Observations of the swash zone on a gravel beach during a storm using a laser-scanner (Lidar)

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ABSTRACT

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The collection of detailed field measurements from the swash zone during storms is an extremely challenging task which is difficult to execute with traditional in-situ deployments (e.g., scaffold rigs with instruments). The levels of difficulty increase for gravel beaches where the wave energy reaches the beach face with almost no loss of energy, leading to violent plunging wave breaking on the beach face that can produce large vertical morphological changes and extremely strong uprushes that can easily and rapidly damage, bury or detach instrumentation. Remote-sensing techniques emerge as the most appropriate solution to perform field measurements under such adverse conditions since they have the ability to perform measurements without being deployed *in-situ*. A mid-range (~ 50 m) Laser-scanner mounted on a tower (~ 7 m high) in the mid beach face of a gravel beach (Loe Bar - SW England) was used to measure bed-level changes and runup at a sampling rate of 2 Hz along one beach profile during a storm. The results from the comparison of this system with other state-of-the-art instruments (e.g., ultrasonic bed level sensors, GPS and video cameras) indicate that the quality of the measurements obtained is within the accuracy of the standard methods. The advantages of this system is the reduced logistical infrastructure required for the deployment, the capability to perform surveys with high spatial and vertical resolution, during day and night, and to reach areas of the swash zone where no other instrument can be deployed safely. Measurements performed with a laser-scanner on a gravel beach (Loe Bar) show complex and fast-changing morphology on the gravel beach, which appears to be a form of negative morphodynamic feedback to controls the hydrodynamic evolution in the swash zone.

ADDITIONAL INDEX WORDS: *Swash, remote-sensing, gravel-beach, storm.*

INTRODUCTION

The swash zone is characterized by strong fluid motions and rapid morphological changes, being one of the most dynamic regions in the nearshore (Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006). During storms the beach response (erosion and recovery) is strongly controlled by the swash zone and for this reason it is crucial to acquire field data to help understand the fundamental processes in this zone. On gravel beaches the swash zone plays a particularly important role during storms since there is typically no formation of an offshore bar to dissipate wave energy offshore and the characteristic steep beach face gradient allows the propagation of large amounts of wave energy much farther inshore (Austin and Masselink, 2006). As a result, large and violent plunging waves break on the lower beach face, producing a highly energetic swash zone with strong uprushes, which is a notoriously difficult environment to deploy *in-situ* instrumentation (Hughes *et al.*, 1997; Masselink and Puleo, 2006). Remote-sensing techniques emerge as the most appropriate solution to perform field measurements on such adverse conditions since they have the ability to perform measurements without being deployed *in-situ*. The most evident example is video imaging that during the last 30 years has been extensively used to study runup hydrodynamics and which has resulted in the formulation of several runup parameterizations (e.g., Holman, 1986; Stockdon *et al.*, 2006). Despite the high spatial and temporal resolution of video imaging, it presents some significant limitations regarding its use during storms, such as the inability to record useful data during low light conditions and the need for frequently updated topography in order to accurately estimate run-up elevations. The need to track the rapid morphological changes and water motions in the swash zone on a wave-by-wave timescale was the motivation for the recent development of a semi-remote sensing technique based on ultrasonic sensors (Turner *et al.*, 2008). This system is typically mounted on a scaffold frame with several ultrasonic units (bed-level sensors) equally spaced at a certain elevation (~ 1.5 m) from the bed allowing the acquisition of the bed changes at 4 Hz with a accuracy of ±1 mm (Turner *et al.*, 2008). The utility of this system has been very well demonstrated in several applications on sandy and gravel beaches during mild wave conditions (Masselink and

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Turner, 2012; Masselink *et al.*, 2010) and on sandy beaches during storms (Masselink *et al.*, 2009). However, the methodology has not yet been used on gravel beaches during storms. Despite the high vertical resolution of the measurements and the ability to survey during day and night, the spatial resolution is dependent on the number of sensors, which in turn is controlled to some degree to the size of the scaffold structure from which they are mounted. On a gravel beach and during a storm these characteristics can represent some significant disadvantages, since the very energetic swash hydrodynamics can damage or bury the sensors and scaffold structure. More recently, laser technology (e.g., terrestrial laser-scanner or industrial laser-scanners) have been deployed on natural beaches during mild (Blenkinsopp *et al.*, 2010) and storm conditions (Brodie and McNinch, *in press*) to measure swash hydrodynamics and morphological evolution. These instruments are capable of performing high frequency (< 2 Hz) measurements with high resolution in the horizontal (from cm to m) and vertical (from mm to cm) along a swath line, during both day and night. The only requirement to deploy such instrumentation is a stable tower with sufficient elevation to allow the laser beams to be reflected across the free surface within the study area. Nevertheless the application of this technique on a gravel beach during a storm has never been performed before.

