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Editors
D.MOORE
B.C.Hydro Ltd, Burnaby, British Columbia, Canada

O.HUNGR
The University of British Columbia, Department of Earth and Ocean Sciences, Vancouver, British Columbia, Canada

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Coastal landsliding in Cornwall, UK: Mechanisms, modelling and implications

R.K. Shail, J.S. Coggan & D. Stead
Camborne School of Mines, University of Exeter, UK

ABSTRACT: Cornwall forms the westernmost part of the South West England peninsula and has an Atlantic coastline in excess of 500 km. The coastal zone provides significant leisure and recreational activities for visitors to the region. Effective management of this coastal zone, to minimise risk to property and the general public, requires detailed knowledge of cliff instability mechanisms and coastal erosion rates. The paper summarises recent geotechnical investigations into factors controlling coastal instability in Cornwall.

RÉSUMÉ: La Cornouailles représentent la région le plus l’ouest de la péninsule de L’Angleterre et a un littoral Atlantique de plus de 500 km. La zone de la côte fournit des distractions significatives pour les visiteurs qui viennent à la région. La direction effective de cette zone côtière, pour minimiser la risque à la propriété et au public nécessité la connaissance détaillée des mécanismes d’instabilité des falaises et de la vitesse d’érosion côtière. Le papier récapitule les investigations géotechniques en facteurs qui contrôlent l’instabilité en Cornouailles.

1 INTRODUCTION

1.1 Coastal zone management in the UK

An integrated approach to coastal zone management is being increasingly promoted within the UK. The Ministry of Agriculture, Fisheries and Food has encouraged the development of Shoreline Management Plans (SMPs) that should take into account natural processes, planning pressures, and environmental considerations (MAFF 1995). Landsliding is clearly one of the key natural processes that influence management strategy; the Department of the Environment (DoE) has recently emphasized landsliding as a planning issue (DoE 1990, 1992), as well as disseminating information and examples of good practice (Jones & Lee 1994; Clark et al. 1996). Many hard rock coastlines in the UK are somewhat underrepresented in landslide research, possibly due to their perceived stability and conservative rates of recession. The purpose of this paper is to examine some of the causes and consequences of coastal landsliding in such an area.

1.2 Study area

The study area forms the westernmost part of the SW England peninsula (Fig. 1). Cornwall has an area of 3550 km² and a macrotidal storm wave coastline bordering the Atlantic Ocean of 525 km. The western part of the county comprises a dissected plateau at approximately 60-70 m above sea level. The climate is temperate; mean annual rainfall and temperature are 1000 mm and 10 °C respectively; frosts are uncommon in coastal areas. The resident population of approximately 480,000 is considerably increased, particularly in summer months, by an influx of visitors. Approximately 23% of Cornwall’s gross domestic product is generated by tourism.

1.3 Previous work

Shoreline Management Plans (SMPs) are currently being developed for much of the Cornish coast, and have highlighted the paucity of landslide data. Coastal landslides comprise all of the 47 Cornish landslides identified, largely from British Geological Survey 1:10,000/1:10,560 geological maps, in the recent DoE review (Jones & Lee 1994); this probably underestimates the true number. Few landslides have been investigated in detail and there are only sparse publications (e.g. Coard et al. 1987; Sims & Ternen 1988). The data presented here forms part of a preliminary assessment carried out by the SW Landslide Research Group at Camborne School of Mines, based on data collected by staff and former students.
2 GEOLOGY

Cornwall predominantly comprises metasedimentary and igneous rocks of Devonian to Permian age. A series of marine sedimentary basins, locally floored by oceanic lithosphere, were developed during Devonian to earliest Carboniferous rifting. These subsequently underwent intense deformation and low-grade regional metamorphism during the Variscan orogenic event (Carboniferous) and were intruded by Lower Permian granites (Selwood et al. 1998). Although Mesozoic and Tertiary sedimentary rocks are preserved in the offshore basins surrounding the peninsula, the Upper Palaeozoic lithologies onshore are unconformably overlain by only a variable thickness of poorly consolidated Quaternary sediments; these record periglacial activity and sea level fluctuations during recent ice ages. Made ground is locally present.

