination of unusually high tides and large waves tends to produce a disproportionate amount of scour, as evidence from major storm events shows. This factor may be influenced by geology where weak strata overlie strong, and become subject to wave attack only in certain tide situations. The aspect of the coast with regard to direction of wind/wave and fetch is important and has been classified as part of the recent FutureCoast project, based on CEFAS wave buoy data combined with offshore bathymetry. Exposed clay-rich lithologies may also be subject to seasonal swell/shrink, and other rock types to freeze/thaw, and associated terrestrial erosion processes.

Factors influencing coastal instability:

- Stratigraphy (sequence & thickness of strata, e.g. in relation to landslides and wave attack)
- Lithology (including fabric, cementing etc.)
- Structure (faults, joints, bedding, inclusions)
- Weathering (cliff & platform profiles)
- Topography & geomorphology (cliff height, cliff slope, platform slope, cliff top slope angle & direction, intertidal & offshore bathymetry)
- Geotechnical properties (strength, density, particle-size distribution, permeability, clay suction, swell/shrink, erodibility)
- Homogeneity / heterogeneity (affects instability & erosion regimes)
- Hydrogeology (water table, perched water-tables, seepage, springs, clay suction, permeability)
- Coast aspect (wind / wave statistics, fetch, shrink/swell, freeze/thaw)
- Foreshore morphology (platform features, beach type & thickness)

The methodology for classifying coasts in terms of instability hazard will be based on the rating scheme used for GeoSure. It will deal solely with digital data available to the BGS. It will thus have a different emphasis to the Halcrow/DEFRA/BGS scheme for 'cliff behaviour' as part of the FutureCoast project, most of which is qualitative and engineering case-based. It will also differ from DEFRA's 'RASP' risk methodology, originally developed for flooding and proposed for coastal instability, where man-made influences such as population and defences come into play.

The proposed GENI coastal instability scheme, as with the GeoSure scheme, assigns scores to identified influential factors according to their importance. Each of these may or may not be linearly scaled. A scheme may be partly based on established schemes for individual factors, but also partly on in-house judgements where no scheme exists. The scheme does not include time factors, such as historical or predicted behaviour, as does FutureCoast. The scheme will be verified against assessments of actual coastal instability, derived either from monitoring (e.g. Cliff Stability project) or from historical records (e.g. FutureCoast), and adjusted if necessary. It is thus a semi-quantitative scheme, which incorporates intuitive factors derived from a wider, sometimes quantitative, knowledge.

2 Fundamental variables

2.1 ROCK LITHOLOGY / STRATIGRAPHY

Description: Lithology is a prime factor in erosion and landsliding. The composition of the rock mass and its homogeneity must be assessed. The lithology affects geotechnical properties and hence the cliff's ability to resist erosion and landsliding.

The stratigraphy (sequence of lithologies) and bed thicknesses at a particular location should also be considered.

However, this information is not universally available.

Method: Classify according to age, relative thickness, whether is cohesive or non-cohesive, soft or hard. An established geotechnical 'rock mass rating' (RMR) scheme may be used.

Source: Obtained from GeoSure, DigMap50k, Superficial Thickness model, and literature.

2.2 ROCK STRUCTURE

Description: The presence of discontinuities within the rock mass affects stability, e.g. rock falls bounded by bedding planes and joints at cliff toe. Faults may also act as landslide boundaries and possibly a source of differential weathering and erosion. Subsidiary or anomalous lithologies such as glacial rafts, volcanic intrusions, concretions etc may influence type and disposition of landslides.

Method: Classify according to established 'rock mass rating' (RMR) scheme

Source: Obtained from literature, Geosure, BGS datasets, DigMap10k (where available)

2.3 ROCK WEATHERING

Description: The presence of a weathering or glacial disturbance profile is a specific instance of change to the lithology and particularly to the geotechnical properties. These changes may be locally very variable in depth and type. Bedrock weathering (per se) may be widely persistent whereas glacial gelifluction may be very localised. Rapidly eroding coasts have less opportunity to retain or develop weathering profiles. The presence of superficial deposits may suppress contemporary bedrock weathering and may have affected fossil weathering.

Method: Few classification schemes exist, and are generally geotechnically derived and formation-specific (e.g. Lias Group, Mercia Mudstone Group). It will be difficult to produce a comprehensive scheme or rating for this factor.

It may be advisable to discount this factor, at least as part of the rating scheme.

Source: BGS sources (e.g. UK Rocks & Soils project).

2.4 TOPOGRAPHY & GEOMORPHOLOGY

Description: Cliff height, cliff slope, platform slope, slope landward of cliff may be used.