The objective of the present work is to demonstrate the capabilities of a mid-range (~ 50 m) laser-scanner to perform measurements of the topography and runup in the swash zone of a gravel beach (Loe Bar, UK) during a storm. The work is divided in three sections: (1) topographic extraction, where a comparison is made between the laser-scanner measurements, bed level sensors and GPS surveys; (2) runup extraction, where the laser-scanner runup measurements are compared with the runup measurements obtained with a video camera; and (3) swash zone observations, where the morphological evolution of the swash zone is related to the swash hydrodynamics (runup) and offshore wave conditions, thus demonstrating the potential of the laser-scanner to contribute to research of fundamental sediment transport processes that occur during storms.

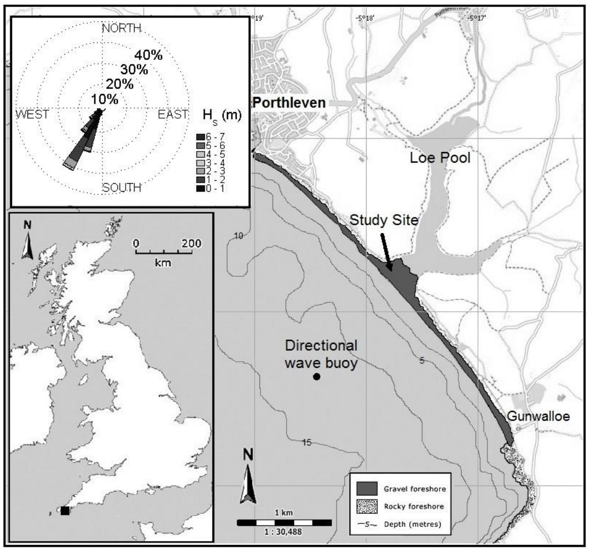

Figure 1. Location of study site (Loe Bar) close to Porthleven, including position of the nearshore wave buoy. The directional wave plot is based on data collected from October 2011 to October 2012 (adapted from Poate *et al.*, *in press*).

METHODS

STUDY SITE

A field survey was conducted between 23 February and 28 March 2012 at Loe Bar (Cornwall County, Southwest of England – Figure 1) with the aim of monitoring the storm response of a gravel beach (cf., Poate *et al.*, *in press*). The data used in the present work were obtained during this experiment on 24 and 25 of March 2012. Loe Bar is part of a 4.3 km long gravel beach (D_{50} = 2–4 mm) that extends from Porthleven, in the north, to Gunwallow, in the south (see Figure 1). Loe Bar barrier fronts Loe Pool and extends 430 m between the adjacent headlands. At its widest point Loe Bar barrier is 250 m wide.

With a NW-SE shoreline orientation (see Figure 1) the barrier faces the south-westerly waves with an average significant wave height (H_s) of 1.2 m and average peak period (T_p) and direction (θ) of 9.1 seconds and 235º respectively (Poate *et al.*, *in press*). The tidal regime is macrotidal with MHWS (mean high water spring) reaching 5.5 m and MLWS (mean low water spring) 0.8 m CD (Chart Datum). The offshore wave conditions experienced during this field campaign were measured by an offshore wave buoy located at ~ -10 m CD and indicate that the maximum H_s observed during the storm reached 2.5 m with a peak of period 14 seconds from SW direction (Figure 2).

