INITIAL SAND LOSSES AND LIFE SPAN PREDICTIONS FOR MEGA-NOURISHMENTS ALONG THE DUTCH COAST

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In the summer of 2011 about 19 million m^3 of sand was dumped near Ter Heijde, The Netherlands to protect the rather small beach-dune system at this location. On the long term this mega-nourishment will be gradually smoothed out along the coast, feeding the adjacent beaches and dunes. The initial sediment losses over the first years of this mega-nourishment have been modelled successfully using both 1D and 2DH coastal models. Based on a series of computations for mega-nourishments with various length-to-width ratios and volumes, design graphs for erosion rate and life span of mega-nourishments have been derived. These design graphs have been applied to estimate erosion volumes and maintenance volumes for mega-nourishments near Katwijk and Noordwijk, The Netherlands.

Keywords: mega-nourishment; coastal morphodynamics; process-based modeling; The Netherlands

INTRODUCTION

The Netherlands

The Netherlands is located in the Southern part of the North Sea and has a total coastline length of more than 400 km. (see Figure 1). Commonly the Dutch coast is divided into three regions: the Delta coast in the south, the Holland coast in the centre and the Wadden coast in the north. Some 15% of the coast consists of sea dykes and other man made sea barriers, some 10% are beach flats along the tips of the northern Wadden islands, 75% are dune areas of varying widths from less than 100 metres to several kilometres. About 60% of the sandy coast is subject to structural erosion.

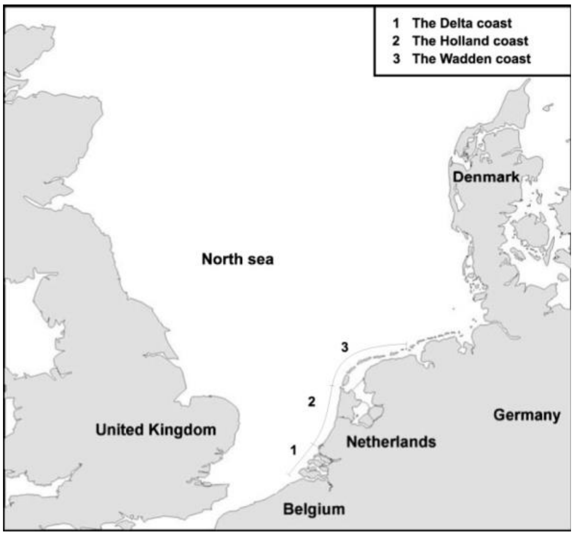

Figure 1. Location of the Netherlands and sub-sections of the Dutch coast.

Nourishment policy since 1990

In 1990 the Dutch government decided on a policy of “Dynamic Preservation” to stop structural erosion, using nourishments as the preferred intervention to maintain the coast line. Defining the 1990 coast line position as the reference coast line (referred to as Basal Coast Line – BCL), the main objective of the policy is sustainable preservation of safety against flooding and of functions in the dune area.

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In 2000 it was decided that in order to achieve *sustainable* preservation, it was necessary to extend the policy to a larger scale. In addition to the operational objective of maintaining the coast line, a second (larger scale) operational objective was defined: maintaining the sand volume in the coastal foundation, i.e. the active sand volume in the area between the -20 m depth contour and the landward boundary of the dune massive. The annual average nourishment volume, 6 Mm^3 since 1990, was raised to 12 Mm^3 (see e.g. Van Koningsveld and Mulder, 2004).

In parallel to the policy of Dynamic Preservation of coast line and coastal foundation, aimed at sustainable preservation of safety and functions, the Water Safety policy aims at the preservation of momentanous safety against flooding. In a 5-yearly test procedure, the residual strength of all dunes is established under design conditions related to the local safety standard.

