

Rock Coasts



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Definition

A rocky coast is one “*that is cliffed and yet composed of consolidated material irrespective of its hardness*” (Sunamura 1992, p. 2), i.e., it ranges from very hard rock coasts (e.g., granite, basalt) to soft cohesive fluvial or glacial deposits, and they represent some 75% of the world’s coastlines. Erosion on such coasts is irreversible and is a function of wave energy and rock strength (Fig. 1). They are usually high, and consequently there is an inherent danger for injury or even death to coastal visitors, so good signage is important (Fig. 1).

Cliff Erosion

Coastal erosion is becoming an acute problem within the coastal zone, and because of global warming/sea level change, *El Nino* effects and greater storminess are likely to increase the risk of cliff failure and reduce human utilization. The general processes responsible for rock coast cliff erosion are well known and have been extensively discussed elsewhere (Sunamura 1992; USACoE 2002; Woodroffe 2002; Trenhaile 1997). Quantifying erosion controls is however rather difficult (Van Jones et al. 2015).

An extensive body of literature supports the significance of mechanical action within the wave erosional system (cf. Sunamura 1992). Realistically, failure depends upon many additional factors, such as hydro-geological processes and ground water seepage through the cliff mass. The retreat rate of rock cliffs varies but depends upon the:

Strength of the Rock Material Forming the Cliff

Axiomatically the harder the rock, the slower is the erosion rate. Rock and joint strength parameters (Table 1) can be derived from field measurement, such as Schmidt hammer readings and tilt tests, and laboratory analyses, for instance, uniaxial compression/tensile strength, point loading tests with values incorporated into standard rock mechanics formulae, such as given below:

$$\text{JRC} = (\alpha - \phi_b) / \log_{10}[(\text{JCS} / \sigma_n)] \quad (1)$$

$$\phi_b = (\phi_b - 20) + 20 (r / R) \quad (2)$$

$$\sigma_n = \gamma_h \cos^2 \alpha \quad (3)$$

$$t_p = \sigma_n \tan [\phi_b + \text{JRC} \cdot \log_{10}(\text{JCS} / \sigma_n)] \quad (4)$$

where JCS = Joint Compressive Strength, e.g. via Schmidt hammer, JRC = Joint Roughness Coefficient (varies from 0 - very rough to 20, α = joint tilt angle at failure, ϕ_b = residual angle of friction along the joint, σ_n = mean value of normal stress induced by the sliding block weight, r = uniaxial compressive strength for wet rock samples, R = uniaxial compressive strength for dry rock samples, h = block thickness, γ = bulk density, t_p = peak shear strength.

Basal Wave Energy

Coastal cliff erosion is a complex system and variations in the geological, erosional, and weathering environment are



Rock Coasts, Fig. 1 The Glamorgan Heritage Coast, UK

Rock Coasts,
Table 1 Geomorphic rock mass strength classification for limestone/shales in Lias age rocks, Glamorgan Heritage Coast, Wales (GHC), UK (after Selby 1980; Fig. 1)

Parameter	Limestone	Shale
Intact rock strength	18	5
Weathering	9	5
Joint spacing	21–28	15–21
Orientation	14	14
Width	6	2
Continuity	4	4
Totals	78–85	48–54



Rock Coasts, Fig. 2 Golfo di Orosei, Sardinia: Active notch at the sea level and last interglacial fossil notch at approx. 8 m a.m.s.l. in a limestone cliff

reflected in the general cliff erosion rates derived from field and laboratory observations. Many investigations have established the links between basal erosion, notching (Fig. 2), cliff instability, and recession (Sunamura 1992; Rosser et al. 2013). Cliff surface deterioration and cliff base erosion are

related especially to the assailing force of waves. Quasi-periodic wave erosion is more efficient when high tides coincide with storms whereby basal erosion by waves produce notching, and a laterally extending cliff base hollow. They are clear indicators of cliff erosion.

