

MORPHOLOGICAL DEVELOPMENT OF A MEGA-NOURISHMENT; FIRST OBSERVATIONS AT THE SAND ENGINE

M.A. de Schipper^{1,2}, S. de Vries¹, M.J.F. Stive¹, R.C. de Zeeuw², J. Rutten³, B.G. Ruessink³, S.G.J. Aarninkhof⁴ and C. van Gelder-Maas⁵

Large (mega-scale) nourishments have been proposed as a promising alternative for traditional beach and shoreface nourishments, especially for locations with large structural erosion and sufficient sediment to dredge. This paper examines the initial bathymetric evolution of the Sand Engine, a mega-nourishment of 17 million m³ protruding almost 1 km seaward from its surrounding coast. Topographic surveys show that, despite the blunt initial shape of the nourishment, the sediment is reworked into a nearly symmetrical (bell curve like) shape in less than 1.5 years. The cross-shore extent decreased by 150 m in this period which is a reduction of 15 % of its original extent. Simultaneously, the alongshore size of the nourishment increased by 60 % as the sediment is redistributed to the adjacent coasts. This is also reflected in the large 1.6 million m³ loss of sediment on the peninsula. Almost 70 % of this volume is found to accrete in adjacent coastal sections. Although not all sediment loss from the peninsula could be relocated, the findings reveal that the Sand Engine mega nourishment is feeding its surrounding coast substantially.

Keywords: feeder nourishment ; mega nourishment ; coastal safety

INTRODUCTION

The aim of the current paper is to discuss the evolution of the Sand Engine ('Zandmotor' in Dutch) nourishment in the first 18 months after construction. Large parts of the Dutch coast are chronically eroding and nourishments are used to mitigate the erosion starting from the last century onwards (Hanson et al., 2002). As nourishment volumes are projected to increase, alternative methods to apply large quantities of sediment to the coast are proposed (Stive et al., 2013). The Sand Engine peninsula is a first pilot project for a concentrated mega-nourishment, designed to feed a wide stretch of coast and increase the time interval between nourishments. It is located between the cities of Rotterdam and The Hague on the west coast of the Netherlands, and faces the shallow (20-80 m deep) North Sea basin. After its construction in July 2011 (Fig. 1, left), the peninsula is approximately 1 km in seaward direction and 2 km along its base. Its highest point is +7.3 m above sea level which is well above the average annual storm surge level. No vegetation, buildings or roads are present on the peninsula. The volume of the peninsula is over 17 million m³ and the envisioned lifetime is in the order of 15 years. This reflects the average annual amount of sediment that has been nourished in this coastal cell, which is about 1 million m³. However, being the first of its kind and a difficult shape to forecast in a numerical morphodynamic model, it was beforehand not exactly clear what lifetime and behavior could be expected at the Sand Engine or such mega nourishments in general.



Figure 1: Aerial pictures of the Sand Engine peninsula in July 2011 (left) and October 2012 (right). Images courtesy of the Dutch Ministry of Infrastructure and the Environment/Joop van Houdt.

¹ Faculty of Civil Engineering and Geosciences, Section of Hydraulic Engineering, Delft University of Technology, Delft, The Netherlands.

² Shore Monitoring and Research, The Hague, The Netherlands.

³ Department of Physical Geography, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands.

⁴ Royal Boskalis Westminster NV, Hydronamic, Papendrecht, The Netherlands. Also at: EcoShape, Building with Nature, Dordrecht, The Netherlands.

⁵ Dutch Ministry of Infrastructure and the Environment.

The aerial photographs in Figure 1 show substantial changes in the shape of the coastline in the first period after construction. Next to these photographs, regular topography surveys are executed as part of a broad multi-disciplinary monitoring campaign. In this paper these topography data are used to quantify the development of the Sand Engine based upon three main aspects: 1. The change in the coastline (mean sea level isobath) position and the plan form shape of the nourishment, 2. The sediment budgets of the peninsula and the adjacent coastal sections, and 3. The impact of seasonality on the feeding of adjacent coastal sections in the first period.

