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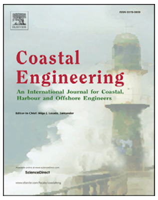

Physical model study of beach profile evolution by sea level rise in the presence of seawalls

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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).

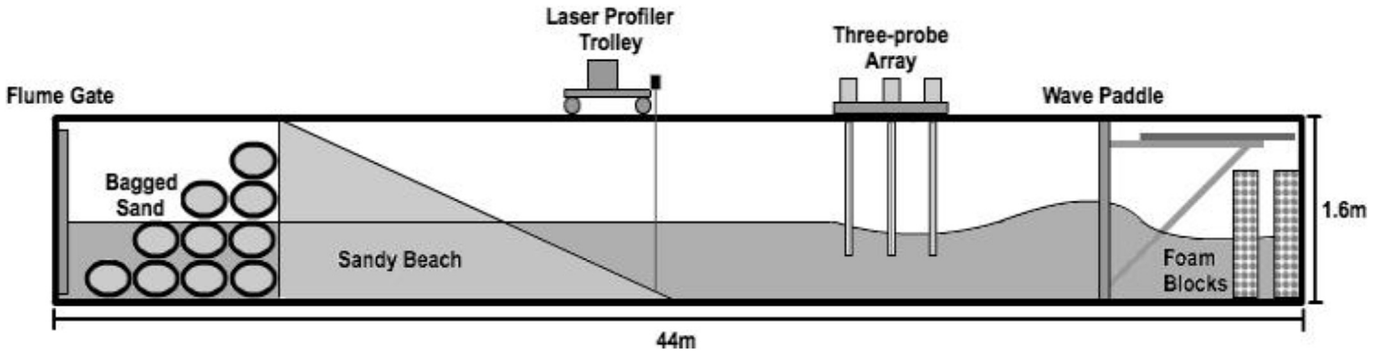


Fig. 1. Schematic of the flume setup used in experiments.

2.2. *Experimental program*

2.2.1. *Overview*

The experimental program was designed to investigate the effect of seawalls on beach response to SLR. Beach profiles were built in the wave flume and subject to water level increases to emulate SLR. Five distinct test cases were completed, totalling more than 320 h of wave action in the flume. These experiments (Table 1) comprised modelling beaches with:

- Erosive waves, no seawall, multiple small water level increases (E1);
- Erosive waves, no seawall, single large water level increase (E2);
- Erosive waves, reflective vertical revetment, multiple small water level increases (EV3);
- Erosive waves, dissipative rubble mound seawall, multiple small water level increases (ER4); and
- Accretive waves, reflective vertical revetment, multiple small water level increases (AV1).

Table 1
Summary of the experimental program. ‘E’ refers to erosive and ‘A’ to accretionary wave conditions, ‘V’ and ‘R’ refer to the inclusion of the vertical (reflective-impermeable) and rubble mound (dissipative-permeable) model structures examined. The water levels for each test case are denoted in units of millimetres relative to the wave flume bottom.

Test Case	Initial Profile	Wave Climate	Structure	Water Levels (mm)	Run Time (hrs)	Profiling Frequency
E1	Planar 1 V:10H	Erosive: $H_s = 0.15$ m $T_p = 1.25$ s	None	1000	7.67	20min
				1015	4.67	
				1030	3	
				1045	3	
				1060	3	
				1075	12.67	
E2				1000	6	20min
				1075	29.83	
EV3			Vertical Revetment	1000	30	20min for first hour, hourly thereafter
				1015	8	
				1030	8	
				1045	8	
				1060	8	
				1075	20	
ER4			Rubble Mound Seawall	1000	30	20min for first hour, hourly thereafter
				1015	8	
				1030	8	
				1045	8	
				1060	8	
				1075	20	
AV1		Accretive: $H_s = 0.1$ m $T_p = 2.5$ s	Vertical Revetment	1000	30	20min for first hour, hourly thereafter
				1015	8	
				1030	8	
				1045	8	
				1060	8	
				1075	20	

For each experiment, prior to any implementation of SLR the experiment-specific wave conditions were run until profiles reached equilibrium (Section 2.2.4). The aim of test cases E1 and E2 was to produce baseline results against which to compare subsequent profiles with seawalls. These test cases further served the practical purpose of establishing whether a single step increase in water level could be adopted instead of several smaller incremental increases so as to accelerate the experimental program. Test cases EV3, ER4 and AV1 then investigated the impact of seawalls on profile response to raised water levels. While it is unlikely in practice that a seawall would be required in an accretive environment, the accretive test here, AV1, was performed as a point of comparison to the erosive tests and to inform future studies on the effects of SLR on sandy coastlines in variable wave climates. Note that, for consistency and to assist the interpretation of results presented, the test case naming convention used here is that ‘E’ refers to erosive and ‘A’ to accretionary wave conditions, ‘V’ and ‘R’ refer to the vertical (reflective-impermeable) and rubble mound (dissipative-permeable) model structures examined, and specific water levels are denoted ‘WL’ followed by the water level in units of millimetres relative to the wave flume bottom (e.g., WL1000 corresponds to a water level of 1.0 m).

2.2.2. *Waves and water levels*

Irregular waves (JONSWAP spectrum) with significant wave height $H_s = 0.15$ m and peak wave period $T_p = 1.25$ s were used to simulate erosive conditions, and $H_s = 0.1$ m, $T_p = 2.5$ s for accretive conditions. The initial water level relative to the flume bed was 1.0 m for all experiments. A maximum water level increase of 0.075 m (i.e., 50% of maximum H_s) was applied incrementally in steps of 0.015 m for all test cases, apart from E2 in which a single step of 0.075 m was used. This relative magnitude of water level change in the wave flume was chosen to approximately represent the higher end of current global SLR projections for the year 2100 (~0.75 m) (IPCC, 2014) relative to ‘typical’ global wave heights along energetic coastlines (~1.5 m).

2.2.3. *Model structures*

A reflective vertical revetment (with a reflection coefficient, C_r, of 0.35) was constructed using 18 mm thick form plywood. This was driven to a depth of 0.7 m into the sand profile to exclude the possibility of undercutting by scour, and the crest was sufficiently high to prevent overtopping. The dissipative rubble mound seawall ($C_r = 0.25$) had a slope of 1 V:1.5H and was composed of a 2-units thick primary armour surface layer and 2-units thick underlayer, founded on a geofabric base. The primary armour units were angular rock of mean mass $M_{50} = 0.75$ kg and the underlayer units were angular rock with a mass approximately 10% that of the primary armour. For comparison to the model structures, the natural profile, prior to the construction of a structure, had a C_r of 0.28. It should be noted that the tested structures extended across the length of the flume, and as such, the impact of end-effects was not considered. Further, it is acknowledged that in practice coastal protection structures could be modified and adapted to changing water levels, however this was not considered in the presented experiments.