DATA COLLECTION

Two cross-shore transects (T0 and T5) alongshore spaced by 5 m were established at the central area of the barrier (Figure 3, top panel). On T0 an array of 45 bed-level sensors mounted on a large scaffold frame (70 m long and 2.5 m wide) was deployed from the MHWS to the crest of the bar (Figure 3, bottom panel). Following the methodology outlined by Turner *et al.* (2008), the sensors were mounted ~ 1.5 m above the bed with cross-shore spacing of 1.5 m and programmed to record at 4 Hz.

On T5 a laser-scanner (SICK LDOEM3100) was deployed on top of a 5 m aluminum tower with a scaffold base on the lower beach face (Figure 4). The LD-OEM5000 is a mid-range laser scanner (~ 50 m, depending on the reflectance of the target) that measures the distance to a target using the time delay between the transmission of an eye-safe (class 1) pulsed laser beam (λ = 905 nm) and the detection of the reflected signal. The pulsed laser is deflected by an internal mirror that rotates to provide multiple points within the laser-scanner 360º field of view at an angular resolution of 0.1250º. The scanner was programmed to scan at 2 Hz and covering only 180º of the field of view, scanning from the top of the berm until the lower beach face.

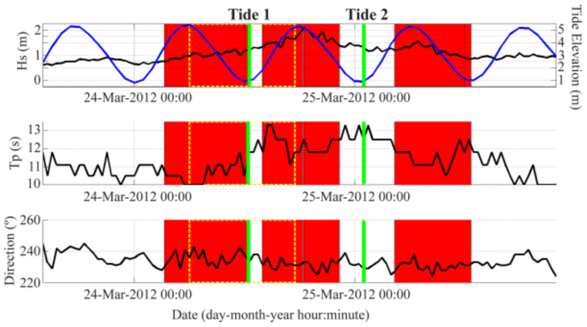

Figure 2. Offshore wave conditions and tides for the survey period with the indication of measurements performed with the different instruments: GPS (green lines); laser-scanner and bed level sensors (red areas); video (box with yellow dashed line).

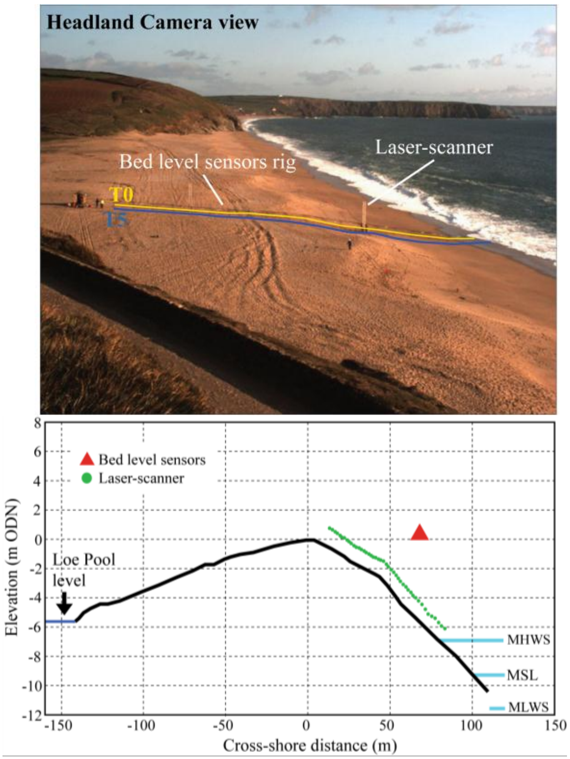

Figure 3. Headland camera view snapshot (upper figure) with the location of T0 and T5 transects. Beach profile with the field instrumentation deployed (lower figure).

The swash dynamics were also logged using a Pointgrey Grasshopper 2MP CCD camera with a wide angle lens (8 mm), located in the top of the headland (see Figure 3, top panel). This camera covered the nearshore region and collected 17-minute pixel time stacks every 30 minutes along the T5 transect at 3 Hz. Pixel time stacks were used to calculate runup excursion and from this the 2% runup exceedence level ($R_{2\%}$) was derived, following the same methodological approach developed by Stockdon et al., (2006).

