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# Hydrodynamics and Morphology on Composite Beaches

Chris Blenkinsopp<sup>1</sup>(✉), Alex Minnigin<sup>1</sup>, Ollie Foss<sup>2</sup>, and Paul Bayle<sup>3</sup>

<sup>1</sup> Department of Architecture and Civil Engineering, University of Bath, Bath, UK  
c.blenkinsopp@bath.ac.uk

<sup>2</sup> School of Engineering, University of Aberdeen, Aberdeen, UK

<sup>3</sup> Department of Hydraulic Engineering, TU Delft, Delft, The Netherlands

**Abstract.** Composite beaches, characterised by a dissipative sand beach backed by a steep cobble berm, exhibit unique hydro and morphodynamic behaviors due to their bimodal sediment size distribution. This study analyzes morphological variability and wave runup on a composite beach in Borth, Wales, using continuous Lidar data collected from July 2021 to October 2024. Results indicate that the lower berm face is dynamic due to regular swash inundation, while the primary berm crest remains stable with minimal changes. Secondary berms located seaward of the primary berm can be formed and removed within a single tide. This is in contrast to sand beaches where they tend to translate landward, controlled by the neap-spring tidal cycle. Existing wave runup equations provide reasonable estimates of total water level, but perform worse than previously observed at other composite beach locations due to a higher dependence of wave runup on offshore wave height.

**Keywords:** Composite beach · Wave runup · Swash · Gravel beach · Gravel berm

## 1 Introduction

Composite beaches were defined by Jennings & Schulmeister [1] as consisting of a typically dissipative sand beach backed by a steep cobble berm and are common in many countries (e.g., UK, USA, Ireland, NZ). These beaches differ from mixed sand and gravel beaches primarily due to the bimodal nature of the sediment size distribution and a much higher proportion of sand relative to coarse material. Cross-shore sorting by waves leads to a generally dissipative lower foreshore of sand ( $\tan\beta \approx 0.01$  to  $0.05$ ) backed by a steep, permeable and reflective upper foreshore or backshore ridge of cobbles ( $\tan\beta \approx 0.1$  to  $0.25$ ). The differences in the slope, roughness, permeability, and groundwater characteristics of the sand and gravel components of composite beaches means that both the hydro and morphodynamics vary with water level and they behave differently to both pure sand and pure gravel beaches. Effectively, composite beaches represent a combination of the two most stable states at either end of the morphodynamic classification of Wright and Short [2], making them relatively stable in response to changing hydrodynamic conditions. The dissipative sand beach component exhibits

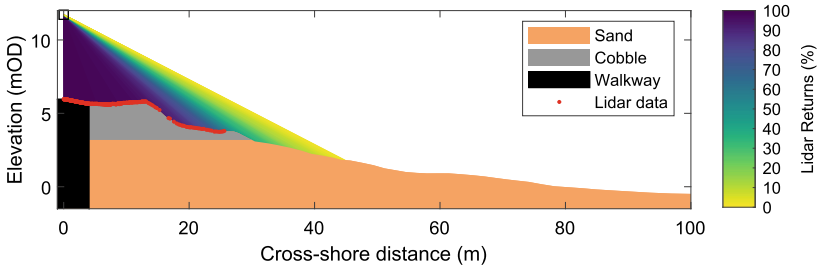
lower mobility because the low gradient promotes a wide surf zone, within which wave energy is gradually dissipated leading to smaller short-wave heights at the shoreline. The steep cobble ridge derives its stability primarily from its porous nature which promotes swash asymmetry [3]. As a result, while strong swash uprush flows can relatively easily transport cobbles up the slope, infiltration of water into the cobble matrix during uprush and flow reversal means that the backwash is weakened, which limits seaward transport of material even during highly energetic conditions and leads to cross-shore sediment sorting and a steep slope.

Compared to their pure sand or gravel counterparts, research into morphological change and hydrodynamics on composite beaches is lacking with few dedicated studies. This paper presents initial analysis of the morphological variability and wave runup on a composite beach at the tide-by-tide timescale over a 3-year period.