Method: Classify according to scheme based on multiple factors derived from BGS's NEXTMap digital terrain model (intertidal bathymetry will not be available nationwide). This requires selection of a coastal 'strip' within the bounds of which the classification is made. The resolution of the terrain model will be carefully considered; probably lying in the range 5 – 10 m. The thickness of this strip may have to be variable (e.g. wide for 'soft' cliffs) possibly of the order of 300m. Zones without cliff stability issues (that is, probably all zones without cliffs or sufficient relief) will be assigned a rating of zero. FutureCoast's continuous fly-by video & stills will be used to delineate new coastal behaviour units and sub-units, or those already identified by FutureCoast (Coastal Behaviour System, CBS, and Local Scale Response System, LSRS). The CBS is sometimes referred to as a Coastal Behaviour Unit (CBU).

Source: BGS's DTM (NEXTMap), FutureCoast

The BGS's DigBath database covers the whole UK offshore but at only 10m contours. There is no bathymetry better than this with nationwide coverage. *Note: Futurecoast does not cover Scotland or N. Ireland.*

2.5 ROCK GEOTECHNICAL PROPERTIES

Description: The geotechnical properties of cliff and platform determine nature and rate of erosion, landsliding, and hence instability. These may be sub-divided into:

a) index properties, e.g. particle-size (fundamental to the material), and

b) mechanical properties, e.g. strength (variable according to environment)

Method: It will be possible to directly use, adapt, or extend the existing Geosure rating based on LexRock. This scheme is based on lithology, discontinuities/bedding, and slope angle. Otherwise, a general classification according to established geotechnical principles (e.g. BS5930, BS1377).

Source: Geosure, BSI, BGS's geotechnical databases

2.6 SOIL/ROCK HYDROLOGY

Description: The response of soil and rock to rainfall

Method: Computer model of UK catchment response to rainfall/runoff etc

Source: 'Hydrology of Soil Types' (HOST), joint SSLRC/CEH project: digital 1km nationwide classification based on 29 classes from 11 catchment response models. *<u>Note:</u> Does not include N. Ireland*.

2.7 ENVIRONMENT

Description: Wave power (height & period), wave direction, wind (amount & direction), rainfall (amount & intensity), storm (amount, frequency, duration, direction), soil moisture deficit, temperature etc.

Method: Attempt to classify according to historical data, and predictive data. These data would probably be derived rather than raw (e.g. regional rather than weather-station specific). Wave / climate / aspect data are probably best obtained from FutureCoast which has comprehensive assessment of waves for about 100 coastal locations. These have been interpolated from CEFAS wave buoy and bathymetric data.

Site specific and up-to-date rainfall data are available from the Met Office for a charge, or in some forms of synthesised data without charge. Soil Moisture Deficit (SMD) is perhaps a more useful parameter than rainfall, but databases and maps from different sources do not produce the same result.

Source: Met. Office (rainfall, wind), FutureCoast, British Atmospheric Data Centre (BADC), otherwise published data. Climate change data (forecasts /models – Tyndall Centre etc.). Futurecoast contains wave statistics from offshore buoys. Soil Survey, SSLRC (Soil Moisture Deficit, SMD).

<u>Note:</u> It may be advisable to completely ignore this group of factors as they are time-dependent variables, and both time consuming and expensive to hindcast or forecast. Sufficient expertise probably does not exist at BGS.

3 Existing landslide complexes

Description: Large, well-established, coastal landslide complexes are capable of being mapped and described. However, a means of dealing with these digitally will have to be developed.

Method: Literature review. Aerial photo interpretation. Use of LiDAR, DTMs, digital linework.

Source: Futurecoast's CBU & imagery. Engineering SI data (Halcrow, Rendel Geotechnics etc.), BGS DigMap50k digital line work.

Item 3 is not included in the coastal landslide scheme at this time, but may be used in validation process.

4 Non-environmental 'Change' factors

Description: Peculiar to the coast are factors which, whilst varying with time, are non-environmental. This will be a combination of some factors listed above but assessed in terms of their likely change with ongoing coastal recession. For example, a significant change in geology or topography along a line perpendicular to the direction of recession will have a major influence on the future rate of recession and future processes of erosion (equally, such factors may have affected hindcasting of recession rates). Similarly, accreting coasts will undergo a change in geology and topography.

Method: Attempt to classify according to likely future change within chosen 3D corridor: e.g. ground slope rating (perpendicular to cliff), lithology change rating.

Source: BGS DigMap50k, derived models (receding coast). FutureCoast (accreting coast).

Currently Item 4 is not included in the GENI coastal instability scheme. Any 'change' factors may be considered in future versions.

5 Scoping study

An attempt has been made to produce a landslide hazard potential model for three trial coastal sections: Filey Bay (North Yorkshire), Beachy Head (Sussex), and Lyme Bay (Dorset) using the following information:

1) Definition of coast (coast / bay / estuary) - European Water Framework Directive (WFD)

2) Coastal Behaviour Units (CBU) (FutureCoast)

3) Geology – BGS 2D model (DigMap50k) + superficial thickness model

4) Terrain models – DTM, DSM, derived slope angle, cliff height (NEXTMap)

5) Geosure - BGS (LexRock based) slope stability hazard classification

6) Wave / climate / aspect (FutureCoast),

7) Recession / accretion (FutureCoast),

8) Validation with FutureCoast and Cliff Stability output, with BGS DigMap 'landslides', and with historical recession rates, where appropriate.

