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Wave breaking and runup of long waves approaching a cliff over a variable bathymetry

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Abstract

Long waves approaching a cliff are significantly affected by a variable bathymetry. Wave breaking is observed, and determined by both the bathymetry and nonlinear interactions of the waves with the cliff and other waves. Geometric and kinematic measures are applied to determine a breaking criteria, however there are inconsistencies in both when the wave parameters are close to breaking/non-breaking interface values. Wave crest–cliff interaction is discussed in terms of its effect on the phase and fluid velocities. Runup amplification increases with the number of waves in the approaching wavepacket, their amplitude, and the bathymetry slope, but is approximately independent of the wave period. Runup amplifications approaching a factor of 12 are observed for a bathymetry approximating that of the Aran Islands, Ireland.

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1. Introduction

Extreme waves interact violently with coastal cliffs[1,2], with large runup amplifications and overtopping. This may result in onshore mass transport, including of very large boulders (VLBs). Considering the Aran Islands, Ireland, each winter, Atlantic storms have resulted in coastal boulder movement at elevations up to 40 m above the high-water mark and 250 m inland from the high-water line[3]. Further examples of wave-induced (as opposed to tsunami) VLB movement are reported in France[4,5], Malta[6], and many other locations.

Runup amplification over a flat bathymetry is significantly larger than that given by linear theory (factor of 5+ as opposed to 2) due to a combination of reflection, constructive interference, and nonlinear effects such as dispersion[7,8,9]. Furthermore, strong variations in depth enhance the amplification of waves[10]. The mounting evidence for storm waves transporting VLBs[3,11,12,13,14] suggests the extreme power that these waves possess. We study long-wave interactions with cliffs over a variable bathymetry that better represents real conditions.

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The influence of the bathymetry on the wave conditions is evident. The runup of breaking or non-breaking waves is a consideration for the type of impacts and overtopping flow that may be observed at a cliff[15]. The interaction of a breaking wave with a cliff can be dramatic, significantly increasing the water velocity, especially if the interaction occurs during the inception of overturning. The breaking creates turbulence and pockets of trapped air, generating a water jet when the steep wave-front impacts the cliff[16]. The overtopping flow is characterized by spray sheets. Non-breaking waves may lead to a surge overtopping with a fast bore developing form the collapsing surge[15].

In numerical simulations over a flat bathymetry, small-amplitude long waves do not exhibit breaking during runup at a cliff. However, once a variable bathymetry is introduced, steep wave fronts develop. As the Euler code used cannot resolve the breaking process, we must identify the onset of wave breaking for a variable bathymetry when the waves interact with a cliff structure. Physically, the breaking of water surface waves is the overturning of the wave crest. The onset of wave breaking is typically characterised by a steep asymmetric wave, spilling, and and the formation of whitewater (due to entrained air from turbulence) at the crest tip that spills down the face of the wave[17,18]. The physics of a breaking wave leads to several different criteria for determining the onset of wave breaking: geometric[19], kinematic[19,20], energetic[21]. An important consideration is that these criteria are evaluated locally, as the extremal conditions for wave breaking may not be seen in global wave-parameter values.

In this paper we consider wave breaking and runup amplification as a wave packet approaches a cliff. A complementary paper to appear[22] highlights further aspects to this study, specifically how the wave height to depth ratio during extreme runup corresponds to non-breaking waves with large geometric and kinematic measures. A further paper is in preparation to expand on these results.

2. Model

We consider the runup of a packet of long waves approaching a cliff over a variable bathymetry, with profile $b(x)$. The wave packet's motion is described by the Euler equations (1),

$$\nabla^2\Phi = 0 \qquad 0 < x < 2L, \quad b(x) < y < \eta(x,t), \tag{1a}$$

$$\eta_t = -\Phi_x\eta_x + \Phi_y \qquad y = \eta(x,t), \tag{1b}$$

$$\Phi_t = -\frac{1}{2}\left(\Phi_x^2 + \Phi_y^2\right) - g\eta \qquad y = \eta(x,t), \tag{1c}$$

$$\frac{\partial\Phi}{\partial x}\frac{\partial b}{\partial x} + \frac{\partial\Phi}{\partial y} = 0 \qquad y = b(x), \tag{1d}$$

where η is the free surface, Φ is the velocity potential, and g is the acceleration due to gravity. We solve (1) with a conformal-mapping spectral method[23], using a mirror wave image to impose the cliff boundary condition at $x = L$ and for periodicity[8]. Hence, $0 < x < L$ is the physical domain and $0 < x < 2L$ is the computational domain, with periodic boundary conditions imposed at $x = 0,\ 2L$. The incoming wavepacket experiences runup amplification, R, at the cliff wall, given by

$$R(t) = \frac{\eta(x = L, t)}{a_0}, \tag{2}$$

where a_0 is the initial amplitude of the incoming wavepacket.

The bathymetry considered is related to that of the Aran Islands off the west coast of Ireland. Fig. 1 shows three transects taken with Infomar data from Geological Survey Ireland[24]. The slope near the coast is an order of magnitude greater than that further out. To represent this bathymetry, we approximate this data as a piecewise-linear function with a slope of order 0.01 for the first 4 km from the coast, followed by constant value (the dashed line in Fig. 1). Note that the dashed line overestimates the data. This is because there is no data from the shoreline for approximately 750 m, and has been extrapolated. The depth at the cliffs is approximately 40 m and the ocean depth is approximately 80 m. We scale all lengths with the constant ocean depth, $H = 80$ m, and time with $\tau = \sqrt{H/g} \approx 2.859$ s.

We model an initial incoming wave starting from the flat bathymetry coming towards the non-flat bathymetry leading to the cliff wall. The wave packet is well defined away from the cliff, characterized (independent parameters) by the number of waves, N_w, the initial amplitude, a_0, and the period, P. Other parameters (angular frequency, ω,