2.1 Lithologies

The distribution of the principal hard rock lithologies is shown in Figure 1. The Lizard complex comprises variably serpentinitized peridotites, gabbros and dolerites; it represents a Devonian ophiolite. The underlying Devonian metasediments of the Gramscatho Group are predominantly interbedded siliciclastic sandstones and mudstones; they are locally intercalated with metabasite sills and lavas. The post-orogenic granites, and their attendant metasedimentary envelope are associated with Sn-Cu vein mineralization and a variety of wallrock alteration styles such as kaolinization and hematization.

All of the previous lithologies may be covered by 0-15 m of poorly-consolidated Quaternary sediments that typically thicken in palaeovalleys. These usually comprise solifluction and gelification breccias, but can be underlain by raised beach (conglomerates and sandstones), clay, peat and aeolian sands (e.g. Scourse 1996). Made ground typically represents waste from coastal mining activities.

2.2 Structural geology

The Variscan orogenic episode involved the NNW-directed translation of major thrust nappes. Deformation in the metasedimentary rocks is represented by tight to isoclinal folds, at a variety of scales, and an intense regional cleavage. Bedding and primary cleavage throughout the study area are subparallel; they usually dip gently to moderately SSE or are subhorizontal (e.g. Rattey & Sanderson 1984). Post-Variscan deformation during the latest Carboniferous to Early Permian was characterized by the NNW-SSE extension of previously thickened crust; it brought about the reactivation of thrust faults WSW-ENE to NE-SW, with mean throw of 0.4 m (e.g. Pickering 1997). Recumbent folding, related to mine workings at Wheal Prosper, and cambayn faults WSW-ENE and NNW-SSE were probably active during the Tristatian and late Carboniferous to Early Permian.

3.1 Areal distribution

Geology of Hard Rock deposits in
landscapes (Romana 1998). The
provenance of coastal placer deposits have been related to circular Dilkays and diving dates, which include Paleocene and Late Jurassic times (Moss & Romanowicz 1984). The seabed was therefore mechanism of oceanic floor spreading. All data from Table 1 are representative of the area in Figure 1.

Figure 1. A simplified geological map of west Cornwall (UK location inset) showing the distribution of principal hard rock lithologies (thin lines are Sn-Cu lodes). A variable thickness (typically 0-15 m) of Quaternary sediment is present throughout the area. Numbers indicate localities referred to in the text and Table 1.

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faults and the development of high angle ENE-WSW trending extensional faults and joints in the metasediments and peridotites (Shail & Alexander 1997). The granites were emplaced during this regime and consequently the majority of Sn-Cu vein mineralization, and some kaolinitization, in granites and country rock, is strongly controlled by the ENE-WSW trending fracture set. All the above lithologies were subsequently affected by Late Permian - Triassic ENE-WSW rifting which generated NNW-SSE trending high angle faults and joints that cut earlier structures (Shail & Alexander 1997).

3 LANDSLIDE MECHANISMS

Geological and geotechnical mapping of coastal landslides has been integrated with slope mass rating (Romana 1993), rock mass classification (e.g. Hoek & Brown 1997) and stereographic analysis to provide an indication of actual and/or potential coastal landslide mechanisms in Cornwall. These have been classified according to the schemes of Dikau et al. (1996) and Turner & Schuster (1996). A diverse range of failure types have been identified, including discontinuity-dominated failure (translational), multi-discontinuity rotational failure, and pseudo-circular failure; subsidiary types (locally dominant) include toppling, block slide, fall and wedge. Localities where examples of the different mechanisms occur are shown in Figure 1 and related data summarized in Table 1; schematic representations of failure mechanisms are provided in Figure 2.

Recognition of key parameters or the overall mechanism is not always straightforward as nearly all landslides involve more than one type of movement. These may either act concurrently in different parts of the failure (compound landslides), or evolve downslope i.e. primary failure to subsequent secondary deformation (complex landslides). Rock mass disaggregation can also complicate identification.

4 CONTROLS ON LANDSLIDING

The following sections discuss the principal controls on the occurrence of the landslide mechanisms summarized in Table 1 and Figure 2.

