A PROPOSED METHODOLOGY FOR ROCKFALL RISK ASSESSMENT ALONG COASTLINES

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Many of the general public use the coastal zone for recreation during the summer. They often spend time in the vicinity of cliff exposures that may constitute a risk from instabilities. Rockfall hazard appraisal and risk assessment techniques were applied to a length of Cornish coast, predominantly in sandstones and mudstones between Hayle and Portreath, to assess the threat to the public on the adjacent beaches. The methodology used was similar to assessments of rockfall on highways. Even though risks are voluntary, the general public should be informed of the risks of rockfall. The results of the analysis suggest that, for an occasional beach-user, the risk may be small, when compared to the risk from other voluntary activities such as rock climbing. Increased exposure and the nature of the recreational pursuit may increase risk.

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INTRODUCTION

The detrimental effects of coastal landslide activity have received extensive coverage in the national press in recent months, following one of the wettest winters for more than 100 years. Many of the public visit the coastal zone for recreation. Where beaches are backed by cliffs, the public often spend time in areas that may constitute a risk from instabilities. With the predicted increase in wet-winters and storm-related damage as a result of climate change, then increased rates of coastal recession are forecast. Coastal cliff instability must, therefore, be a consideration for users of the coastal zone for business, tourism and recreational purposes. Instability can directly affect both coastal paths and beaches. The potential for instability may therefore have a detrimental impact on small businesses, local maritime authorities, private landowners, highway authorities and the general public. This is important for Cornwall as over 20% of the gross domestic product is generated by tourism (Shail *et al*., 1998), and the coastline is over 200 miles long.

Assessment of landslide activity, and the instability of the Cornish coastline, has been carried out under Shoreline Management Plans (SMP), using qualitative evaluation. The data incorporated within the SMP was based on a review of available literature, air photograph surveillance and field visits. The risk or likelihood of injury to persons from rockfall when using beaches backed by cliffs for recreation has not been quantified.

Rockfall hazard appraisal and risk assessment techniques were applied to a length of the Cornish coast between Hayle and Portreath to assess the threat posed to the public when using the beach-area for recreation. Limited geotechnical mapping was undertaken to develop a qualitative risk zonation map, prior to more detailed quantitative assessment for areas identified as posing a rockfall hazard. The proposed methodology for assessment of risk was similar to that developed for rockfall on highways (Bunce *et al*., 1997). The methodology described within this paper highlights the factors that should be considered for quantification of the likelihood of harm from falling rock in specific geological and erosional environments. Future research in this area will include attempts at benchmarking against rockfall accident statistics.

COASTAL LANDSLIDING IN CORNWALL

Recent Shoreline Management Plans (SMPs) (Halcrow Group, 1999) highlighted the paucity of landslide data for much of the Cornish coast despite much visual evidence. Coastal landslides comprise all 47 Cornish landslides identified, largely from British Geological Survey 1:10,000/1:10,560 geological maps in the Department of the Environment review of landsliding across Great Britain (Jones and Lee, 1994). Few landslides have been investigated in detail and there are only sparse publications (Coard *et al*., 1987; Sims and Ternan, 1988).

Shail *et al*. (1998) provided a review of coastal landsliding in Cornwall and noted that it is more widespread than the traditional view of a hard, stable coastline would suggest, even when the disproportionate influence of the Quaternary sediments is taken into account. A diverse range of failure types was identified, including discontinuity-dominated failure (translational), multi-discontinuity rotational failure, and pseudo-circular failure; subsidiary types (locally dominant) included topple, fall, block slide and wedge. The principal controls on the occurrence of specific mechanisms of failure were lithology, weathering and/or alteration of the primary lithology, discontinuity orientation, spacing and persistence, the presence of groundwater and coastline orientation. Coastline orientation was found to be particularly important in governing the nature of the interaction between the cliff lithology, fair weather/storm wave energy and tidal currents that collectively control the rate of cliff erosion or recession.