Three main processes affect a cliff's base:

- Cumulative hydraulic action related to breaking waves, water spray, and high speed droplets. Hydraulic forces that include compression, tension, impact, and shearing actions, which combine to achieve wave quarrying; all of these result in repeated stress placement on rock surface layers.
- Turbulent water currents that lift boulders, pebbles, and sand from the shore platform and beach.
- Shell feeding algae and other organism living in the intertidal band.

Mathematically, the major factors of basal erosion are given by Sunamura's (1992) equation:

$$x = f(F_w, s_r, t) \quad (5)$$

where x is the basal cliff erosion distance, F_w is the wave induced force, s_r is cliff material resistance, and t represents time.

If F_w is ≤ 0 no erosion occurs; when $F_w > 0$ erosion takes place.

Amount of Abrasive Material Available at the Cliff Base

Almost by definition, the loose sediment associated with cliff erosion occurs in the pebble-boulder range, which, if in sufficient quantity, is the best beach that nature could envisage to retard erosion. Beach sediment, usually in the pebble-boulder range, can accentuate erosion processes by either being an abrasive agent (boulders can smash into a cliff face) or can hinder it to form a protective beach. Increasingly strong wave action produces large hydraulic forces that are accentuated by the abrasive force of rock fragments hurled at the cliff base. The latter set up "*impact stresses on the rock surface, the stress increasing as the mass and/or angle of velocity of the impacting particles are increased*" (Sunamura 1992, p. 78). If the water depth in front of the cliff is higher than approximately half the wavelength, sediment is moved at the base and abrasion does not occur and the cliff becomes more stable (Plunging cliff: C type in Sunamura rock coast classification; Fig. 3).

Mass Movement

The coastal zone has a high frequency of cliff mass failures, which reflect the ability of high energy waves to exploit the well-jointed/interbedding nature of "very strong" and "moderately weak" rock materials. Wave undercutting is a critical control of many toppling and joint block detachment forms of failure. The Factor of Safety reduces as the ratio of undercutting depth to distance from the cliff face of tension fractures increased and as thrust forces within joint systems

increase due to water infill by wave and tide factors, freeze-thaw and clay infill expansion and contraction.

The main forms of cliff falls are: Toppling (Fig. 4 left), Translation (Fig. 4 center), Buckling, and Falls rock (Fig. 4 right, debris and earth), where the bulk of the mass falls as a free body; in soft rocks, flows can occur, where movement is faster towards the upper area of a moving body, that is, no block movement. The first two are usually the predominant mechanisms. Toppling occurs when an eccentricity develops so that overturning moments exceed resisting ones and little free fall movement occurs. A fulcrum is necessary along a hard rock band and it occurs when:

$$b/h < \tan \theta \text{ and } \psi < \theta \quad (6)$$

where b = block base dimensions; h = block height dimensions; θ = angle of frictional resistance; ψ = basal plane angle.