METHODOLOGY

Regular (nearly monthly) topographic surveys of the peninsula and adjacent coastal sections are executed since the completion of the nourishment works in July 2011. The survey domain extends in cross-shore direction from the dune fence (at approximately 4 m NAP⁶) to beyond the -10 m NAP depth contour and covers an alongshore stretch of nearly 5 km. The alongshore spacing between transects is about 80 m in the offshore region and is refined to about 40 m in the dynamic marine zones such as the surfzone and near the lagoon entrance. At important areas these are complemented with measurements along the isobaths to capture changes around scarps and (tidal) gullies on the length scales of 10's of meters (Fig. 2). The sections of the transects below the low tide water level, - 0.5 m NAP, are measured using a PWC (jetski) survey system (van Son et al., 2010), sub-aerial parts of the profile are measured using an ATV (quad bike), and shallow runnels and channels are surveyed by walking a wheeled GPS.

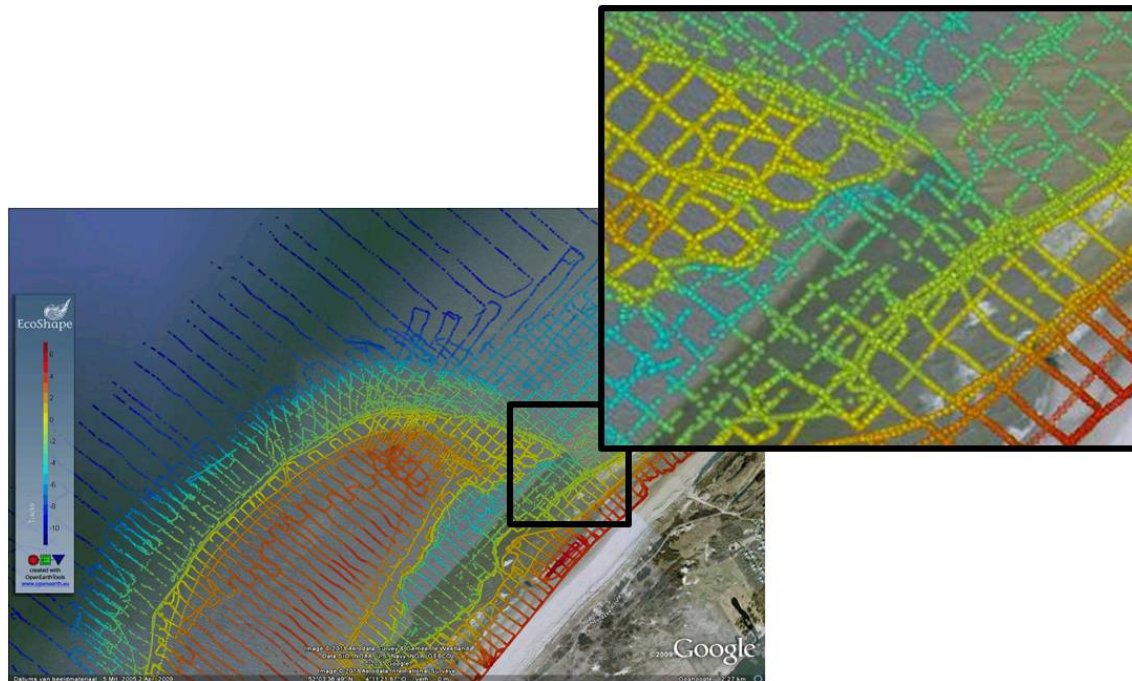


Figure 2: Combined jetski, quad and wheeled survey points (x_p, y_p, z_p) for the November 2011 survey. Colors indicate the height of the bed. Image data: Google, Aerodata.

The x_p, y_p, z_p point data of all three survey platforms are combined and rotated to a local shore-orthogonal coordinate system. For the upcoming analyses the data are presented in the shore-orthogonal coordinate system and are linearly interpolated to a 10 by 10 m rectangular grid.

