Coastal cliff failures at Colhuw beach, Wales, UK

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Abstract

Several numerical models of cliff failure have been utilised in an attempt to understand failure mechanisms at Colhuw beach located in the Glamorgan Heritage Coast, Wales, UK. An understanding as to why falls occur is pre requisite for any management scheme, particularly with the current concern for public safety and consequent financial liabilities Translation failure was common at heavily limestone buttressed cliff sites of Jurassic *bucklandi* - limestone dominated cliffs and in areas where mudstone dominated *angulata* series outcropped. Toppling was common at vertical and overhanging cliff sites which exhibited basal undercutting and/or where a hard, thick limestone fulcrum existed in the cliff face on which the block could rotate and topple. The factor of safety reduced as the ratio of undercutting depth (d) to tension fracture distance (D) in the cliff face increased. Instability forces can be modest ranging from 1.7 to 2.7 MNm^{-2}, but this is enough to exceed cross joint strength as weathering takes place. Sea notching is evidenced at many sites and is a result of wave hydraulic forces, pebble impact, clay expansion and contraction and joint weakening by water movement /seepage and ice.

Introduction

Cliff instability has been long associated with Colhuw beach, Llantwit Major, UK (Williams and Davies, [7,10]; Williams *et al*, [11,12], Davies and Williams, [2], Davies *et al*, [3]). Geomechanically, the rock structure represents one of the most complex of rock mechanic problems, i.e. interbedded, geotechnically diverse strata. Rock resistance ratings (Selby, [5]) indicate that the mudrocks reach as low as 48, whereas competent limestones can exceed 85 (Williams and Davies, [8]).

The Physical Background

The Llantwit Major cliff area is composed of Lias limestone rock, of which *bucklandi* sequences form the major cliff sequences that outcrop at the beach area, Colhuw. Trueman [6] formulated the classic zonal division of these series (*bucklandi/angulata*), dividing the *bucklandi* into 69 distinct horizons. At Llantwit, horizons 1-50 occur. The *bucklandi* consist of alternating layers of mainly limestone rock separated by thinner layers of shales/mudstones; *angulata* consists of mainly mudstones with thin limestone layers. The latter exhibit low angled fractures as a result of tectonic horizontal shear. Uniaxial compression strength values of 261 MPa for the limestones are typical but due to discontinuities for example, much lower levels occur (~ 10 MPa). Failure is partly a result of interlock and subsequent shear strength reduction. The Barton-Choubey [1] empirical relationship for peak strength along rock joints gave a figure of 1.36MPa for weathered limestone. Low Poisson ratios and values for Youngs Modulus for moderately competent shale (Table 1) could suggest that aspects of rebound have taken place with small horizontal movements. Typical enginering properties for these mudrocks were dry density 2.53g/cm^2; plastic limit 17%; Plastic index 7%; Linear shrinkage 5.04%; Equilibrium moisture content 1.87%; Hamrol's Absorption coeficient 5.03%; Slake durability index 93.2%.

Specimen	UCS	ASF . 10^{-6}	E. 10^3 MPa	PR
Moderately competent shale loaded at right angles to fissility	48	5,000#	3.25#	0.084#
As above but parallel to fissility	33	3,150	17.0	0.26
As above but strain measured in the same plane as the fissility		1360	32.5	0.08
Flaggy limestone > 30 cm. thick-intact strength	230	4,200	56	0.26

Table 1 Uniaxial compression test data (Ax size specimen)

KEY

UCS.	Unconfined compression strength
ASF.	Axial strain at 50% of failure load.
E.	Tangent of Elastic modulus as 50% of failure load.
PR.	Poisson Ratio at 50% of failure load.
#	Strain gauge bonding broke at 52% of failure load.

Cliff failure mechanisms are generally toppling, translation, buckling and joint block detachment (Davies and Williams, [2] Davies *et al*, [3], Williams and Davies, [9], Williams *et al,* [11,12]). For toppling to take place, overhanging cliff faces and or strong limestone bands to act as a fulcrum for the detached block, must occur. Tension crack widening at the cliff top together with wave notching at the base are ideal conditions. Cliff erosion rates are 10 centimetres per annum.