Sliding and toppling occur when

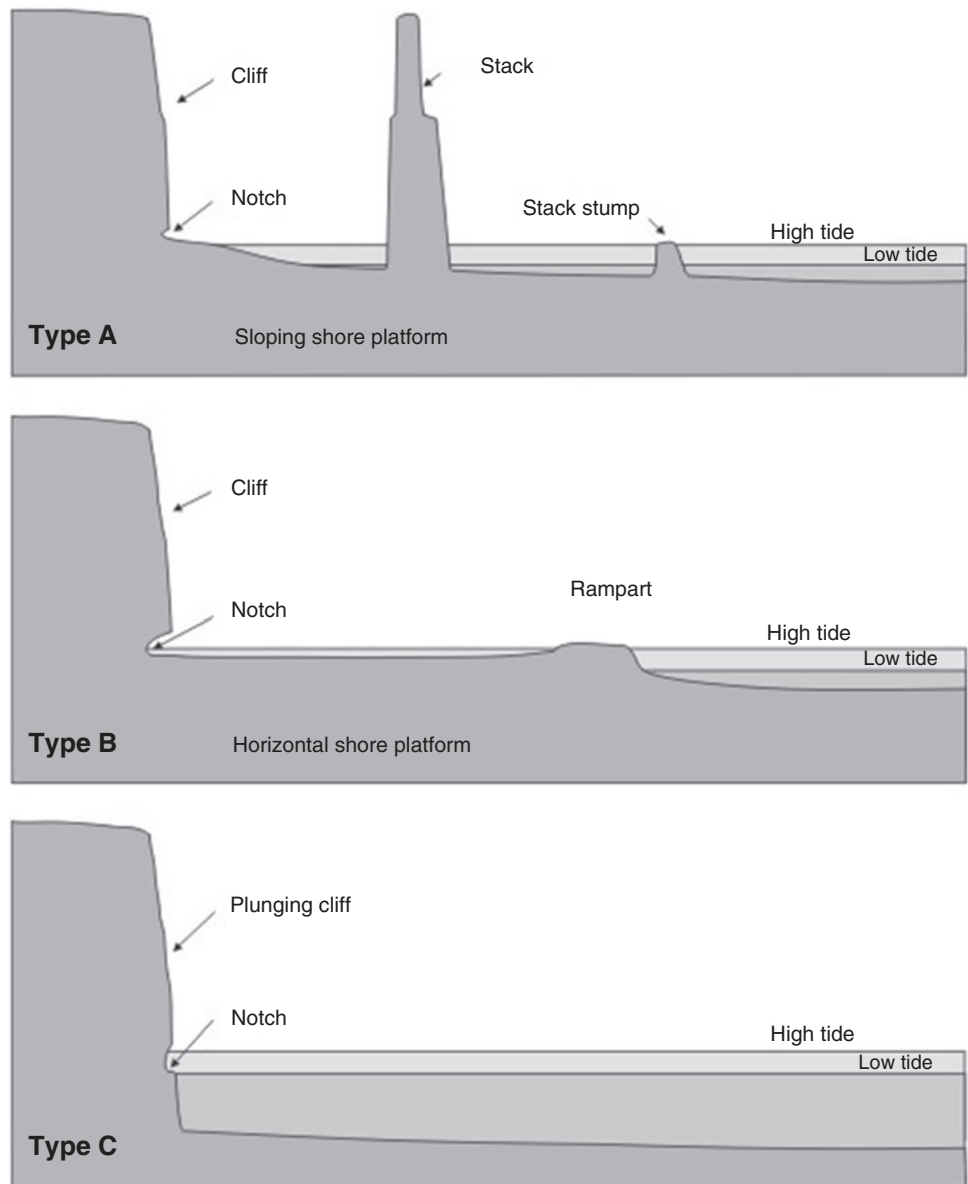
$$b/h < \tan \theta \text{ and } \psi > \theta \quad (7)$$

Shear resistance to toppling usually occurs along discontinuities orthogonal to the cliff strike. For translation to occur a hard rock band usually lies on top of a weaker rock unit and translation along a master joint is normal. The failure surface takes the path of least resistance through the rock mass, usually a curved surface.

Weathering

Weathering (chemical, hydrolysis, hydration, oxidation, and solution) and mechanical (frost, thermal stress, salt crystal growth, unloading, and swelling) decreases a rock's mechanical strength and coastal cliff deterioration due to temperature (nonuniform) variations mainly affecting surface rocks. Heat conductivity is a function of the rock's thermal properties, and discontinuous rocks are more vulnerable to thermal expansion/contraction. Rock composition differences cause thermal conductivity anomalies resulting in large temperature gradients, which cause block cracking and displacement along joint/fault lines. Nivation processes by ice/water, salt crystallization, and so on reduce rock mass strength by entering rock discontinuities. Biological influences also can cause weathering. Plant growth can exert physical pressure on existing discontinuities. Marine organisms causing boring, for example, *Lithotrya*, *Litgophaga*, can also dislodge lithic material from a rock surface (Woodroffe 2002). Algae, fungi, and lichens can cause chemical alteration, especially in the tropics, as well as providing food for grazing organisms that can abrade the surface. This situation is estimated to reflect one-third of the mid-tidal zone at the Aldabra Atoll (Trudgill 1976). The importance of haloclasty (salt weathering) in cliff rock weathering is demonstrated by the ramparts that frequently border rock platforms on the seaward side, where