The SMPs provide useful information concerning the composition, susceptibility to erosion, and typical erosion rates (ranging from 1-3 m per 100 years, but could be as high as 10 m per year for Quaternary sediments). The SMPs also qualitatively assess cliff stability in terms of high, moderate and low hazard. This information has been useful for development of management strategies for coastal defence. The SMPs do not, however, quantify the risk of instability and hence rockfall activity.

RISK OF ROCKFALL

The risk to persons and property from coastal rockfall was recently highlighted by the closure of the beach beneath Stonebarrow, Dorset (to prevent fossil hunters gaining access to the base of unstable cliffs) and the damage caused by rockfall to beach huts at Beer, Devon (Western Morning News, 2001). House (1993) noted that after winter rains particular sections of coastal cliff in Dorset can be extremely dangerous. This was emphasized by the loss of several members of a geological party who were killed in February 1977 by a rock fall of the Purbeck Formation at Lulworth Cove, Dorset. This raises general questions as to how safe are our beaches for leisure activity adjacent to potentially unstable cliffs? There may also be a duty of care required from landowners or maritime authorities where persons and/or property are exposed to a perceived rockfall risk.

In geotechnical engineering, designers are increasingly required to provide quantitative assessment of the likelihood of injury or damage to property caused by specific activities. Risk-based design, using a variety of both qualitative and quantitative risk assessment techniques, is used widely within civil engineering, including landslide evaluation (Cruden and Fell, 1997). It has, therefore, the potential for application in coastal regions.

Figure 1, adapted from Cruden and Fell (1997, page 241), highlights the key questions that need to be addressed when evaluating the threat posed by coastal rockfall. Some of these questions can be more easily addressed than others; for example, the likely failure mechanisms, potential volume of failed material and from which section of the cliff the failure may occur can be assessed during geotechnical site assessment. In contrast, it is more difficult to establish the timing and likely travel distance of any instability. The vulnerability of the element at risk (either person or property) must also be considered in order to effectively determine the 'risk of injury' or 'damage to property'.

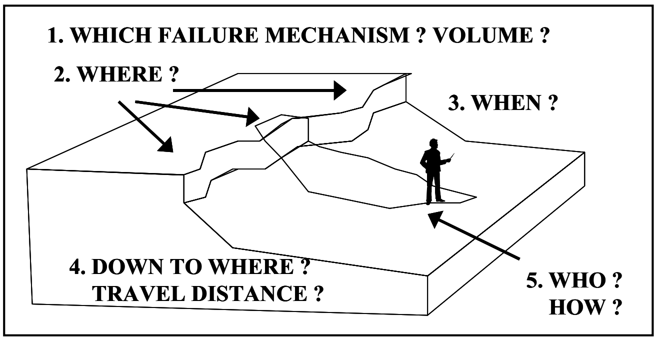

***Figure 1**. Key questions that need to be answered during any risk assessment of coastal cliff stability (modified after Cruden and Fell, 1997).*

