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Observations of gravel beach dynamics during high energy wave conditions using a laser scanner

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ABSTRACT

A 2D laser-scanner was deployed at the high tide runup limit of a pure gravel beach (Loe Bar, Cornwall, England) to measure high-frequency (2.5 Hz) swash hydrodynamics and topographic changes during an energetic wave event. Measurements performed with the laser-scanner were corrected to compensate for levelling and orientation errors, and a variance threshold was applied to separate the beach topography from the water motions. Laser measurements were used to characterise the swash hydrodynamics and morphological changes during one tidal cycle through the calculation of several parameters, such as the 2% exceedence of the runup maxima ($R_{2\%}$), swash flow velocity skewness ($<u^3>$), runup spectra and cumulative topographic changes. Results indicate that despite the small net morphological changes over the tide cycle, significant sediment mobilization occurs. A clear asymmetrical morphological response was found during the different tidal phases: the rising tide is dominated by accretion whilst the falling tide is dominated by erosion. The main factor controlling this asymmetrical morphological response is the step migration that, depending on the tide phase, controls the wave breaking point and consequently the dominant sediment transport direction. During the rising tide, step development decreases the shoreface slope and reduces the runup energy, whilst during the falling tide the step remobilization increases the shoreface slope and energy on the runup.

1. Introduction

Gravel beaches and barriers occur typically along paraglacial coasts (e.g., Canada, UK, Ireland) or coastlines backed by mountains (e.g., Mediterranean, New Zealand), and according to Jennings and Schulmeister (2002) they can be found in nature mainly in three different forms: (1) pure gravel beach; (2) mixed sand and gravel; and (3) composite gravel beach. Pure gravel beaches (hereafter referred as 'gravel beach') are characterised by steep reflective profiles and prominent secondary morphological features, such as ridges, berms, step and cups, but without nearshore bars (Buscombe and Masselink, 2006). During highly energetic wave conditions (e.g., storms), gravel beaches typically dissipate most of the offshore wave energy across a narrow cross-shore section next to the swash zone (Buscombe and Masselink, 2006; Ruiz de Alegria-Arzaburu and Masselink, 2010; Poate et al., 2013). The absence of an offshore bar promotes large collapsing/plunging waves to break on the lower beachface (step) creating extremely energetic boundary conditions for swash motions and enhancing highly turbulent flows capable of mobilizing significant amounts of gravel at individual swash time scales (Austin and Masselink, 2006; Austin and Buscombe, 2008; Masselink et al., 2010). Under such energetic conditions, the complex interactions between the swash hydrodynamics and the beach morphology dictate the occurrence and extension of hazardous events like barrier overtopping or overwashing (Orford et al., 2003 and Matias et al., 2012). The acquisition of full-scale, hydro- and morpho-dynamic measurements is essential in order to provide new insights into the fundamental processes driving coastal change, overtopping and flooding. However, the deployment of any kind of in-situ measurements in such energetic conditions is extremely challenging. Of particular importance to the study of sediment transport in the swash zone is the development of instruments with the ability to acquire reliable measurements of both swash hydrodynamics and bed changes at wave-by-wave time scales.

Recently, a method based on ultrasonic technology brought the innovative capability to quantify bed changes and water motions at a frequency of individual uprush–backwash events with the accuracy of ±1 mm (Turner et al., 2008). This method is typically mounted on a scaffold frame with a large number of ultrasonic units (bed-level sensors — BLS), equally spaced at a certain elevation (~1.5 m) from the bed, allowing the acquisition of the bed changes, swash position and volume at 4 Hz (Turner et al., 2008). The capability of this method has been very well demonstrated in several field (e.g., Masselink et al., 2009, 2010; Blenkinsopp et al., 2011; Poate et al., 2013) and laboratory (e.g., Masselink and Turner, 2012; Williams et al., 2012; Masselink et al., 2013) applications.

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A limitation of having to use a large scaffold frame for mounting the large number of sensors required to obtain data of sufficient spatial coverage is that the methodology is only possible for mild wave conditions. This logistical problem is exacerbated on gravel beaches where typically most of the offshore wave energy is dissipated over the swash zone and the breaker region just seaward of the swash zone (Buscombe and Masselink, 2006; Ruiz de Alegria-Arzaburu and Masselink, 2010; Poate et al., 2013).

Remote sensing methods emerge in this context as the most appropriate solution for this type of field measurements, especially under energetic wave conditions that lead to the most dramatic morphological changes. During the last three decades video imaging has been the most applied remote sensing method to nearshore surveying. The estimation of intertidal topography (e.g., Plant and Holman, 1997) and nearshore bar location (e.g., Lippmann and Holman, 1989) or subtidal bathymetry (e.g., Stockdon and Holman, 2000) are all examples of the wide variety of applications that video can offer. Video data are also extensively used in runup studies and several runup parameterizations (e.g., Holman, 1986; Stockdon et al., 2006) are based on video measurements. Despite the high spatial and temporal resolution that video runup data can offer, video imaging does present some significant limitations regarding their use during storms, such as the inability to record useful data during low light (e.g., during the night) or rainy and foggy conditions (typical conditions during storms). In addition, conversion of video data from image coordinates to real-world coordinates requires information on the beach morphology and this is not a constant during a storm.