4.1 Lithology

The hard rock lithologies may be broadly subdivided into peridotites (Lizard ophiolite), metasediments, and granite. All are very strong to extremely strong in their unweathered state, although the slates are markedly anisotropic. Engineering behaviour is primarily governed by discontinuity characteristics, and structurally controlled failure predominates (Table 1). A secondary control is exerted by weathering and/or alteration of the primary lithology. A Tertiary weathering profile 0-10 m thick, underlying the Quaternary sediments, can be developed in all lithologies, but is particularly marked in the metasediments. Pre-weathering alteration includes serpentinization of the peridotites, and kaolinitization of the granites and metasediments (as a consequence of hydrothermal alteration). Outcrop can vary from fresh rock to, locally, residual soil as a consequence of the above processes.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Lithology</th>
<th>Mechanism(s)</th>
<th>Erosion potential</th>
<th>Key Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Cliffs</td>
<td>Metasediments</td>
<td>Complex</td>
<td>Low - medium (1-5 cm yr⁻¹)</td>
<td>Discontinuity orientation, Toe erosion, Debris removal (unloading)</td>
</tr>
<tr>
<td>Godrevy</td>
<td>Upper cliff: Quaternary sandstones, aeolian sands, solifluction breccias on cemented basal conglomerates</td>
<td>Pseudo circular, Slump</td>
<td>Medium (5-20 cm yr⁻¹)</td>
<td>Differing erosion rates, Aquiclude at base of Quaternary succession, Wave-cut platform, Groundwater</td>
</tr>
<tr>
<td>Lamorna</td>
<td>Lower cliff: metasediments</td>
<td>Translational</td>
<td>Low</td>
<td>Discontinuity orientation</td>
</tr>
<tr>
<td>Praa Sands</td>
<td>Quaternary conglomerate, clay, peat, solifluction breccias</td>
<td>Slump</td>
<td>Medium - high (10-40 cm yr⁻¹)</td>
<td>Wave impact, Toe erosion, Storm damage</td>
</tr>
<tr>
<td>Porthleven</td>
<td>Upper cliff: Quaternary solifluction breccias, made ground</td>
<td>Wave (storm) erosion</td>
<td>High (60-100 cm yr⁻¹)</td>
<td>Differential erosion, Discontinuity orientation, Wave impact, Storm damage, Wave-cut platform</td>
</tr>
<tr>
<td>Pentreath</td>
<td>Peridotite</td>
<td>Translational, Complex</td>
<td>Low - medium</td>
<td>Discontinuity orientation, Joint intill material</td>
</tr>
</tbody>
</table>
The Quaternary sediments, residual soils developed on hard rock lithologies, and made ground are usually weak and permeable, and can behave as aquifers. Pseudo-circular and slump failure mechanisms predominate (Table 1, localities 2, 4). However, some raised beach sandstones and conglomerates, usually present immediately above the unconformity with the metasediments, may possess a ferruginous or carbonate cement. These are moderately strong and impermeable, and can behave as aquicludes, thereby enhancing the degree of saturation, and hence the possibility of failure, in the overlying material (Table 1, locality 2).

4.2 Discontinuities

The regional ENF-WSW and NNW-SSE fracture sets developed during post-Variscan deformation generally constitute the principal discontinuities within the hard rock lithologies (e.g. Fig. 3). Bedding and cleavage in the metasediments, and subhorizontal to moderately inclined sheeting joints within the granites, also form significant discontinuity sets. Bedding and cleavage exhibit local variations in dip direction and magnitude as a consequence of Variscan folding and/or rotation accompanying post-Variscan faulting.

The key discontinuity parameters that influence failure mechanism and magnitude are orientation, spacing and persistence. Joints within the two fracture sets are typically subvertical, closely spaced, and of low- to medium persistence. Areas in which joints are the principal discontinuity type are consequently dominated by low volume falling and toppling failures. Faults, particularly within the ENF-WSW set, are less steeply inclined, extremely widely spaced, and have a very high persistence. Areas in which these faults form the principal discontinuity type include larger volume translational failures. The largest failures are associated with moderately inclined faults that have a dip-parallel persistece exceeding the height of larger cliffs.

There is a partial correlation between lithology and failure mechanism. Moderately-inclined faults are rare within the granites; consequently toppling or falling, controlled by subvertical joints and faults dominates (Table 1, locality 3). The metasediments possess a wide range of discontinuity types and orientations, including moderately inclined faults, and thereby exhibit a range of failure mechanisms, including large volume translation (Table 1, locality 1). The failure characteristics of the peridotites, and metabasites hosted within the metasediments, are intermediate between those of the granite and metasediments (Table 1, locality 6).