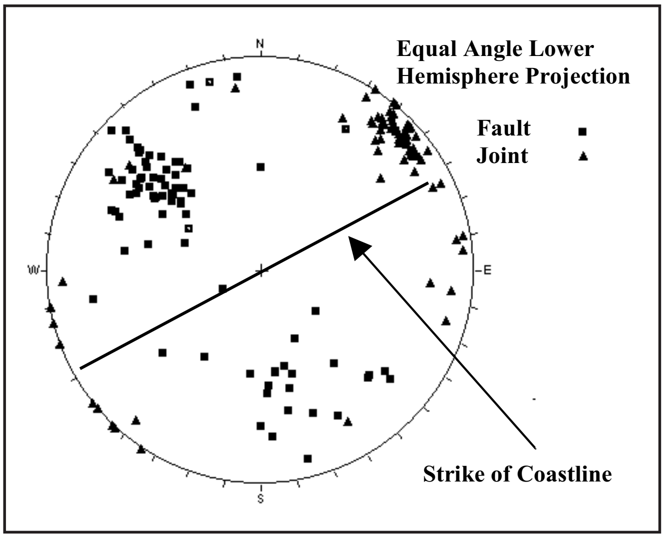

***Figure 2**. Stereographic representation of discontinuities mapped from cliff exposures.*

Qualitative risk assessment

Qualitative risk assessment normally involves a ranking or zonation method to assess parameters that may influence the potential for cliff instability. An example of this is the 'rockfall hazard rating system' used by Bunce *et al*. (1997) to assess the potential for rockfall on a Canadian highway. This involved listing key factors contributing to potential rockfall. Summation of individual parameter weightings was then performed to determine an overall cumulative ranking or rating value. The summed value was then compared to previously defined indicator levels to assess its significance and hence the need for remedial action.

Other qualitative approaches have adopted multipliers of parameter weightings instead of summation. Daws and Elson (1990), for example, described an approach to assess the risk of rockfall from chalk cliffs near Dover. McMillan and Matheson (1997) described a two-stage system for highway rock slope risk assessment that has been adopted by the Transport Research Laboratory. Boggett *et al*. (2000) described the results of a detailed geomorphological mapping exercise, prior to undertaking a risk assessment which resulted in the development of a risk zonation map for a 1 km section of the Cumbrian coastline.

Using a methodology similar to Boggett *et al*. (2000), the length of Cornish coastline investigated was zoned into areas of different lithology for risk assessment purposes. The cliff comprised inter-bedded sandstones and mudstones of the Gramscatho Group, overlain by 2-3 m of poorly consolidated Quaternary sediments. Cliff heights varied from essentially nil (sand dunes) to 20 m. Structural mapping was used to assess discontinuity orientation and the potential block size for rockfall analysis. Stereographic representation of the poles of discontinuities (faults and joints) mapped from cliff exposures are shown in Figure 2. The majority of discontinuities strike parallel and perpendicular with the coastline, which strikes approximately north-east/south-west. Typical spacing of discontinuities varies from close (0.06 to 0.2 m) to moderate (0.2 to 0.6 m). Persistence varies between medium (3 to 10 m) and high (10 to 20 m). This combination of orientation, persistence and spacing provide the necessary blocky cliff exposure for potential rockfall.

During field mapping qualitative risk assessment was undertaken. Ranking scores were assigned to the following parameters based on the values shown in Table 1 (modified after Boggett *et al.*, 2000).

NUMBER	HAZARD	PROBABILITY	RISK VALUE	VULNERABILITY
1	Small failure/erosion	Unlikely	Hard standing areas not in use	Little or no effect
2	Moderate failure and occasional small falling blocks	Possible	Unoccupied building/public right of way (beach)	Minor damage or injury
3	Substantial failure and occasional large falling blocks	Likely	Road/footpath	Major damage or injury
4	Deep failure >30m and large rockfall		Major buildings	Loss of life
5	Major failure		Residential area	

***Table 1**. Ranking scores used for qualitative risk assessment (after Boggett et al., 2000).*

1) Hazard – anticipated size and rate of ground movement
2) Probability – likelihood of occurrence
3) Risk Value – related to occupancy (e.g. buildings, footpaths)
4) Vulnerability – vulnerability of the element at risk (people/ buildings)

ZONE	HAZARD H	PROB. P	RISK VALUE R	VULN. V	RISK NUMBER R_N=HxPxRxV	RISK CLASS
1	2	2	2	3	24	2
2	1	1	2	1	2	1
3	2	3	2	4	48	3
4	2	2	2	3	24	2

***Table 2**. Qualitative rockfall risk assessment for site sub-sections.*

Table 2 shows the results of the qualitative assessment of rockfall for zones identified for the study area. Each zone was then assigned one of five risk classes (1-5), based on the risk class range shown in Table 3. This was used to highlight areas of moderate to high risk for risk zonation mapping purposes and it also provided a qualitative indication of the relative risk between identified zones. Although useful, this still did not quantify the risk posed by rockfall, and the classifications were somewhat arbitrary