RESULTS

General observations

Similar to the aerial photographs, the topography maps from the surveys show a redistribution of sediment in the region around the peninsula (Fig. 3). From the construction onward, a spit-like feature devel-

⁶NAP is the Dutch vertical datum at approximately mean sea level

oped on the northern edge of the peninsula. After approximately 4 months this spit reached the original shoreline, and the entrance of the lagoon was restricted to a small discharge channel at low tide. The inflow and outflow of the tide (with tidal range of 1.7 m on the open coast) in the lagoon caused velocities in the channel of $O(1 \text{ m/s})$. Over time, this lagoon-discharging channel has been elongating and the initial spit like feature has evolved to a large tidal flat. After about a year, the channel started to meander and bifurcated, such that new 'short-cut' channels have been formed on the tidal flat (Fig. 3, bottom). These channels were visually observed to migrate and meander on the timescale of days.

Over time the slopes in surf and intertidal zone flattened as the cross-shore profile adjusts (visible as the wider green and light blue bands in Fig. 3, bottom). Especially at the southern side (at alongshore location $y = -500 \text{ m}$) the intertidal zone is wide (of order 200 m) with multiple ridges and runnels. At this southern end the morphodynamic changes extend till the edge of the surveyed domain.

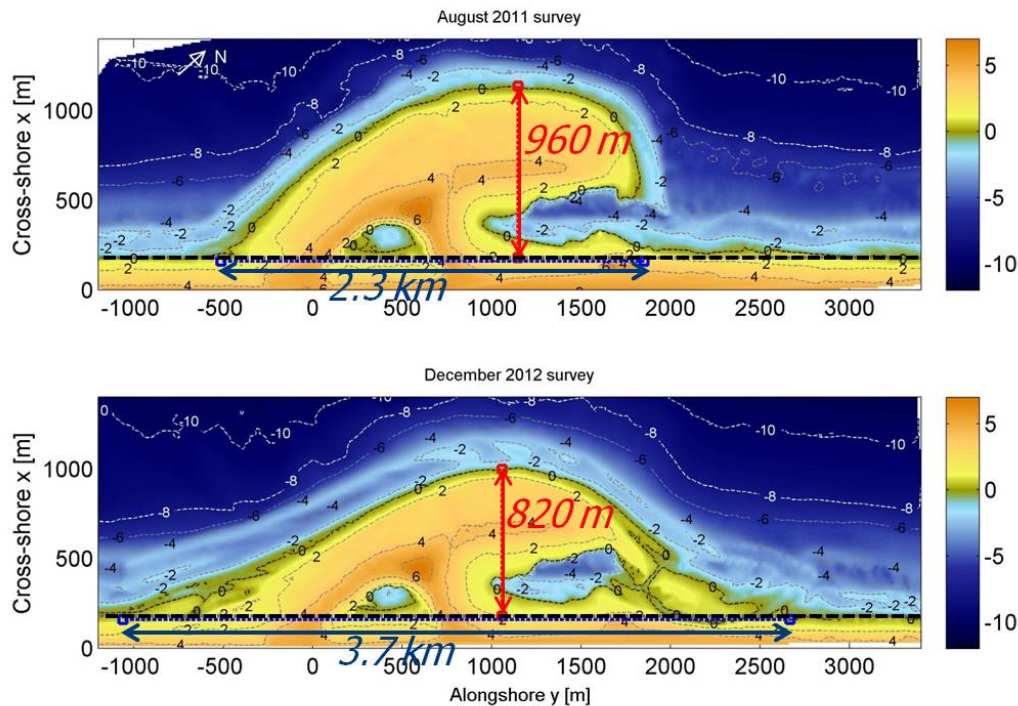


Figure 3: Measured topography shortly after completion of the Sand Engine in August 2011 (top), and in December 2012 (bottom). Colors indicate the height of the bed with respect to NAP (~MSL).