2.2.4. *Assessment of profile equilibrium*

Previous studies (e.g., (Grasso et al., 2009; Larson, 1988; Moore, 1982; Rector, 1954; Wang and Kraus, 2005).,) have demonstrated that complete, stable equilibrium cannot be achieved for sandy beaches in the laboratory, but that approximate equilibrium can be well defined when the rate of morphological change is small. The attainment of equilibrium conditions in the present laboratory experiments was assessed based on the evolution of five morphological indicators: shoreline position, bar position, bar elevation, absolute sediment flux and net sediment flux; all of which have been used to define equilibrium in previous laboratory studies (Larson, 1988; Moore, 1982). To clarify these, the absolute sediment flux Q_a (m^3/m/min) is defined here as the absolute sum of sediment transport across the profile for a given duration of wave forcing (here the time interval between profile surveys) and is an indicator of the amount of sediment being redistributed across the profile, which is expected to reduce as a profile approaches equilibrium. The local sediment transport $q(x)$ (m^3/m/min) at location x on the profile was calculated by:

$$q(x) = \left(\frac{1}{\Delta t}\right)\left[(1-p)\int_{x_0}^{x} \partial z \, \partial x\right] \tag{2}$$

where Δt is the time between individual profile measurements, p is the sediment porosity (assumed to be 0.4 for sand), x_o is the landward location of no profile change (i.e., $q(x_o) = 0$), δx is the cross-shore increment (m) and δz is the observed change in bed elevation (m). The absolute sediment flux was then simply determined by:

$$Q_a = \int_{-\infty}^{\infty} \left| q(x) \right| \tag{3}$$

Similarly, net sediment flux Q_n (m^3/m/min) is the sum of sediment flux (with sign considered) across the profile and indicates whether the net movement of sediment is offshore (positive) or onshore (negative):

$$Q_n = \int_{-\infty}^{\infty} q(x) \tag{4}$$

In this study, ‘equilibrium’ was defined as when the rate of change of a minimum 4 of these 5 measured morphological indicators was observed to be less than 5% of their initial rate of change during the first 20 min of wave action. In practice, it was observed that this typically occurred between 4 and 8 h of wave action in the flume, depending on the specific indicator being considered. To establish the initial WL1000 and final WL1075 equilibrium profiles, longer run times were adopted so as to add further confidence to the results (Table 1).

2.2.5. *Scale effects*

Scale effects are expected in reduced scale physical models (Vellinga, 1982). Importantly, the fundamental principles of geometric similarity and conservation of sediment that are used in models such as the Bruun Rule and are the core focus of this study, remain true at laboratory scales and are not compromised by their application in a wave flume. The aim of the experiments presented here is to apply these geometric and conservation concepts to examine the generalised morphological behaviour of natural beaches to changing wave and water level conditions, rather than replicate a specific site or environmental conditions. To achieve this similarity, the presented experiments were designed so that they satisfied the recommendations of Hughes (1993) with regards to hydrodynamic Froude scaling, preservation of relative density and similarity of the relative fall velocity inclusive of a profile slope term $H \tan\beta/\omega T$ (Hattori and Kawamata, 1980; Dean, 1973; Gourlay, 1968), where the term β represents the profile gradient. Applying these scaling criterion and assuming ‘typical’ global mean significant wave heights along energetic coastlines of the order of ~1.5 m, then the vertical scale of the present experiments could be considered to be ~1:10 ($H_{s,\ model} = 0.15$ m, $H_{s,\ prototype} = 1.5$ m). By this scaling approach, and the initial beach gradient of 1:10 used here (Section 2.2.6), the fall velocity scale is ~1:3. Fixing the model sediment size, this scaling could be considered to correspond to a prototype beach with a gradient of ~1:30, which at natural beaches is indicative of an intermediate beach state (Wright et al., 1985) where the emergence of longshore bars during erosive conditions and significant berm accretion during accretive conditions would be anticipated. Both of these responses were observed in the experiments. Several recent studies (Baldock et al., 2011, 2017, 2010; Van Rijn et al., 2011) have similarly shown that physical models undertaken in wave flume facilities of a similar scale to those used in the present study are capable of reproducing beach profile evolution and sediment transport patterns that are comparable to reported scale physical model data obtained in very large laboratory facilities and field data under a variety of wave forcing conditions.

2.2.6. *Test procedure*

Each test case commenced with a 1 V:10H planar profile and a water level of WL1000, then followed the iterative procedure summarised in Fig. 2, applying the test-specific wave and rising water level scenarios summarised in Table 1. While starting planar profiles may be considered unnatural, they are preferred for their simplicity. In addition, extensive laboratory investigations, of similar scale and grain size to the experiments presented here, conducted by Baldock et al. (2017) show that the starting beach profile shape (planar or concave) does not significantly affect the equilibrium profile developed for given forcing conditions; thus supporting the use of simple planar profiles as an initial starting condition for the experiments presented here. Profile evolution and equilibrium were quantified in each test case by intermittently stopping wave action and measuring the full profile. Measurement intervals ranged

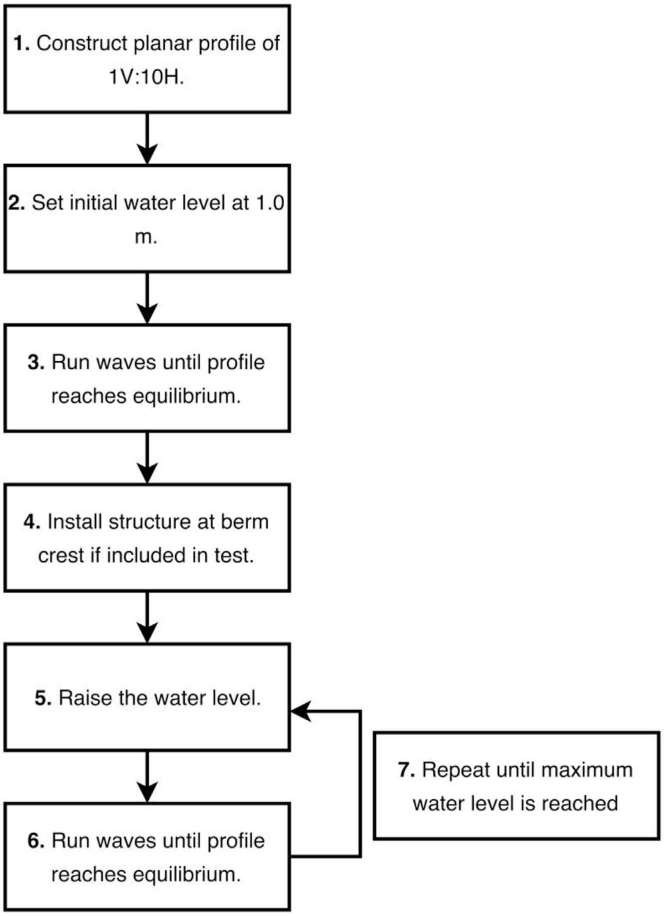


Fig. 2. Flowchart outlining the experimental procedure followed for each test conducted in the wave flume.

