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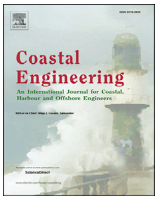

Laboratory investigation of the Bruun Rule and beach response to sea level rise

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ABSTRACT

Rising sea levels are expected to cause widespread coastal recession over the course of the next century. In this work, new insight into the response of sandy beaches to sea level rise is obtained through a series of comprehensive experiments using monochromatic and random waves in medium scale laboratory wave flumes. Beach profile development from initially planar profiles, and a 2/3 power law profile, exposed to wave conditions that formed barred or bermed profiles and subsequent profile evolution following rises in water level and the same wave conditions are presented. Experiments assess profile response to a step-change in water level as well as the influence of sediment deposition above the still water level (e.g. overwash). A continuity based profile translation model (PTM) is applied to both idealised and measured shoreface profiles, and is used to predict overwash and deposition volumes above the shoreline. Quantitative agreement with the Bruun Rule (and variants of it) is found for measured shoreline recession for both barred and bermed beach profiles. There is some variability between the profiles at equilibrium at the two different water levels. Under these idealised conditions, deviations between the original Bruun Rule, the modification by Rosati et al. (2013) and the PTM model predictions are of the order of 15% and all these model predictions are within ±30% of the observed shoreline recession. Measurements of the recession of individual contour responses, such as the shoreline, may be subject to local profile variability; therefore, a measure of the mean recession of the profile is also obtained by averaging the recession of discrete contours throughout the active profile. The mean recession only requires conservation of volume, not conservation of profile shape, to be consistent with the Bruun Rule concept, and is found to be in better agreement with all three model predictions than the recession measured at the shoreline.

1. Introduction

With the recent increased rates of sea level rise (Hay et al., 2015), potential future shoreface response to changing water levels are a persistent concern worldwide. There remains a lack of suitably long-term measurements of shoreface profile change over timescales associated with sea-level-rise, henceforth *SLR* (Leatherman et al., 2000). As an alternative to obtaining natural or prototype data, smaller-scale physical models often behave in qualitatively similar ways to prototype beaches and shorefaces, forming the same characteristic features at a wide range of scales (Hughes, 1993; Van Rijn et al., 2011). Reduced scale modelling can provide valuable information on factors that influence shoreface responses to *SLR*, such as overwash or onshore transport in deeper water, with the benefits of a controllable environment and accelerated timescales. Both overwash and onshore transport in deeper water have recently been proposed as additional mechanisms to be considered alongside the classical Bruun Rule (Bruun, 1962; Rosati et al., 2013; Dean and Houston, 2016).

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The term ‘Bruun Rule’ was first coined by Schwartz (1967) as a result of experiments testing Bruun's (1962) model. It is perhaps the most well-known and common approach used to predict shoreline recession under *SLR*. The basis for the Bruun Rule is related to earlier work on natural beach profiles (Bruun, 1954), which were shown to exhibit a monotonic concave-up mean profile about which natural beach profiles fluctuate over time. The mean (also commonly referred to as a dynamic equilibrium) subaqueous profile shape (Fig. 1) has the form:

$$h = A(x_{sl} - x)^{2/3} \tag{1}$$

for $x \le x_{sl}$, where h is the water depth, with an origin seaward of the offshore limit of wave influence (h_*), x is the cross-shore location, x_{sl} is the still water shoreline location and A [m$^{1/3}$] is a scaling parameter influenced by controls such as sedimentology and wave climate (e.g. Bruun, 1954; Dean, 1991; Short, 1999). The offshore limit is the location where wave driven sediment transport ceases and the corresponding depth h_* is a time dependent variable that is expected to increase with time due to the increased likelihood of larger waves (Hallermeier, 1981); the concept implies that sediment at depths greater than h_* is essentially unavailable through wave driven processes and this defines the seaward location of the active profile. Bruun (1962) used this concept and reasoned that if a mean shoreface profile in dynamic equilibrium with a quasi-steady wave climate is to be maintained relative to the still water level in the presence of *SLR*, sediment can only come from landward of the offshore limit. This results in a net-seaward sediment transport and a landward shift of the active profile to facilitate raising the entire active profile by *SLR*, leading to the following formula which has become known as the Bruun Rule:

$$R = SLR\frac{W}{B + h_*} \tag{2}$$

where all components have units of length. R is the recession of the profile (negative values indicating progradation), W is the horizontal length of the cross-shore active profile, with an onshore limit typically corresponding to a berm with a vertical face at the shoreline and horizontal crest, for which, B is the berm height above the zero-datum, mean sea level (in the field) or still water level (in the lab). All parameters are depicted in Fig. 1. Fig. 1 also demonstrates the coordinate reference system used in the present work. The cross-shore horizontal origin, $x = 0$ m, is located seaward of the offshore limit of profile change, and in the laboratory, it is fixed over the exposed flume bed in the laboratory experiments. The vertical origin, $z = 0$ m, is located at the initial water level; therefore, when the water level rises, the still water level is at the elevation $z = \text{SLR}$.