Upscaling

The present nourishment policy is based on a yearly averaged nourishment volume of 12 Mm^3. Nourishing this volume has succesfully contributed to achieve objectives at the small – and medium scale levels: preserving (and enhancing) dune strength and maintaining of the coast line. However, the contribution to the third and largest scale level (i.e. maintaining of the active sand volume of the coastal foundation) appears to be insufficient.

A latest update of the sediment balance of the coastal foundation (De Ronde, 2008) concludes that in order to achieve the objective of maintaining the active sand volume of the coastal foundation – the yearly nourishment volumes would need upscaling from 12 to 20 Mm^3 per year. However, it is good to realize that this accounts for an estimated sea level rise of 2 mm/ year. As an average observed value of sea level rise in the Netherlands over the last century (Dillingh et al., 2010), 2 mm/year in policy generally is regarded as a good approximation of actual sea level rise. To grow with such a sea level rise rate would require the mentioned upscaling to 20 Mm^3/year; a higher rate of sea level rise requires an equivalently higher upscaling of nourishment volumes.

In this respect, in a study on future adaptation options to climate change in the Netherlands, the authoritive Deltacommissie (2008) suggests a raise of nourishment budgets up to 85 million m^3/year until the year 2050. Considering an ultimate worst case sea level rise scenario of 130 cm in 2100, the Deltacommissie recommends a further pro-active respons by upscaling the yearly nourishment volume equivalent to a sea level rise of 13 mm/yr. The extra buffer this would create, might be beneficial to different societal functions.

Mega-nourishments

In 2011, as an experiment aimed at knowledge development related to upscaling of nourishment volumes, long-term safety and nature- and recreational development, a mega-beach nourishment known as the ‘Sand motor’ was created at the Dutch coastline near Ter Heijde, The Netherlands (Mulder and Tonnon 2010, Stive et al., 2013). In total, about 19 million m^3 of sand was dumped to protect the rather small beach-dune system at that location. On the long term this mega-nourishment will be gradually smoothed out along the coast, feeding the adjacent beaches and dunes. Ever since, mega-nourishments for safety and/or nature and recreational purposes are gaining popularity. In the Netherlands, Mega-nourishments have been carried out or are planned near Ter Heijde, Katwijk, Noordwijk and Petten. Two main types can be distinguished:

(1) land reclamations that are designed to preserve momentaneous safety levels and need to maintain their size and shape and thus need to be nourished (Petten)
(2) mega-nourishments that may erode freely, thus feeding adjacent beaches and dunes with sand for a more natural, dynamic growth (Ter Heijde)

Figure 2. Left: Aerial photograph of the Sand Motor in July 2012 (RWS/Joop van Houdt). Right: Artist impression of the mega-nourishment in front of the sea dike near Petten (Hoogheemraadschap Noorderkwartier, www.kustopkracht.nl).

The design and impact assessment studies of both types of mega-nourishments generally require detailed morphological studies, either to determine the nourishment demand to maintain their size and function (mega-nourishments for safety such as Petten) or to determine the life span of (mega nourishments such as Ter Heijde).

Objectives and approach

This paper aims to provide simple design graphs for mega-nourishments along the Dutch coast to help coastal managers estimate maintenance volumes and the life span of such measures within the initiation and definition phases of coastal reinforcement projects. First, 1D and 2DH coastal models are calibrated on measurement data of the mega-nourishment near Ter Heijde, The Netherlands. Then design graphs for erosion rates and life span of mega-nourishments are derived based on a series of 1D and 2DH computations for mega-nourishments with various length-to-width ratios and volumes. Finally, the design graphs are applied to estimate erosion volumes and maintenance volumes for sandy reinforcements at Katwijk and Noordwijk, The Netherlands and conclusions are drawn.