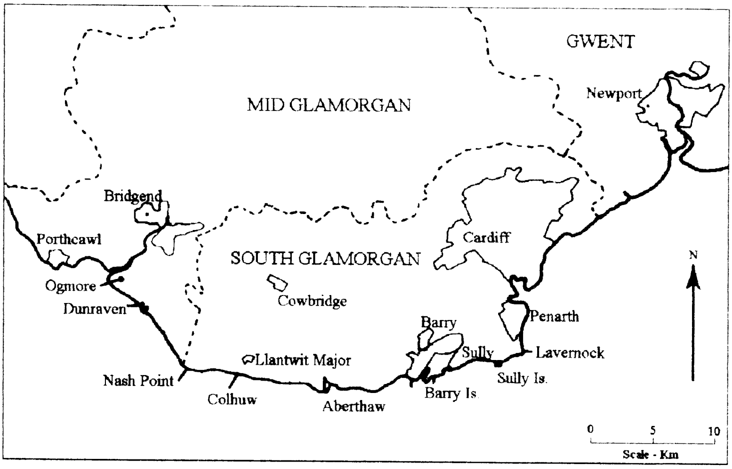

Figure 1:The Location of Llantwit Major and its beach at Colhuw, Wales, UK

Nash Point, lying to the west of Llantwit Major (Fig.1), provides a convenient wave energy fulcrum; areas to the west of it are recipients of high energy waves; areas to the east receive much lower energy waves. The Severn estuary experiences the second largest tidal range in the world (16.4m at Avonmouth; >12m at Colhuw beach. The funneling effect of the estuary and its varied bathymetry play a large part in determining the distribution pattern of wave orthogonals and a refraction coefficient of .33 is standard for this region. Pierson-Moskowitz wave spectra and the Fast Fourier Transform as applied to wave data are shown in Fig. 2. High wave forces are exerted on the cliffs during storm periods. In addition, storm surges enhance wave attack during high sea state conditions. For example, on 18.12 91, a spring tide aided by Force 9 SW winds caused a 1.5m surge in this region. In conjunction with wave slamming forces, pebbles are also thrown at the cliff face and play a role in weakening it. Exact quantification of the percentage erosion that can be attributed to this mechanism is currently unknown but a typical pebble impact trace obtained from an instrument designed to measure such impacts (10 per second; Williams and Roberts, [13]) on shore platforms, breakwaters, cliffs etc. is shown in Fig. 3. The top segment figure of Fig. 3 represents wave action over time on the instrument head. Specially written software selects spectra 'spikes', the shaded bar - from 30-50 seconds of the 1 minute trace, which is then expanded to give detailed analysis of the forces acting over this time period. The impact shown at 41 seconds represents a pebble hitting the instrument head. For further details see Williams and Roberts [13]. Impacts at the commencement of the record and at 10 seconds - see the top trace of Fig. 3, are waves reacting with the head. The instrument is capable of recording 10 impacts per second.

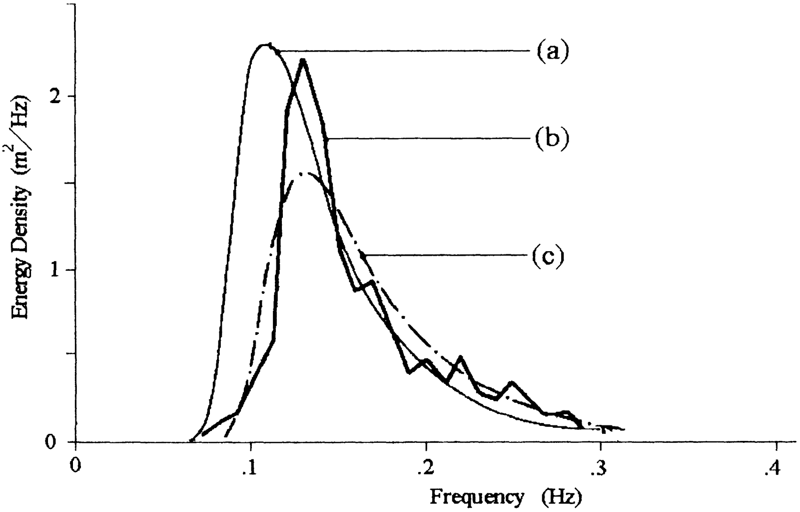

Figure 2. Theoretical and Observed wave spectra

KEY

a) Pierson-Moskowitz (PM) spectrum for H_S = 1.65m, T_Z = 6.0 secs.
b) Fast Fourier Transform (FFT) for H_S = 1.46, T_Z = 5.01 secs.
c) PM spectrum calculated using FFT values of H_S and T_Z.