between 20 min up to 1 h and are summarised in Table 1. Note that for the test cases where armouring was present ('V' – vertical revetment and 'R' rubble mound seawall) the structure was installed at the berm crest after the equilibrium profile at a water level of WL1000 had developed. This approach was adopted to ensure that the presence of the seawall didn't influence the initial equilibrium profile shape developed at WL1000.

3. Results

3.1. Equilibrium profile reproducibility in the laboratory

Independent test cases in the wave flume were observed to produce near identical equilibrium profiles when started from a planar 1 V:10H slope and forced with the same wave conditions. Fig. 3 presents the profile from each erosive wave climate experiment (E1, E2, EV3, ER4) at WL1000 after 360 min of irregular, erosive wave forcing. It is evident that the four profiles developed the same morphology (Fig. 3a), resulting from the same pattern of cross-shore sediment redistribution (Fig. 3b). Fig. 3c shows that the differences between the profiles developed in the independent tests were always smaller than 0.02 m across the active profile. The larger differences outside of the active profile were due to differences in the initially constructed profiles. This confirmed that for a given wave climate, the same profile was consistently produced in the flume, and hence the potential impact of the presence of different seawall configurations could be investigated.

3.2. Time-scales to achieve profile equilibrium

An equilibrium profile is the average state of the profile for a given set of hydrodynamic and morphological parameters and characterises the total response of a beach to a given forcing. Attaining near-equilibrium profiles for all test cases was necessary, to be able to characterise and quantify their differing profile response to water level increases. Fig. 4 shows the time variation of the WL1000 profiles for each erosive test case (E1, E2, EV3, ER4). In general, all five equilibrium indicators demonstrate initially rapid change, but the rate of change decays and approaches an asymptotic value, as has been observed by previous investigators (Larson, 1988; Larson and Kraus, 1989). As was detailed in Section 2.2.4, equilibrium was defined as the point where the rate of change of an indicator dropped below 5% of the initial rate of change observed during the first 20 min of wave action. Fig. 4c and d show that rates of sediment flux stabilised first (<4 h), and are likely to be misleading for identifying equilibrium when used alone. Fig. 4b and e show that shoreline position and bar position took longer to approach equilibrium (~8 h). Fig. 4f suggests that bar elevation did not become fully stable over any test duration conducted, indicating that evolution of this particular morphological feature was still occurring. This observation is consistent with previous studies that have identified cyclic behaviour in bar morphology on an otherwise equilibrium profile (e.g., (Aarninkhof et al., 1998; Ruessink et al., 2007).,). Further, it was noted that the approach to equilibrium in the test cases examined here was non-uniform, confirming previous findings that, even in the laboratory, the concept of 'equilibrium' is a dynamic process (e.g., (Grasso et al., 2009; Larson, 1988; Rector, 1954; Wang and Kraus, 2005).,). While not presented in Fig. 4, for the test case with accretive waves (AV1), the approach to equilibrium was of comparable behaviour and timescales to the erosive tests and is consistent with results reported in laboratory experiments of similar size to the present study (Sanchez-Arcilla and Caceres, 2017).

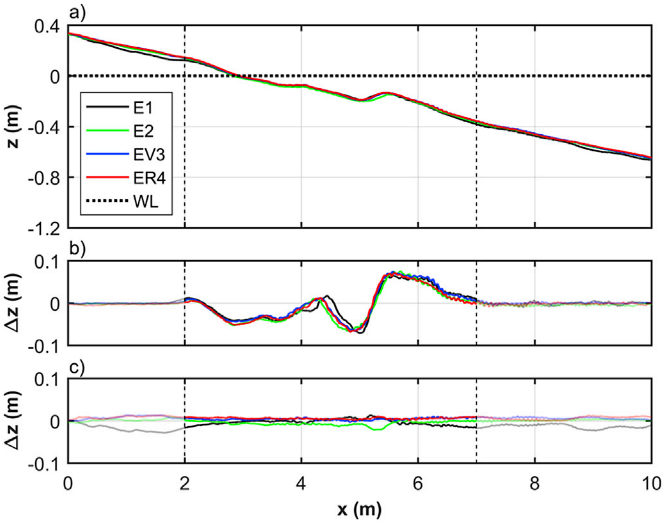


Fig. 3. Plot of the four erosive wave climate tests (E1, E2, EV3 and ER4). a) the full profiles after 360 min of wave action at the initial water level of 1000 mm (WL1000), b) difference between each profile developed after 360 min and its initial planar profile; c) difference of each profile from the mean of all profiles at 360 min. The dashed vertical lines indicate the observed limits of the active profile. Note that each panel presents near identical results, meaning that for a given wave climate, the same profile could be consistently achieved in the flume.

3.3. Profile adjustment to step versus incremental SLR

Large-scale laboratory experiments designed to investigate mobile bed profile adjustment are necessarily time-consuming, and as facilities and resources are often limited, accelerating the process is desirable. The possibility of accelerating the experimental program by applying a water level increase in a single step was investigated, in place of several smaller increments. Experiments E1 and E2 were conducted to compare the morphological response to applying water level increases incrementally in five small 0.015 m steps compared to a single 0.075 m step, respectively. The equilibrium profiles developed at WL1000 and WL1075 of these two otherwise identical experiments are presented in Fig. 5. It can be seen that the WL1075 profiles of both experiments are similar, with a maximum vertical difference between the two profiles of 0.02 m. The comparison provides evidence that both profiles were progressing towards the same equilibrium state and thus it is concluded that the method of implementing a water level increase does not affect the resulting profile, consistent with the concept of an equilibrium beach profile. However, further analysis (not shown here) revealed that while the equilibrium profiles resulting from an incremental versus step sea level rise implementation were the same, the evolution towards equilibrium was different. It is additionally noted that both experiments ran for a similar time (E1 = 2040 min, E2 = 2150 min) meaning that no significant acceleration of the experimental procedure was achieved. As applying a water level increase in a single step precluded the option of monitoring intermediate changes in the profile shape forced by incremental water level changes, and provided no net benefit with regards to accelerated equilibrium, incremental water level rise was used for all test cases with structures (EV3, ER4, AV1).