Discontinuity parameters that are generally of secondary importance are infill, wall strength and seepage. Infill characteristics are variable and influenced by the host lithology; those adversely affecting shear strength include serpentine, talc, carbonate, sepiolite, chlorite (peridotite; Table 1, locality 6), fault gouge (metasediment) and kaolinite-hematite (granite). The latter infill type may be associated with pervasive wallrock alteration which, in the case of multiple structures, may coalesce into kaolized zones which persist over several hundred metres.

Significant historical mining activity in some coastal regions has resulted in stoping along
mineralized fault zones (lodes). The extraction of bridging material, particularly from lodes that parallel the coastline, has locally further contributed to instability. Although grooves and corrugations on ENE-WSW trending fault planes cause considerable waviness, they typically plunge down-dip and do not significantly modify discontinuity shear strength characteristics.

Groundwater flow beneath the weathered zone is discontinuity-controlled, primarily by joints and faults (e.g. Heath 1985). Seepage is frequently observed from coastal fault zones and reduction of effective normal stresses by groundwater is likely to contribute towards failure.

The rock mass characteristics discussed above account for the macroscopic coastline morphology outlined in Figure 1; granites, peridotites and significant accumulations of metabasites within the metasediments form the prominent headlands around the peninsula (at a variety of scales). In contrast, the metasediments form many of the embayments between these headlands. These are particularly marked where a shore platform is overlain by Quaternary sediments (Table 1, localities 4, 5).

4.3 Coastline orientation

The orientation of the coastline is controlled by that of individual cliff sections. Since these generally represent the variably degraded scarps of active or inactive structurally-controlled landslides, a large proportion of the Cornish coastline parallels the ENE-WSW or NNW-SSE trend of the regional discontinuity sets. The orientation of a cliff section determines the potential failure mechanism(s) across a given discontinuity set, e.g. translational failure across ENE-WSW orientated faults is generally favoured by cliffs of a similar trend.

Coastal orientation also determines the nature of interaction between the cliff, fair weather/storm wave energy, and tidal currents which collectively govern the rate of toe erosion. Since fair weather and storm waves are both generally incident from the SW, it is coastal sections facing in that direction which experience maximum mechanical and hydraulic wave action.

The effect of storm wave action on such coastal sections can be particularly severe (e.g. Jarvis 1992a, b). Wave impact and toe erosion, with removal of previous failure material (unloading) causes retrogressive erosion of the cliff profile (Table 1, localities 1, 5). Erosion rates of poorly consolidated Quaternary sediments are governed by their thickness and height above sea level. The presence of a wave-cut platform reduces the erosion rate (Table 1, locality 2). In contrast, east facing coastal sections are often sheltered; toe erosion is minimal and cliffs are usually more extensively weathered.

In summary, the key parameters influencing landslide mechanism/rate, and therefore volume loss, are rock mass characteristics, the orientation and height of cliff sections relative to major discontinuities, and the dominant direction of fair weather waves, storm waves, tidal currents and shore/nearshore sediment transport.

5 MODELLING

The orientations of discontinuities mapped in the metasediments at North Cliffs (Table 1, locality 1) are summarized in Figure 3. The cliffs trend ENE-WSW and are up to 80 m high. The principal discontinuity sets comprise moderately to steeply NNW-dipping faults and gently NNW-dipping bedding/cleavage. Computer modelling, using the distinct-element code UDEC (Itasca 1996), has been used to provide further insights into a landslide occurring at this locality. The landslide appears multi-rotational in view of backward-tilting units, but is complex with primary translational failure controlled by faulting. Initial model geometry, shown in Figure 4, was established to investigate the effects of bedfall/cleavage and major faulting. Sensitivity analyses on critical input parameters, such as discontinuity shear strength, stiffness, and geometry were performed to assess their influence on model behaviour. The effects of toe erosion, by removal of blocks from the toe of the modelled cliff profile, was also assessed.
Figure 4. Initial model geometry for north coast landslide

Figure 5. Displacement vectors for modelled cliff profile
Displacement vectors associated with typical modelled slope behaviour are shown in Figure 5. The modelling suggests translational movement on the major faults with bulging of the slope profile towards the centre and base. This type of failure resembles active-passive wedge type behaviour, controlled by the shear strength characteristics of the major fault, where toe erosion and subsequent unloading would lead to retrogressive instability of the cliff profile. Field observations suggest that the upper weathered profile results in localised rotational failures and backward-tilting scarps within the upper slope.

