EROSION OF LAND RECLAMATIONS PROTECTED BY NATURAL SAND DUNES AND BEACHES

by L. van Rijn, www.leovanrijn-sediment.com

1. Introduction

Land reclamations along exposed coasts often are protected by seadikes in combination with groynes (see **Figure 1.1left**) or detached submerged/emerged breakwaters.
Herein, it is explored to protect land reclamations protruding into the sea by natural sand dunes and beaches (**Figure 1.1right**). This approach requires regular sand maintenance nourishments to compensate the erosion of sand along the dynamic coastline of the land reclamation protruding into the sea along an exposed coast. The dimensions of the land reclamations have been varied: the cross-shore length (extension) is in the range of 250 to 1000 m; the alongshore length at the original water line is in the range of 1625 to 14000 m.

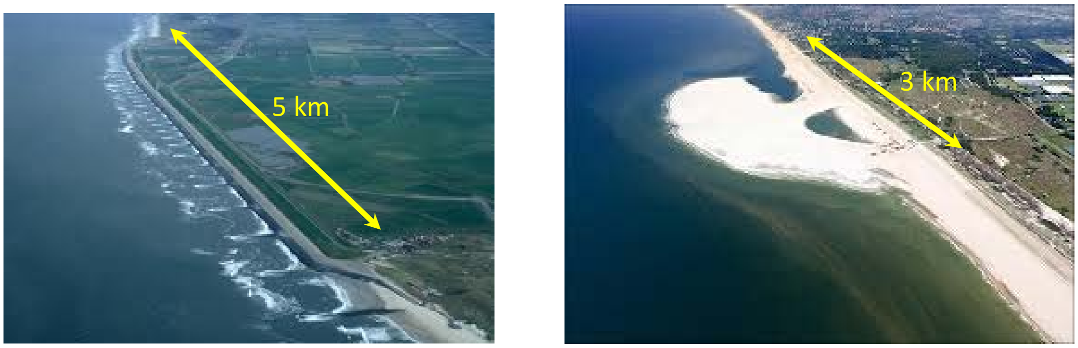

Figure 1.1 *Land reclamation protected by seadike with groynes (left) and unprotected (right)*

The erosion of sand along land reclamations with sand dunes and beaches has been computed by three types of models:

1. Delft3D-model (Deltares), which is a field model consisting of submodels for water levels, flow, waves, sand transport and bed level changes;+
2. UNIBEST-CL (Deltares) and LONGMOR-model, which are one-line coastline models consisting of submodels for wave height at the breakerline, longshore sand transport and coastline changes;
3. CROSMOR-model, which is a 2 dimensional profile model consisting of submodels for waves, velocities, sand transport and bed level changes.

To verify these models, they have been used to simulate the erosion of sand along the mega-nourishment known as the ‘SANDMOTOR’, at the coast of South-Holland. In the summer of 2011 this mega-beach nourishment has been made at the Dutch coastline near Ter Heijde, which is about 10 km south of the city of the Hague. In all, about 19 million m^3 of sand was dumped to protect the beach-dune system at that location. On the long term this mega-nourishment will be gradually smoothed out along the adjacent coasts nourishing these beaches with new sand.

Finally, the results of the present study have been used to predict the annual erosion of sand along a new dune-beach system which will be constructed in front of the seadike near Petten along the North-Holland coast (The Netherlands). The dimensions of this seadike are not sufficient to defend the coast at that location against future storm conditions.

2. Dimensions of land reclamations

Various alternative designs of land reclamations along an exposed coast are herein considered, see **Table 2.1**. The Holland coast is a typical example of an exposed coast. In all, 20 cases have been studied.

Figure 2.1 shows the plan view of four trapezoidal land reclamations (see **Table 2.1**). Each land reclamation consists of a straight central section and two side or transition sections. The length of the transition zone at each side is 2 times the cross-shore extension for all cases.