3.4. Equilibrium profile evolution in response to water level rise

The evolving equilibrium profiles at each water level for test case E1 (no structure, erosive waves) are presented in Fig. 6. A clear upward and landward translation of the bar and trough features is evident. The magnitude of this upward and landward translation observed at each water level increment is similar. As this was the first test case to be run, in hindsight it is now recognised that case E1 was not run for a sufficiently long duration at WL1000, with the result that the inshore bar and trough were not fully developed, and the outer bar was more pronounced, when compared to the WL1000 profile of the subsequent test case EV3 shown in Fig. 7 (identical wave conditions, longer duration). These

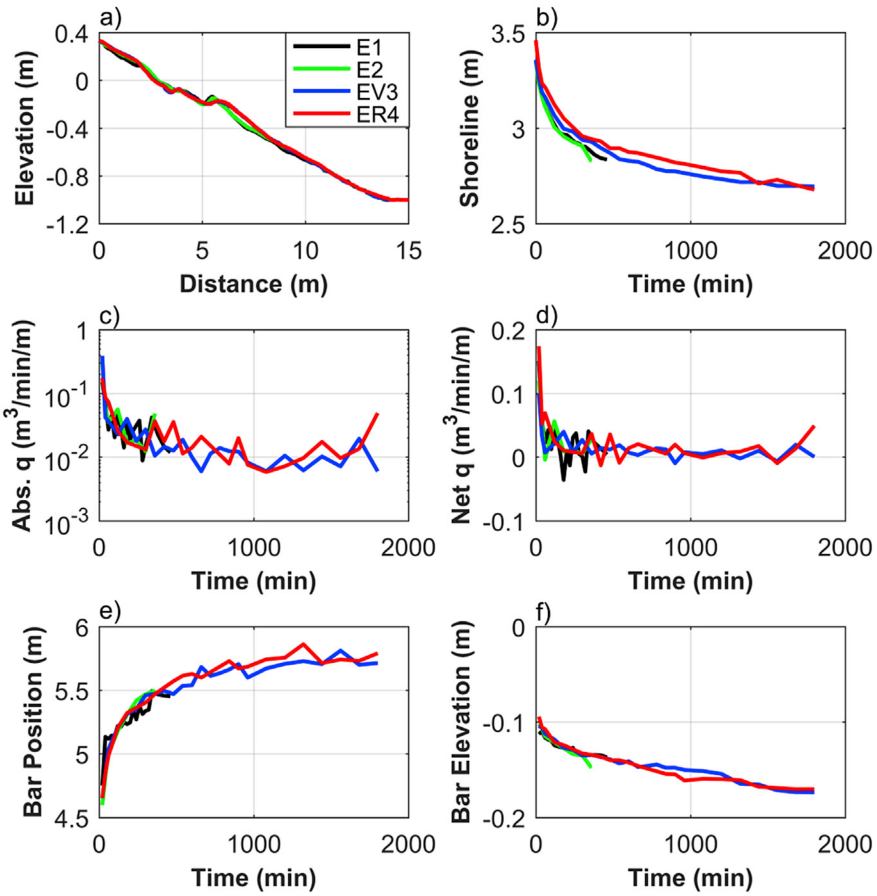


Fig. 4. Morphological features of E1 (460 min), E2 (360 min), EV3 (1800 min), and ER4 (1800 min). a) profiles, b) cross-shore shoreline position, c) absolute sum of cross-shore sediment flux, d) net sum of cross-shore sediment flux (+is offshore flux, - is onshore flux), e) cross-shore bar position, f) corresponding bar elevation. Note that features approach asymptotic states over time, reflecting a progression towards equilibrium.

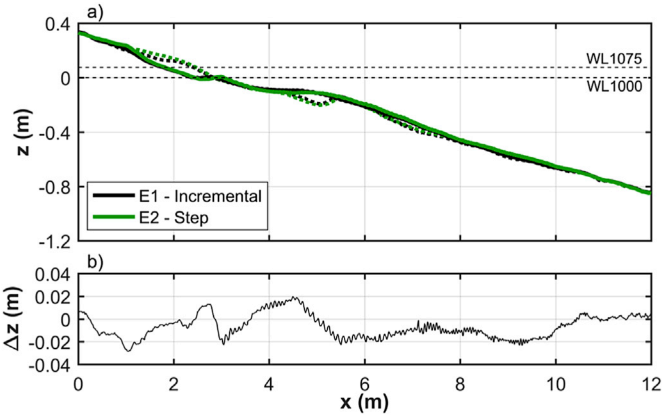


Fig. 5. Comparison of test E1 (incremental water level rise, wave action = 2040 min) and E2 (single step water level rise, wave action = 2150 min). a) profiles; thin dashed lines are the initial profiles developed at WL1000, thick lines are the final profiles at WL1075, b) difference between the final WL1075 profiles of each test.

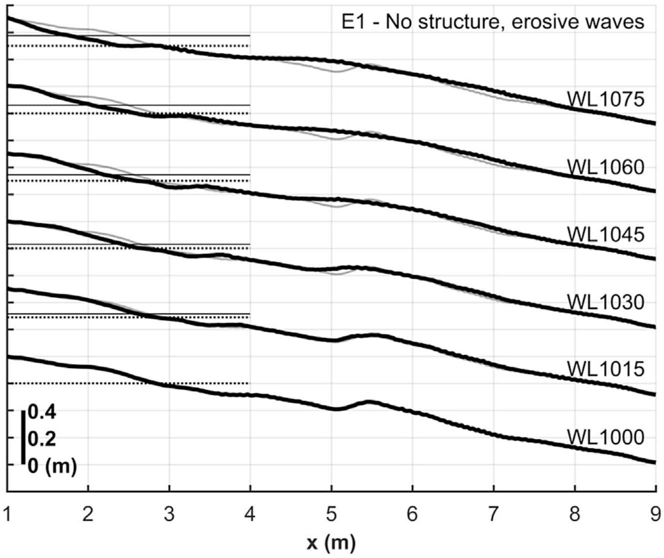


Fig. 6. Evolution of test E1 (no structure, erosive waves). Profiles at each water level are stacked to allow visualisation. The thick black line is the profile developed at the labelled water level, the thin grey line is the initial profile at WL1000 (acting as a datum for observing profile changes), the horizontal solid and dotted lines are the location of the labelled water level and WL1000 for each profile respectively. Landward and upward translation of the profile is apparent at all water levels.

morphological features across the profile became better defined as wave action continued and the water level increased; but the results of subsequent test cases indicate that this specific observation should not be interpreted as the result of the applied water level increase. Instead, the more general conclusion from this first test case E1 is that, as the water level rose incrementally, the profile retained an equilibrium shape (in this specific case fully evolved by WL1045) that translated upward and landward in response to the imposed water level increase.