## 2 Methodology

Continuous Lidar data was collected between July 2021 and October 2024 at Borth, a macrotidal (range = 5.1 m), west-facing composite sand-gravel beach in Wales. The cobble berm at Borth, Wales provides essential coastal flooding protection to the town, which lies at approximately the elevation of the berm crest.

A SICK LMS511 2D Lidar was installed on the side of the Royal National Lifeboat Institution building at the south end of the beach. The Lidar was located at  $x = 0$  m,  $z = 11.8$  m above UK Ordnance Datum, corresponding to 6 m above the cobble berm crest and sampled at 2.5 Hz (Fig. 1). This enables the beach profile to be captured every low tide (2205 in total) and inner surf/swash data during high tides. The range of the Lidar is restricted to 45 m which coincides approximately with the typical position of the berm toe which is marked by the boundary between cobbles and sand, generally around mean high water (MHW) Note however that many profiles are shorter and are affected by factors including obstruction by lifeguard operations, people and heavy rain. These factors also restrict the ability to detect maximum total water level (the elevation of maximum runup  $R_{max}$ ) from the high tide Lidar data to only 463 high tides. Runup extraction was particularly limited by low energy swash towards the seaward limit of the Lidar data and heavy rain, especially during storms. Power issues also meant that no data was available for 698 of the 2205 tides.

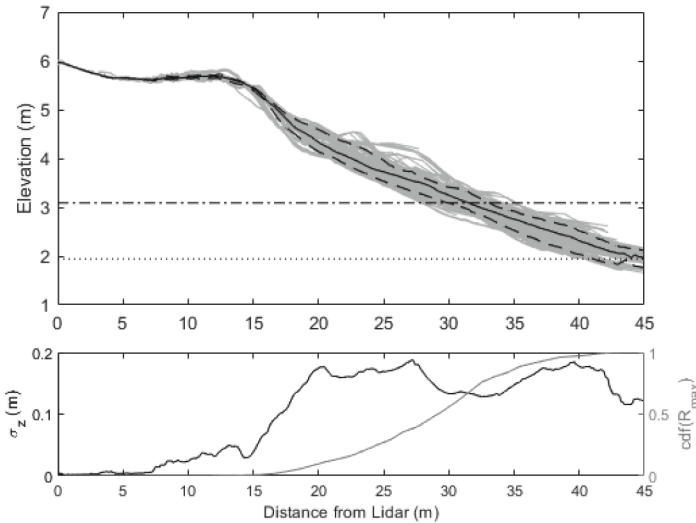


**Fig. 1.** Cross-section of the beach at the Lidar installation location. The colour bar indicates the percentage of valid Lidar returns at each cross-shore location. Note that the surface intersection between sand and gravel was unusually high on the day of installation and is more typically at approximately  $x = 40$  m,  $z = 2.5$  m.

### 3 Results

#### 3.1 Morphology Change

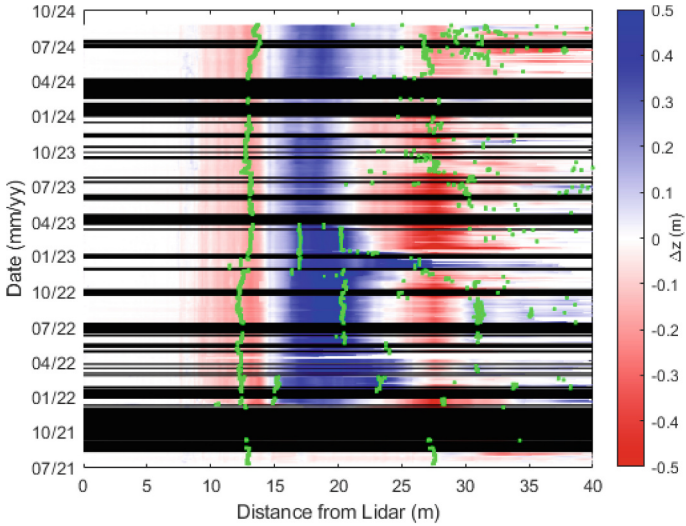
Figure 2 shows the cross-shore profile of the cobble berm extracted from the continuous Lidar data. The lower part of the cobble berm between 20 m and 40 m from the Lidar was dynamic, with a consistent 10–90th percentile range of approximately 0.6 m and standard deviation of bed elevation between 0.11 m and 0.18 m. This region corresponds to the part of the beachface that is consistently inundated by swash, with runup reaching  $x = 20$  m on 9% of high tides. Landward of  $x = 18$  m, the median berm face slope steepens and is only reached during high tides associated with large runup.



