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The initial morphological response of the Sand Engine: A process-based modelling study

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ABSTRACT

Sand nourishments are presently widely applied to maintain or enhance coastal safety and beach width. Over the last decades, global sand nourishment volumes have increased greatly, and the demand for nourishments is anticipated to increase further in coming decades due to sea level rise. With the increase in nourishment size and the request for more complex nourishment shapes, an adequate prediction of the morphodynamic evolution is of major importance. Yet, neither the skill of current state-of-the-art models for such predictions nor the primary drivers that control the evolution are known. This article presents the results of a detailed numerical modelling study undertaken to examine the model skill and the processes governing the initial morphological response of the Sand Engine and the adjacent coastline. The process-based model Delft3D is used to hindcast the first year after completion of the mega-nourishment. The model reproduces measured water levels, velocities and nearshore waves well. The prediction of the morphological evolution is consistent with the measured evolution during the study period, with Brier Skill Scores in the 'Excellent' range. The model results clearly indicate that the sand eroded from the main peninsular section of the Sand Engine is deposited along adjacent north and south coastlines, accreting up to 6 km of coastline within just one year. Analysis of model results further show that the erosional behaviour of the Sand Engine is linearly dependent on the cumulative wave energy of individual high energy wave events, with the duration of a storm event being more dominant than the maximum wave height occurring during the storm. The integrated erosion volume due to the 12 events with the highest cumulative wave energy density accounts for about 60% of the total eroded volume of the peninsula, indicating that the less energetic wave events, with a higher probability of occurrence, are also important for the initial response of the Sand Engine. A structured model experiment using the verified Delft3D model indicates that wave forcing dominates the initial morphological response of the Sand Engine, accounting for approximately 75% of the total erosion volume in the first year. The vertical tide is the second most important factor accounting for nearly 17% of the total erosion volume, with surge, wind and horizontal tide playing only a minor role.

1. Introduction

Around 75% of the Dutch coast consists of dune areas that provide protection from flooding for the low-lying hinterland [4,30]. Besides that, the sandy coast is also important for ecological and recreational functions and fresh water extraction. Large sections of the Dutch coast have been eroding for centuries [40,36,37,41] which has traditionally been negated with measures such as groynes and/or managed retreat, and since the 1990s, beach/shoreface nourishments. Over the years, the total annual sand nourishment volume along the Dutch coast has steadily increased [10,6] to its present value of approximately 12 million m^3/yr.

In 2008, a Dutch State Committee (the 2nd Delta Committee [33]) provided critical advice for protecting the Dutch coast and the low-

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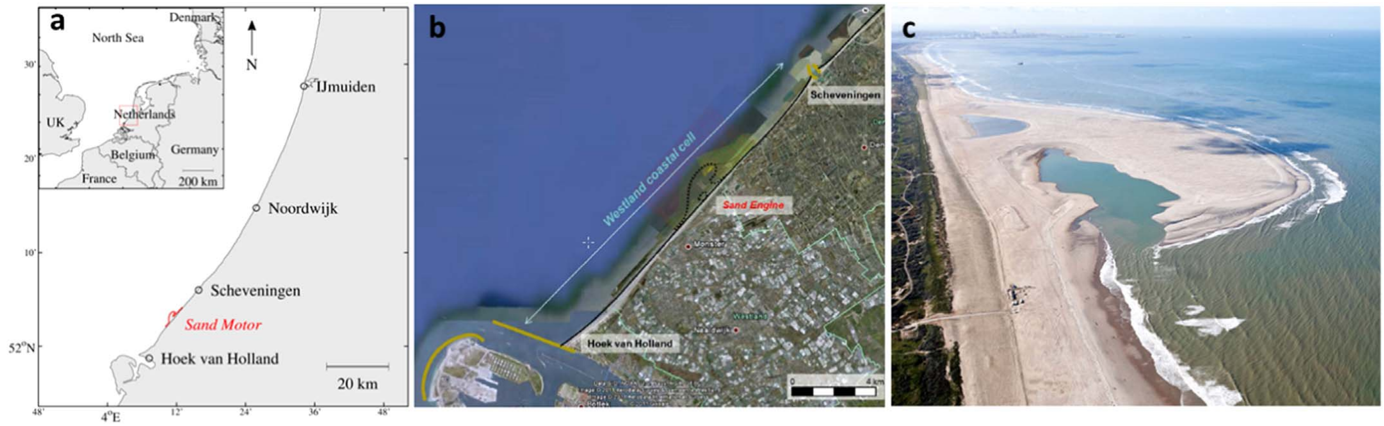

Fig. 1. (a) Overview of the Dutch Coast, (b) the Delfland coast showing the location of the Sand Engine (harbour structures in yellow), and (c) aerial photograph of the Sand Engine in July 2011 just after construction (courtesy: Rijkswaterstaat/Joop van Houdt). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this paper.)