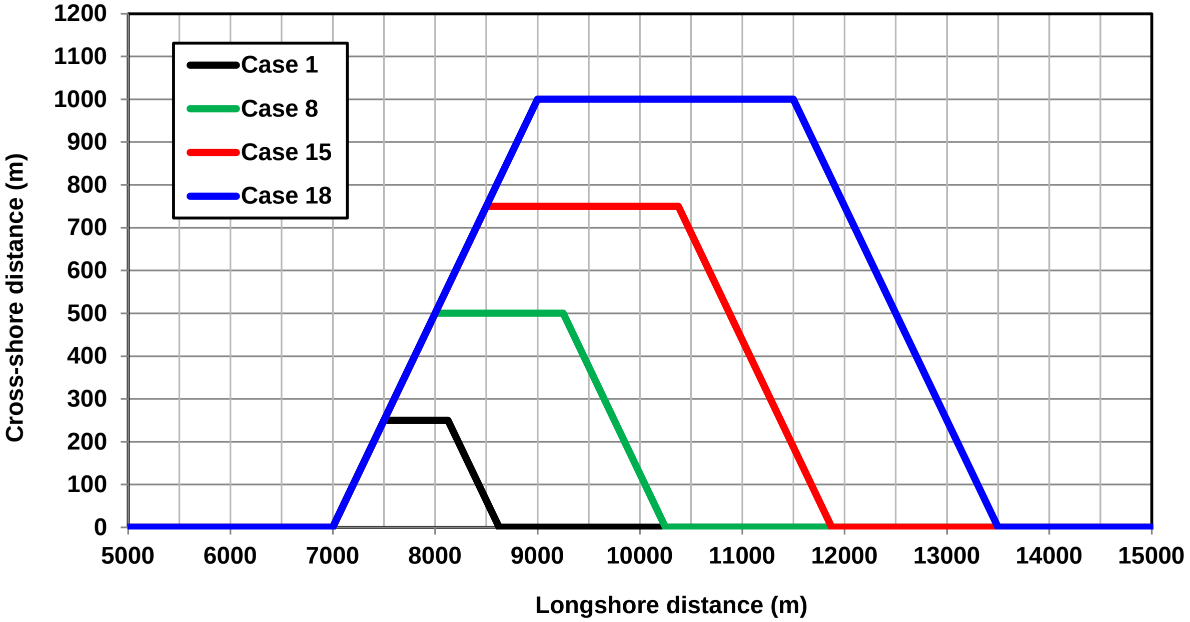

Figure 2.1 *Plan view of land reclamations (Cases 1, 8, 15 and 18)*

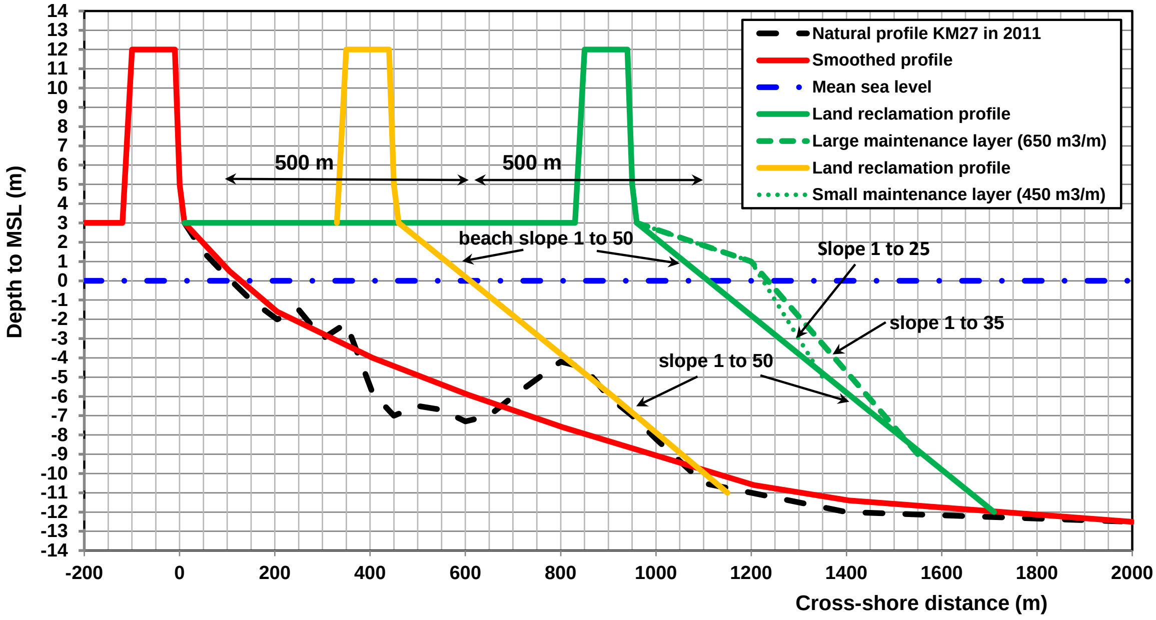

Figure 2.2 *Cross-shore dimensions of typical profile along coast of North-Holland (km 27) and two profiles of land reclamations*

Figure 2.2 shows a typical cross-shore profile near the beach village Bergen (km 27) along the coast of North-Holland. The 'smoothed' cross-shore profile can be schematized in 4 sections, as follows:

- beach slope of 1 to 35 between +3 and 0 m NAP;
- slope of 1 to 70 between 0 m and -3 m NAP;
- slope of 1 to 100 between -3 and -6 m NAP;
- slope of 1 to 125 between -6 m and -10 m NAP.

Figure 2.2 also shows the cross-shore profiles of two land reclamations. The beach slope is set to 1 to 50 between +3m and 0 m NAP and the shoreface slope is also set to 1 to 50. The sea defence consists of one dune row of sand with a cross-sectional area of about 800 m^3/m.

A maintenance cover layer of sand is required to compensate the coastal erosion for about 3 to 5 years. The volume per unit length of the maintenance layer is in the range of 450 to 650 m^3/m, see **Figure 2.2**. The maintenance layer has to be replaced every 3 to 5 years, see Chapter 5.
The erosion of sand strongly depends on the net longshore transport rate, the cross-shore dimensions of the coastal extension and the applied annual wave table. The net longshore transport has been varied in the range of 100,000 to 500,000 m^3/year. The cross-shore extensions are in the range of 250 to 1000 m.

CASE	**Cross-shore extension; horizontal shift of mean waterline (m)**	**Ratio of seaward length and cross-shore extension (-)**	**Longshore length (at seaward and landward sides) (m)**	**Beach slope landward of mean waterline (-)**	**Shoreface slope seaward of mean water line (-)**	**Total required volume per unit length of coast (m^3/m)**
1	250	2.5	625; 1625	1 to 50	1 to 50	2500
2	250	5	1250; 2250	1 to 50	1 to 50	2500
3	250	10	2500; 3500	1 to 50	1 to 50	2500
4	250	30	7500; 8500	1 to 50	1 to 50	2500
5	333	2.5	833; 2166	1 to 50	1 to 50	3000
6	333	5	1666; 3000	1 to 50	1 to 50	3000
7	333	10	3333; 4663	1 to 50	1 to 50	3000
8	500	2.5	1250; 3250	1 to 50	1 to 50	4400
9	500	5	2500; 4500	1 to 50	1 to 50	4400
10	500	10	5000; 7000	1 to 50	1 to 50	4400
11	500	30	15000; 17000	1 to 50	1 to 50	4400
12	666	2.5	1666; 4330	1 to 50	1 to 50	5500
13	666	5	3333; 6000	1 to 50	1 to 50	5500
14	666	10	6666; 9330	1 to 50	1 to 50	5500
15	750	2.5	1875; 4875	1 to 50	1 to 50	6000
16	750	5	3750; 6750	1 to 50	1 to 50	6000
17	750	10	7500; 10500	1 to 50	1 to 50	6000
18	1000	2.5	2500; 6500	1 to 50	1 to 50	11550
19	1000	5	5000; 9000	1 to 50	1 to 50	11550
20	1000	10	10000; 14000	1 to 50	1 to 50	11550

Table 2.1 *Dimensions of land reclamations*

3 Description and verification of models

3.1 Model description

Various types of models have been used to compute the initial (first years) erosion of sand along the new coastal land reclamations: 1D models LONGMOR and UNIBEST-CL; 2DV model CROSMOR and 2DH model DELFT3D.