Rock Coasts, Fig. 3 Sunamura's rocky coast features classification:
 (a) sloping shore platform,
 (b) horizontal shore platform,
 (c) plunging cliff (from Pranzini 2004, modified)



Rock Coasts, Fig. 4 (a) Toppling failure, Glamorgan Heritage Coast, UK (left); (b) Translation on glacial deposits, Poland (center); (c) Rock fall, Sardinia, Italy (right)



Rock Coasts, Fig. 5 Rock platform and rampart (Australia)

the rock does not dry even at low tide due to constant exposure to spray. Salt does not precipitate and the process is not active leaving that ridge higher than the more sheltered platform (Fig. 5).

Parameter Interaction

Many models exist to show parameter interactions for soft coasts. Interaction of all the parameters discussed previously results in a rate of recession for the cliff mass the erosion function, which can account for erosion forces and rock strength, as assumed by Sunamura (1992), Eq. (5), and also for the decrease of wave erosion intensity with cliff height. The variety of different mechanisms characterized by diverse time/space scales, process intensities, etc., in a general form can be expressed for the evolution of a 2-D cliff profile under marine influences (Williams et al. 1996; Belov et al. 1999) as:

$$(df/dt)^2 = k(z, t) \left\{ (df/dy)^2 + (df/dz)^2 \right\} \quad (8)$$

where $f = f(y, z, t)$ is the function defining the cliff profile, $k(z, t)$ is the erosion function – the vertical distribution of erosion intensity and also temporal variation of storm-tide periodicity which modulates impact amplitude.

This equation is eikonal, an uncommon approach for geological literature, reflecting long-term cliff profile change in 2-D Cartesian coordinates. Cliff erosion defined by the erosion function is dependent on the nondimensional erosion amplitude parameter v , which in turn is contingent upon breaking wave energy, storm/tide cyclicity, and cliff geometry. While the speed of cliff retreat is also influenced by cliff geology, strength, and geomorphology of the rock mass, it is implicitly subsumed in v , as a complex parameter.

Conclusions

Pre-sea level rise morphological differences, rock variability in petrography and structure, diversity in climate, tidal range, and wave energy interact to make each rock coast segment a different case as far as landscape, processes, and erosion rate. Sunamura (1992) lists some 220 case studies from the literature and gives cliff erosion rates: most of them are less than 1 cm/yr, with some cliffs almost stable for centuries, but sand, silt, clay, and generic glacial deposits can retreat as much as 10 m/yr. Values of coastal retreat for recently deposited pyroclastic material reach as high as 80 m/yr.

Being that most of the processes are nonlinear with time, cliff failure events, or even single rock falls, are rarely forecasted, and this exposes people and values to a significant risk. Since cliffs are among the most attractive elements of coastal landscape monitoring, signage and restrictions are an integral part of coastal management.

Cross-References

- [Armour Stone](#)
- [Beach Replenishment](#)
- [Biological Weathering](#)
- [Boulders](#)
- [Breakwaters](#)
- [Chemical Weathering](#)
- [Classification of Rocks](#)
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- Landforms
- Landslide
- Mass movement
- Mechanical Properties
- Near Shore Structures
- Physical Weathering
- Risk Assessment
- Risk Mapping
- Rock fall
- Rock Laboratory Tests
- Rock Mass Classification
- Rock Mechanics
- Rock Properties
- Sea Level
- Shear Stress
- Stabilization

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