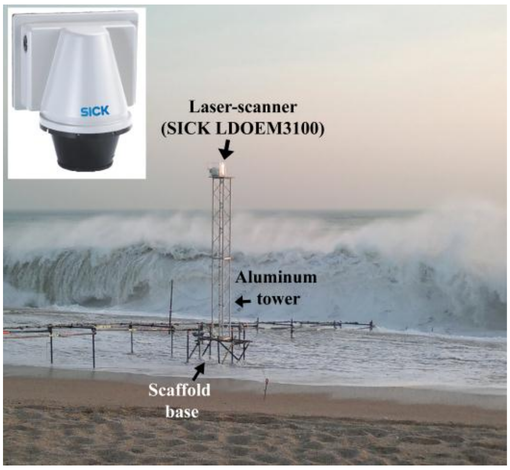

Figure 4. Field photo showing the laser-scanner tower deployed on the beach face. On the left corner of the figure is an image of the SICK LD-OEM3100 laser scanner used in the present work.

Topographic surveys were undertaken every low tide using real-time kinematic GPS (RTK-GPS – Trimble 5800) along the T0 and T5 transects, using a local geographic coordinated system with the origin (x, y and z = 0) on the top of the berm in line with T0 (see Figure 3, lower panel - the conversion between the local vertical datum and the OS datum is z_{local} = 0 m is equal to z_{OS}= 9.43 m).

TOPOGRAPHIC EXTRACTION

The laser-scanner was initially post-processed using a 3-point running average in both space and time, together with a variance threshold, to extract the topography (stationary measurements that were below the variance threshold). In addition to this automatic processing, some manual elimination of outliers was performed before obtaining the final data (Figure 5 – top panel). The extracted topography time-series was compared with the bed level sensors and GPS topographic measurements to evaluate the quality of the laser data.

RUNUP EXTRACTION

The time-varying vertical position of the water's edge on the foreshore of the beach (runup) was obtained from the raw laser-scanner measurements by subtracting the extracted topography (‘dry’ bed) from the raw measurements, and using a threshold water depth to define the instantaneous shoreline (see Figure 5). The threshold water depth used in this study was 5 cm, which was determined by means of sensitivity testing. The runup limit of individual swash events was computed by indentifying the local maxima in the runup time series, and these runup limits were used to determine the 2% runup exceedence level ($R_{2\%}$). Before the calculation of the $R_{2\%}$ the measured tide (measured with a pressure transducer deployed inside the Portheleven port) was subtracted from the runup time series to eliminate the tide and surge signal. The $R_{2\%}$ was subsequently compared between the laser-scanner and video data by selecting concurrent measurement.

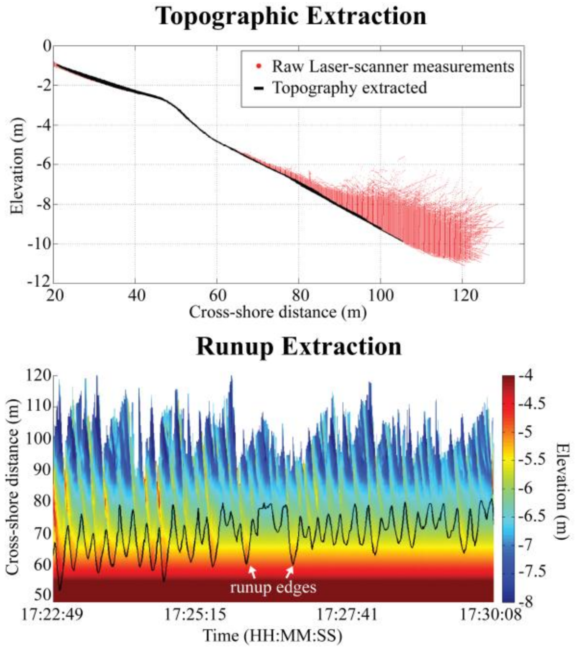

Figure 5. Top figure: Example of raw laser-scanner measurements (red dots) and the extracted topography (black line) for 42 minutes of measurements at 2 Hz; Bottom figure: Coloured contour map with the raw laser-scanner measurements in time and the computed runup limit (black line).

SWASH ZONE OBSERVATONS

The offshore wave conditions were measured by an offshore wave buoy (Figure 1), which together with the measured tide level provide a good estimate of the forcing imposed to the beach during the storm. This information was combined with the swash zone runup evolution and morphological response to make novel, investigatory analysis of the storm response of the gravel beach during the event using detailed and integrated field data.