OBSERVED INITIAL SAND LOSSES OF MEGA-NOURISHMENT ‘SAND MOTOR’

Bathymetric data

Since the completion of the project, the topographic and bathymetric evolution of the mega-nourishment ‘Sand Motor’ is monitored on monthly basis. Figure 3 shows the measured bathymetry in December 2012 (colorscale to NAP, about mean sea level) and the measured position of the 0m NAP line in August 2011 (grey line). The red line indicates the area used for the analysis of initial sand losses. The length of the mega nourishment is about 2.5 km. The maximum cross-shore extension is about 1 km with respect to the old coastline. The initial coastline of the Sand Motor (gray line) had a smooth curved shape (peninsula-shape) enclosing a small bay on the northern side.

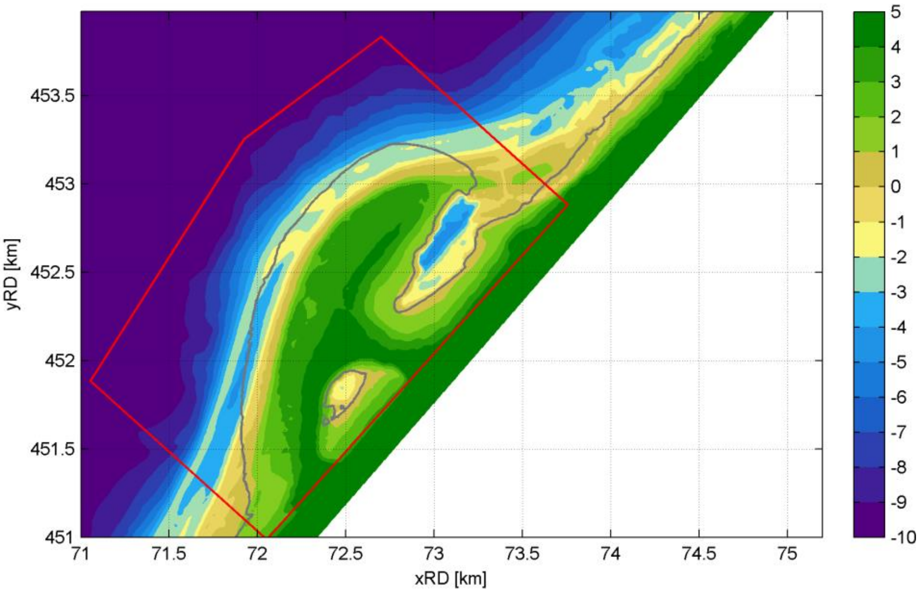

Figure 3. Measured bathymetry of the Sandmotor in December 2012 (color scale to NAP, about mean sea level) and position of the 0m NAP line in August 2011 (grey line); the red polygon indicates the area used for the analysis of initial sand losses.

Erosion volume

Based on the analysis of the bathymetric data, the erosion volume for the Sand Motor peninsula (red polygon) is estimated to be about 1.5 million m^3 after 1 year and about 2.5 million m^3 after 2.5 years, see Figure 4. The coastline recession of the water line along the central section of the Sand Motor is about 160 m in the first year and about 60 m in the second year. The relatively large erosion volume of the first year is primarily caused by the large coastal extension (about 1000 m) in combination with a very steep initial beach slope.

MODEL DESCRIPTION AND CALIBRATION

DELFT3D

DELFT3D is an open-source process-based numerical model based on the equations of motion and continuity (Lesser et al., 2004). The flow model can be coupled to a spectral wave model (SWAN). Based on the computed velocity and wave field, the sand transport capacity is computed. Bed level changes follow from the gradients of sand transport and from entrainment and deposition of sediment.

A representative DELFT3D model for the Dutch coast was set-up, calibrated and applied to model a series of mega-nourishments with various length-to-width ratios and volumes. The flow domain comprises about 24 km alongshore and about 4 km cross-shore, while the wave domain stretches some 4.5 km further on both lateral boundaries to minimise boundary effects. The grid resolution in the area of interest is about 20x20m. The flow model applies Neumann boundary conditions (Roelvink and Walstra, 2004) at both lateral boundaries and water levels at the sea boundary. The model uses the M2 and M4 tidal components as representative tidal forcing. The TRANSPOR2004 sediment transport model was applied (Van Rijn, 2007abc) using a d50 of 200 µm. The model is calibrated to result in a net annual alongshore transport along a straight coast of 200.000 m^3/year. The parallel-online approach (Roelvink, 2006) was used to simultaneously compute the weighted bed changes resulting from ten representative wind/wave conditions. The DELFT3D models were used to simulate 5 years.