The 1D model LONGMOR is a coastline model which computes the mean position of the coastline from the gradients of the longshore transport capacity (Van Rijn, 2006, 2012; Deltares 2014). In this approach the coastal profile over the active zone is represented by a vertical line. The rotation of the coastline is assumed to be present up to the offshore boundary. Hence, all depth contours are assumed to rotate parallel to the coastline.

The 1D model UNIBEST-CL is the coastline model of Deltares and computes the mean position of the coastline from the gradients of the longshore transport capacity. This model has more advanced options to compute the longshore transport. The longshore transport gradient dQ_s/dx is schematized into $(dQ_s/d\varphi)(d\varphi/dx)$ with Q_s= longshore transport and φ= coastline angle. First, the longshore transport is computed as function of φ, which is known as the Q_s-φ curve. Based on that, the gradient $(dQ_s/d\varphi)$ is computed. The model has an option to rotate the depth contours over a preset (input) cross-shore distance only. The depth contours beyond this distance are not rotated but kept similar to the initial value (t=0). This option is known as the dynamic boundary condition. The value of the cross-shore distance has a strong effect on the results as it determines the refraction process of the waves.

The 2DV model CROSMOR is a coastprofile model which computes the position of the seabottom along a cross-shore profile from the gradients of the cross-shore sand transport. The model includes various submodels: tidal velocities, wave transformation, wave skewness and asymmetry, wave set-up and near-bed return currents, wave-induced streaming, longshore and cross-shore sand transport (Van Rijn 2006, 2012; Van Rijn et al., 2003). The CROSMOR-model has been verified extensively using the COAST3D data at Egmond (Van Rijn et al., 2003).

The DELFT3D-model is an area (field) model based on the equations of motion and continuity. The model has been used in depth-averaged mode. The flow model is coupled to a 2D 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.

The models have been calibrated using the available erosion data of the mega-nourishment 'sandmotor'.

3.2 Mega-nourishment 'sandmotor'

In the summer of 2011 the mega-beach nourishment known as the 'sandmotor' was made at the Dutch coastline near Ter Heijde which is about 10 km south of the Hague (Province of South-Holland). In all, about 19 million m^3 of sand was dumped to protect the rather small beach-dune system at that location.

Figure 3.1 shows the measured bathymetry of the 'sandmotor' in December 2012 (color scale to NAP; NAP is approximately mean sea level) and the measured position of the 0 m NAP line of August 2011 (grey line). The red line indicates the area used for the analysis of the 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 new initial coastline has a smooth curved shape (peninsula-shape) enclosing a small bay on the northern side.

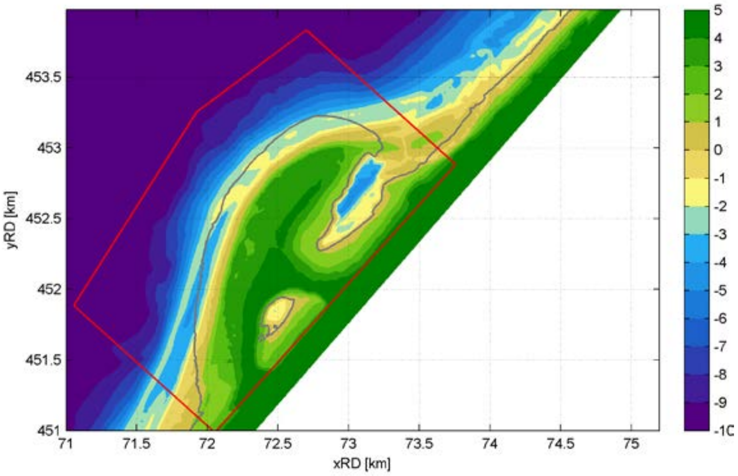

Figure 3.1 *Measured bathymetry 'sandmotor', December 2012 (color scale) and position of waterline in August 2011 (grey line); red line indicates the area used for the analysis of initial sand losses.*

Based on the analysis of detailed soundings, the erosion volume of the central section is estimated to be about 1.3 million m^3 after 1 year and about 1.7 million m^3 after 1.5 years. 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.

Figures 3.2 and 3.3 show the coastline (0 m NAP) and cross-shore profiles of the 'sandmotor' on 5 June 2011 and 31 June 2012. The grid size in both directions is 500 m.

Figure 3.4 shows cross-sshore profiles (108.41 and 108.94 km) on 2 August 2011, 26 June 2012 and 17 Februari 2013.

These plots show that during a period of about 1 year, a strip of sand of about 150 to 350 m wide (about 15% to 30% of the initial coastal extension) has been eroded over an alongshore distance of about 1500 to 1800 m.