The trial section between Cayton Bay (The Wyke) and Bridlington is 20 kilometres in length and 300 - 500m in width, and covers at least one CBU (FutureCoast). The coastal section includes one of the Cliff Stability project's 12 test sites (Speeton Sands) for which up to 4 years of recession monitoring data are available. The other two sites are less extensive but also include Cliff Stability project test sites.

Note: None of the eight factors listed above directly involves environmental data (e.g. wave, rainfall), as described in section 2.7, or historical (recession rate) elements. The reason for this is that no elements of monitoring are built into the primary objectives of the project. However, the inclusion of the coastal 'wave / climate / aspect' factor as additions to the Geosure scheme, allows historic climatic elements to be used in a derived form.

6 Coastal landslide hazard classification

It is essential that any methodology that is to be applied to a nationwide dataset features a set of universal variables. Any dataset that is incorporated into the coastal landslides methodology must have a continuous coverage for the whole of Great Britain. Whilst it is acknowledged that there are several pieces of research and other projects that could lay some weight to this particular study, these cannot be incorporated, as it would run the risk of creating a series of sub-studies, which may in turn understate areas that are not so well documented. The data from the more detailed research and projects can be used to validate the work done here.

The GIS methodology attempted to incorporate the factors listed in section 2. Each dataset will be converted into an ESRI grid. These grids are then weighted depending on the influence of the variable, and simply add together to form one continuous grid. This raster is then sub-categorised into hazard classes A – E. The algorithm is shown in Appendix 1.

Below is a run down of which factors were used and how. It also outlines which factors where omitted and why.

6.1 ROCK LITHOLOGY / STRATIGRAPHY

It has been noted earlier in the report that lithology is a prime factor in erosion and landsliding, and as such it must be included in the methodology. The current GeoSure Landslide assessment (version 2) scores each lithology in DiGMap-50 between 1 and 13 (Forster et al, 2005). A lithology with a score of one is generally considered a stable rock and is typically granite. At the other extreme are deposits that are less stable, which in this investigation are known mass movement deposits. The scores for each lithology have been extracted from the DiGMap-50 LEX_ROCK and ROCKDESC attributes, and supplemented by the description in the BGS lexicon and, where necessary, geological memoirs.

These values have been extracted and joined to the DiGMap-50 shapefile, converted into a grid and used in the GIS methodology.

6.2 ROCK STRUCTURE

The presence of discontinuities and bedding affects stability. This factor has also been recognised and scored in the current GeoSure landslide assessment (Forster et al, 2005). Each lithology found in DiGMap-50 has been scored on a scale of 1 to 9, where one is assigned to very thick beds (>2000mm), and nine to very thin, laminated beds (<60mm).

These scores have been directly used in the coastal landslide GIS methodology in the same manner as the lithology scores above.

6.3 ROCK WEATHERING

Weathering was discounted from the GIS methodology as there are few classification schemes that exist, and none that can be easily incorporated into the coastal landslide scheme.

6.4 TOPOGRAPHY AND GEOMORPHOLOGY

Currently the BGS has access to NEXTMap, which is a high resolution Digital Terrain Model (DTM) that covers England, Wales and Southern Scotland (Northern Scotland will be available shortly). The NEXTMap data have been derived from an airborne survey and sampled to a 5m-grid size. Its high resolution means that it can pick up slight variations in slope as well as defining morphological features such as cliff lines. Although a 5m grid does have a tendency to under-emphasise vertical and near vertical cliffs (this is discussed in section 7), it is still the highest resolution data that the BGS has access to, and which provides near-nationwide coverage.

NEXTMap has been used in this scheme for 2 separate factors; height of the cliff; and slope of the cliff.

The slope of the DTM has been calculated in ArcInfo 8 Workstation using the ESRI slope algorithm that identifies the maximum rate of change in value from one cell to its neighbours (Burrough, 1986). Using a 500m buffer of the coastline, the slope angle was subset as a 5m grid, with each cell representing the change of slope from its neighbours. This raster was then sub-categorised and given a score of 1 to 10 depending on the slope angle. See Appendix 1 for more information.

The height of the land surrounding a 500m buffer of the coastline was extracted as a 5m grid. Again, this was subcategorised and each grid cell assigned a score of 0 to 5. See Appendix 1 for more information.

No other topographical or geomorphological factors are included at this time. The use of FutureCoast Coastal Behaviour System and fly-by video are both excellent resources, but are limited to England & Wales, and are qualitative, rather than quantitative. As such they are not currently incorporated in the coastal landslides methodology. However, they will be of use when verifying the model.