The Bruun Rule was developed under the assumption of a dynamic equilibrium profile, which is the long-term mean profile, shaped under a quasi-steady wave climate. To determine the existence and shape of the dynamic equilibrium profile requires a dataset of regularly measured profiles that captures the envelope of profile change that occurs with all water level and climate fluctuations (e.g. storms, spring-neap tides and longer scale climatic atmospheric and oceanic oscillations). Continued profile monitoring would be required to determine the maintenance of the dynamic equilibrium profile and the response to *SLR*. Thus, while numerous field experiments intended to investigate the applicability of the Bruun Rule have occurred, given the temporal constraints required to capture the development and response of the dynamic equilibrium profile, compromises in experimental design are usually required. For example, instead of mean profiles, instantaneous profiles that feature perturbations such as bars and berms have been used along with proxies for *SLR*, such as rising lake levels (e.g. Hands, 1979), varying tidal ranges (Schwartz, 1967) and land subsidence (Mimura and Nobuoka, 1995). Even in reduced scale laboratories, generating a dynamic equilibrium profile as well as assessing its subsequent response to a slow change in water level would require prohibitively long duration experiments due to the simulation of a variable wave climate of sufficient complexity and duration. However, the qualitative similarity in morphological responses and profile development observed at smaller scales may provide useful insights into natural, prototype profile responses.

To date, there has been no published laboratory based experiment on the recession response of the shoreline (or any other vertical datum) to sea level rise. There has only been one laboratory study conducted, in which the Bruun Rule was partially assessed using bar-forming, monochromatic waves in very small scale conditions (Schwartz, 1967). These cases are discussed in more detail in Section 2. Therefore, further investigation into the applicability of the Bruun Rule on beach profiles shaped by wave action is warranted. This paper presents the findings of a recent assessment of the original Bruun Rule, as well as the Rosati et al. (2013) recent variant, under controlled laboratory conditions at a larger scale than those of Schwartz (1967), and which include both barred and bermed profile responses. A new method for assessing the recession of a profile with a constant change in mean water level is also introduced in the discussion section. Recession of individual contours, such as the still/mean water shoreline can easily be affected by short-temporal fluctuations with different wave conditions and natural bar/berm responses of the beach profiles, introducing noise into the dataset which leads to uncertainty in quantifying the general profile recession. However, if the profile is in a state of dynamic equilibrium, maintained at each water level, and the limits of the profile change are known, the mean recession of all contours in the active profile between the depth of closure and the runup limit, relative to each still water level, should be the recession predicted by Eq. (2). If this is the case, any two

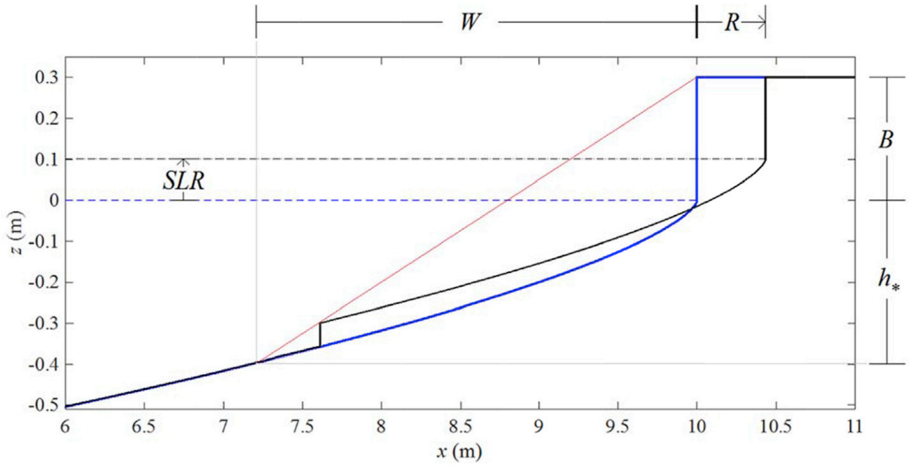

Fig. 1. Bruun rule profile response and framework applied to an idealised profile with offshore shape corresponding to Eq. (1). The red line indicates the slope of the dynamic equilibrium active profile, between the offshore limit and berm crest. The z-axis origin is at the initial water level (blue line), the x-axis origin is located off the plot, seaward of the offshore limit of the profile at the initial water level (x, z) = (7.2 m, −0.4 m). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)