The EV3 (vertical wall, erosive waves) equilibrium profiles corresponding to each step change in water level during the first test case with a structure present are presented in Fig. 7. Upward and landward

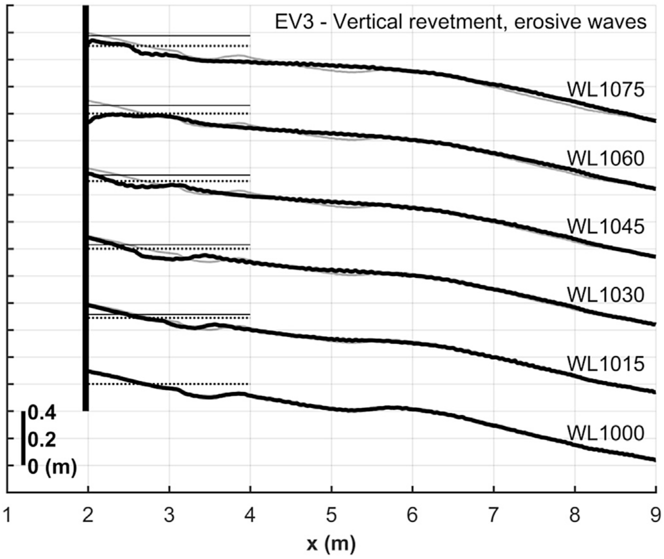


Fig. 7. Evolution of test EV3 (vertical wall, erosive waves) profiles. Profiles at each water level are stacked to allow visualisation. The thick black line is the profile developed at the labelled water level, the thin grey line is the initial profile at WL1000 (acting as a datum for observing profile changes), the horizontal solid and dotted lines are the location of the labelled water level and WL1000 for each profile respectively. Note that landward translation is evident in the progressions, but the profile shape changes as the water level increases.

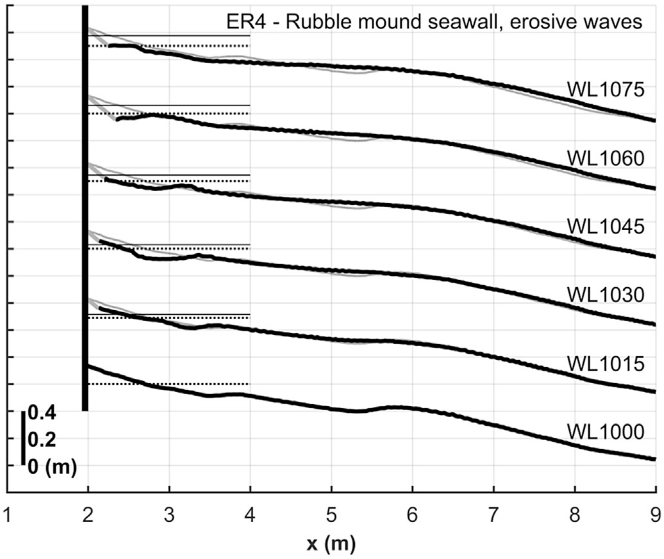


Fig. 8. Evolution of test ER4 (rubble mound, erosive waves) profiles. Profiles at each water level are stacked to allow visualisation. The thick black line is the profile developed at the labelled water level, the thin grey line is the initial profile at WL1000 (acting as a datum for observing profile changes), the horizontal solid and dotted lines are the location of the labelled water level and WL1000 for each profile respectively. Segments of thick grey line adjacent to x = 2 m indicate an exposed rubble mound seawall. Note that landward translation is evident in the progressions, but the profile shape changes as the water level increases.

translation of the profile is again evident throughout the experiment, but is more challenging to characterise because the initial equilibrium profile shape at WL1000 is not retained during the applied water level increases, due to the influence of the structure. The degree to which the profile deviates from the initial equilibrium profile at WL1000 is proportional to the level of wave-structure interaction. At low water levels, wave runup rarely reached the structure and the profile translated upward and landward in response to water level increases as if no structure were present (WL1000 and WL1015 in Fig. 7). At WL1030 and WL1045, wave run-up was observed to frequently impact the vertical revetment, noticeably influencing swash flows and causing the inshore trough to grow and the offshore bar-trough system to flatten out. Continued water level increases resulted in further wave-structure interaction and changes to the profile morphology. Notable profile lowering was observed at the toe of the structure at WL1060 due to the inshore trough translating to the toe of the structure, however this was ameliorated at WL1075 as the inshore bar translated landward and infilled the prior scour hole. The final equilibrium profile observed at WL1075 was significantly different to the initial equilibrium profile at WL1000, confirming that the presence of a structure had changed the equilibrium profile shape.

Fig. 8 reveals that the evolutionary behaviour observed in test ER4 was virtually identical to that described above for experiment EV3, despite the contrasting structure types of a reflective vertical revetment versus a dissipative rubble mound seawall. Wave breaking and splashing on the dissipative rubble mound was observed to be much less than the vertical wall. Despite this, these new experimental results suggest that the dominant influence of rising water levels on the equilibrium profile in the presence of shoreline armouring is the presence/absence of a structure, rather than differing structure-wave-sediment interaction. Given that the model structures in experiments EV3 and ER4 had different reflection characteristics ($C_r = 0.35$ and $C_r = 0.25$ for the vertical revetment and rubble mound seawall respectively) but evolved the same profiles when subjected to the same water level increase, it is concluded that deviations from the initial equilibrium profiles at WL1000 were primarily due to the truncation of the available sediment budget.