6.5 ROCK GEOTECHNICAL PROPERTIES

The geotechnical properties of each lithology have not been included directly. The lithology scoring from the current GeoSure landslide assessment has in part addressed this, and so, almost by default, it has been considered for the coastal landslide methodology.

6.6 SOIL/ROCK HYDROLOGY

At present soil/rock hydrology is not being considered for use in the GIS methodology. The HOST data detailed in section 2.6 has not been explored fully. It should be something under consideration for the future.

6.7 ENVIRONMENT

Wave direction and wave power have been adapted from the FutureCoast dataset. The FutureCoast dataset has divided the coastline of England and Wales into unique coastal behaviour units (CBU). Each CBU then has certain statistics and observations recorded about it. FutureCoast contains an abundance of data for England and Wales, however, for inclusion in this methodology, Scotland will need to be considered. Data for the Scottish coasts will have to be researched or an alternative dataset found.

The FutureCoast data contains information on nearshore wave characteristics, which is essentially a tally of wave count, direction of origin and wave height. This information can be fed directly into a viewshed model. For this methodology the viewshed was calculated using the Spatial Analyst extension in ESRI's ArcMap 8.3. The dominant wave direction, as specified in FutureCoast, was set as the azimuth, and the vertical extent was defined as 0. The output from this is a grid, with a value of either 1 or 5 (sheltered or exposed). This is then easily incorporated into the model.

Total wave energy is also recorded in FutureCoast. These data can be split into categories so that areas with the highest wave energy are scored 4, and areas with the lowest wave energy scored 1. Again these data can be converted into a grid with values ranging from 1 to 4.

Rainfall is a contentious issue. It now appears that global warming has contributed to rainfall events that are becoming more frequent and more intensive. There is no measure for this. However, it is possible to look at the rainfall over the last 30 years and pick out areas that are more susceptible than others. Average rainfall data from the Met Office for 1971 to 2000 shows the west of Britain has been wetter than the east. These simple patterns have been extracted and used in the methodology. The average rainfall data from 1971 – 2000 can be gridded and reclassified to give values of between 1 (lower annual rainfall) to 5 (higher annual rainfall) for Great Britain. The IPR issues for the commercial use of this dataset need to be investigated.

In summary the datasets being used are:

- GeoSure landslide lithology ratings and DiGMap-50
- GeoSure landslide discontinuities / bedding ratings and DiGMap-50
- Digital Terrain Model (NEXTMap)
- Slope angle model (derived from NEXTMap)
- Nearshore wave direction (FutureCoast)
- Nearshore wave energy (FutureCoast)

- Average Annual Rainfall 1971 – 2000 (Met Office)

The above scheme will be used to classify the open coast test sites in terms of **coastal slope stability hazard potential**.

7 Problem issues

7.1 GEOLOGY

Problem

A key problem is associated with the geology. This is where the 2D geology data do not relate to the 3D reality at the coast. Examples are shown in Figures 1, 2, & 3. A simple block diagram representing an idealised coastal 'unit' is shown in Figure 1.

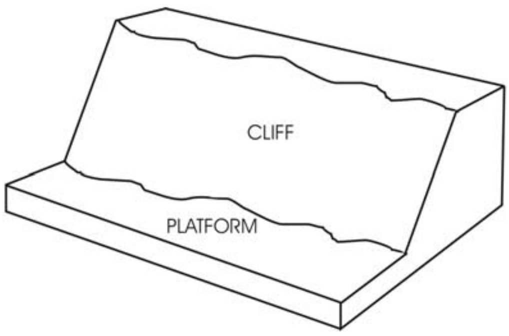


Figure 1 Block diagram of coastal unit

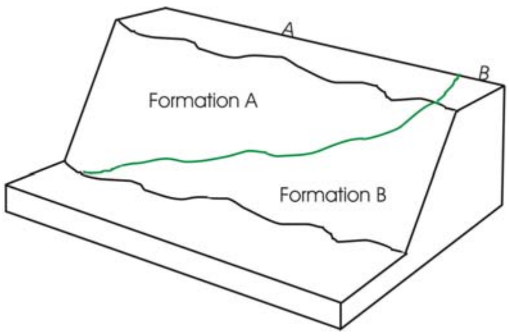


Figure 2 Inclined geological boundary

A common geological succession at the coast is shown in Figure 2. Here, Formation A overlies Formation B along an inclined boundary. This may be, for example, folded, faulted, discontinuous, glacial etc. The problem is that the 2D geology data depict this unit as 90% Formation A, whereas the behaviour of this coastal unit is influenced at least 50% by Formation B, but probably in a complex way depending on the lithologies of A and B and the relative contributions of mechanical abrasion and landslipping. If Formation A was a till and Formation B a competent bedrock formation, then the contribution of A would probably dominate with this geometry. However, if Formation B was a glacial sand then this would not be the case.

