Coastal Engineering 99 (2015) 148–166

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Land–sea interaction and morphogenesis of coastal foredunes — A modeling case study from the southern Baltic Sea coast

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ARTICLE INFO

Article history:
Received 8 November 2014
Received in revised form 13 March 2015
Accepted 16 March 2015
Available online 28 March 2015

Keywords:
Coastal dunes
Aeolian transport
Cellular automata
Extreme wind event
Vegetation

ABSTRACT

Coastal foredunes are developed as a result of the interplay of multi-scale land–sea processes. Basic driving mechanisms of coastal foredune morphogenesis as well as natural processes and factors involved in shaping the foredune geometry are quantitatively studied in this paper by a numerical model. Aeolian sediment transport and vegetation growth on the subaerial part of a beach is simulated by a cellular automata (CA) approach, while the sediment budget in the subaqueous zone, serving as a sediment source/sink for the foredune ridges, is estimated in a process-based model. The coupled model is applied to a 1 km-long section of a barrier coast (Swina Gate) in the southern Baltic Sea for a 61-year (1951–2012) hindcast of its foredune development. General consistency is shown between the observational data and simulation results, indicating that the formation of an established coastal foredune results from a balance between wind-wave impacts and vegetation growth. Driven by an effective onshore wind and a boundary sediment supply, small-scale dunes develop on the backshore and migrate landward. They are then trapped in a narrow strip characterized by a large density gradient of vegetation cover which separates the hydrodynamically-active zone and the vegetated zone. Continuous accumulation of sediment in this strip induces the development of a foredune ridge. According to the simulations, the formation of an established coastal foredune has to meet three preconditions: 1. an effective onshore aeolian transport; 2. a net onshore or lateral sediment supply; and 3. a climate favoring vegetation growth. The formation of a new foredune ridge in front of an already existing foredune is determined by a combination of the sediment supply rate, the extreme wind-wave event frequency and the vegetation growth rate. Simulation results demonstrate a remarkable variability in foredune development even along a small (1 km) coast section, implying that the medium-to-long term land–sea interaction and foredune morphogenesis is quite sensitive to boundary conditions and various processes acting on multi-temporal and spatial scales.

1. Introduction

Dunes are a common morphological feature in many coastal and arid environments. The basic factors involved in the formation of a dune are a certain amount of movable sediment on the surface, a flow (of e.g., water or air) acting on the bed surface which is strong enough to transport the sediment and an obstacle or perturbation which triggers a settling of the moving sediment. However, although the mechanism for the formation of a dune is clear, combinations of different flow strength and directions, sediment properties (e.g., grain size and composition), constraints of local topography and boundary conditions (e.g., source supply) can lead to quite different and complex dune patterns (Werner, 1999; Kocurek and Ewing, 2005). The interplay among aeolian transport, vegetation cover and hydrodynamic forces (e.g., storms) makes the morphological development of coastal dunes even more variable compared to dunes in an arid environment (e.g., desert) and imposes challenges to researchers for a comprehensive study of the dune morphogenesis (Hesp, 2002).

Among various dune patterns developed at the backshore, foredunes are most vulnerable as they stand at the foremost seaward line on the edge of the backshore, persistently reshaped by hydrodynamic and aerodynamic forces. Foredunes are able to develop where winds are effective in moving sediment onshore and a trapping of the moving sediment by a line of shore-parallel obstacles exists. This trapping of sediment is usually caused by vegetation (e.g., pioneer grasses and shrubs). Foredunes can range from relatively flat terraces to markedly convex ridges (Hesp, 2002) due to a variation of the driving wind spectrum, the sediment supply, the vegetation coverage and the growth rate. On a longer time scale their morphology is affected by climate change such like sea level oscillations (Tamura, 2012). Morphological development of a coastal foredune can be generally divided into three phases: incipient (or

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http://dx.doi.org/10.1016/j.coastaleng.2015.03.005
0378-3839/

embryo) period, established period, and relict period (Hesp, 2002). However, as there are many environmental factors (e.g., wind strength and direction, storm frequency, beach width and migration, vegetation growth, sea level change) involved in the evolution of foredunes, some natural coastal foredunes may not go through all these three phases. For example, the foredune plains developed on a barrier coast (Swina Gate) at the southern Baltic Sea (as shown in Fig. 1) are characterized by well-preserved established sequences with a relatively stable accretion rate during the last several millenniums (Reimann et al., 2011).