**Fig. 2.** (Top) shows all measured low tide beach profile data in grey. Solid black line indicates the median profile, with the dashed lines indicating the 10th and 90th percentile profiles. Horizontal dot-dash and dotted lines show the elevation of MHWS and MHW respectively. (Bottom) cross-shore variation of standard deviation of bed elevation and probability of runup exceedance.

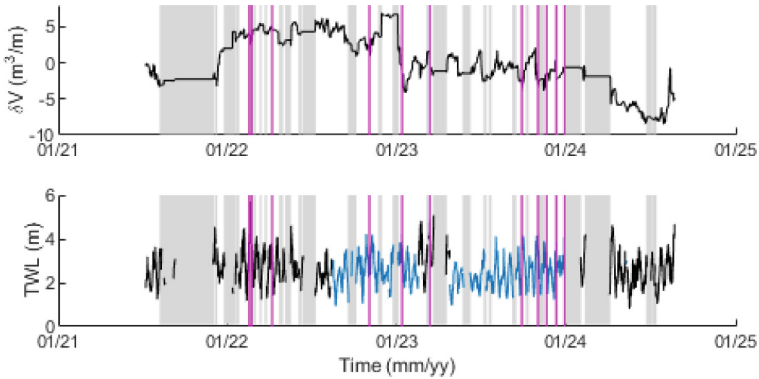
The timeseries of morphology change presented in Fig. 3 highlights the different timescales of morphology change with cross-shore position. The lower berm face ( $x = 30\text{--}45$  m) undergoes regular changes because wave runup reaches these positions on the majority of high tides (Fig. 2). The frequency of measured morphology change decreases moving landward. Between 17 m and 30 m, changes in the berm geometry are more episodic, caused by intermittent high-energy swash conditions coinciding with high tide, after which the berm profile remained approximately constant until the next high-energy event. The primary berm crest geometry is consistent throughout the measurement period with only minor changes caused by occasional wave overtopping.

Figure 3 also indicates the position of any berm crests, obtained by detecting local peaks in the detrended beach profile. The primary berm has a consistent position at approximately  $x = 12.8$  m throughout the deployment. Some movement is shown in the plot, but this is thought to be due to the sensitivity of the berm detection method to small changes caused by people walking on the beach. Swash driven change to the berm caused by wave overtopping of the crest was only confirmed to occur during 5 high tides, though these changes were minor leading to changes in crest elevation no larger than 0.09 m. Figure 3 further provides the location of any secondary berms present on the berm face. Such berms are present in more than 90% of low tide profiles, however their behaviour is quite different to that observed by Phillips et al. [4] in their Lidar study of a sand beach. They demonstrated that the position and crest elevation of secondary berms was primarily governed by neap-spring variations in total water level, with berms initially forming near the swash runup limit during neap tides on the lower beachface and translating landward with increasing tidal elevation. At Borth, berm formation/removal is observed during a single tide. Berms are typically formed during moderate to energetic conditions around the high tide runup limit, however after formation, they are not observed to translate, but typically remain at their original location until they are overtopped during a subsequent high tide.



**Fig. 3.** Timeseries contour plot of morphology change relative to the initial measured profile. Green symbols indicate the crest location of local berm features.

The timeseries of detected berm volume change is presented in Fig. 4. These data indicate that volume changes are relatively small, with the detected berm volume only varying over a range of  $15 \text{ m}^3/\text{m}$  which is almost an order of magnitude smaller than that commonly observed on sand beaches (e.g. Harley et al. 2022), though it is noted that the cross-shore width of berm investigated here is relatively small. A further feature is the apparent lack of seasonal behaviour which is a common feature on sand beaches. Inspection of Fig. 4 suggests that sudden changes in volume tend to be, but aren't always, related to occurrences of high total water level ( $\text{TWL} > 4 \text{ m}$ ). Because runup couldn't be consistently detected for all high tides using the Lidar data, TWL is estimated using Blenkinsopp et al. [5] to estimate wave runup when the water depth above the berm toe,  $d_{toe} < 5/3H_0$  and Poate et al. [6] for larger values of  $d_{toe}$ .