lying hinterland from the consequences of foreshadowed climate change in the 21st century. In line with a key recommendation of the Delta Committee, an innovative pilot project was developed to achieve a more efficient and sustainable nourishment approach; the Sand Engine ('Zandmotor' in Dutch; hereafter referred to as ZM). This mega-nourishment, built in 2011 along the Delfland coast (see Fig. 1a) consists of a total sediment volume of 21 million m^3. The ZM is a combined beach/shoreface nourishment and consists of a manmade peninsula of about 128 ha [32]. It is expected that over the next 20 years, natural coastal processes will redistribute the sand in the peninsula along the coast between Hoek van Holland and Scheveningen (see Fig. 1b and c), leading to an increase of the footprint of the dunes of 33 ha [20].

The scale of the ZM is unprecedented for a sand nourishment. A comprehensive multidisciplinary five-year monitoring programme was launched in 2011 to monitor and investigate multiple aspects of the initial ZM evolution and coastal response to the ZM. The monitoring campaign provides valuable data on both the forcing conditions and the behaviour of the ZM. However, the observed morphological behaviour cannot be directly related to specific forcing conditions due to the relatively low temporal resolution (~monthly) of the bathymetric surveys of the ZM. A numerical model that to a high degree of detail can reproduce the observed behaviour is therefore the only means of understanding the physical processes that govern the initial evolution of the ZM and the adjacent coast. Therefore, this study uses data acquired in the first 12 months following the completion of the ZM (August 2011–August 2012) in conjunction with state-of-the-art process based morphodynamic modelling to gain insights into the initial response of the nourishment and the adjacent coastline as well as the dominant physical processes. The study period of the first 12 months is selected here to focus on the initial development from a man-made shape to a more smooth shape, a transition which is poorly produced in one line models and vital to the overall development [11]. These insights are anticipated to provide a guide for other large-scale sandy strategies such as artificial islands, land reclamations, (mega-) nourishments worldwide.

Specifically, this study attempts to answer the following:

(1) Can a state-of-the-art 2DH process-based morphodynamic model reproduce the initial morphological evolution of the ZM and the adjacent coast with sufficient accuracy?
(2) What are the forcing conditions that govern the initial morphological evolution of the ZM?

This article is arranged as follows. Section 2 introduces the ZM project and the available monitoring data used in this study. In Section 3 the morphodynamic modelling approach, verification, and the evaluation of the model performance are described. Section 4 investigates the relationships between environmental forcing and the initial morphological evolution of the ZM and the adjacent coast as well as the relative contribution of the different forcing mechanisms. Finally, Section 5 presents the conclusions of this work.

2. The Sand Engine project

2.1. Coastal setting

The Delfland coast is the southern section (16.5 km) of the Holland coast between Hoek van Holland and Scheveningen (see Fig. 1a and b). The nearshore zone is characterised by a rather uniform, gradually sloping beach profile with occasionally a nearshore bar [42]. The width of the dune area from the dune foot varies from narrow (i.e. 150–250 m width) in the central section of the Delfland coast to very wide (500 m width) at Hoek van Holland and just north of the ZM. The dune height is generally between NAP +10 m to NAP +15 m, but locally, dunes can reach over NAP +20 m.

The tide at Scheveningen is semi-diurnal with a spring/neap tidal amplitude of 1.98/1.48 m. The tide is asymmetric with on average a rising period of 4 hours and 21 minutes, while the falling period lasts for about 8 hours. This causes asymmetric alongshore velocities with maximum flood tidal currents of 0.7 m/s (northeast directed) and maximum ebb tidal currents of 0.5 m/s (southwest directed). The 1-year return period surge level at Hoek van Holland is 2.35 m.

The wave climate along the Dutch coast shows little spatial variation but is characterized by a distinct seasonal signal with average winter (Nov–Jan)/summer (Apr–Aug) offshore wave heights (H_s) of 1.7/1 m. Small waves ($H_s < 1$ m) originate predominantly from the northwest, average waves ($1.5\ m < H_s < 3.5$ m) predominantly from both the southwest and northwest while the highest waves ($H_s >$ 4.5 m) originate predominantly from the west and northwest (see Fig. 2a). The 1-year return period offshore wave height H_s is 4 m.

The Delfland coast consists of sandy beaches with an average median grain size (D_{50}) of 242 μm with a standard deviation of about 50 μm [43]. Previous studies on the sediment transport along the Dutch coast indicate a northward longshore transport between 50,000 to 170,000 m^3/year at the location of the ZM [36,35]. Near Hoek van Holland the alongshore sediment transport is completely blocked due to the presence of a large groyne called the *Noorderdam* protruding 4.2 km into sea (see Fig. 1b). In contrast, the relatively small harbour moles of Scheveningen harbour allow sediment bypassing. The Delfland coast is subject to chronic erosion due to the sediment demand by neighbouring tidal inlet systems, relative sea level rise