RISK NUMBER	DESCRIPTION	RISK CLASS
>100	HIGHEST	5
60-100		4
30-60	MODERATE	3
10-30		2
<10	LOWEST	1

***Table 3**. Risk class assignment based on magnitude of risk number.*

Quantitative risk assessment

Figure 3 summarises, in the form of an influence diagram, some of the key factors affecting the likelihood of rockfall resulting in injury or loss of life. In order to quantify the risk posed by rockfall it is necessary to quantify both the frequency of occurrence and the hazard consequence. An example of the use of quantitative risk assessment is given by Bunce *et al*. (1997), who provided a probabilistic evaluation of the likelihood of being struck by a rockfall on a Canadian highway. This example is useful in that it highlighted the main issues involved and provided techniques to assess probability, vulnerabilities and risk. Further examples of the use of quantitative techniques, for landslide risk assessment, are provided by Cruden and Fell (1997) and Turner and Schuster (1996).

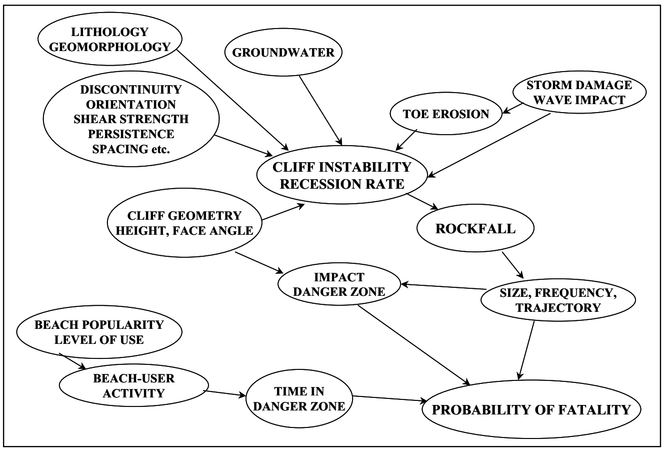

***Figure 3**. Influence diagram to show key factors that affect the likelihood of rockfall, and the potential of the rockfall to result in harm or loss of life.*

Bunce *et al*. (1997) used the binomial theorem for estimating probability whereas Hungr and Beckie (1998) suggested that simple multiplication of conditional probabilities provided acceptable estimates of risk. The approach adopted for this study followed the suggestions of Hungr and Beckie (1998) and Hungr *et al*. (1999), whereby simple multiplication of conditional probabilities was used to quantify risk, on an order of magnitude basis.

Annual probability of fatality

In order to evaluate the risk posed by rockfall several simplifying assumptions have been made as part of the current study. A spreadsheet was developed to allow rapid evaluation of the potential effects of parameter variation on the probability or risk posed by rockfall at the site. Figure 4 provides a schematic representation of the cliff face investigated, highlighting the designated rockfall impact zone. Figure 5 provides example results from the spreadsheet for the beach site. The following input parameters were evaluated within the spreadsheet to estimate the risk of rockfall:

1) Total number of blocks falling from cliff per annum (frequency)
2) Fraction of total number of falling blocks during critical periods/danger time (probability)
3) Number of "cells" traversed by blocks during critical periods/danger time (frequency)
4) Occupancy of cells during critical periods/danger time (probability)
5) Vulnerability of persons if simultaneously within a traversed cell (probability)