UNIBEST-CL+

UNIBEST-CL+ is a 1D coastline model that computes coastline changes as a result of wave driven longshore sediment transport (single layer in the cross-shore direction) at specific locations along the coast (WL | Delft Hydraulics, 1994). The sediment transport is then translated to shoreline migration, which results in changes of the sediment transport in time. UNIBEST-CL+ can be applied for uniform coasts with revetments, groynes and breakwaters.

The alongshore extent of the model is 180km, of which the middle section of 25km contains the area of interest and features a resolution of 50m. At both lateral boundaries a constant coastline position has been applied which is allowed since the boundaries are located far away from the area of interest. One representative coastal profile is used within the model. The active height applied is 7m. Futhermore the TRANSPOR2004 sediment transport formulations (Van Rijn 2007abc) are applied using a d50 of 200 µm. A schematized wave climate with 269 wave conditions was applied as forcing. The UNIBEST-CL+ models were used to simulate 200 years.

CALIBRATION RESULT

Figure 4 shows the measured and computed erosion volumes for the mega-nourishment Sand Motor at Ter Heijde, The Netherlands. It can be seen that both DELFT3D and UNIBEST-CL+ capture the general trend in measured erosion volumes over the first 2.5 years after construction. However it can be seen that the measurements show relatively fast erosion in the first 6 months after construction followed by lower erosion rates up and sudden increase after about 2.5 years. Analysis of wave time series showed that this behavior coincides with a number of big storms in the first 6 months after construction and in the winter of 2013, about 2,5 years after construction. Both models apply yearly-averaged wave climates and therefore do not show the effects of individual events. The computed erosion rate thus is the long-term averaged erosion rate.

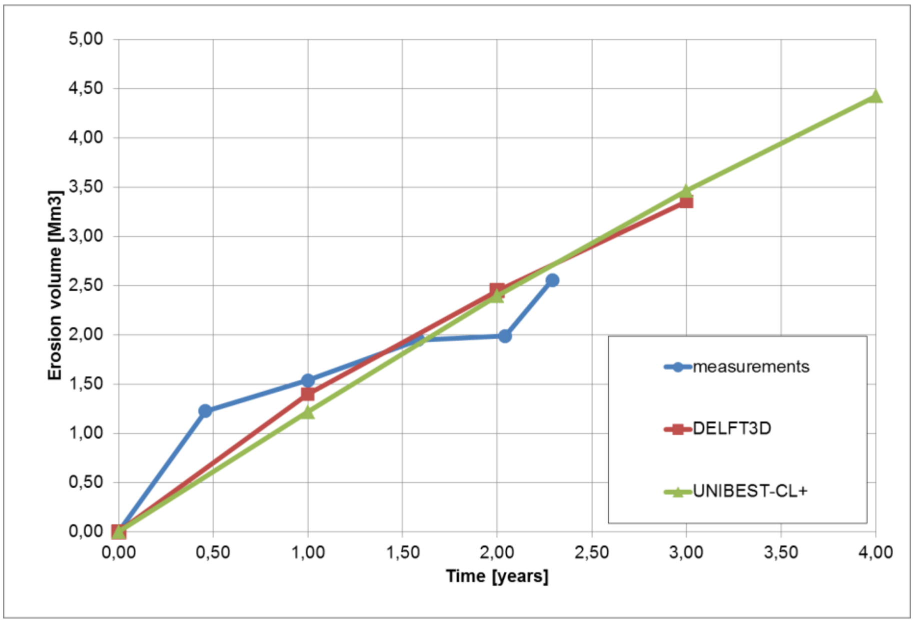

Figure 4. Measured and computed erosion volumes for the mega-nourishment ‘Sand Motor’ at Ter Heijde, The Netherlands

