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Measuring high spatiotemporal variability in saltation intensity using a low-cost Saltation Detection System: Wind tunnel and field experiments

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ABSTRACT

The commonly observed over prediction of aeolian saltation transport on sandy beaches is, at least in part, caused by saltation intermittency. To study small-scale saltation processes, high frequency saltation sensors are required on a high spatial resolution. Therefore, we developed a low-cost Saltation Detection System (SalDecS) with the aim to measure saltation intensity at a frequency of 10 Hz and with a spatial resolution of 0.10 m in wind-normal direction. Linearity and equal sensitivity of the saltation sensors were investigated during wind tunnel and field experiments. Wind tunnel experiments with a set of 7 SalDec sensors revealed that the variability of sensor sensitivity is at maximum 9% during relatively low saltation intensities. During more intense saltation the variability of sensor sensitivity decreases. A sigmoidal fit describes the relation between mass flux and sensor output measured during 5 different wind conditions. This indicates an increasing importance of sensor saturation with increasing mass flux. We developed a theoretical model to simulate and describe the effect of grain size, grain velocity and saltation intensity on sensor saturation. Time-averaged field measurements revealed sensitivity equality for 85 out of a set of 89 horizontally deployed SalDec sensors. On these larger timescales (hours) saltation variability imposed by morphological features, such as sand strips, can be recognized. We conclude that the SalDecS can be used to measure small-scale spatiotemporal variabilities of saltation intensity to investigate saltation characteristics related to wind turbulence.

1. Introduction

Coastal dunes act as a primary defense against flooding of the hinterland by the sea. The erosion of coastal dunes by storm-surges and wave motion has been studied intensively (e.g., Vellinga, 1982; Thornton et al., 2007; de Winter et al., 2015), resulting in well-developed dune-erosion models for use in scientific and applied studies (e.g., Roelvink et al., 2009; Kobayashi et al., 2009; Ruessink et al., 2012). However, the recovery rate of coastal dunes by natural aeolian transport processes on beaches is not well understood, and existing models (e.g. Durán and Moore, 2013; Keijsers et al., 2016) are predominantly exploratory. This arises from the determination that the magnitude of the maximum aeolian transport rate, predicted by empirical transport equations (e.g., Bagnold, 1941; Kawamura, 1951; Zingg, 1953; Owen, 1964; Kadib, 1965; Hsu, 1971; Lettau and Lettau, 1978; Sorensen, 2004), exceeds the maximum transport rates measured in the field (e.g., Sherman and Li, 2012; Barchyn et al., 2014) and, consequently, measured dune recovery rates are over predicted (Davidson-Arnott and Law, 1996; Keijsers et al., 2014). Besides the influence of surface characteristics (e.g. grain size, soil moisture content, surface roughness and morphology), this dissimilarity is related to wind turbulence (Stout and Zobeck, 1997).

Wind turbulence causes strongly intermittent aeolian saltation (Sterk et al., 1998; Leenders et al., 2005) when the mean wind speed is close to threshold of motion (Davidson-Arnott and Bauer, 2009). With increasing wind speed aeolian sediment transport becomes more continuous but considerable unsteadiness and hence transport intermittency remains (e.g., Stout and Zobeck, 1997; Baas and Sherman, 2005; Baas and Sherman, 2006; Baas, 2008; Davidson-Arnott and Bauer, 2009). The non-continuous flow of sediment on small spatiotemporal scales (centimeters and seconds) causes transport to be confined to a smaller amount of time and consequently affects the sediment transport rate on large timescales (Davidson-Arnott and Bauer, 2009; Barchyn et al., 2014). The demand to measure aeolian sand transport on small spatiotemporal scales is of primary interest to investigate the influence of near-bed wind turbulence on time-averaged aeolian sand transport. To measure small-scale spatiotemporal variability in sediment transport, high-frequency (1–10 Hz) saltation sensors are required

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at a high spatial resolution in a horizontally oriented sensor array perpendicular to the prevailing wind direction, containing a mutual sensor distance of at least 0.10 m (Baas and Sherman, 2006).

Existing sensors that can measure saltation transport on high frequencies are based on various techniques: piezoelectric (Sensit (Stockton and Gillette, 1990), Safire (Baas, 2004), Buzzer Discs (Sherman et al., 2011), piezoelectric sensor (Raygosa-Barahona et al., 2016)), acoustic (Saltiphone (Spaan and van den Abeele, 1991; Poortinga et al., 2015), Miniphone (Ellis et al., 2009)), and laser (Wenglor Particle Counter (Hugenholtz and Barchyn, 2011; Barchyn et al., 2014; Duarte-Campos et al., 2017)). Commonly used high-frequency saltation sensors are the Saltiphone, Safire, and Sensit. The Saltiphone is an acoustic saltation sensor which can measure saltation at a temporal scale up to 16 Hz, using a microphone. Its design, containing two wind vanes at the back of the Saltiphone, ensures that the sensing area is directed into the prevailing wind direction. At the same time, this design prevents the Saltiphone from being used at a high spatial resolution, since the vanes cause the instrument to have a large (0.19 m) wind-normal span. The Safire and Sensit are both tubular sensors designed with piezo-electric technology. These instruments generate electrical pulses by converting the impact energy of particles into a particle count flux. The size and curved shape of the sensing area ensures the performance of point measurements on a high spatial resolution and omni-directional sensitivity. These sensors have the disadvantage that individual sensors show different sensitivity under seemingly identical conditions (Baas, 2004; Barchyn and Hugenholtz, 2010; Sherman et al., 2011), which makes it difficult to determine the mutual variability in saltation intensity in a multi-sensor set-up. As a result, it is required to normalize the sensor signals prior to data analysis, assuming a uniform cumulative transport rate on relatively large timescales (Baas, 2008; Lee and Baas, 2015). Furthermore, all three sensors are rather expensive, hindering high spatial resolution measurements of saltation intensity.