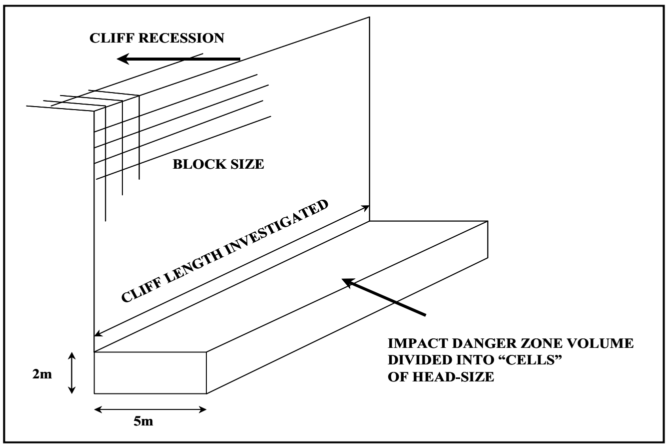

***Figure 4**. Schematic representation of the cliff face investigated, highlighting the designated rockfall impact zone.*

Based on the Shoreline Management Plan for the site, estimates of coastal recession rate were combined with field estimates of block size to give an indication of the potential number of blocks that may fall within a given time period (annual total number of rockfalls). Estimates were then made of probability of rockfalls occurring during occupancy of the beach. Clearly this excluded storm periods, high tides and most of the winter months.

In order to assess the potential for harmful impact an "impact danger zone" was defined, as indicated in Figure 4. This was assigned based on a volume containing a number of "cells" of an equivalent volume to a person's head. An estimate of the likelihood of a cell being occupied by an individual at the same time as a traversing block was based on estimates of beach-user activity and time spent in the impact danger zone. This was based on beach popularity, or use, and nature of the recreational pursuit.

Different assumptions are required, for example, for an occasional beach-user (i.e. tourist sunbathing for a few hours or an individual walking at the base of the cliff) compared to a professional fossil-hunter (who may spend extended periods at the base of a cliff). In order to simplify the calculations, vulnerability of the individual was assumed to be unity, in that a 'direct hit' from a rockfall would always result in loss of life, which is clearly a worst-case scenario.

Based on the above assumptions, the annual probability of loss of life from rockfall for an occasional beach-user, at the site investigated, is of the order of 5×10^{-6}. The annual probability of a single fatality within the whole population of beach users is of the order of 1×10^{-2}. To assess the implications of this risk, and put it into perspective, it can be compared with published acceptance criteria, and other 'voluntary' activities such as rock climbing, smoking and travelling by road or rail.

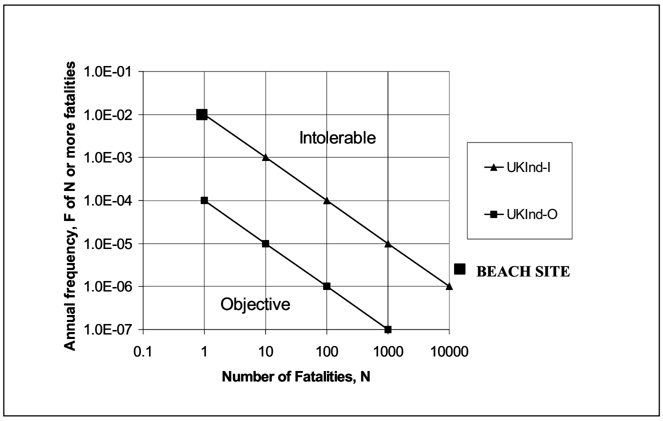

***Figure 6**. Comparison of risk criteria with risk from rockfall for the beach site.*

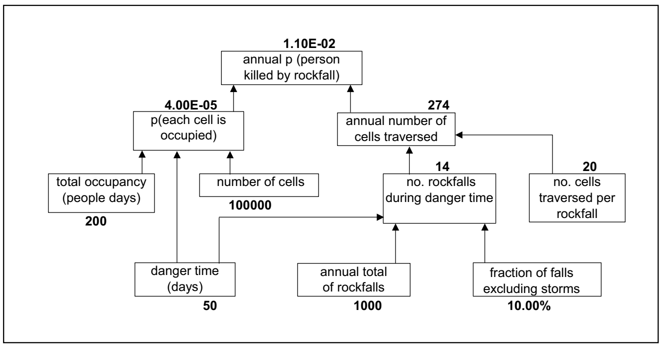

***Figure 5**. Example spreadsheet for determination of risk for the beach site, highlighting required input and assumptions made for the analysis.*

Acceptance criteria

Risk acceptance criteria have been developed for fatality frequencies (extremely low values) based on industrial applications in many countries (e.g. nuclear power plants, large chemical production facilities, large dams and large construction projects). Figure 6 provides an example of United Kingdom risk acceptance criteria in the form of annual frequency (F) versus number of fatalities (N) curves (Health and Safety Executive, 1992).