MODEL SCENARIOS AND RESULTS

Model scenarios

Herein, a series of 1D and 2DH computations for 9 mega-nourishments scenarios with various length-to-width ratios and volumes are described. Based on the results from both UNIBEST-CL+ and DELFT3D computations, design graphs for erosion rates and life span of mega-nourishments are derived. Table 1 shows the 9 scenarios as modelled using UNIBEST-CL+ and DELFT3D including the initial volume of the mega-nourishments considered. Three values for the seaward extent of mega-nourishments are considered: 333, 667 and 1000m, and are combined with seaward extent to alongshore width ratios of 1:2.5, 1:5 and 1:10. All scenarios are modelled over 5 years using DELFT3D and over 200 years using UNIBEST-CL+.

Table 1. Model scenarios: code, extent to width ratio, extent, width and initial volume.

scenario	extent to width ratio [-]	seaward extent [m]	alongshore width [m]	initial volume [Mm^3]
SCEN01	1:2.5	333	833	3.1
SCEN02	1:5	333	1665	5.0
SCEN03	1:10	333	3330	8.9
SCEN04	1:2.5	667	1668	12.5
SCEN05	1:5	667	3335	20.3
SCEN06	1:10	667	6670	35.8
SCEN07	1:2.5	1000	2500	28.0
SCEN08	1:5	1000	5000	45.5
SCEN09	1:10	1000	1000	80.5

Results

Figure 5 shows the volume development in time as computed using UNIBEST-CL+ for scenarios SCEN04 to SCEN06 with a seaward extent of 667m and seaward extent to alongshore width ratios of 1:2.5, 1:5 and 1:10. Volumes are computed using a polygon around the initial shape of the mega-nourishment. Results for the remaining scenarios and for DELFT3D results have not been plotted, but follow a comparable, exponential decay. From the volume development, erosion volumes can be computed for each mega-nourishment scenario. It was found that the average erosion volume did not scale with the alongshore length of the mega-nourishment. The average erosion rate are therefore also averaged over the three different seaward extent to alongshore width ratios and have been plotted against seaward extent only. Figure 6 shows the erosion volumes, averaged over the first year and over 5 years, plotted against seaward extent for both the UNIBEST-CL+ and DELFT3D computations. It can be seen that the erosion rate in the first year is about 50-100% higher than the erosion rate averaged over 5 years.

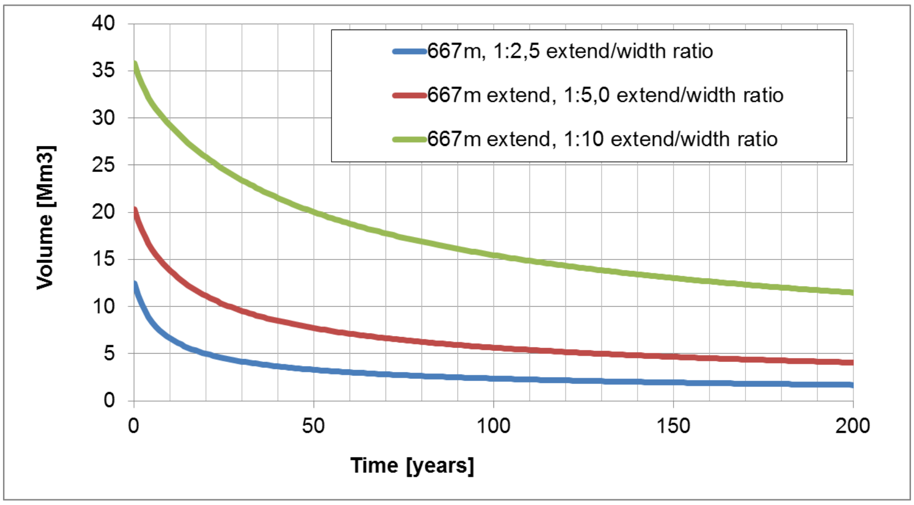

Figure 5. Volume development in time for the three scenarios with a seaward extent of 667m and seaward extent to alongshore width ratios of 1:2.5, 1:5.0 and 1:10.