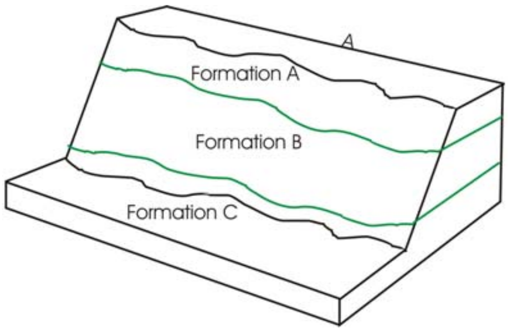


Figure 3 Horizontally bedded geological boundaries

A further, and possibly more serious problem is shown in Figure 3. Here Formation B is sandwiched between Formations A and C without outcropping on the cliff-top or the platform. Thus if the cliff is steeply sloping, Formation B is unlikely to feature atall in the 2D geology data, despite the fact that it has an important influence on coastal behaviour, particularly if it represents a weak material. Also, Formation C will not feature if the platform is unmapped.

Solution

It is considered that at present it would not be feasible to determine the true 3D geology at the coast without considerable expenditure. Whilst some well-known locations could be completed rapidly, the great majority of the British coastline could not. It may be possible to ‘alter’ the computer-generated model manually in areas of major known 2D - 3D anomalies. For the most part, however, the solution might be to estimate the errors and introduce an uncertainty element (weighting) to the rating scheme.

Another solution that goes half-way to answering this problem is to identify the superficial thickness and use this to generate a score based on the ratio of superficial and bedrock in a coastal section. Both the bedrock and superficial geology is mapped at 1:50,000 and the score from the current GeoSure landslide assessment can be assigned to each mapped deposit. It is possible to combine these values with the superficial thickness layer and the NEXTMap DTM to produce a score that relates to the percentage of bedrock and superficial deposits (see Appendix 2 for the details of the algorithm).

7.2 TOPOGRAPHY

Problem

A key problem associated with topography, and the digital terrain or surface models used to depict it, is that vertical and near-vertical cliffs will not be correctly identified by the aerial Airborne Survey method used to create the 3D model (e.g. NEXTMap). The NEXTMap model has a minimum plan spacing of 5m. A non-vertical cliff will tend to have the possibility of giving a correct overall slope angle because its width allows more than one Airborne Survey point to fall upon it (red arrows in Figure 4). Whether or not the slope angle derived (blue line) is correct or not depends on the algorithm used. Clearly, averaging the slope over more than two points would, at least in the example shown, produce an incorrect slope angle. Similarly, if the Airborne Survey was inclined unfavourably to the ground surface (orange arrows in Figure 4) then slope angle errors would increase.

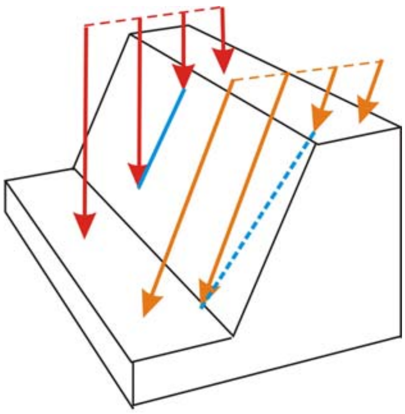


Figure 4 Non-vertical cliff: errors in derivation of slope angle (slope and Airborne Survey)

However, a vertical cliff will produce a significantly erroneous slope angle, typically about 70^{o} inclination, as shown in Figure 5. However, this error will decrease with increasing cliff height. Similarly, a cliff with distinct vertical scarps within it, or featuring overhangs, will not be depicted correctly.

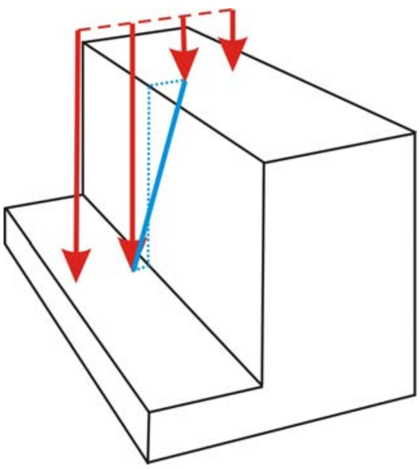


Figure 5 Vertical cliff: significant slope angle errors

Unfortunately, these errors in slope angle are non-conservative; that is, they give a better stability rating than is truly the case.

Solution

A solution may be to estimate the errors and include them in the rating scheme, as for the 2D – 3D geology anomalies. The *FutureCoast* classification includes a 'confidence' rating.

It is also important to examine the specifications for NEXTMap's derived factors such as 'slope angle' and thus estimate their influence on the errors.

Care must be taken when estimating errors on a slope model derived from NEXTMap data. It is possible to assign a rating to a vertical cliff to compensate for the NEXTMap grid spacing underestimating the slope. However, it is not possible to assign this rating to every section as there may be graduated cliffs where a NEXTMap slope model is returning a true answer.