Cliff Failure

Numerical models for cliff failures in Lias limestones developed by the authors, have shown that because of the unstable blocks' limited thickness, sliding is a translation mechanism and overturning could be considered as a tension crack toppling mechanism which is usually anticipated by tension cracking combined with bottom erosion (Goodman and Bray, [4]). Pressure release joints, weathering etc. reduce interlock to such an extent that discrete columns exist in the cliff mass. Excavation of low durability limestones, master joint displacement and a fulcrum along a hard limestone band ensures that toppling failures may occur when overturning moments exceed resistance moments, especially within the *bucklandi* sequences. Major discontinuity joint sets often strike parallel to the cliff face with others orthogonal to it. Resistance is also generated by torsion shear strength mobilised on discontinuities orthogonal to the cliff face, but efficiency is reduced by weathering so stresses can outweigh the limiting equilibrium and is very common below horizons 39 and 49. Translation failure is usual in *angulata* sequences, the failure surface following master joint surfaces especially with backward tilted strata. The failure surface takes the line of least resistance through the rock mass. Joint block detachment and buckling phenomena also take place albeit on a much smaller scale but on a more frequent basis.

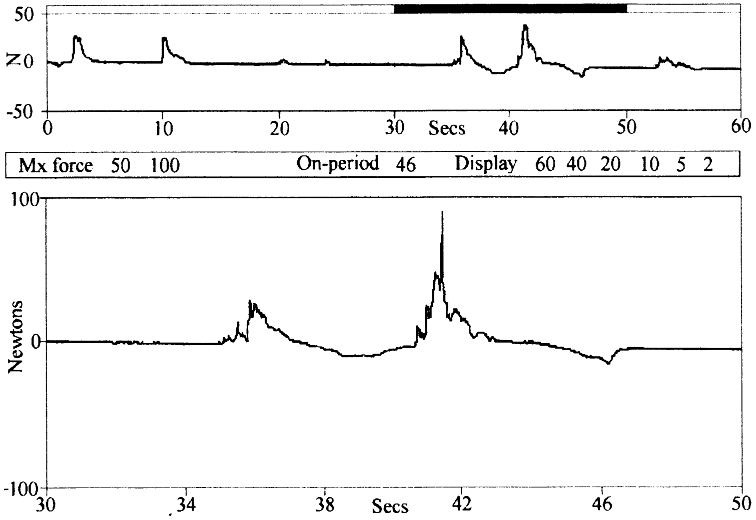

Figure 3. Wave forces and pebble impacts - see text

Instability over a large number of years has resulted in several unsuccessful attempts to stabilise these cliffs. In 1969, a cliff blasting experiment attempted to form a talus cone of some 150,000 tonnes of material which abutted against the cliff face (Williams and Davies, [7]). Some 250 metres of cliff had 85 holes, ~ 17m in depth drilled into the cliff top, which were filled with explosives (Quarrex and low density gelignite) and tamped down. Efficient longshore drift and wave action effectively removed this material in a matter of years and blast transmission into the cliff face caused myriads of joint failure planes to occur which enhanced erosion rate at this site. Recently (1993 - 1996), the local Authorities have built a large groyne, later filled with large, 7 tonne Carboniferous Limestone blocks to form a 50m long, 30m wide and 7m high coastal revetment comprising several hundreds of these blocks.

The cliff, essentially composed of *bucklandi*, has a highly variable morphology. Cliff height is from 10m to 40m comprising geological strata up to 1m in thickness and with a high joint density. Where undercutting is absent, translation is the more common failure mode with a stability factor close to 1.0 for a whole range of forces (Table 2). This in itself highlights the unstable nature of the site with respect to translation failures. Once undercutting occurs (d in Table 2), toppling failure is more likely to occur modest undercut, e.g. d = D/4 in Table 2 (where D is the distance from the cliff edge of the cliff top tension crack). Water, infill and ice pressure thrust forces can be critical in controlling toppling and these forces vary enormously with fluctuations in the hydrostatic or hydrodynamic pressures. Davies *et al* [3], demonstrated at Colhuw that the factor of safety reduced from 1.88 to 0.44 under conditions of extreme storm generated thrust forces.