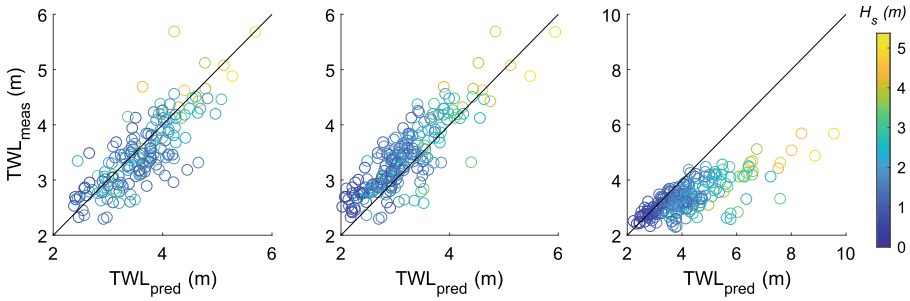


**Fig. 4.** (Top) Timeseries of detected berm volume change. (Bottom) Timeseries of predicted high tide TWL. Grey regions indicate when no valid profile data was available. Vertical magenta lines indicate storms where  $H_s$  reaches the 99th percentile and remains above the 95th percentile for at least 2 h. In the bottom plot, data is plotted in blue for periods when surge residual data was available and black where no surge data was available.

### 3.2 Wave Runup

While it was only possible to confidently extract maximum TWL for 463 high tides, this represents a substantial dataset against which to test composite and gravel beach runup equations. Figure 5(left) compares measured and predicted TWL at high tide using the Blenkinsopp et al. [5] equation for all high tides where surge residual data was available. Note that the measured TWL takes the maximum observed runup height, while [5] predicts  $R_{2\%}$  and so might be expected to slightly underestimate. It is observed that equation enables reasonable prediction of TWL with a root mean square error of 0.25 m. As expected, the largest values of TWL occur during spring tides and storm surge when the water depth at the berm toe. Interestingly however, there is a clear influence of offshore significant wave height on wave runup (Fig. 5). This is in contrast to observations at the 3 field sites used to develop the equation, where it was found that wave runup elevation was decoupled from the wave height offshore due to the dissipative nature of the surf zone.

Figure 5(mid) and (right) show the performance of the Poate et al. [6] equation developed for pure gravel beaches using the sand beach and gravel berm slope respectively. When the berm slope is used it is found that the equation substantially overestimates wave runup and hence TWL. However, if the equation is applied using the slope of the fronting sand beach, the predictive ability at Borth is comparable to Blenkinsopp et al. [5], which was developed specifically for composite beaches.



**Fig. 5.** Comparison of measured and predicted total water level using (Left) Blenkinsopp et al. [5] ( $rmse = 0.25$  m), (Middle) Poate et al. [6] using  $\tan B_{sand}$  ( $rmse = 0.25$  m) and (Right) Poate et al. [6] using  $\tan B_{berm}$  ( $rmse = 0.78$  m). Results are coloured according to  $H_s$  offshore.

## 4 Conclusions

This paper presents an initial analysis of morphological change and wave runup over a 3-year period on a composite beach. It was demonstrated that the cobble berm structure itself was very stable at the tidal timescale: the berm volume varied by around an order of magnitude less than on sand beaches with an absence of seasonal behaviour, the primary berm crest saw minimal change ( $\Delta z < 0.09$  m) and was only overtopped during 5 high tides. It was also found that secondary berm behaviour is very different to that on sand beaches, with berms formed/removed in a single tide. Finally, existing wave runup equations were able to provide reasonable estimates of total water level, but there was a clear influence of offshore wave height on runup which is contrary to previous observations on composite beaches.

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