At present this issue has not been addressed in the current study. The potential for error is recognised, but tolerated for use in the coastal landslide model.

8 Results

The results of the scoping study are shown in Appendix 3 in the form of maps and tables. The three sites selected: Filey Bay, Beachy Head, and Lyme Bay are shown with their slope stability rating in colour (red = unstable, blue = stable). The results are discussed individually, and then collectively, referring in each case to the Appendix maps.

8.1 FILEY BAY

The Filey Bay scoping area includes the whole of Filey Bay plus The Wyke to the north, and the south-facing section of Flamborough Head. The areas highlighted as least stable are The Wyke and the central part of the Bay (Reighton and Speeton). The high chalk cliffs of Bempton are unstable, whereas the lower chalk cliffs of Flamborough are more stable. Notably, the chalk cliffs on the south-facing side of Flamborough Head are shown as significantly more stable (see Appendix 3). This is probably due to the combination of cliff height, angle, and wave aspect, both of which are more favourable than the north-facing side of the Head. This is countered to some extent by the superficial thickness and cliff angle factors (Figure 6).

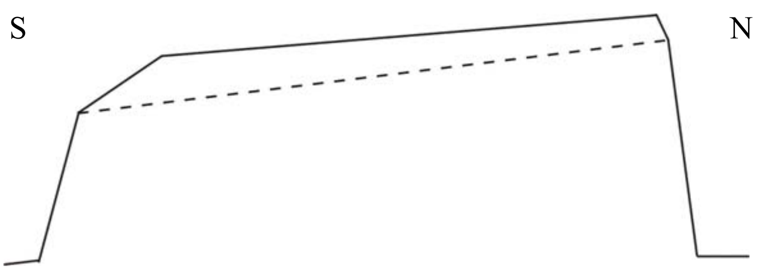


Figure 6 Cross-section of Flamborough Head chalk cliffs (not to scale) showing relative superficial thickness and cliff slope angles on north and south-facing sides.

A possible weakness of the scheme may be shown in the user's inability to determine the actual position of the cliff within the 300 m corridor, and the fact that the steeper the cliff is, then the narrower the line representing it. To some extent the Filey Bay example does distinguish very broadly the shallow-angled till cliff of the northern & central part of the bay from the steep-angled chalk section to the south; the latter having a high stability rating (blue) for most of the 300 m corridor width, this representing the flat-lying tracts inland of the steep cliff.

8.2 BEACHY HEAD

The Beachy Head example stretches from the Seven Sisters in the west to beyond Eastbourne in the east. This shows several interesting features. Firstly, the area of high landslide activity at, and immediately to the east of, Beachy Head lighthouse (Figure 7) has been faithfully reproduced as a zone of low stability (red) extending the full width of the corridor (see Appendix 3). This zone is influenced by structural and stratigraphic factors within the chalk, and also the gradual emergence of the Gault Formation eastward above platform height. Secondly, the Seven Sisters area to the west of Birling Gap picks out the coombes (lower cliff height), and like Flamborough Head the cliff itself is picked out as a very thin red line with the rest of the corridor shown in blue. One factor brought out by this example is the influence of man's activities in urban areas, in this case Eastbourne. Most coastal towns feature large-scale engineered defences, slope remediation, and landscaping. These affect the GENI rating scheme, which contains no man-made input factors, and probably precludes its use in these urban areas.

Figure 7 Cliff immediately east of Beachy Head lighthouse (arrowed)

8.3 LYME BAY

The Lyme Bay example shows the entire corridor as very poor to moderate stability (red, orange & yellow), with three notably high areas at Black Ven (west), Stonebarrow Hill (centre), and Golden Cap (east) (See Appendix 3). The Black Ven landslide complex has been distinguished as a series of 'benches', which is in fact the case. The massive lower cliff (Lias mudstone) and upper embayment (Greensand/Gault) at Stonebarrow Hill have also been picked out. Similarly, Golden Cap has been well distinguished. These three areas of high relief, similar geology (Greensand & Gault overlying various Lias Group formations) and active instability are faithfully reproduced, at least at the reasonably large map scale shown. This is despite the failure of the model to include any hydrogeological factors, which are of undoubted importance on the Dorset coast.