Recent studies reporting the use of laser-scanners on natural beaches (Blenkinsopp et al., 2010; Brodie et al., 2012; Almeida et al., 2013) and laboratories (Blenkinsopp et al., 2012) have demonstrated the ability of the laser technology to measure swash hydrodynamics, as well as bed evolution, on the swash event time scale remotely (i.e., without the need to deploy the instrument within the region of interest). The versatility and precision of 2D laser-scanners have enabled the development of a large range of useful non-contact measurement applications ranging from medicine (e.g., Pallejà et al., 2009), forestry (e.g., Miettinen et al., 2007), to robotics (e.g., Vásquez-Martín et al., 2009). Using a simple ‘time of flight’ working principle to compute the distance between the laser sensor and the ‘target’, this method allows the acquisition of high-frequency and fine spatial resolution measurements along a swath line within the laser beam range.

Comparisons between 2D laser-scanners and state-of-the-art instrumentation, such as ultrasonic altimeters, video cameras and capacitance wave probes, have showed that the accuracy of the laser is comparable to that of the standard methods (Blenkinsopp et al., 2010, 2012; Almeida et al., 2013), but these preliminary comparative efforts present limited information on important aspects of the laser technique, such as instrument deployment and data processing.

The aim of the present work is to provide guidance on how to deploy a 2D laser-scanner in the field to collect high-frequency topographic and hydrodynamic data from the swash, together with methods to process the raw laser measurements. As a demonstration of the capabilities of this instrument we also present a detailed analysis of the morphodynamics of a gravel beach (Loe Bar, UK) during an energetic tidal cycle.

2. Methods

2.1. Study site and field deployment

A field experiment was conducted between 23 February and 28 March 2012 at Loe Bar in the southwest of England (Fig. 1) with the aim of monitoring the response of a gravel beach to varying wave conditions (cf. Poate et al., 2013). 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 Gunwalloe, in the south (Fig. 1). The Loe Bar barrier fronts Loe Pool and extends 430 m between the adjacent headlands, with an average width of 200 m and a typical seaward gradient of 0.1. With a NW–SE shoreline orientation, the barrier faces south-west and is exposed to energetic Atlantic swell with an annual average significant wave height (H_s) of 1.2 m, an average peak period (T_p) of 9.1 s and a direction (θ) of 235° (wave statistics were derived from Porthleven wave buoy measurements from October 2011 to October 2012; data can be downloaded freely from http://www.channelcoast.org). The tidal regime is macrotidal with MHWS (mean high water spring) and MLWS (mean low water spring) at, respectively, 2.5 m and −2.2 m ODN (Ordnance Datum Newlyn; 0 m ODN ~ 0.2 m above mean sea level in UK coastal waters).

A 2D laser-scanner (SICK — LD-OEM3100) was deployed on the top of an aluminium tower (5.2 m high), fixed to a scaffold frame inserted into the beach around the high tide runup level and stabilized by guy ropes (Fig. 2). External power supply (28 V) is provided to the scanner during operation and measurements are streamed to a laptop, by an RS422 cable, where data are recorded using the SOPAS (SICK) software interface.

A pressure transducer was deployed just above the high water level (Fig. 2) to measure swash/wave conditions (at 4 Hz) in the lower swash zone during mid- and high-tide conditions, and offshore wave conditions were measured by a Porthleven directional wave buoy located at approximately 10 m water depth at low tide (Fig. 1). Tide measurements were performed at Porthleven port (Fig. 1) by a pressure transducer deployed around the MLWS level, and the beach topography was surveyed at each low tide along the laser-scanner profile using a dGPS (Trimble 5800).

2.2. The 2D laser-scanner and working principle

The LD-OEM3100 laser scanner model was selected for the present work. This model is a two-dimensional mid-range (maximum range ≈ 100 m; SICK, 2009) laser-scanner that emits pulsed laser beams (invisible infrared light; λ = 905 nm) that are deflected on an internal mirror (inside the scanner head) that rotates at regular angular steps and scans the surroundings (360°) in a circular manner (Fig. 3). The scanner head rotates at 2.5 Hz with an angular resolution of 0.125° and the distance to the target is calculated from the propagation time that the light requires from emission to reception of the reflection at the sensor.

The measurements are logged at 2.5 Hz and consist of two dimensional polar coordinates (d_i, α_i), where i is the scan number (complete cycle of scanner field of view), d is the distance measured between the laser-scanner and the target and α is the relative angle of the measurement. The number of measurements per scan is given by the scan angle divided by the angular resolution, e.g., for a scan angle of 120°, the number of measurements is 960.

3. Results

3.1. Correction of the laser measurement position and orientation

Laser polar measurements (d_i, α_i) are initially converted to Cartesian coordinates (x_i, z_i), where x is the cross-shore position and z elevation, by applying a polar transformation. This new coordinate system is referred to a local coordinate system, where the cross-shore origin ($x = 0$) is at the top of the barrier and the vertical datum is referred to the Ordnance Datum of Newlyn (ODN).

It is extremely difficult in the field to deploy the laser tower perfectly vertical; therefore, the laser measurements are characterised by an orientation offset with respect to the ground level. A beach profile derived from the laser scanner data will therefore have inaccuracies when compared with the real profile (Fig. 4). To correct this orientation problem, the Horn's quaternion-based method for absolute orientation (Horn, 1987) is implemented. This method minimizes the sum of the squared