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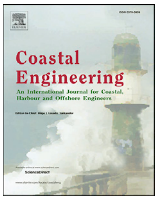

Physical model study of beach profile evolution by sea level rise in the presence of seawalls

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ABSTRACT

Persistent and accelerating sea level rise (SLR) may have a significant impact on the evolution of sandy coastlines this Century. The response of natural sandy beaches to SLR has been much discussed in the literature, however there is a lack of knowledge about the impact of SLR on engineered coasts. Laboratory experiments comprising over 320 h of testing were conducted in a 44 m (L) x 1.2 m (W) x 1.6 m (D) wave flume to investigate the influence of coastal armouring in the form of seawalls on coastal response to SLR. The study was designed to investigate the effects of contrasting types of seawalls (reflective-impermeable versus dissipative-permeable) on beach profile response to increased water levels, in the presence of both erosive and accretionary wave conditions. The results obtained showed that seawalls alter the evolution of the equilibrium profile with rising water level, causing increased lowering of the profile adjacent to the structure. Under erosive wave conditions, modelled profiles both with and without seawall structures in place were observed to translate landward in response to SLR and erode the upper profile. It was found that the erosion demand at the upper beach due to a rise in water level remains similar whether a structure is present or not, but that a seawall concentrates the erosion in the area adjacent to the seawall, resulting in enhanced and localised profile lowering. The type of structure present (dissipative-permeable versus reflective-impermeable) was not observed to have a significant influence on this response. Under accretive conditions, the preservation of a large shoreface and berm resulted in no wave-structure interaction occurring, with the result that the presence of a seawall had no impact on profile evolution. A potential two-step method for estimating the observed profile response to water level rise in the presence of seawalls is proposed, whereby a simple profile translation model is used to provide a first estimate of the erosion demand, and then this eroded volume is redistributed in front of the seawall out to the position of the offshore bar.

1. Introduction

Global sea level rise (SLR) has been accelerating since the late 19th century (Church and White, 2006; IPCC, 2014) and is considered to represent a significant threat to coastal environments in the future (Holman et al., 2015; Ranasinghe, 2016). Studies continue to investigate coastal response to SLR (e.g., (Dean, 1991; FitzGerald et al., 2008; Nicholls and Cazenave, 2010).,), and though the consensus is that sandy coasts are likely to erode, the physical processes and magnitude of the (anticipated) coastal recession remain unclear. To protect land-based assets, coastal armouring by the construction of hard structures such as permeable rubble mound seawalls and impermeable vertical revetments (hereafter collectively referred to simply as ‘seawalls’) have been built along many high value coastlines worldwide. Seawalls are effective at protecting land-based assets during extreme storm events; however, current knowledge is limited on the effect of coastal armouring at sandy coastlines subject to chronic and sustained SLR in the future. The purpose of the study presented here is to provide new insight to the observed interaction between coastal armouring by seawalls and the seaward sandy profile, by reporting the results of physical laboratory experiments.

The most common approach to estimate the response of sandy beaches to SLR is the application of the so-called ‘Bruun Rule’ (Bruun, 1954, 1962, 1988). This is based on the concept of an equilibrium profile, defined by a long-term average profile shape extending from the shoreline to a seaward depth of closure. There is general consensus that the shape of this so-called ‘equilibrium profile’ is some function of sediment

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size and the prevailing wave climate (Dean, 1991). Bruun (1962) proposed that the equilibrium profile is maintained during SLR and rises vertically to match the increase in sea level. Assuming a zero net longshore sediment transport and a closed sediment budget across the active profile, Bruun (1962) considered the equilibrium profile in a 2D geometry such that the sediment required to raise the equilibrium profile could only be provided by shoreline recession and erosion of the berm. Based on this concept, Bruun (1962) provided the following and now widely used equation for predicting the horizontal shoreline recession R (m), due to SLR by a vertical height S (m), as a function of the active profile length L (m), berm height B (m), and the depth of closure h (m):

$$R = \frac{L}{B+h}S \tag{1}$$

Since this geometric relationship between SLR and sandy coast shoreline recession was first proposed, there have been many contradictory findings of how well the Bruun Rule can be relied upon to predict coastal response to SLR (Ranasinghe et al., 2012; Cooper and Pilkey, 2004; Ranasinghe and Stive, 2009).

It is self-evident that there are many inherent challenges to observing and quantifying the net impact of SLR on equilibrium profile evolution and the resulting recession of a shoreline in nature, whereby timescales spanning decades and longer must be considered. It is therefore surprising that the only reported laboratory study of the Bruun Rule was undertaken 50 years ago by Schwartz (1967). This work comprised two small-scale laboratory tests, the largest of which used a wave basin measuring 1 m × 2.3 m, and resulted in a qualitative conclusion that the Bruun Rule could be used to estimate shoreline recession caused by SLR. In contrast, and some 25 years after the results of this laboratory study were reported, the Scientific Committee on Ocean Research (Scientific Committee on Ocean Research Working Group 89, 1991) completed a review of all the available evidence at that time, concluding that the Bruun Rule should be used only for a regional approximation of shoreline recession. More recently, Cooper and Pilkey (2004) reviewed these same studies in the light of new field observations, advising that the Bruun Rule should be abandoned from current coastal engineering practice.

