



Sandy berm and beach-ridge formation in relation to extreme sea-levels: A Danish example in a micro-tidal environment



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ABSTRACT

The formation of berms and their transformation into beach ridges in a micro-tidal environment is coupled to wave run-up and overtopping during extreme sea levels. A straight-forward comparison between extreme sea levels due to storm-surges and active berm levels is impossible in the semi-enclosed bays along the Baltic Sea. Quite often, the maximum water levels do not coincide with the maximum intensity of the wave driven processes because of seiches in the Baltic. In this paper, we look into the joined distribution of extreme water levels and high-energetic wave conditions at Feddet, a sandy prograding spit on the south-eastern Baltic shores of Zealand, Denmark. The modern, sandy beach at this location consists of a beachface with a shallow incipient berm, a mature berm, and a dune-covered beach ridge. It borders a beach-ridge plain to the west, where more than 20 N–S oriented beach ridges and swales are present. Measured water-level data from 1991 to 2012 and topographical observations, carried out during fair weather period and during a storm event, provided the basis for a conceptual model exhibiting berm formation and transformation into the local beach-ridge system. The character of extreme sea level events is identified using thirty-three well described extreme events throughout a period of 15 years. Analysis of the meteorological conditions during these events revealed that berm formation only occurred during 20% of all extreme events when onshore winds, high-energy wave action and elevated water coincided. These berm-forming events had a mean return period of once every three years. The average age between successive beach ridges on the beach-ridge plain was about 180 years, which means that the transformation of a berm into a single beach ridge is the result of a large number of storm episodes with high-energy waves and extreme water levels.

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1. Introduction

Berms, beach ridges, and their intermediate swales have been discussed by many geomorphologists and other scientists in the last century (e.g., Johnson, 1919; King, 1959; Psuty, 1967; Hine, 1979; Komar, 1998; Isla and Bujaleski, 2000; Otvos, 2000; Neal et al., 2003; Clemmensen et al., 2012) and various definitions of these coastal landforms exist. A berm is a depositional feature on the beach near the highest water line and it is the active equivalents of a beach ridge (Otvos, 2000). The formation of berms is still under debate (e.g. Taylor and Stone, 1996; Isla and Bujaleski, 2000; Otvos, 2000; Rodriguez and Meyer, 2006; Nott et al., 2009; Clemmensen et al., 2012). Most authors state that elevated water levels and high-energy waves during storms are essential for berm formation (e.g., Johnson, 1919; Hine, 1979; Sandweiss et al., 1998; Komar, 1998; Isla and Bujaleski, 2000; Neal et al., 2002; Hesp et al., 2005; Weir et al., 2006; Nielsen and Clemmensen, 2009; Nott et al., 2009; Clemmensen et al., 2012), while few argue that berm formation occurs during fair-weather processes (e.g. Tanner, 1995). Previous studies on berms and beach

ridges have often been qualitative and they have focused on conceptual models of berm formation. Psuty (1967) studied internal structures of a prograded beach-ridge system in Tabasco, Mexico and differentiated between summer and winter beach profiles. He argued that sediment transported onto the upper beachface in a summer profile was deposited during high water events with energetic wave conditions to construct a berm. Net progradation of beach ridges on a beach-ridge plain (inactive berms) thus occurred by seasonal variation in wave energy and water levels. Hine (1979) studied a spit in Cape Cod, Massachusetts and presented three different mechanisms for berm development: the first mechanism was controlled by significant differences in spring and neap tide conditions, the second mechanism was attributed to the migration of a swash bar and its welding onto an existing bar, and the third mechanism pointed at the development of wide, broad swash bars built close to spring tide level forming a berm. Bascom (1953) described the berm height paradox where he noted that “storm waves which erode a beach also build a berm during the erosion”. This was also recognized by Carter (1986) who stated that “the major storms, responsible for the ridge sand supply, are often the agents of destruction for the preceding ridge”. The berm receives material and grows vertically as material is added to the berm during these high energy periods. Simultaneously, the lower part of the upper beachface is

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eroded and flattens during these periods (Masselink et al., 2006). Nielsen and Clemmensen (2009) and Clemmensen et al. (2012) studied a modern beach-ridge system in a microtidal environment at Anholt along the Kattegat, a semi-enclosed sea between the North Sea and the Baltic Sea in Denmark. They concluded that these berm ridges were formed under storms with elevated water levels and onshore sediment transport by waves near the water line.

The formation of a berm on a sandy beach is closely related to the behavior of bars and associated wave-related processes near the water line. The bars are oriented parallel to the coast and are present at coasts with shallow gradients (e.g. Bascom, 1953). The number of bars present on the beach is depended upon the wave height, the off-shore beach gradient, and the tidal range (e.g. Bascom, 1953). The bars migrate landward during low to moderate energy conditions (Wijnberg and Kroon, 2002; Masselink et al., 2006) and the upper intertidal bar merges with the beachface and is deposited as a shallow ridge on the upper beachface. After merging, the bar has formed an incipient berm. Berms are characterized by a wedge-shaped, relatively narrow ridge parallel to the coast (e.g. Otvos, 2000). The berm experiences overwash during succeeding high water levels and onshore sediment transport, and material is deposited on top and landward of the berm. This causes the berm to grow both vertically and horizontally (Masselink et al., 2006; Weir et al., 2006) and the berm becomes a mature berm. During a storm, the elevated water levels rise and the total storm wave run-up, i.e. the mean water level plus the wave set-up and the wave run-up, increases, and material is deposited on top and landward of the mature berm. The height of the storm berm crest reflects the limit of wave run-up during the storm episode (Okazaki, 1996; Wells, 1996; Komar, 1998, among others). The berm can become inactive if a coast progrades and a new berm forms further seaward on the beach. When the berm is no longer affected by waves, the correct term for the feature would therefore be beach ridge.