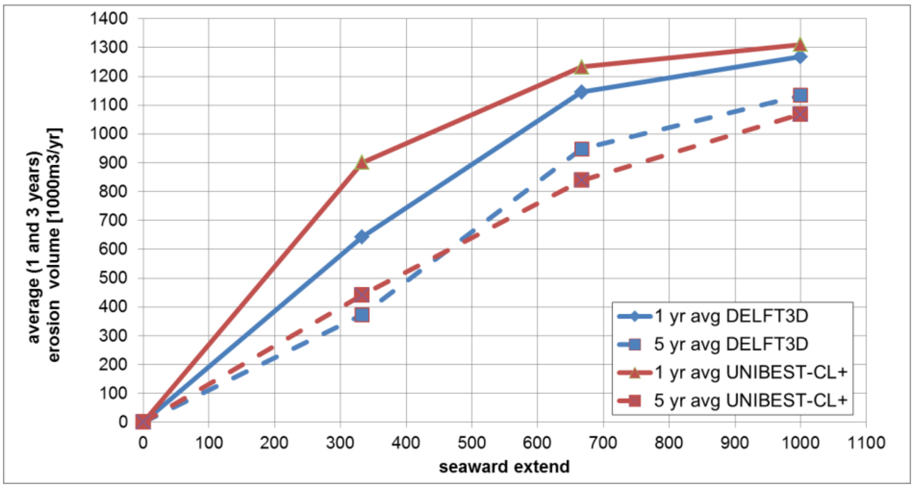

Figure 6. Average erosion volume per year over 1 and over 5 years for DELFT3D and UNIBEST-CL+ as a function of seaward extent.

Finally, half-time values for the volume decay of mega-nourishments have been derived for the UNIBEST-CL+ results and are plotted against the initial volume of the mega-nourishments in Figure 7. It can be seen that the relation between the half-time and initial volume is linear, which is expected in UNIBEST-CL as transports are calculated with the S-φ curve and local coastline angle. The sediment transport rates therefore do not depend on the volume or the size of the mega-nourishment. Since half-times could not be determined based on the 5 year computations using Delft3D, the effect of for example wave sheltering due to the nourishment size have not been investigated.

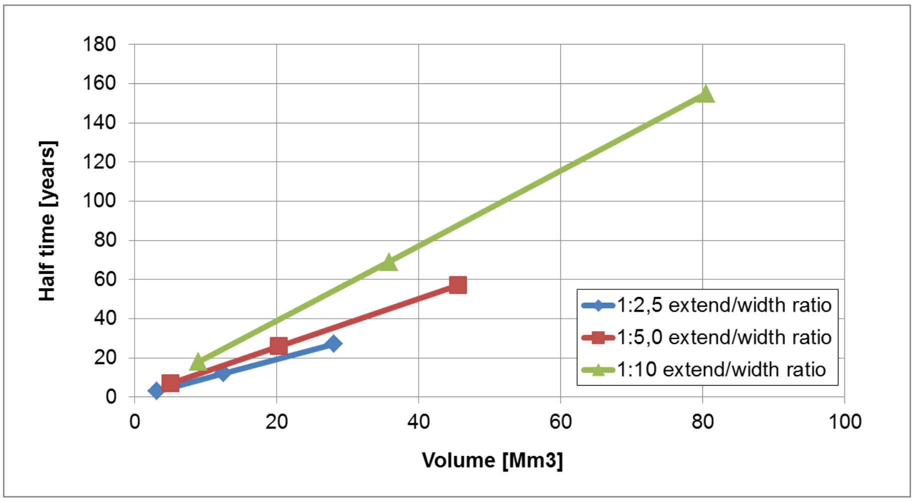

Figure 7. Half-time values of the volume of mega-nourishments with different seaward extent to alongshore width ratios plotted against initial volume.