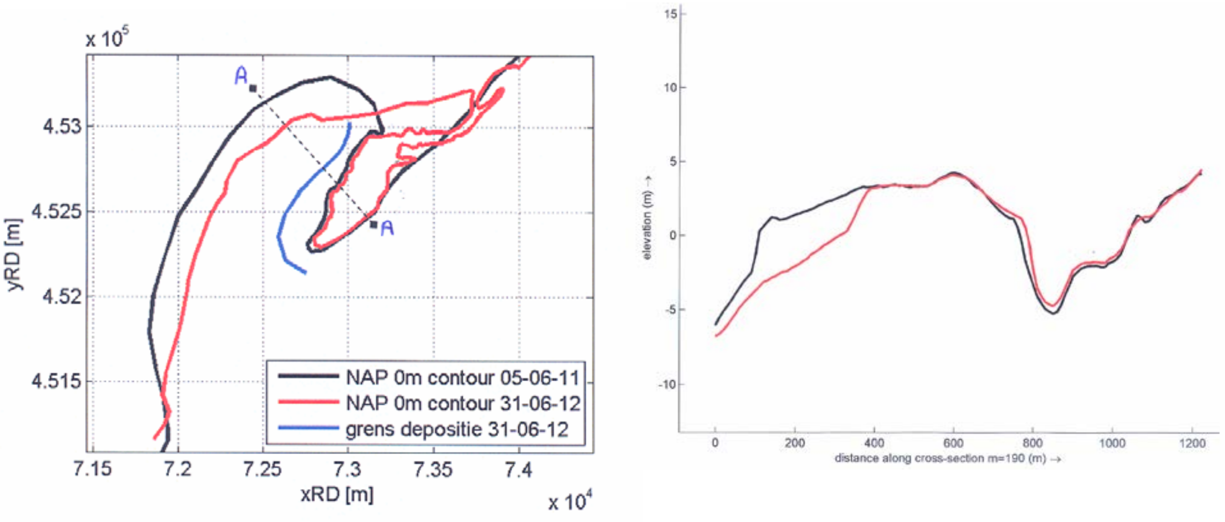

Figure 3.2 *Coastline (left) and cross-shore profile (right) on 5 June 2011 and 31 June 2012*

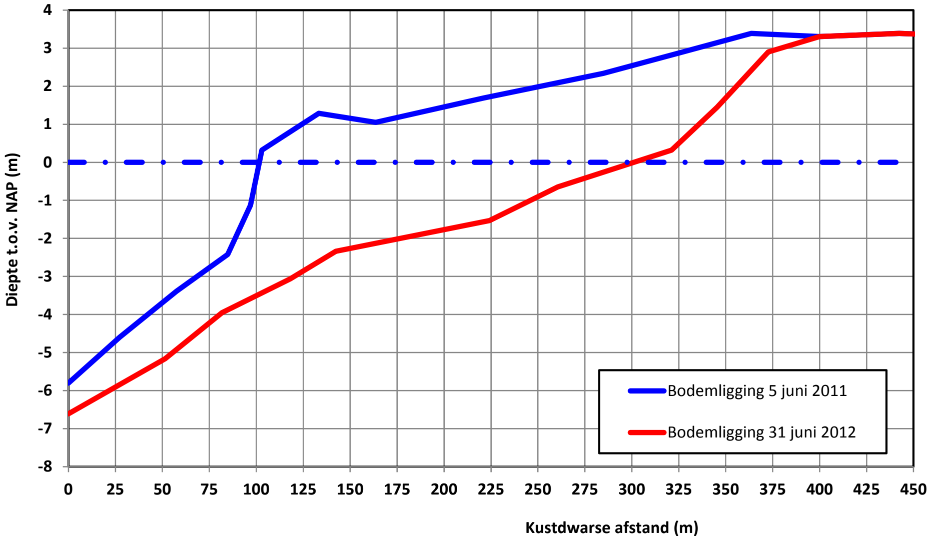

Figure 3.3 *Cross-shore profile A-A between 0 and 450 m on 5 June 2011 and 31 June 2012*

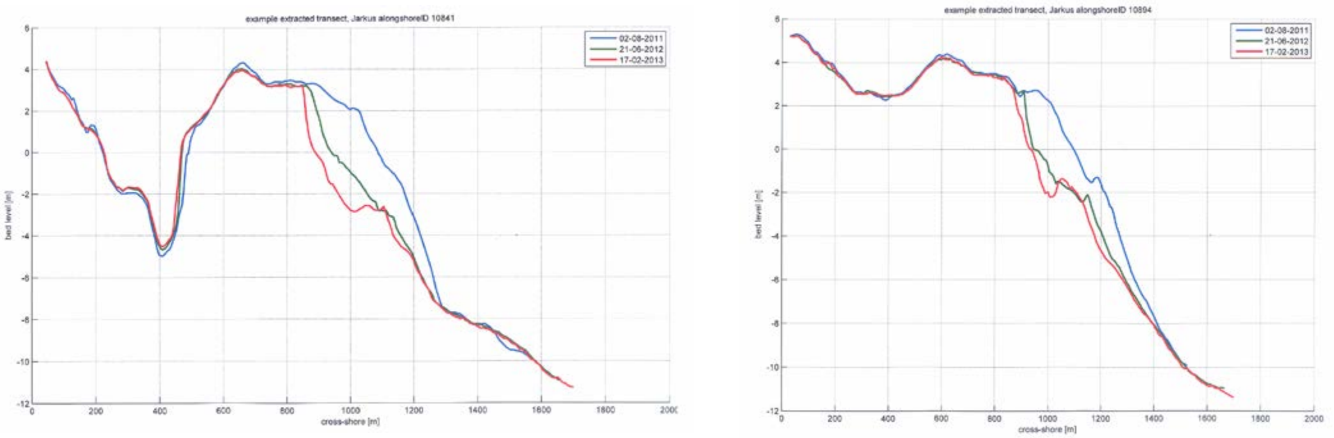

Figure 3.4 *Profiles 108.41 km (left) and 108.94 km (right) on 1 August 2011, 21 June 2012 and 17 Februari 2013*

The eroded sand volume over a period of about 1 year at Profiles 108.41 and 108.94 km is about 800 to 900 m^3/m. This large volume of coastal erosion is partly caused by the relatively steep beach profile (about 1 to 10) between +1 and -3 m NAP.