RESULTS

TOPOGRAPHIC EXTRACTION

The comparisons of the GPS surveys with the bed level sensors and laser-scanner measurements (Figure 6) indicate that both remote sensing instruments present a very good agreement with the *in-situ* measurements performed with the GPS. The obtained residuals (Figure 6) present very limited bias and show that the computed differences are in the order of magnitude of the GPS accuracy (± 5cm). The highest residual was obtained between the laser-scanner and GPS for Tide 2 on the lower beach face (between x > 85m and x < 100 m – see Figure 6). This result is likely to be due to the fact that the topography measured with the laser-scanner and used to compare with the GPS measurement for Tide 2 was collected before the tide had completely retreated, whereas the GPS data were collected at low tide.

The difference between the bed-level sensors and laser-scanner topographies are very low until approximately the cross-shore position x = 40 m, and increase towards the lower part of the beach. This trend can be observed for both tides and is attributed to alongshore variations in the beach profile because the profiles were measured in different locations (see Figure 3). To support this suggestion, Figure 6 presents the difference between GPS surveys taken along T0 and T5, which show the same trend in elevation differences on the lower section of the beach.

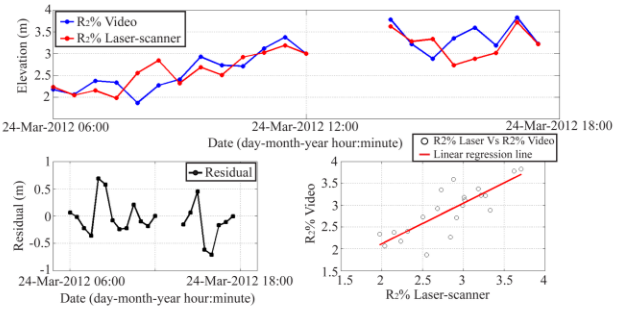

Figure 7. Comparison between the $R_{2\%}$ computed with the laser-scanner and video camera (upper figure); the difference between the $R_{2\%}$ computed with both techniques (lower left figure) and the dispersion diagram with the overlap of a linear regression line (lower right figure).

RUNUP EXTRACTION

The computed $R_{2\%}$ for both video and laser-scanner runup datasets are presented in Figure 7. Despite some occasional differences where the residual exceeds 0.5 m both instruments present similar temporal trends. The good correlation between both $R_{2\%}$ datasets (r^2 = 0.7 and *rms* = 0.26 m) quantifies the good agreement between both instruments in quantifying the runup evolution over time.