It is evident from the results presented above that, in erosive conditions, profiles tend to translate upward and landward in response to an increase in water level, however the presence of a structure affects this process. For comparison, the results of the AV1 test case (vertical wall, accretive waves) are presented in Fig. 9. The accretive profile was observed to undergo minor upward and landward translation due to increased water levels, and the initial equilibrium profile developed at

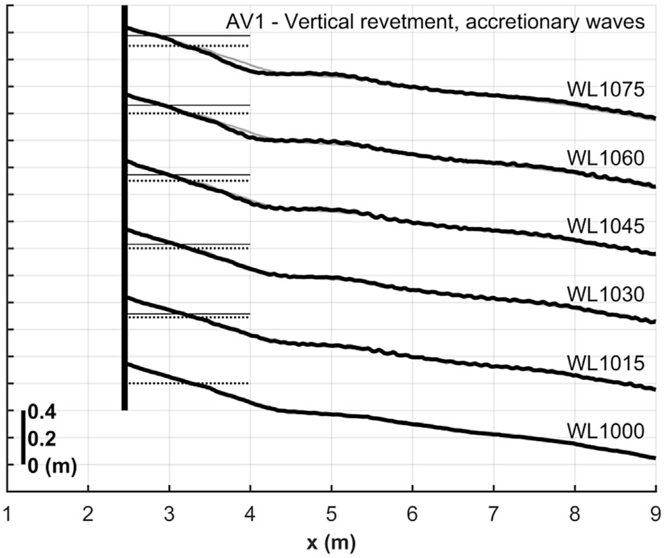


Fig. 9. Evolution of test AV1 (vertical wall, accretive waves) profiles. Profiles at each water level are stacked to allow visualisation. The thick black line is the profile developed at the labelled water level, the thin grey line is the initial profile at WL1000 (acting as a datum for observing profile changes), the horizontal solid and dotted lines are the location of the labelled water level and WL1000 for each profile respectively. Minimal profile change occurs due to the applied water level increases, however it should be noted that the preservation of a large shoreface and berm meant that no wave-structure interaction occurred at any water level.

WL1000 was retained throughout; with the exception of the highest water levels (WL1060 and WL1075), where some erosion of the lower shoreface was observed. During this experiment, the preservation of a large shoreface and berm meant that no wave-structure interaction occurred, with the result that the structure had no impact on profile evolution. These results suggest that under accretive wave conditions, the profile subjected to rising water levels may be anticipated to undergo reduced recession and less morphological change when compared to a profile subjected to erosive wave conditions.

4. Discussion

4.1. Impact of seawalls on profile response to sea level rise

At present, coastal engineers and scientists have inadequate understanding of SLR-induced coastal evolution, and minimal guidance of how this may differ in the presence of seawalls. A primary observation from this study is that beach profiles on which seawalls are present respond differently to increased water levels than profiles without seawalls. Further to this, for the range of test conditions presented here, these results suggest that it is the presence of a seawall, rather than any seawall-wave interaction, that is the dominant control. These key findings are summarised in Fig. 10, which illustrates the general conclusion that seawalls caused a lowering of the profile adjacent to the model structures when compared to the natural profile equivalent (Fig. 10a), but that the differences between the two equilibrium profiles with different structure types (EV3: reflective, ER4: dissipative) was minimal (Fig. 10b).

4.2. Predicting profile response to SLR in the presence of seawalls

As outlined in the Introduction, the Bruun Rule (Eq. (1)) is currently the most commonly used method to predict profile response to SLR. The Bruun Rule assumes that a constant equilibrium profile will translate upward and landward in response to an increase in water level and characterises the response in terms of the recession of the shoreline. While this behaviour predicted by the Bruun Rule is evident in the natural beach test cases (E1 and E2) presented here, for the test cases with structures (EV3 and ER4) the presence of a structure directly limits recession of the shoreline and has also now been confirmed to change the equilibrium profile shape with rising water levels (Fig. 10). Thus, to be able to compare observations and predictions of equilibrium profiles with and without structures subject to water level increases, it was found to be more informative to characterise profile response in terms of volumetric changes of the upper shoreface, rather than horizontal recession of the shoreline. For the test cases presented, the net change in upper shoreface volume for a given increase in water level is defined as the observed net change in volume landward of the offshore bar, calculated from the equilibrium profiles developed pre- and post-water level rise. Because predictions of volume change are not explicitly defined by the Bruun Rule, here we adopt a geometric profile translation approach referred to here as a Profile Translation Model or 'PTM' [Atkinson et al. (*this issue*)]. Briefly, the predicted net change in volume caused by a given increase in water level is calculated by translating the equilibrium profile upward and then landward at the elevation of the new water level, until geometric conservation of volume is achieved. In the case where a structure is present, the PTM only considers conservation of sediment seaward of the structure. The predicted volume change of the upper shoreface for a given rise in water level can then be compared to the equivalent observed volume change, calculated from the measured equilibrium profiles developed pre- and post-water level rise.

As an initial test, the PTM was applied to the natural beach test cases (E1 and E2) and compared to observations. Fig. 11 shows a comparison of the erosion of the upper shoreface as predicted by the PTM, and the measured erosion volumes at each increment in water level. Referring to this figure, the PTM can be seen to predict the trend of increasing erosion of the upper shoreface with increasing water levels for natural profiles, though it is noted that the predicted erosion tends to underestimate the measured erosion and so indicates a lower bound of the observed erosion across the upper profile.

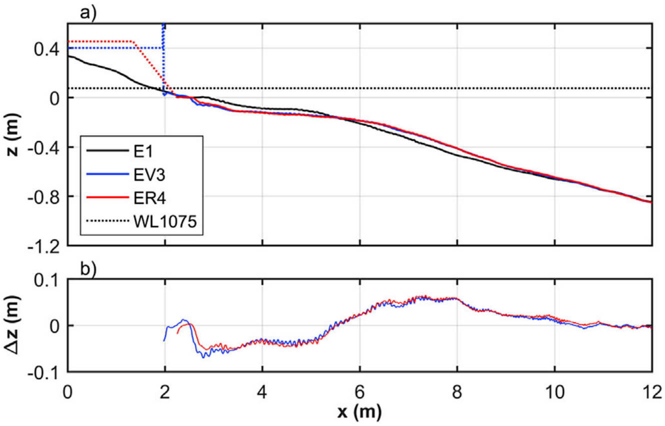


Fig. 10. Comparison of tests E1 (no seawall), EV3 (reflective vertical revetment), and ER4 (dissipative rubble mound seawall) at WL1075 after an applied incremental water level increase of 0.075 m a) cross-shore profiles, showing that the presence of a seawall lowers the profile adjacent to the seawall, b) profile difference between E1, EV3 and ER4, showing that, despite different structure types, the profiles with seawalls that developed after the applied water level increases are essentially identical.