This paper aims to measure and analyze the spatiotemporal variability in saltation intensity on time-scales of 10 Hz with a spatial resolution of 0.10 m on a natural beach. To that end, we developed a low-cost system with multiple saltation sensors, called Saltation Detection System (SalDecS). This paper describes the technical aspects of the SalDecS, and resolves the characteristics (linearity and equal sensitivity) of the Saltation Detection sensors using wind tunnel and field measurements. In this paper we continue with a description of the physical and electronical design of the SalDecS in Section 2. The wind tunnel and field experiments are described in Section 3, followed by the results (Section 4). In Section 5 we discuss the linearity and equal sensitivity of the SalDec sensors. We finish with the conclusions in Section 6.

Fig. 1. Saltation Detection System installed at the beach. The horizontally oriented array contains 32 sensors, spaced with an interval of 0.10 m and the vertical array at the left end contains 8 sensors. A sonic anemometer is additionally present just to the right of the middle of the horizontal bar.

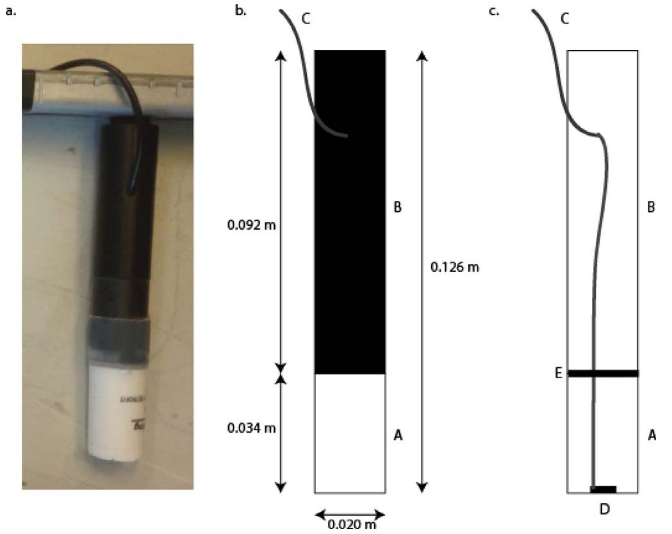

Fig. 2. Physical design of a Saltation Detection sensor, with a) photo, b) schematic exterior view and c) schematic interior view. The separate parts are A) sensor head, B) PVC-body, and C) wire to base unit, D) piezo-electric element, and E) silicone membrane.

2. Instrument description

The Saltation Detection System (SalDecS) (Fig. 1), developed and manufactured at the Department of Physical Geography of Utrecht University, The Netherlands, comprises 40 individual SalDec sensors on a carrier bar. Below, we first describe the physical design and electronics of the SalDec sensor in Sections 2.1 and 2.2, respectively. This is followed by a description of the full 40-sensor SalDecS in Section 2.3.

2.1. Physical design of the SalDec sensor

A SalDec sensor (Fig. 2) is a tubular instrument, inspired by the design of the Safire (Baas, 2004), the Buzzer Disc (Sherman et al., 2011) and the Sensit (Stockton and Gillette, 1990), and consists of a sensor head (A, Fig. 2) mounted to a tubular body of PVC with a length of 0.092 m and a diameter of 0.020 m (B, Fig. 2). The sensor head of the saltation sensor is constructed out of the PVC housing of a TL lighting starter (brand: Sylvania, type: FS-22 RAF, mean wall thickness: 7.8×10^{-4} m) and has a curved surface area with a height of 0.034 m and an outer diameter of 0.020 m. The total sensing area facing saltation transport is thus 1.07×10^{-3} m^2. Double-sided tape, with a thickness of 2.3×10^{-4} m, was used to glue a piezo-electric element (brand: Murata, type: 7bb-12-9) inside the center of the bottom of the sensor head. The nearly invariable thickness of double-sided tape enables the reproducible assembly of the piezo-electric element and sensor head, and thus an equal transfer of vibrations in every sensor. The cabling from the piezo-electric element leaves the sensor via a mounting hole in the PVC body (C, Fig. 2). To limit the detection of noise vibrations from outside the sensor head, vibrations are mechanically damped at two locations. Firstly, the sensor head is connected to the sensor body with a rubber shock absorber (brand: Saint-Gobain Performance Plastics, type: Folding Skirt Stopper DX467020-20) (E, Fig. 2). Secondly, the sensor is screwed to the carrier bar via a rubber grommet. In this way, sand grains hitting the sensor body or the carrier bar will not be detected by the piezo-electric element.