Figure 8 **View westward of Black Ven landslide complex.**

9 Conclusions

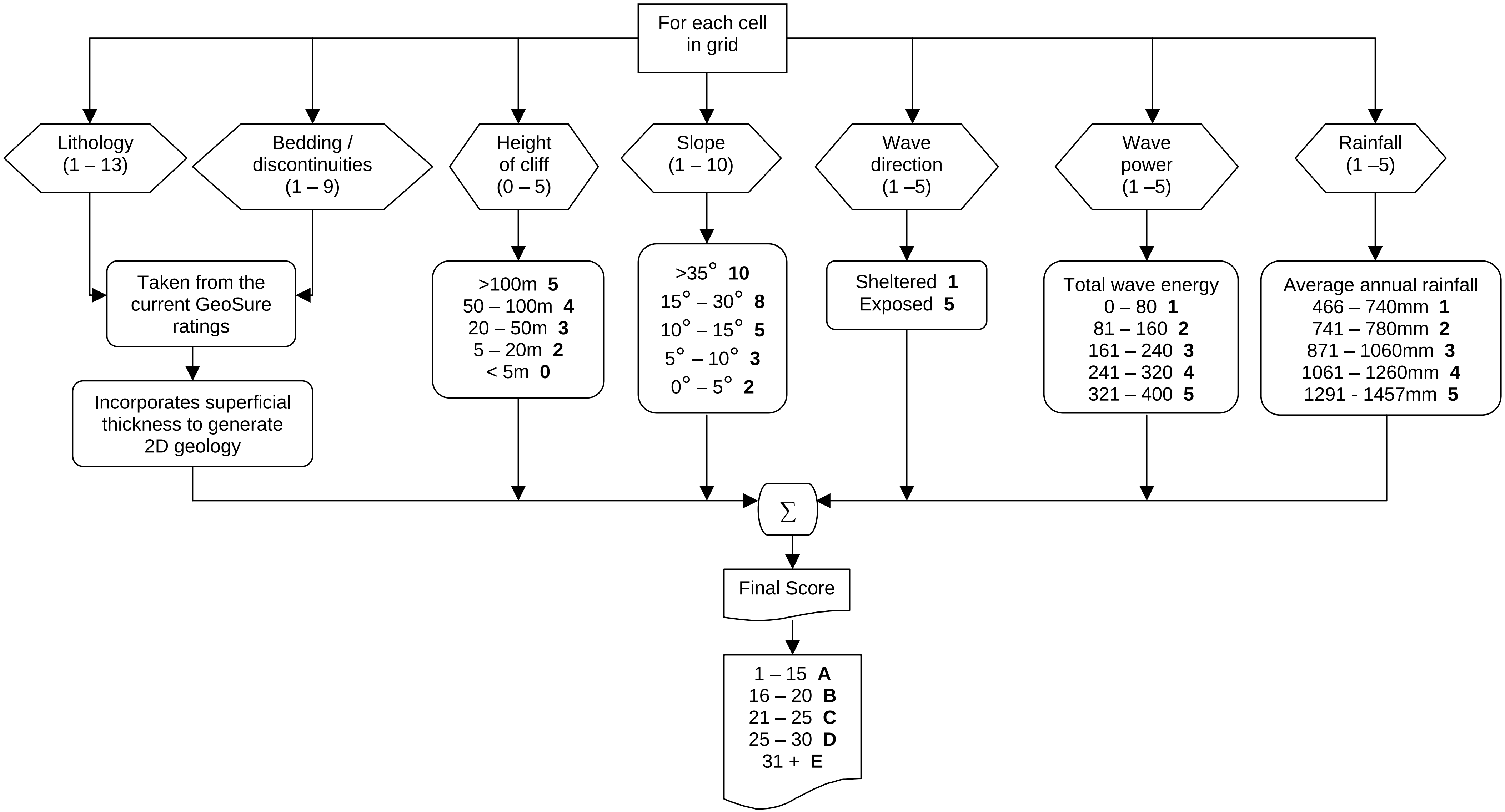
It is clear that large landslide complexes, such as Black Ven, should be reasonably well defined by the model. Steep-angled cliffs are also reasonably well defined. However, truly vertical cliffs of any scale are probably not well represented either numerically or visually using the model and presentation methods shown here. It may be possible to develop an alternative graphic for vertical cliffs.

The role of superficials is sometimes difficult to determine. In some cases they simply react to the instability of the underlying solid strata. In others they contribute to the instability. In some situations cliff height as a contributory factor to instability may be misleading. For example, the Holderness coast has relatively low cliff height, but high instability and very high erosion rate.

The stability hazard presented here should not be confused with stability risk or with erosion risk or potential. The inability to represent the true 3D geology of the cliff introduces errors to the model. The extent and significance of these errors is likely to be very variable along the coast.

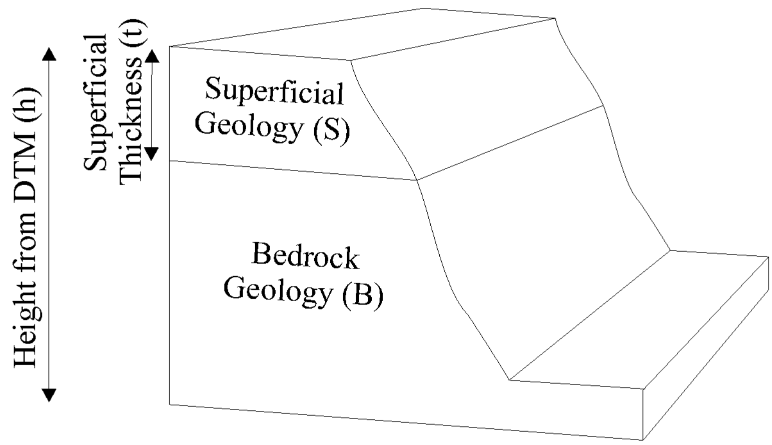
Further development and validation of the model should be made using a wider variety of cliff types. This should include some 'hard' rock cliffs, and further 'soft' rock cliffs (e.g. Holderness). This will allow comparisons to be made with Halcrow's *FutureCoast* instability rating (England and Wales only). This was based on local knowledge and engineering data, rather than on a weighted scoring scheme of the type used here.