Implicit in these criteria are the concepts of intolerable (too high), tolerable and negligible (objective) annual frequencies related to the number of fatalities per event. For example, in the UK the objective limit for industrial applications is 1 in 10,000 (10^{-4}) for 1 fatality per year. The objective limit forms the basis of the lower diagonal line on Figure 6. In addition, consideration should be given to whether the risk is voluntary or involuntary (i.e. the public may have little information on which to base any decision to avoid the risk posed by the hazard). The distinction between voluntary and involuntary risk is the distinction between risks arising from activities that are chosen, say rock climbing, and those that are imposed (e.g. bridge failures). Typically the courts have imposed more severe standards on imposed risks.

The comparison of the data for the beach site with the F-N curves in Figure 6 shows the risk level of 10^{-2} for a single fatality to be high compared with tolerable 'industrial' risks. The latter risks are essentially imposed. It should be emphasized here that the 10^{-2} value is probably a conservative (high) estimate by a currently unknown amount. For example, the percentage of rock volume falling within critical periods may be substantially less that 10%, and the postulated rockfall may cause injury, but not death in many cases.

The risk level is also relatively high if considered in terms of fatal accident rate (FAR), after Hambly and Hambly (1994). An approximate value of 200 ($\times 10^{-8}$/hour) is indicated for this beach site compared with rock climbing at 4000 and travel by car at 15.

Implications

Hambly and Hambly (1994) noted that perceptions of risk are frequently based on news: and news is sold by sensationalism, not realism. It is important, therefore, to retain perspective and proportion when assessing the results from any risk assessment exercise. For management purposes imposed risks should be kept "As Low As Reasonably Practicable" (ALARP). In order to achieve this, the risk must first be quantified in a systematic manner and managed accordingly.

Identification of a possible risk posed by rockfall to beach-users should address the problem of the responsible authority and whether it can be considered voluntary or imposed. In either case, does the landowner, maritime authority or responsible body have a duty of care to provide safe recreational facilities? Management in these circumstances may involve provision of signs informing the general public of risks, periodic inspection, periodic scaling or other remedial measures taken to reduce the risk to more acceptable levels.

CONCLUSIONS

In view of the predicted increase in wet winters and storm-related damage, as a result of climate change, there is a case for systematic hazard classification and risk assessment in order to quantify the potential for coastal rockfall. Qualitative risk assessment techniques are useful for risk zone mapping, to highlight areas of relatively high risk. They do not, however, quantify the likelihood of coastal rockfall.

A methodology has been proposed that allows risk quantification at an order of magnitude level. Based on informed judgement, the annual probability of loss of life from rockfall for an occasional beach-user, at the site investigated, is of the order of 5×10^{-6}. For the whole population of users the value is of the order of 10^{-2}. This level of risk may be too high for uninformed users when the risk may be considered 'imposed'. However, further study is required to validate the values against rockfall accident statistics.

The study identified a need for improved education of the general public, to highlight the potential dangers associated with rockfall when using the coastal zone for recreation, particularly where beaches are backed by cliffs. This may take the form of improved signs at strategic locations, and exclusion zones in severe cases.

Once the responsible authority becomes aware of a significant risk, there is a duty to inform the public. In order to provide effective coastal zone management it is desirable that the risk from rockfall be assessed and preferably quantified. With an ever more litigious environment the requirement to undertake risk assessment is likely to grow.

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