Assuming that the Profiles A-A, 108.41 and 108.94 are representative for the most seaward section of the 'sandmotor', the total erosion volume along the central section of the 'sandmotor' is about 1 to 1.5 million m^3 during the first year.

Figure 3.6 shows the erosion volumes (green values) as function of time based on analysis results of Deltares (Stam 2014). The measured erosion after 1 year is about 1.5 million m^3. The erosion is most excessive after 0.5 to 1 year due to adjustment of the relatively steep, initial beach profiles.

Assuming an active profile height of about 10 m (between +3 and -7 m) and a section length of about 2000 m, the average erosion after 1 year is about 1.5 10^6/(2000x10) = 75 m. The erosion at the waterline varies between 150 en 350 m. Thus, most of the erosion occurs in the upper part of the profile (between +3 and -3 m NAP). The measured erosion values are given in **Table 3.1**.

Location	**Erosionvolume after 1 year (m^3)**	**Erosionvolume per unit length after 1 year (m^3/m^1)**	**Coastline recession averaged over height of active zone (+3 to -7 m NAP) after 1 year (m)**	**Coastline recession at waterline (0 m NAP) after 1 year (m)**
Profile 108.41 km	-	900	90 (900/10)	150
Profile 108.94 km	-	800	80 (800/10)	160
Over central section (2000 m)	1.5 million	750 (1500000/2000)	75 (1500000/(2000x10))	140 (minimum) 240 (average) 350 (maximum)

Table 3.1 *Measured erosion values of 'sandmotor', South-Holland*

3.3 Model verification

The observed bulk erosion at the central section of the 'sandmotor' can be used to verify the various models applied. The erosion along the 'sandmotor' is caused by longshore and cross-shore transport processes. Most likely, the longshore transport processes due to tide and wave-driven forces are dominant on the long term. The presence of the large, initial coastal extension will result in flow contraction and, hence, in an increase of the longshore current velocities. The relatively steep profile of the new beach will lead to an increase of the longshore transport capacity during the first years due to increased wave attack, wave breaking and turbulence production. The cross-shore return currents will transport the sediments to the zone between 0 m and -7 m NAP, where they are carried away by longshore tansport processes.

3.3.1 DELFT3D computations

The DELFT3D model system offers the most accurate and integrated solution for the simulation of both longshore and cross-shore transport processes. The model used in 2DH-mode (depth-averaged mode) was calibrated by adjusting the schematized wave climate to give a net longshore transport of 200.000 m^3/year in the nearshore zone (undisturbed situation), which is a representative value for this coastal section (Deltares, 1995a,b). The calibrated wave climate consisting of 10 wave conditions is given in **Table 3.2** and **Figure 3.5**.

Figure 3.6 shows the computed erosion volume in the central section of the 'sandmotor' nourishment as function of time (3 years) based on the results of the DELFT3D model. The DELFT3D results are quite good after 1 and 2 years. The measured values after about 0.5 years are considerably underestimated.
The measured erosion values are relatively large due to the adjustment of the initial steep beach.

Time (days)	**Significant wave height at deep water $H_{s,o}$ (m)**	**Peak wave period T_p (s)**	**Angle wave direction at deep water to coast normal (degrees)**
0	1.08	5.2	58
71	1.08	5.2	58
71.1	2.43	6.9	56.6
82.	2.43	6.9	56.6
82.1	0.89	5.2	30.3
141.	0.89	5.2	30.3
141.1	2.64	7.2	30.4
149.	2.64	7.2	30.4
149.1	0.84	5.7	-1.5
212.	0.84	5.7	-1.5
212.1	0.72	5.2	-58.3
263.	0.72	5.2	-58.3
263.1	2.61	7.5	-1.6
270.	2.61	7.5	-1.6
270.1	0.82	5.9	-30.3
356.	0.82	5.9	-30.3
356.1	2.64	7.9	-25.4
364.	2.64	7.9	-25.4
364.1	2.24	7.0	-55
365.	2.24	7.0	-55

Table 3.2 *Schematized annual wave climate (10 conditions) of the Dutch coast; Delft3D*