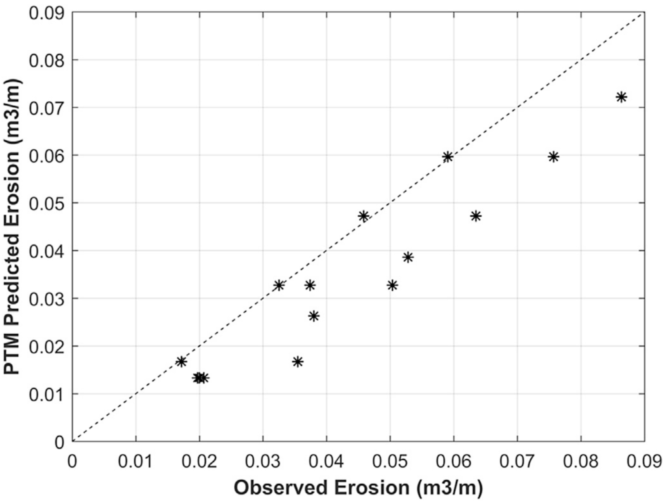


Fig. 11. Comparison of erosion volumes of the upper shoreface as predicted by a profile translation model that models water level change induced translation by balancing erosion and accretion volumes across the active profile (y-axis) and that observed in experiments (x-axis) for the natural profile results obtained from tests E1 and E2. The profile translation model predictions appear to represent a lower bound for the observed erosion volumes of the upper profile.

A comparison of the PTM-translated and observed profiles at each water level for the test cases with structures, EV3 (vertical wall) and ER4 (rubble-mound revetment), are presented in Fig. 12. It was found that the range of horizontal profile translations required to balance erosion and accretion volumes in the PTM were in the range 0.15–0.22 m. However, while Fig. 12 suggests that the position and elevation of the inner bar in the observed and PTM-translated profiles match reasonably well up to WL1045, the profiles diverge to an increasing degree from the initial WL1000 profile, with each incremental rise in water level. This divergence is attributed to profile self-similarity not being conserved during the applied change in water level; the PTM assumes an equilibrium profile is retained during water level rises, however the new laboratory

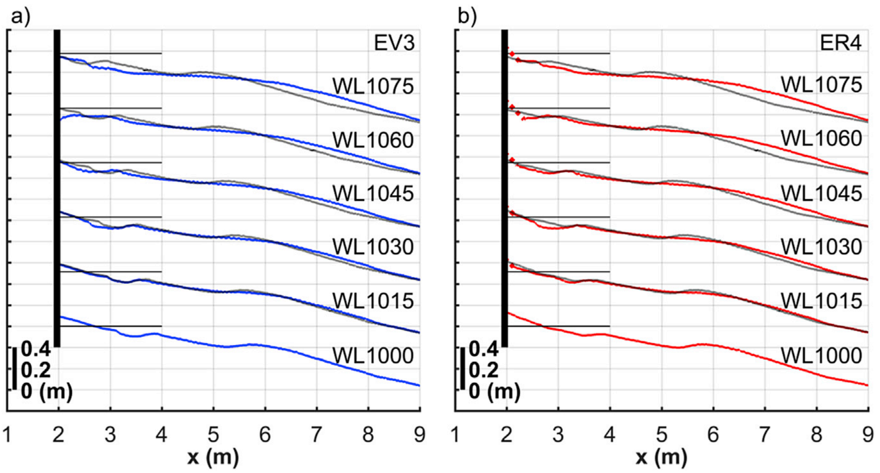


Fig. 12. Comparison of the observed profiles with a seawall (thick solid line), and the profile predicted to develop using a translation model that models water level change induced translation by balancing erosion and accretion volumes across the active profile (thin solid line) for tests EV3 (a) and ER4 (b). The observed and modelled profiles diverge increasingly as the water level rises and the initial equilibrium profile shape changes.

observations presented here show that the presence of a structure increasingly changes the equilibrium profile with rising water levels.

From the results and discussion presented, it is evident that the evolutionary dynamics of beaches with and without seawalls are different, and that a new method for predicting coastal response to SLR in the presence of seawalls is required. As future beach management strategies to combat rising ocean water levels will likely involve building seawalls along at-risk coastlines, it is of interest to investigate whether the results of the laboratory experiments reported here can be used to interpret whether a similar volume of sand can be anticipated to be eroded from the beach face, irrespective of whether a seawall is built or not. This comparison is presented in Fig. 13a, and suggests that for the test cases examined there is a clear linear relationship between the erosion volumes observed on profiles with and without shore protection structures present, although the erosion volume of the upper shoreface for profiles with seawalls is typically equal to or slightly less than that observed on a natural (i.e., no seawall) profile. The observed relationship suggests that for a given wave and water level condition, the erosion demand on the upper beach remains similar whether a structure is present or not. Combining this result with the observation that a simple PTM can be used as a lower-bound estimate of the erosion volume for a given water level increase on a natural profile (Fig. 11), it is conceptually possible to estimate the erosion volume in front of a seawall by applying the PTM to the original, natural profile before a structure was introduced. Fig. 13b illustrates this concept by comparing the observed erosion volume in front of the seawalls, with the volume predicted to occur by translating the initial equilibrium profile using the PTM. While the dependency between these two volumetric quantities obtained from the laboratory test cases reported here is weaker than that evident in Fig. 13a, the existence of a generally linear relationship is indicated. Notably, at higher water level increases (resulting in the larger erosion volumes on Fig. 13b), the observed erosion volume is consistently greater than the erosion volume predicted to occur using the PTM. This is a result of the structure changing the equilibrium profile shape and increasing lowering and erosion of the upper shoreface adjacent to the seawall (Fig. 10).

Fig. 13 suggests that for the test conditions presented the presence of a seawall does not significantly change the volume of erosion occurring on the upper profile due to SLR. For the natural profiles this erosion demand was observed to be distributed across the shoreface and berm. However for profiles with a seawall, where the available active profile was effectively truncated, the berm could not erode and it was observed that these profiles experienced enhanced profile lowering adjacent to the structure (Fig. 11). Consequently, it is proposed that a seawall will not mitigate the erosion demand induced by the rise in water level, but that the erosion is confined to the region in front of the structure, resulting in profile lowering extending seaward to approximately the position of the outer bar for the natural profile (Fig. 10). From the limited results that are available from this physical model study, this observed behaviour is likely to be a result of the seawall limiting the upper beach sediment available to facilitate the erosion demand placed on the profile due to the increase in water level, with the result that the required deficit is made up for by additional erosion of the profile adjacent to the seawall. A schematic of this concept is shown in Fig. 14.