Modelling has confirmed the dominant influence of discontinuity geometry and shear strength characteristics on failure mechanism. Conventional limit equilibrium solutions can provide valuable information and are particularly useful for providing probabilistic analysis, and likelihood of failure, for subsequent risk analysis. The UDEC analysis, however, provides additional insight into the more complex multi-discontinuity deformational behaviour, which is difficult to analyse using conventional techniques. This type of analysis is therefore extremely useful for improved understanding of complex landslide failure mechanisms.

6 COASTAL ZONE MANAGEMENT

Coastal landslides have previously been somewhat neglected in Cornwall, but should form a key part of an integrated coastal management strategy, not least because predictions of sea-level rise and storm frequency imply increased rates of coastal recession (CCIRG 1996). The development of Shoreline Management Plans provides an excellent opportunity for data on coastal landsliding to be incorporated into effective planning policies. The following sections consider some of the issues relating to landslide management in Cornwall.

6.1 Public exposure to landslide hazards

Cornwall is economically dependent upon its coastal zone as a tourist resource; over 90% of visitors cite spectacular scenery and recreational opportunities in the coastal zone as an important factor in their choice of holiday destination (26% of England’s Heritage Coast and 17% of Britain’s bathing beaches are located in Cornwall). Large numbers of tourists and residents spend time in the vicinity of active or inactive coastal landslides, particularly during summer months. Small volume rockfalls constitute a risk on most beaches backed by cliffs. Maritime district councils, as the statutory coastal protection authority, have done much to highlight the potential dangers through signing, but there is a common public misperception that hard rock cliffs are permanent rather than transitory geomorphological features. The potential for large magnitude low frequency failures above all principal beaches should be assessed and a systematic hazard classification adopted.

6.2 Risk to property

The majority of the unprotected, unstable coastal slopes and cliffs in Cornwall are undeveloped or relatively undeveloped. The benefit to cost ratio renders coastal protection unviable and “do nothing” or “managed retreat” will be the most common shoreline management strategies. Development in such areas is unlikely to be permitted under revised planning guidelines (Cornwall County Council 1995, policy MAR3); until recently, this has not necessarily been the case (e.g. Coard et al. 1987). A systematic zonation of the coastal zone in terms of landslide potential could be of particular use to the statutory planning process.

Hard engineering protection schemes have been used in areas of highly developed coastal slope, where a favourable benefit to cost ratio can be demonstrated, or local considerations prevail, e.g. £1.8 million has been spent on constructing a mass concrete granite faced battered retaining wall at Porthleven to prevent damage to property and utility services. All new coastal protection work will, wherever possible, make use of soft engineering solutions (Cornwall County Council 1995).

6.3 Highways and footpaths

Many secondary roads are at risk of landslip for at least short sections of their route. Many sections of the South West Coast Path, a major national trail which is estimated to bring more than £15 million per year into the regional economy, are also at risk. There are a large number of other public rights of way in or across the coastal zone which are adversely affected by landslip activity. The maintenance and re-routing of these highways and footpaths requires considerable expenditure from the County and district councils (benefit to cost ratios favour retreat rather than protection in most instances). A systematic survey to delineate those sections of path and highway at highest risk of landslide could considerably assist the planning process.

6.4 Pollution

Landslips in certain areas could potentially affect sewerage infrastructure, or cause remobilization of contaminated ground (mine waste).
7 CONCLUSIONS

Coastal landsliding in Cornwall is more widespread than the traditional view of a hard rock stable coastline would suggest, even when the disproportionate influence of the overlying poorly consolidated Quaternary sediments is taken into account. In part this reflects the paucity of research within the area. Variation in rock mass characteristics and coastline orientation give rise to a variety of failure mechanisms into which further insights can be obtained by modelling.

Benefit to cost ratios in the majority of localities mitigate against hard coastal protection schemes. Due to the significant leisure activity promoted in the coastal zone, public exposure to landslide hazards, particularly large magnitude low frequency events, must be constantly evaluated. The most effective solution to minimize risks and disruption is to anticipate the natural processes involved, plan accordingly, and educate a wider public.

Data relating to the distribution, nature and recession rates of coastal landslides should form a key part of integrated coast zone management. A simplified rock mass classification and hazard zonation scheme, in a format suitable for GIS, should be adopted to inform statutory and non-statutory planning processes.

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