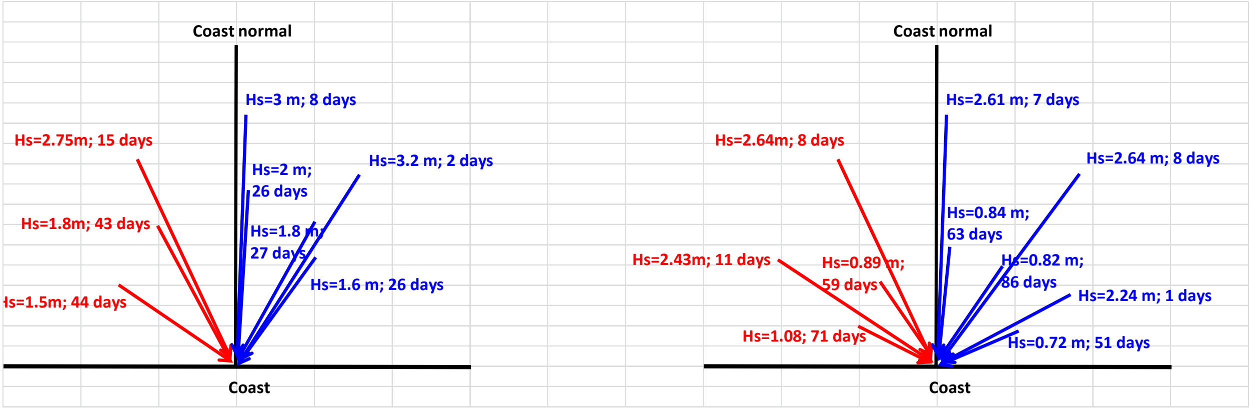

Figure 3.5 *Wave climate Table 3.3 (left) and wave Table 3.2 (right)*

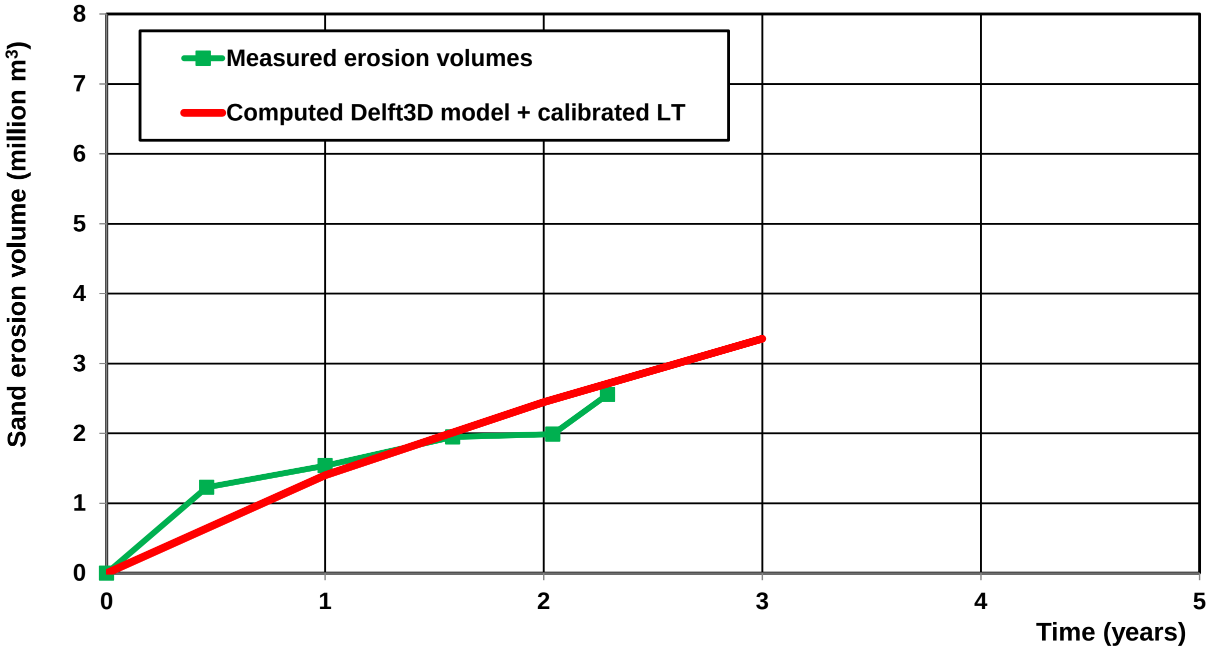

Figure 3.6 *Measured and computed Delft3D erosion volumes; sandmotor*

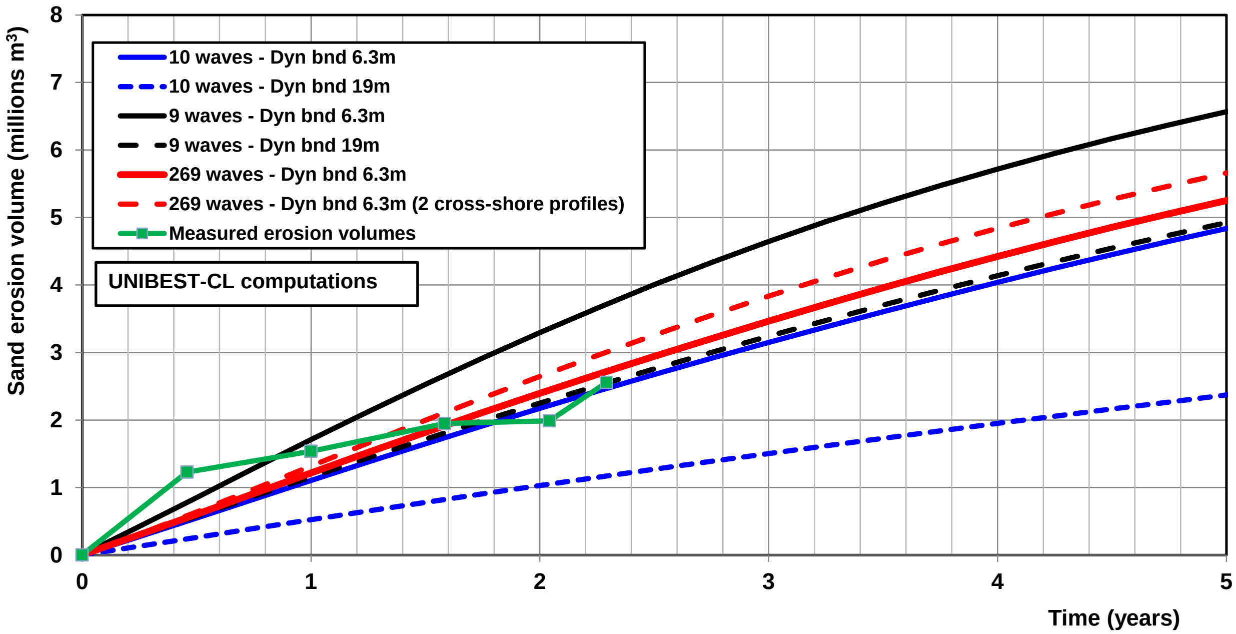

Figure 3.7 *Measured and computed UNIBEST-CL erosion volumes; sandmotor*

3.3.2 UNIBEST-CL computations

Figure 3.7 shows computation results of the 1D UNIBEST-CL model. Various wave climates have been used, as follows:

- detailed North Sea wave climate of South-Holland consistingof 269 wave conditions;
- schematized wave climate of 10 conditions of South-Holland as used in DELFT3D model;
- schematized wave climate of 9 wave conditions of North-Holland as used in LONGMOR-model.