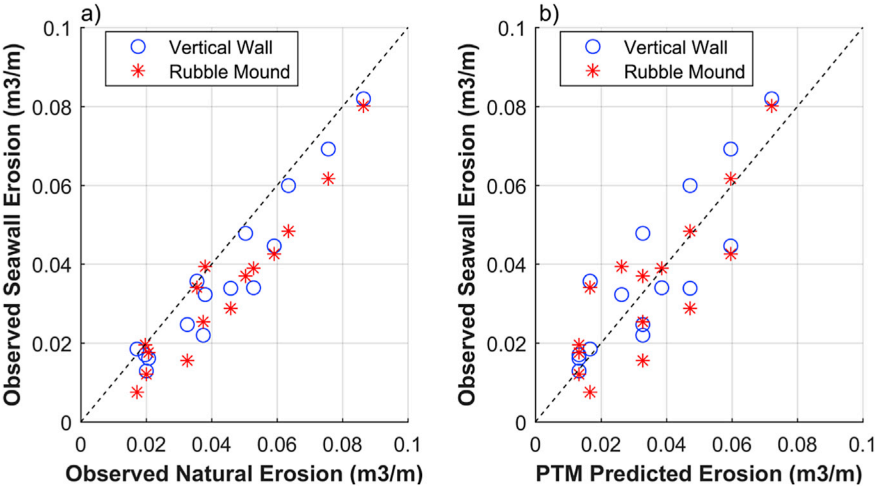
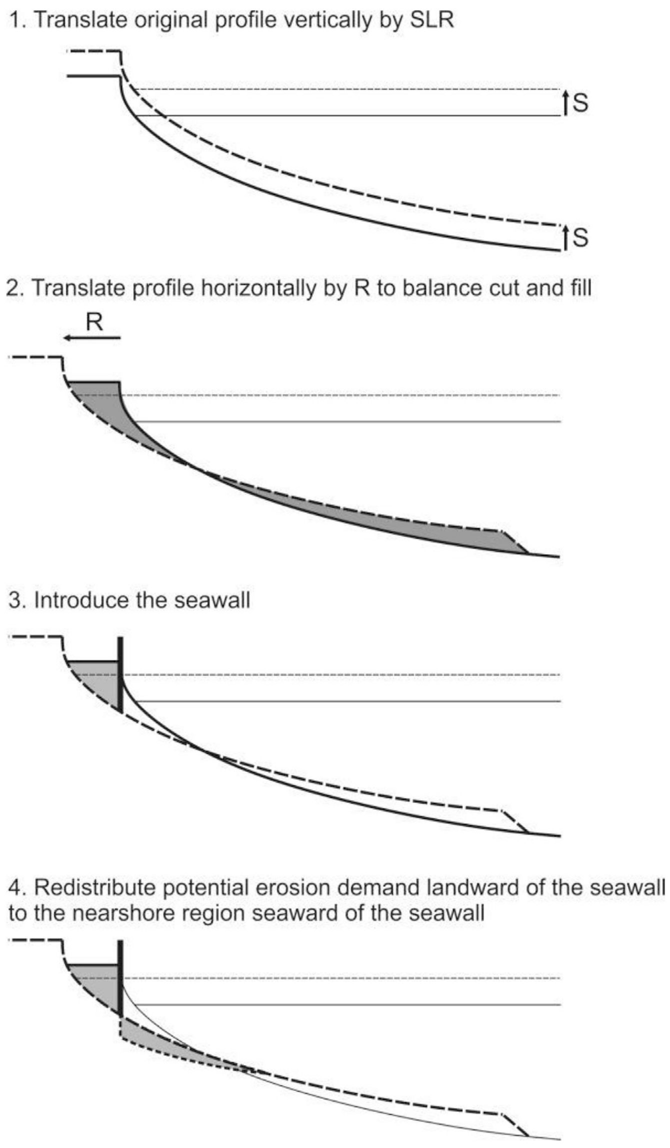


Fig. 13. a) Comparison of the erosion volume observed to occur in front of a seawall (EV3 and ER4) and the erosion volume observed to occur on the equivalent profile without a seawall (E1) due to water level increases. The correlation suggests that the presence of a seawall does not affect the erosion demand placed on a profile due to a water level increase. b) Comparison of the erosion volume observed to occur in front of a seawall (EV3 and ER4) due to water level increases and the erosion volume predicted to occur on an equivalent profile (E1) without a seawall using a profile translation model. The linear relationship suggests that despite the presence of a seawall, the volume of erosion occurring due to a water level increase is not affected, and that the profile translation model gives an approximate indication of this volume.



1. Translate original profile vertically by SLR

2. Translate profile horizontally by R to balance cut and fill

3. Introduce the seawall

4. Redistribute potential erosion demand landward of the seawall to the nearshore region seaward of the seawall

Fig. 14. Conceptual schematic of a proposed method for predicting profile change following installation of a protective structure. A profile translation model is used to estimate the future erosion demand due to SLR, the structure is then installed, and the erosion demand is redistributed seaward of the structure out to the position of the offshore bar.

5. Conclusion

Despite accelerating and persistent SLR throughout the 20th and now 21st centuries, coastal response to rising ocean water levels is still not well understood, and knowledge is limited of how the presence of seawalls may further impact this response. A primary observation from this physical model study is that, when subject to an increase in the water level in the wave flume, the presence of seawalls resulted in increased erosion and lowering of the profile adjacent to the structure, when compared to equivalent profiles without seawalls. When subject to an increase in water level in the presence of erosive wave conditions, for both non-structure and structure tests cases undertaken, the modelled profiles were observed to translate landward and erode the upper profile. The presence of a seawall did not reduce this erosion demand, but concentrated it in the area adjacent to the seawall, resulting in enhanced profile lowering. This response was observed to be independent of the two quite different structure types that were tested (dissipative-permeable versus reflective-impermeable). For the accretive conditions examined, the preservation of a large shoreface and berm resulted in no wave-structure interaction occurring, with the result that the presence of the structure had no impact on profile evolution. These results from the laboratory suggest a potential methodology for estimating the response to SLR along a coastline where shoreline armouring is present or planned. First, a profile translation model is used to provide a first estimate of the erosion demand due to SLR; and then as a second step in the presence of a structure at the shoreline, this eroded volume is redistributed in front of the seawall out to the position of the offshore bar. For the laboratory observations presented here, this two-step methodology represents a reasonable approach to predict the observed differences in profile response in the presence/absence of structures.

To our knowledge, this study is the first published laboratory experiment to investigate beach response to raised water levels in the presence of seawalls. It would be valuable (though time-consuming) to now extend this work by the completion of additional test cases, with the objective that observations obtained will inform coastal planners, modellers, and engineers to better consider and plan for the likely impact of seawalls along coastlines subject to SLR.

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