Foredune dynamics is investigated usually within a framework of beach–dune interaction (e.g., Psuty, 1988; Hesp, 2002; Saye et al., 2005; Ollerhead et al., 2012). Cycles of sediment exchange between the foredune system and the beach, and between the beach and the nearshore submarine zone are recognized in this framework, within which processes involved in the beach–dune interaction and foredune evolution are studied at a range of spatial and temporal scales. On a short-term scale characterized by a temporal scale of seconds to days and a spatial scale of tens of meters, considerable efforts and progress have been made by field experiment (e.g., Hesp, 1983; Arens, 1994; Davidson-Arnott et al., 2005; Bauer et al., 2009) and modeling (e.g., Kriebel and Dean, 1985; Arens et al., 1995; Bauer and Davidson-Arnott, 2003; Jackson et al., 2011) to improve the knowledge about mechanisms that control the morphological development of coastal dunes. For the medium-term (temporal scale of months to decades and spatial scale of hundreds to thousands of meters) and long-term (temporal scale of centuries to millennia and spatial scale of kilometers to tens of kilometers) morphological evolution of coastal dune fields most of the existing studies are conceptual and descriptive (e.g., Hesp, 1988, 2002; Sherman and Bauer, 1993; Orford et al., 2000; Aagaard et al., 2007; Anthony et al., 2010; Reimann et al., 2011; Ollerhead et al., 2012; Tamura, 2012; de Vries et al., 2012). Only recently numerical modeling became a tool for investigation of medium-to-long term coastal dune morphogenesis (e.g., Baas, 2002; Nield and Baas, 2008; Luna et al., 2011). Morphogenesis of some coastal dune types such as parabolic, nebkha and transgressive dunes has been studied numerically. However, there seems to be still a lack of a numerical model which is able to simulate a complete morphogenesis and evolution of coastal foredunes and foredune sequences on a medium-to-long term, probably due to the multi-scale characteristics of the physical and biological processes acting on a beach system and technical challenges in accurately describing the morphological response of the system to these processes.

In fact, although a coastal system is composed of two parts, i.e., subaqueous and subaerial, little effort has been done to combine these two parts into one integrated numerical model. Existing modeling studies on medium-to-long term coastal morphological evolution may underestimate the contribution of the subaerial coastal part to the whole system, especially the role of fordunes played in the transition between land and sea (Zhang et al., 2012). Thus, the main target of this

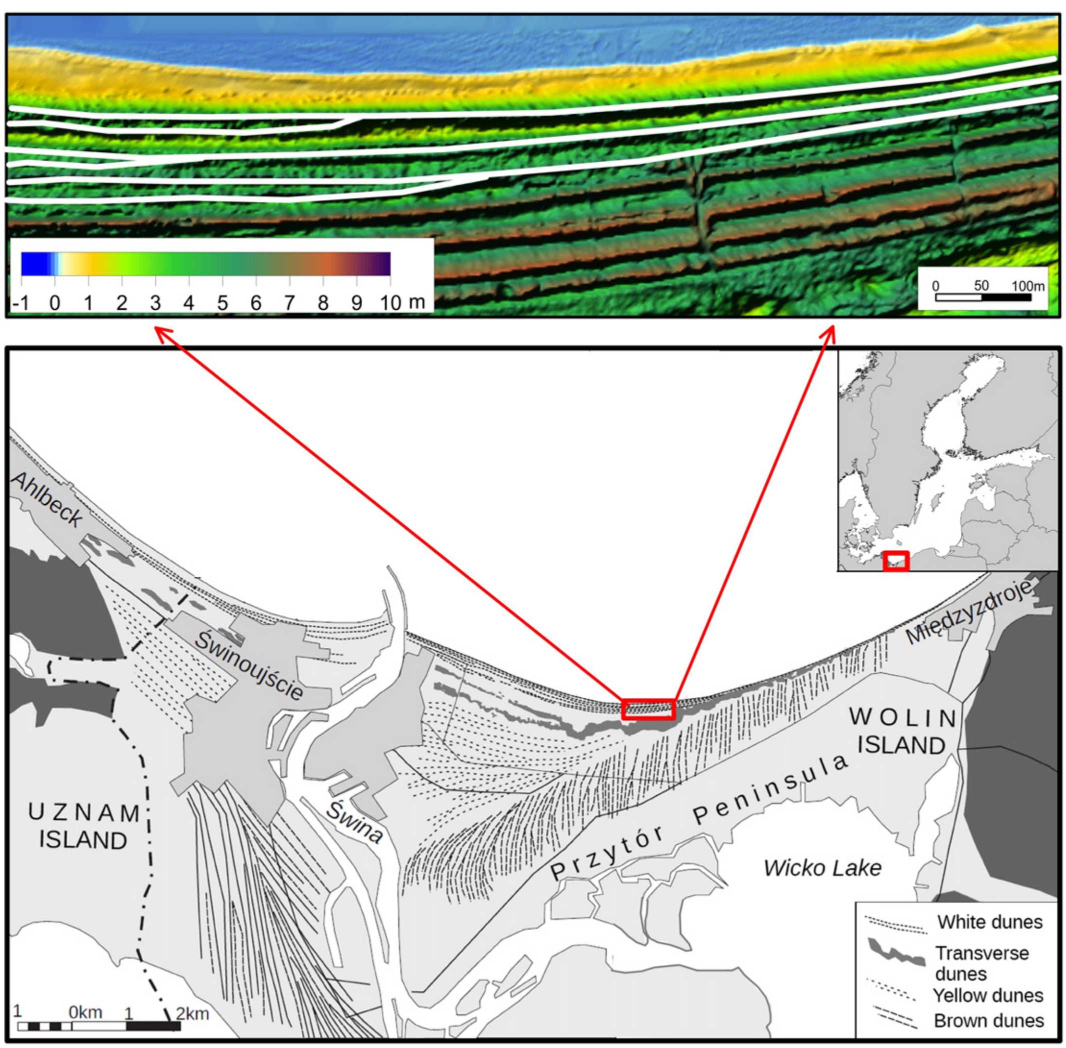

Fig. 1. The Swina Gate barrier (southern Baltic Sea) with its well-preserved foredune sequences (modified from Łabuz, 2005). The foredune ridges developed since 1951 in a 1 km-long section of this system are marked by white lines in the upper panel.