The dynamic offshore boundary is set at 19 m (all depth contours are rotating similar to the computed coastline rotation) and at 6.3 m (only the depth contours in the surf zone are rotating similar to the computed coastline rotation).

The best results are obtained for the detailed wave climate in combination with a dynamic boundary condition at the surf zone (6.3 m). The wave climate of 10 wave conditions and the dynamic boundary at 6.3 m yields almost the same results. It can be seen that the dynamic boundary condition at the offshore boundary of 19 m yields significantly smaller erosion volumes.

3.3.3 LONGMOR computations

Longshore transport

The 1 dimensional LONGMOR-model computes the longshore transport and gradients and, based on that, the coastline changes over the height of the active zone defined between +3 m and -7 m NAP (layer of 10 m).

The longshore transport is described by the following equation (Van Rijn 2014):

$$Q_{t,mass} = 0.00018\ \rho_s\, g^{0.5}\, (\tan\beta)^{0.4}\, (d_{50})^{-0.6}\, (H_{s,br})^{3.1}\, \sin(2\theta_{br}) \qquad (1)$$

with: $H_{s,br}$ = significant wave height at the breakerline (m), θ_{br}= angle (^{o}) between the wave vector at the breakerline and the local coast normal, $\tan\beta$= beach slope, d_{50}= median particle size (m), ρ_s = sediment density (2650 kg/m^3), g= acceleration of gravity (m/s^2).

Various wave climates have been used (**Tables 3.2, 3.3, 3.4** and **3.5**).

Effect of wave angle

Equation (1) shows that the longshore transport varies with $\sin(2\theta_{br})$. In the case of a relatively large angle ($\theta_{br} > 45^o$), the longshore transport will decrease. This may occur at the transition zones between the original beach and the new seaward beach of the land reclamation (see **Figure 2.1**).

The variation of the longshore transport in situations with relatively large wave angles has been studied for a straight coast (0.25 mm sand) using the cross-shore profile model CROSMOR (file Egmon3.inp). The wave angles were varied in the range of 10^o to 85^o. The rms-wave height (H_{rms}) at the offshore boundary (500 m from the beach at a depth of -8 m) was 2 m and the peak wave period was T_p= 8 s. The water level was constant (no tide).

Figure 3.8 shows the maximum longshore velocity and the integrated longshore transport as function of the wave angle θ. The maximum longshore velocity and the longshore transport strongly decrease for wave angles larger than about 50^o. Thus, the assumption: longshore transport $\approx \sin(2\theta_{br})$ seems to be quite reasonable.

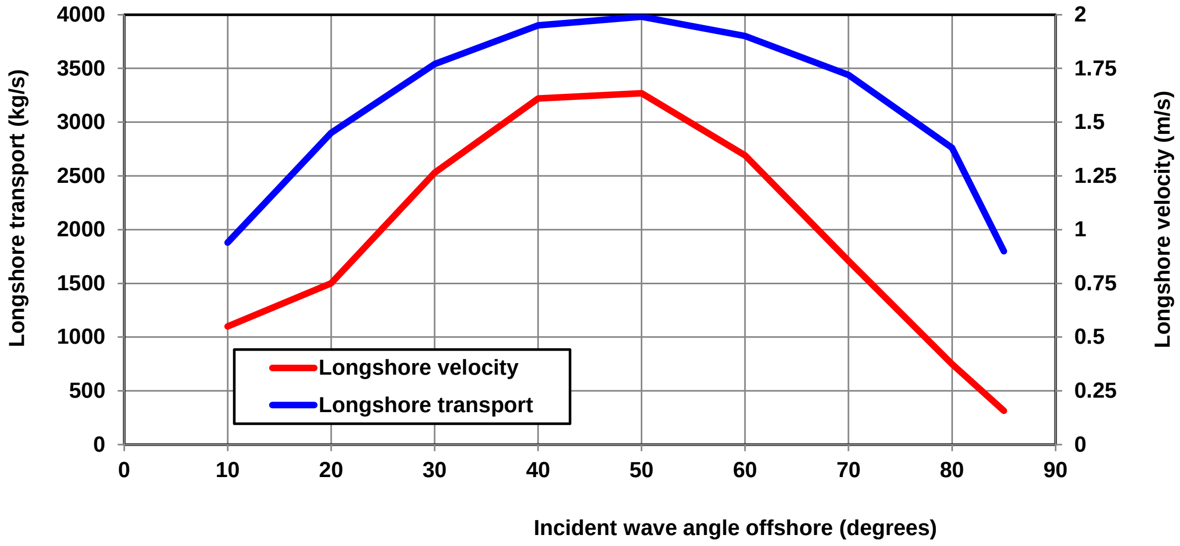

Figure 3.8 *Longshore velocity and longshore transport as function of the wave angle; CROSMOR*

Time (days)	Significant wave height at deep water $H_{s,o}$ (m)	Peak wave period T_p (s)	Angle wave direction at deep water to coast normal (degrees)	Storm surge[1] (m)
0	1.5	4.9	58	0
44	1.5	4.9	58	0
44.1	1.8	5.4	28	0
87	1.8	5.4	28	0
87.1	2.75	6.6	28	0.5
102	2.75	6.6	28	0.5
102.1	2.0	5.7	-2	0
128	2.0	5.7	-2	0
128.1	1.8	5.4	-32	0
155	1.8	5.4	-32	0
155.1	1.6	5.1	-32	0
181	1.6	5.1	-32	0
181.1	3.0	6.9	-2	0.5
189	3.0	6.9	-2	0.5
189.1	3.2	7.2	-32	0.5
191	3.2	7.2	-32	0.5
191.1	0.5 m (no wind)	0.5	5.	0
365	0.5 m (no wind)	0.5	5.	0

[1] Storm surge values have only been used in CROSMOR-model (see Section 4.3)

Table 3.3 *Schematized annual wave climate (9 conditions) of the North-Holland coast (1980-1988)*

Effect of wave order and smoothing parameter

The computation of the coastline using the LONGMOR-model is dependent on the applied wave climate and the wave order. Furthermore, the computation of the coastline position involves a smoothing parameter to suppress numerical oscillations of the computed coastlines. The coastline position is numerically computed from an explicit Lax-Wendorf scheme including a smoothing-parameter. The value of the smoothing parameter (in the range of 0.0001 to 0.001) has to be determined by trial and error.