APPLICATION

Katwijk reinforcement

At Katwijk, The Netherlands, the primary sea defence was located within the city centre and parts of the city were therefore not protected in case of extreme storm surges which was also posing a threat to surrounding areas and the hinterland. To tackle this problem, a dike in dune solution was designed and constructed, in which a hard sea dike is completely covered by sandy dunes. In addition a large beach nourishment was designed to move the beach in seaward direction. The length of this beach nourishment is about 1500m with an approximate seaward extent of 50m. The volume of sand of the entire nourishment is approximately 2.9 million m^3 including a wear layer of 200.000 m^3 and including a construction loss of 5% (Arcadis, 2013). An artist impression of this project can be seen in Figure 8.

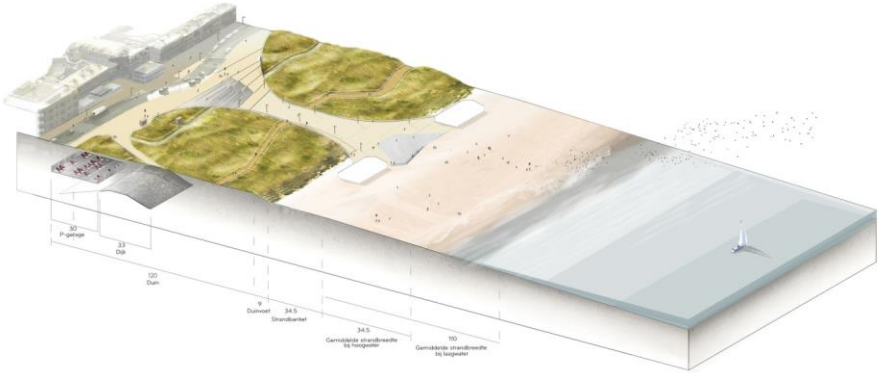

Figure 8. Artist impression of dike in dune (Dutch: dijk in duin) reinforcement at Katwijk, The Netherlands (Kunstwerk Katwijk, 2013)

To apply the design graphs and obtain initial sediment losses, first the net annual alongshore transport needs to be determined near Katwijk. According to a detailed report about the morphological impact of the coastal intervention near Katwijk, the net alongshore transport is in the order of 230.000 ± 30.000 m^3/year (van Rijn, 2011).

Once the seaward extent of the nourishment and the net annual alongshore transport are known the design graphs can easily be applied. To do this, the amount of seaward extent can be read on the x-axis to obtain erosion rates, which are displayed on the y-axis. When applying the design graphs for an alongshore transport of 200.000 m^3/year, erosion rates of 50.000 m^3/year averaged over 5 years can be estimated, which results in a maintenance volume of 5 * 50.000 = 250.000 m^3 after a 5 year period.

Previous studies by Arcadis using the PONTOS model and Deltares using the CROSMOR and LONGMOR models predicted maintenance volumes in a range of 125.000 – 200.000 m^3 after a period of 5 years (Arcadis, 2013). The design graphs derived in this paper thus provide a 25 - 50% higher estimate for the maintenance volume after 5 years.

Noordwijk reinforcement

Between September 2007 and April 2008, a similar reinforcement as that in Katwijk has been carried at near Noordwijk, The Netherlands (Figure 9). In this case, the beach is extended by approximately 45m in seaward direction and the total volume of the nourishment is approximately 3 million m^3 (Kustvisie Zuid-Holland).