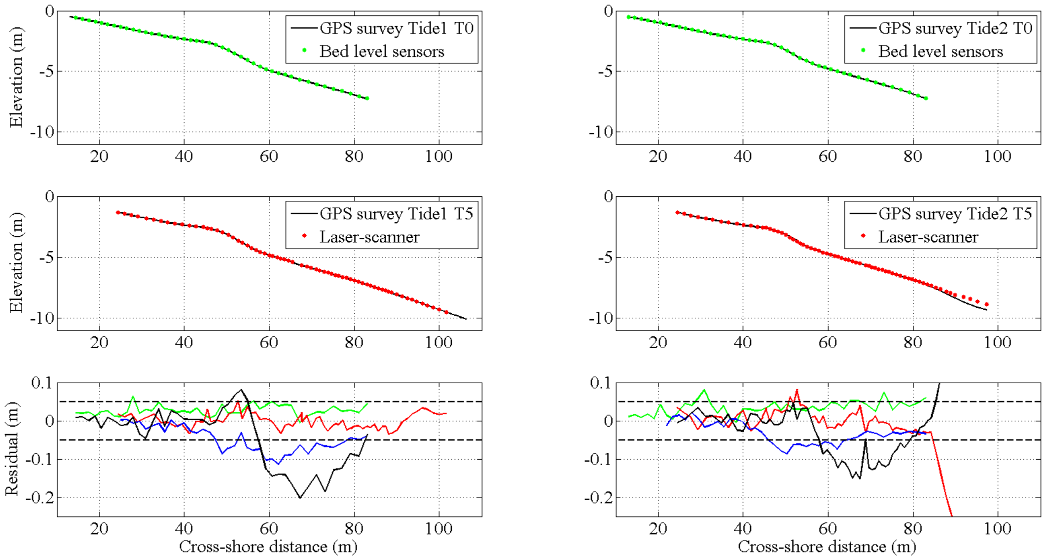

Figure 6. Comparison between GPS measurements at T0 and bed level sensors for tides 1 and 2 (top two panels); comparison between GPS measurements at T5 and the laser-scanner scan for tides 1 and 2 (middle two panels) and residual between all the instruments: GPS vs bed level sensors (green line), GPS vs laser-scanner (red line), Laser vs bed level sensors (blue line) and GPS vs GPS (black line) (lower two panels).

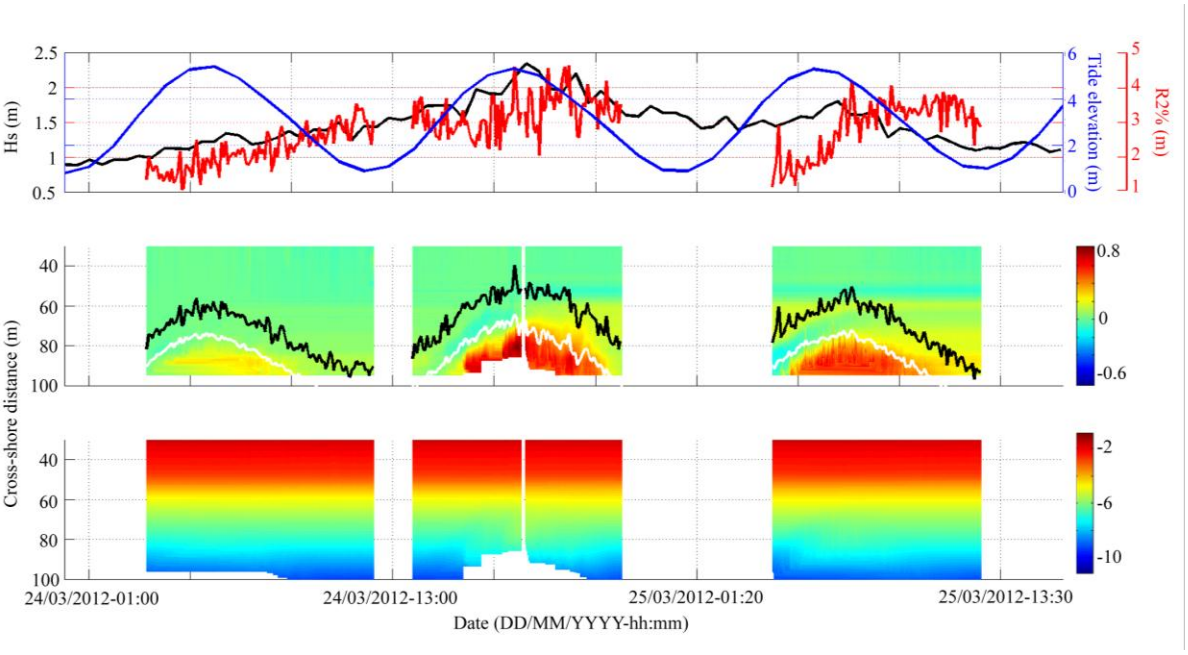

Figure 8. Significant wave height (black), predicted tide (blue) and $R_{2\%}$ computed for intervals of 5 minutes during the experiment (upper panel); cumulative differences between the consecutive laser transect scans with the mean (white line) and maximum (black line) runup elevation observed every 5 minutes (central panel); contour map of bed level extracted from laser-scanner data (lower panel)

SWASH ZONE OBSERVATIONS

The $R_{2\%}$ was computed for the entire storm using a 5-minute window of runup measurements and compared with the cumulative differences of the morphology and the offshore wave conditions (Figure 8). During the first high tide measurement with the laser-scanner, the $R_{2\%}$ presents a linear increase that coincides with the increase in the offshore H_s. The morphological changes on the beach are not very significant during this period; however, it is possible to observe the formation of a small (~25 cm high) deposit on the lower beach face ($x > 80$ m). This feature is formed during the rising tide and dissipates during the falling tide (Figure 8).