Along- and cross-shore extent

The redistribution of sediment causes a reduction in the cross-shore width and an increase in the along-shore size of the peninsula. To quantify the changes the position of the most seaward location of the 0 m NAP (~MSL) isobath was traced for the first and last survey (Fig. 3). The extent is then given by comparison to the position of the 0 m contour prior to the construction (Fig. 3, dashed line). Before the construction of the peninsula, the coast was nearly alongshore uniform. The dunes started at cross-shore location $x=0$ and beach widths were about 150 m meter. After construction, in the first survey, the peninsula was at its widest point 960 m seaward from its prior position. After 18 months this has reduced to 820 m, which is a retreat of the waterline of about 150 m. Simultaneously, an expansion of the nourishment in alongshore direction was observed. The spit and tidal flats area formed on the northern side; on the southern side the sharp concavity in the coastline has filled in. As a result the alongshore extent has increased from 2.3 km to 3.7 km, which is a lengthening of 1.4 km.

Planform shape

The planform shape has altered significantly with the changes in the morphology. Just after construction the shape of the peninsula is rather blunt. After 18 months it has however become nearly symmetric. The planform shape of the most seaward location of the 0 m isobath is shown in Figure 4. Almost along the full outer edge a retreat of about 140 m can be observed. The erosion and accretive sections reshape the nourishment such that it resembles a bell curve with erosion seaward of the inflection points and accretion towards the original coastline.

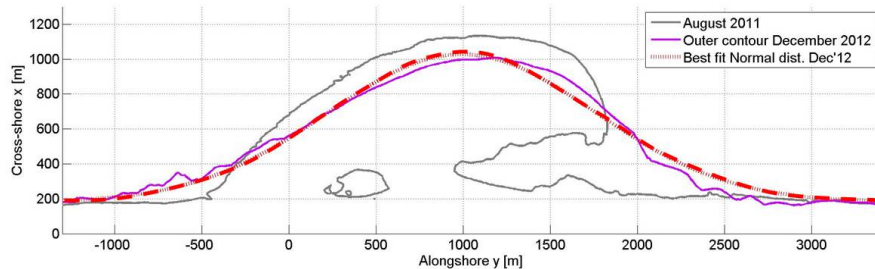


Figure 4: Change in the planform shape of the nourishment. Lines indicate the 0 m NAP isobath in August 2011 (in gray), the most seaward location of the 0 m NAP isobath in December 2012 (in purple) and the best fit normal distribution approximation of the December 2012 outer contour (red).

A normal distribution function is fitted to the outer contour positions x_0 , to visualize to what extent the shape has become symmetric and a Gaussian hump. To this end a standard normal distribution function is used, giving the approximation x_0^* of the shoreline as function of alongshore location y :

$$x_0^* = a_1 \exp \left\{ - \left(\frac{y - b_1}{c_1} \right)^2 \right\} \quad (1)$$

where a_1 , b_1 and c_1 are fitting parameters that control the amplitude, spread and lateral shift of the curve respectively. These fitting parameters are optimized on the least squares error between x_0 and x_0^* .

This normal distribution function fits well to the shape after 18 months, with linear regression parameter R^2 of over 0.9. When the data is compared with the normal distribution it shows a slight asymmetry, with the nourishment skewed northward. The origin of this skewness is part of ongoing research, and could be in part a remnant of the initial asymmetry in nourishment, or a result of the obliqueness in the wave climate. The resemblance between the perimeter and the Gaussian hump shape is of importance, as it implies that the nourishment quickly starts to resemble the classical case of diffusion of a nourishment.

Sediment budgets

An important quantification of the feeding behaviour of the nourishment is found by the bulk volumetric changes in the domain. The domain is hereto divided into two sub-domains, one encompassing the peninsula only and one for the adjacent coastal sections combined (Fig. 5). The volumetric changes in these sub-domains are calculated with respect to the first survey in August 2011.