Potential thrust force (MN/m)	**Translation safety factor**	**Toppling Safety Factors**			
		d = 0	**d=D/6**	**d=D/4**	**d=D/3**
0	2.26	*	*	1.92	1.49
0.26	2.12	*	2.46	1.68	0.91
0.57	1.91	1.81	1.42	0.77	0.42
0.93	1.68	0.95	0.77	0.4	0.22
1.26	1.40	0.61	0.49	0.26	0.14

Table 2. Potential thrust forces and safety factors at Colhuw
(*No toppling ; D = cliff edge tension crack distance, d = undercut depth)

This study is an attempt to provide further insight into the development of basal notches and the mechanisms of failure. Shallow notches (< 1m deep) have been cut into a number of weathered mudstones horizons but were most pronounced (up to 4m) when the *angulata/bucklandi* junction was at the cliff base. A simple mechanical model can relate undercutting depth (*d(t)*), height of cliff (*H*) and the physical properties of the limestone rock. Toppling depends on complex processes which accompany cliff base notching. Cliff stability is governed by the angular momentum balance equation which in general terms yields:

$$\frac{d(t)g}{2}\int_0^{d(t)}\int_0^{T}\rho(x,y,t)dxdy+\int_0^{H-T}\sigma_{xy}(x,y,t)ydy=0. \qquad (1)$$

where $\rho(x,y,t)$ is the rock mass density and $\sigma_{xy}(x,y,t)$ is the stress tensor which is a function of the cohesive rock forces, faulting, the depth of tension crack development (*T*) and distance of the tension crack from the cliff edge (*D*). These values depend on the characteristic time $\tau* = 1$ year relating to physical transformations in the cliff mass (Williams, *et al* [12]). The undercutting depth *d(t)* is found from the cliff profile function $f(x,y,t) = 0$.

$$\left(\frac{df}{dt}\right)^2 = k^2(y,t)\left[\left(\frac{df}{dx}\right)^2+\left(\frac{df}{dy}\right)^2\right] \qquad (2)$$

where $k(y,t)$ is the erosion rate which depends on the intensity of hydraulic wave action, pebble impact, weathering and rock fatigue forces. The end result is rock mass movement away from the vertical culminating in toppling.

Stereonet analysis indicates no major discontinuity striking parallel with the Colhuw valley, but strata dip measurement suggested an anticlinal axis exposing *angulata* zone horizons in the lower cliffs, i.e. some 6m are exposed. Strong discontinuity orientation joint trends can be found striking at 255° and 145° and infrequent planar discontinuities striking at 210° are of considerable significance to stability. Spacing between planar major discontinuities which are often persistent for some tens of metres, drops to less than 60 cm at many locations and minute Griffith cracks are common. Joint spacing is typically some 6-20 mm which strike parallel to the major discontinuity trends and are often filled with calcite. The end result is block cleavage along vertical planes giving tabular like blocks. Fracture surface types most commonly observed were hackled marked, the hackles radiating from the propagation point. The best developed formed chevron type structures which were common on major and minor fracture planes in both uniaxial and triaxial compressive tests. Observations on these friable surfaces showed shear failures, striae parallel with, and ridges orthogonal to, the shear direction.

The basal thick mudrock is the upper horizon of an eastward trending argillaceous dominant *angulata* stratum. They are exposed increasingly in a low amplitudinal flex which culminated when a large fault down throws *bucklandi* strata (horizons 39-49) to shore platform level. The shale band at horizon 28 indicates an inherent weakness within the cliff section, forming a seepage line and a notched series even though it is above the level of normal marine attack. Thermal gravity analysis of this layer showed that cation exchange capacity was higher than might be expected and isomorphic substitution in the clay crystallite lattice had occurred because of weathering, the resulting larger negative surface charges being neutralised by double layers of greater ionic strength. Illite dominates the clay fraction, interspersed with illite/smectites and quartz. The presence of these minerals help to explain shale weakening due to exposure to geomorphological processses.

Conclusions

Colhuw beach has been the scene of many rock failures and subsequent attempts to protect the cliff. The main failure patterns have been toppling and translation; the main protection measures cliff blasting to form a talus cone against the cliff face and a coastal revetment. Toppling failures can occur anywhere in the cliff profile as long as a thick massive limestone can act as a fulcrum for movement due to tension crack expansion and undercutting has occurred. This is common in *bucklandi* sequences; translation along a curved

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slip surface is common in the *angulata* sequences. Numerical modelling has shown the veracity of these processes.

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