At the beginning of the second high tide, the increase in $R_{2\%}$ coincides with the rising of the offshore significant wave height and water level.The morphological response of the beach at this stage is slight erosion of the lower beach face, followed by the formation of a large deposit at approximately the same location as that observed during the first high tide ($x > 80$ m, Figure 8). In turn, this morphological response seems to coincide with a stabilization of the $R_{2\%}$ elevations: the tidal level and wave height are still rising, but $R_{2\%}$ is relatively constant. This result is in agreement with visual observations made in the field. During the falling tide of the second high tide the measurements indicate a slight increase in $R_{2\%}$, which seems to be mainly linked to the morphological response since the wave height is decreasing. At this stage the deposit on the lower beach face starts to become smoothed out with some of this sediment being deposited on the upper beach face up to $x = 60$ m. The influence of the drop in the offshore wave height is evident on the beginning of the third high tide where the $R_{2\%}$ suffers a significant decrease.

The consequence of this fact is the erosion of the lower beach face. However, with the rising tide another deposit is formed, similar in shape and position to that described in tide 2. The size of this new depositional feature is small in comparison to that of the previous tide, which may be a consequence of the smaller offshore wave height.

DISCUSSION

In the initial part of this work a comparison between the laser-scanner measurements and state of the art techniques to measure topography and runup is presented. The results show in general a good agreement, indicating that the laser-scanner performs these two tasks very well. This result reinforces the good results obtained in the laboratory and in the field with mild wave conditions by Blenkinsopp *et al.* (2010, 2012) using similar laser instruments.

Some advantages and disadvantages can be noted between the laser-scanner and the other remote sensing instruments regarding measurements and logistics. Compared to ultrasonic bed level sensors, the laser tower requires much less scaffold to be mounted, the sensor is less exposed to the wave action and the range of the scanner allows it to measure water and bed levels in regions lower on the beach where it would be impossible to deploy bed level sensors. In addition, the laser-scanner does not typically suffer from becoming submerged, and thus unable to record the water surface level. During the storm this characteristic can be important since several waves reached the beach with elevations significantly superior to the elevation of the bed-level sensors. One of the main disadvantages of the laser-scanner compared to the bed-level sensors is that the laser relies on a single scaffold structure that can become very vulnerable when under strong wave action.

Regarding the video cameras, one of the main advantages of the laser technology is the fact that it can perform measurements during day and night, which traditional video cameras cannot do. During a storm, morphological changes occur very fast, as Figure 8 demonstrates, and for this reason it is essential to have instruments that can track changes continuously in order to better understand the underlying processes. The main disadvantage of the laser compared to video is the alongshore limitation of the measurements, since the laser can only survey along a single line, while the video cameras can cover a much wider area. Despite these differences it was clear from the results of this study that the laser-scanner technique has the ability provide very good coverage of the swash zone during storm events.

The morphological response of a gravel beach observed during this survey with the laser scanner is in agreement with the field observations of Austin and Masselink (2006), who also found an onshore net transport during energetic conditions on a gravel beach. The observed changes indicate a general pattern of the formation of a significant deposit on the lower beach face during large wave conditions that is initiated by modest erosion on the lower beach face. During the rising tide this morphological response coincides with a reduction in wave runup levels and during the ebb this feature is smoothed with a slight increase in runup levels. These results clearly show that complex and fast-changing morphodynamics take place on the beach, which in turn appear to form a negative feedback on the driving nearshore hydrodynamics.

CONCLUSION

A mid-range laser-scanner was tested to perform topographic and hydrodynamic measurements on the swash zone of a gravel beach during a storm. The results from the comparison of this system with other state-of-the art instruments (bed level sensors, GPS and video cameras) indicate that the quality of the measurements performed with this instrument is within the accuracy of the standard methods. The advantages of this system compared to the other tools is the reduced logistical infrastructure required for the deployment, the capability to perform surveys during day and night, its high spatial and temporal resolution and its ability to reach areas of the swash zone where no other instrument can be deployed safely. Measurements performed with a laser-scanner on a gravel beach (Loe Bar) during a storm have provided an insight into the temporal and spatial scales of the complex morphodynamic feedback between the gravel beach, waves and tides.

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