Contemporary researchers have generally adopted more holistic approaches to the use of the Bruun Rule when considering its application to coastal planning and design, that accounts for additional sources and sinks to the active profile sediment budget (e.g. Dean and Houston (2016), Davidson-Arnott (2005), Rosati et al. (2013).). However these studies have still largely fallen short in isolating the efficacy of the Bruun Rule itself to predicting SLR-induced shoreline recession. Despite remaining ambiguity in its predictive capabilities and application, the Bruun Rule (Eq. (1)) continues to be a widely used tool for predicting coastal response to SLR in coastal policy and management, simply because of its relative ease of application and the lack of a practical alternative.

The evolution of armoured sandy coastlines subject to SLR where hard structures such as seawalls are present has received very little attention in the literature to-date. It is well recognised that seawalls are effective at protecting coastal assets during extreme storm wave events; however, there is conflicting opinion as to whether or not their presence has an adverse effect on the prevailing local morphology. Weggel (1988) noted that the influence of a seawall on local coastal processes and morphology depended on the position of the seawall relative to the active profile: when located above the active profile, a seawall does not interact with coastal processes, below this elevation a seawall will interact with hydrodynamic-sediment processes and may cause morphological changes. Kraus (1988) and Kraus and McDougal (1996) reviewed the literature on seawalls and surmised several mechanisms relevant to the present study for which seawalls could change local morphology:

1. Seawalls can reduce the sediment budget available for profile change by retaining sediment landward of the wall;
2. Seawalls may alter nearshore processes, specifically causing enhanced wave reflection, increased surge level, and increased setup; and
3. Wave-structure interactions may mobilise sediment at the structure toe, resulting in local scouring and profile lowering.

What is less clear is whether or not SLR has the potential to enhance (or reduce) the above effects, leading to differing morphological changes in response to SLR at beaches where seawalls are present. In what appears to be one of the few examples of related literature, Dean (1991) proposed an equation for estimating profile changes seaward of a seawall due to water level changes. However, the suggested approach is based on an idealised profile without perturbations, does not account for the potential influence of seawalls on nearshore processes such as reflection and scouring, nor has it been verified by field, laboratory, or numerical investigation.

In summary, sandy coastline response to SLR is still not well understood, and at the present time the existing models and methods to predict these changes are largely untested or verified. Furthermore, very little knowledge exists of how the presence of coastal armouring in the form of seawalls may alter this response. To begin to address these questions, this paper investigates coastal evolution to SLR through physical laboratory experiments; to the authors' knowledge, the first of their type to be reported since the small-scale experiments undertaken in the 1960's by Schwartz (1967). The work presented here evaluates coastal evolution to SLR at beaches armoured by seawalls. This work complements and extends extensive laboratory investigations by Atkinson et al. (*this issue*) evaluating coastal evolution to SLR on beaches with no structures (hereafter referred to as 'natural beaches') and the efficacy of the Bruun Rule to predicting the observed profile evolution. The specific aims of the work presented here are fourfold: (1) To describe the observed behaviour and evolution of beaches with seawalls subjected to raised water-levels; (2) Explore the influence of different types of seawall (reflective-impermeable versus dissipative-permeable) on this observed behaviour; (3) Investigate the potential influence of wave climate (erosive versus accretionary); and (4) Propose a new methodology for predicting profile evolution to SLR where seawalls are present.

2. Methodology

2.1. Equipment and instrumentation

The experiments described here were conducted at the Water Research Laboratory, UNSW Sydney (www.wrl.unsw.edu.au) in a wave flume 44 m long, 1.6 m deep, 1.2 m wide, and equipped with a piston-type wave maker (Fig. 1). Quartz beach sand (d_{50} = 0.35 mm, d_{10} = 0.24 mm, d_{90} = 0.48 mm) was used to form the model beach profile.

Profile measurements along the length of the flume were obtained using a laser measurement system described in Atkinson and Baldock (2016). The advantage of this system is that it enabled rapid and repeat measurements of the bed elevation to be obtained throughout the experimental program, without the need to drain the flume. The system comprises a cross-flume array of 5 x SICK DT50-P111 class 2 laser distance sensors mounted vertically on a rolling trolley that was manually moved along the top rails of the flume. The sensors have an accuracy of order ±0.002 m for the range used. The precise horizontal position of the trolley along the wave flume was obtained using a SICK OLM100 barcode reader also mounted on the trolley, and a barcode tape secured along the length of the flume. The measurement accuracy of the OLM100 is of order 0.0001 m and the profiling system sampled at 10 Hz. A three-probe array of capacitance wave gauges (measurement error of ±0.001 m), was used to obtain wave measurements and estimate reflection coefficients by the method of Mansard and Funke (1980).