In general, the maximum level of the berm crest on beaches is closely related to the local storm water level and the exposure of beaches to wave impact. The measured water level during a storm flood is an addition of at least five components: the astronomic tide level, the storm surge level due to the passage of a low-pressure system and due to the wind set-up, the wave set-up level due to the propagation of waves in the inner nearshore zone and the wave run-up due to the swash and backwash on the beach. An estimation of these water level components on the beach is based on different theories and data sets. The astronomic tide level, which is based on the site-specific harmonic components, is small (under 0.20 m) and tidal predictions are based on data of the Danish Maritime Safety Administration. Storm surge level due to the passage of a low-pressure system is estimated by a simple relation: a change of 10 hPa atmospheric pressure induces a reversed response of the water level by 0.10 m. The local wind set-up is estimated by a simple semi-empirical relationship (Pugh, 2004):

$$S = \Delta z / \Delta x = (C_d \rho_a W^2) / (\rho g d) \quad (1)$$

with S is the surface gradient of the water level, z is the vertical water level adjustment over a cross-shore distance x , $C_d = (0.8 + 0.065 W) \cdot 10^{-3}$, ρ_a is atmospheric density ($1293 \text{ kg} \cdot \text{m}^{-3}$), W is the wind velocity, ρ is the water density ($1020 \text{ kg} \cdot \text{m}^{-3}$), g is the gravitational acceleration ($9.82 \text{ m} \cdot \text{s}^{-2}$) and d is the mean depth of the water. A wave transformation model based on an energetic approach is used to estimate the propagation of waves over a cross-shore profile (e.g. Grasmeyer and Ruessink, 2003). The wave set-down and wave set-up in the nearshore zone are included in this model by using the classical radiation stress theory equations. The wave run-up due to the swash and backwash on the beach is estimated with simple relationships from Stockdon et al. (2006). However, the wave run-up is

not directly influencing the mean water levels, but does have an impact on overtopping and flooding.

Beach ridges have been used as indicators of ancient shorelines (Thompson, 1992; Calhoun and Fletcher, 1996; Wells, 1996; Otvos, 2000; Nichol, 2002; Bristow and Pucillo, 2006; Rodriguez and Meyer, 2006; Bjørnsen et al., 2008; Clemmensen and Nielsen, 2009), as proxy of fluctuations in lake- or sea-levels (Bigarella, 1964; Alexander, 1969; Thompson, 1992; Lichter, 1995; Tanner, 1995; Delcourt et al., 1996; Rodriguez and Meyer, 2006; Fernández-Salas et al., 2009) or as indicator for a paleo storm climate (Nott et al., 2009). Successive beach ridges on a beach plain have thus been used to construct paleo sea-level curves (Turq et al., 1986; Zazo et al., 1994; Taylor and Stone, 1996; Wells, 1996; Bjørnsen et al., 2008; Clemmensen et al., 2012).

Many of these studies, however, have not addressed the correlation between the berm heights and the locally observed water level heights during ridge formation, and no detailed explanation of the formative conditions has been given. The correlation between berm height and water level is however essential to optimize geologic interpretations of beach ridges and relative sea-level curves in sedimentary records, and to improve predictive flooding-models and associated prediction of flooding-risks in exposed coastal areas. The purpose of the present paper is to present a conceptual model for sandy berm formation and transformation into beach ridges in micro-tidal environments and to discuss processes and formative agents during the formation of berms through analyses of thirty three high-water events between 1997 and 2012.

2. Study area

The peninsula Feddet is a sandy spit at the south-eastern shore of the island of Zealand in Denmark (Fig. 1). The spit faces the Baltic Sea and has a length of 5 km and a maximum width of 1.8 km and consists of a number of N–S trending beach ridges separated by swales. Most of the sediments on Feddet originates from eroding glacial bluffs in the north and are transported to the south by wave-driven alongshore currents. The northern part of Feddet is connected to the mainland and was subject to erosion during recent years. However, the central and southern part of the spit experienced accretion and progradation over at least the last 5000 years (Clemmensen et al., accepted for publication, submitted). The orientation of the east-facing coastline is N–S, and the study area is located at the central part of the coastline. The present beach at Feddet consists of a) several bars, situated both below and above mean sea-level, b) an incipient berm, c) a narrow trough, d) a mature berm, and e) a dune-covered beach ridge (Fig. 2).

This dune-covered beach ridge borders the active beach from the inactive beach-ridge plain. The sandy beachface is about 15 m wide and the mean beach slope is 5–8° in a seaward direction (Hede et al., 2013). The bars are shallow in height (about 0.20 m) and have a width of ca. 8 m. Their location and height change under varying meteorological conditions and associated waves and water levels. The narrow trough is partly covered with seaweed and shells. The mature berm exhibits a seaward dip of approximately 6° with a nearly flat landward side and thus exhibits a terrace structure. The landward located beach ridge is draped with aeolian sediments and covered by vegetation as *Leymus* (lyme grass). This dune-covered beach-ridge crest reaches a height of ca. 2 m above mean sea level.

The most frequent wind direction at Feddet is from the west (29%) with an associated mean annual wind speed of 6.6 m/s. Winds of strong gales only occur 5.1 day a year on average (Cappellen and Jørgensen, 1999). Waves along the beaches of Feddet are mostly of local character (sea) and small (significant wave height well below 1.0 m). The winds are often offshore directed, or the fetch is too limited to generate high energetic wave conditions. Waves over 1.0 m can only be expected in less than 10% of the time when they come from easterly directions with fetch lengths between 90 km (Swedish coast), 160 km (Bornholm), and over 300 km (south-eastern Baltic Sea). Swell

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