Over the first 1.5 years a volumetric loss of 1.6 million m^3 was found at the peninsula alone. Although this is a large amount, it represents only $\sim 10\%$ of the original added volume of the peninsula. On the adjacent coastal sections a gain of sediment of ~ 1.1 million m^3 is observed, i.e. 70% of the sediment loss of the peninsula was compensated for by accretion in adjacent coasts. Although one cannot differentiate with this data between accreted sand originating from beyond the domain (i.e. blocked alongshore sediment transport) and the accreted sand originating from the peninsula, it seems reasonable to assume that a large part of the sediment accreted in these adjacent coastal sections is originating from the Sand Engine. Over the total survey domain a loss of 0.5 million m^3 is observed (Fig. 5), which could be in part due to the south end of the peninsula reaching the end of the survey domain (See also Fig. 3).

The volumetric changes and concurrent feeding of the adjacent coasts varies from month to month. The average wave conditions at the Dutch coast can be characterized as wind sea with short wave periods and an average waveheight of 1.2 m (Wijnberg, 2002). Periods with large (oblique) wave action are often found during autumn and winter. At the Sand Engine the magnitude of the volume changes are found to coincide

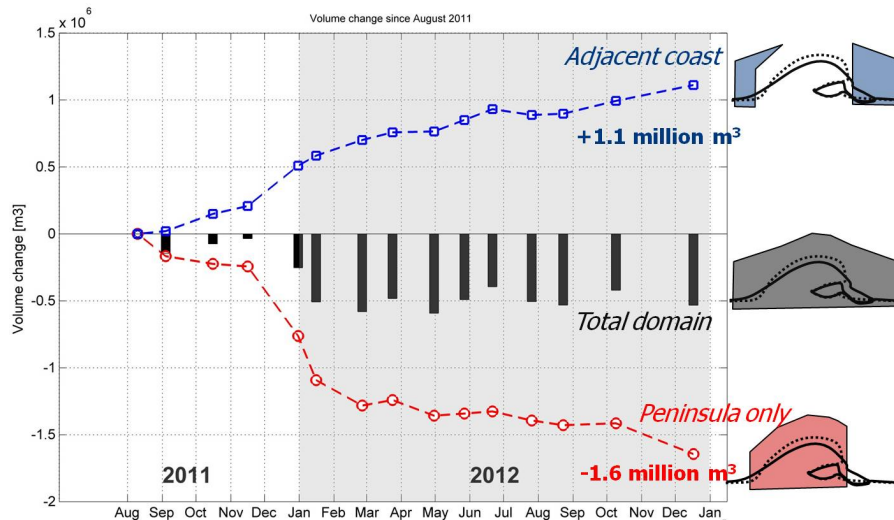


Figure 5: Cumulative volumetric changes of the Sand Engine peninsula (in red) and the combined adjacent coastal sections North and South (blue) with respect to the survey of August 2011. Black bars indicate the volume change in the total surveyed domain.

with months with strong wave forcing, where especially the severe storms of the winter of 2011/2012 caused large volumetric changes. In contrast, months with mild wave action (spring 2012) show hardly any change in volumes.

CONCLUSION & OUTLOOK

The present paper discusses the initial feeding of the Sand Engine nourishment in the period after its completion. During this period the topographic surveys show the following:

1. A rapid change in the outline of the nourishment. Although the nourishment shape is quite blunt initially, the outline is observed to quickly transform into a near symmetrical shape.
2. A large loss of sediment of about 1.6 million m³ is observed from the peninsula, about 10 % of the total added sediment. The majority of the sediment loss at the peninsula is compensated for by accretion on the two sides.
3. In this first period, the feeding from the peninsula to adjacent shores primarily occurs during the energetic months in fall and winter. In the first spring after construction the volumetric changes were small.

In all, topographic surveys show that the concentrated mega-nourishment has resulted in an increase in sediment volume on the adjacent coasts, thus 'feeding' its surrounding coastal sections. The man made shape and size of the nourishment also triggered behaviour unlike the adjacent coastal sections, e.g. tidal flat formation, meandering channels and large ridge runnel systems.

After the first period discussed here, topographic surveys are pursued on bimonthly basis. Data from these surveys and comparisons with numerical modelling will be reported in the upcoming years.

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