Appendix 1 Coastal landslides – GIS Algorithm



Appendix 2 Algorithm for identifying ratio of superficial and bedrock deposits

The following is a description of the algorithm used to determine the lithological and discontinuities/bedding score. It uses the height from the NEXTMap DTM and the results of the superficial deposits thickness model, both of which are held as grids. The bedrock and superficial scores from the current GeoSure landslide scheme are joined to the DiGMap-50 layers and the values exported as grids. When all four data layers are held as rasters, the following algorithm can be applied to find the values for each grid cell.



B = Bedrock score

S = Superficial score

h = Height from DTM

t = Thickness of superficial deposits

WHERE $\left(\frac{t}{h}\right) < 0.1$ take Bedrock score

WHERE $\left(\frac{t}{h}\right) > 0.9$ take Superficial score

WHERE $\left(\frac{t}{h}\right) > 0.1$ AND < 0.9 then $\left(\left(S - B\right) \times \left(\frac{t}{h}\right) + B\right)$

EXAMPLES

Variable	**Score**
DTM height	50m
Thickness of Superficial deposits	25m
Bedrock score	2
Superficial Score	6
Final Score	**4**

Variable	**Score**
DTM height	100m
Thickness of Superficial deposits	0m
Bedrock score	2
Superficial Score	6
Final Score	**2**

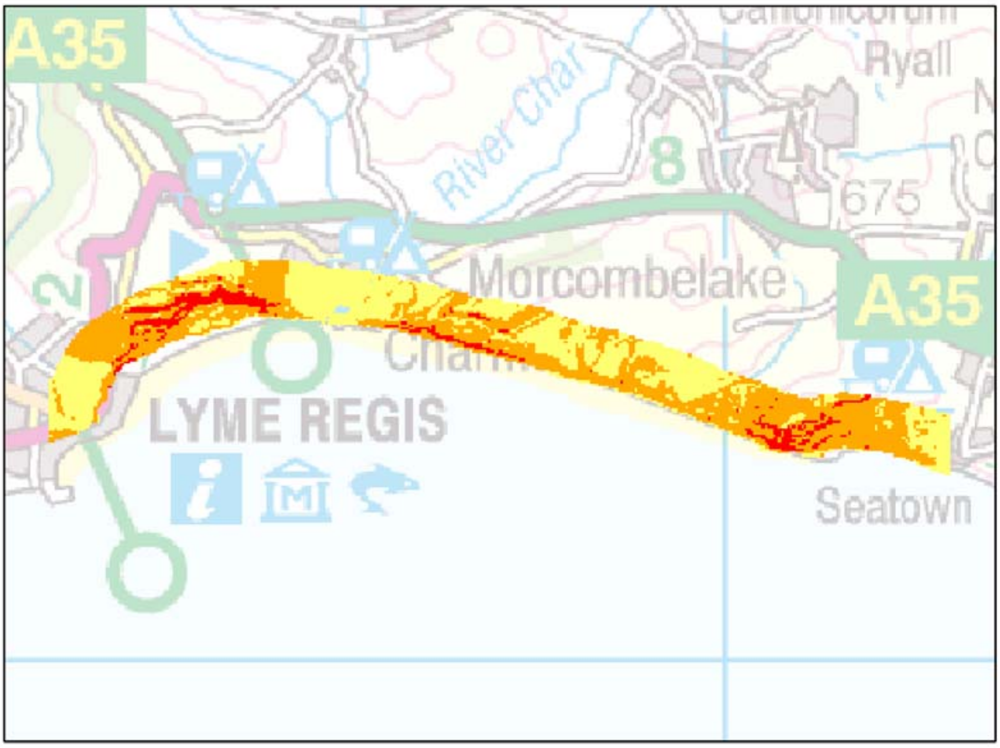
Variable	**Score**
DTM height	40m
Thickness of Superficial deposits	37m
Bedrock score	2
Superficial Score	6
Final Score	**6**

Appendix 3 Results from GIS Potential Landslides model

RESULTS FROM FILEY BAY

RESULTS FROM BEACHY HEAD

RESULTS FROM LYME BAY



References

The references listed below are held in the Library of the British Geological Survey at Keyworth, Nottingham. Copies of the references may be purchased from the Library subject to the current copyright legislation.

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