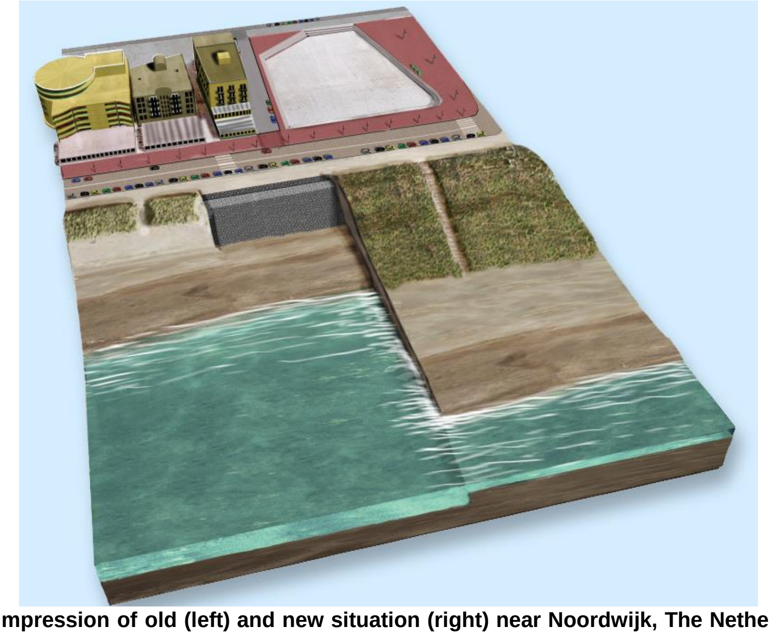

Figure 9. Artist impression of old (left) and new situation (right) near Noordwijk, The Netherlands (Kustvisie Zuid-Holland).

According to Van Rijn (2011), a slightly lower net alongshore transport of 200.000 m^3/year can be found at Noordwijk, which is located approximately 5 km north of Katwijk. In the first year (2008 – 2009), measurements of sand losses have been carried out which showed an eroded sand loss of 65.000 m^3. Van Rijn (2011) states that this sand loss occurred during a relatively calm year and argues that a sand loss of 75.000 to 100.000 m^3 can be found during a year with average wave forcing. According to the design graphs based on an alongshore transport of 200.000 m^3/year and averaged over a period of 2 years (Figure 6), the erosion rate with a seaward extent of 45m is approximately 100.000 m^3/year which is in excellent agreement with the previous analysis by Van Rijn (2011).

CONCLUSIONS

The initial sediment losses over the first 2,5 years of the mega-nourishment ‘Sand Motor’ near Ter Heijde, The Netherlands have been modelled successfully using the 2DH area model DELFT3D and using the 1D coastline model UNIBEST-CL+. The latter despite the fact that substantial cross-shore related losses were observed at the Sand Motor resulting in a coastline recession of about 160 m in the first year. The fact that a 1D model can be used indicates that deposition is within the active profile and that breaker bars created during storms are eroded by alongshore transport and sediment is transported in alongshore direction.

Based on a series of computations for mega-nourishments with various length-to-width ratios and volumes, design graphs for erosion rate and life span of mega-nourishments have been derived The initial erosion rates and maintenance volumes of mega-nourishments are mainly determined by the seaward extent of the nourishments and the coastline angle of the transition zone between the nourishment and the adjacent coast, the alongshore length is of less importance.

The design graphs have been applied to estimate maintenance volumes for coastal reinforcements near Katwijk and Noordwijk, The Netherlands. According to the design graphs the maintenance volume at Katwijk is about 250.000 m3 after 5 years, about 25 – 50 % higher than found in the design studies for this reinforcement. The erosion rate at Noordwijk according to the design graph is about 100.000 m^3/year which is in agreement with Van Rijn (2011).

It is recommended to study the effect of the mean incident wave angle of the wave climate on the initial erosion and life span of mega-nourishments to further generalize the results and design graphs.

ACKNOWLEDGMENTS

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