The applied offshore wave climate (9 conditions) is given in **Table 3.3**. This schematized wave climate represents annual-averaged conditions over a period of about 8 years (1980-1988; North-Holland) and was

cailbrated to give a net longshore transport of 200,000 m^3/year along the coast in northern direction (from left to right in **Figure 3.9A,B,C**). Positive wave angles yield longshore transport to the right in **Figures 3.9A,B.C**.
To evaluate the effect of the wave order, the waves of **Table 3.3** have been applied in:

- positive-negative order; all waves with positive wave angles are taken first;
- negative-positive order (reversed order); all waves with negative wave angles are taken first;
- alternating order; waves with alternating positive and negative angles.

TIme (days)	**Significant wave height at deep water $H_{s,o}$ (m)**	**Peak wave period T_p (s)**	**Angle wave direction at deep water to coast normal (degrees)**
0	2.2	7.0	30
50.	2.2	7.0	30
50.1	2.0	6.0	-30
100.	2.0	6.0	-30
100.1	1.8	6.0	0.
130.	1.8	6.0	0.
130.1	0.5	4.0	0.
365.	0.5	4.0	0.

Table 3.4 *Simple annual wave climate; 4 conditions*

Significant wave height H_s (m)	**Peak wave period T_p (s)**	**Wave direction to shore normal θ (°)**	**Duration (days)**	**Significant wave height H_s (m)**	**Peak wave period T_p (s)**	**Wave direction To shore normal θ (°)**	**Duration (days)**
0.75	5	-60	9.7	2.75	7	-60	0.3
		60	11.8			60	2.0
		30	9.1			30	2.0
		-30	8.9			-30	1.1
1.25	6	-60	6.2	3.25	8	-60	0.1
		60	10.4			60	0.9
		30	7.4			30	1.1
		-30	6.4			-30	0.4
1.75	7	-60	2.2	3.75	8	-60	0.04
		60	6.9			60	0.4
		30	5.3			30	0.9
		-30	3.5			-30	0.1
2.25	7	-60	0.4	4.25	9	60	0.2
		60	3.4			30	0.4
		30	3.4			-30	0.07
		-30	1.7	5.0	10	60	0.1
						30	0.4
						-30	0.1
Total			97 days				11 days
							108 days

Positive wave angle yields transport to north-east (dominant longshore transport direction)

Table 3.5 *Detailed annual wave climate (34 conditions) of South-Holland coast 1980-1988*

Figure 3.9A shows computed coastlines for a coastal extension of 1000 m (Case 20 of **Table 2.1**) and a net longshore transport of 500,000 m^3/year (by adjusting the coefficient of Equation (1)) based on waves in positive-negative order. Positive wave angles yield longshore transport to the right in Figure 3.8A,B,C. The grid size is 50 m and the time step is 0.005 day (432 s). The numerical oscillations are relatively large if the smoothing = 0. The oscillations can be suppressed by using smoothing= 0.0005 and 0.001. The computed coastline is asymmetric, which is in agreement with the net longshore transport to the right. Using a smoothing= 0.0005, stable, but inaccurate results are obtained. The asymmetry of the computed coastline is suppressed.

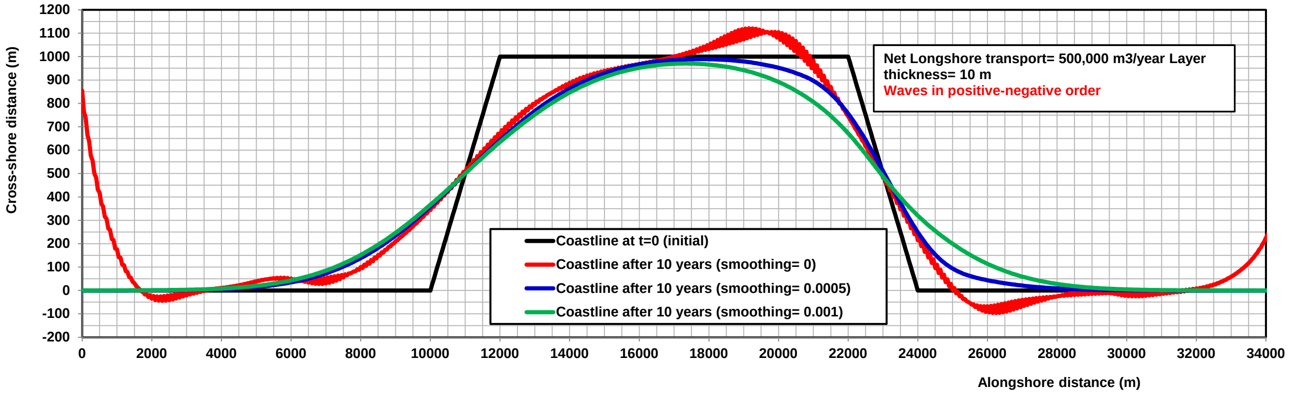

Figure 3.9A *Coastlines; effect of wave order and smoothing parameter; positive-negative wave order*

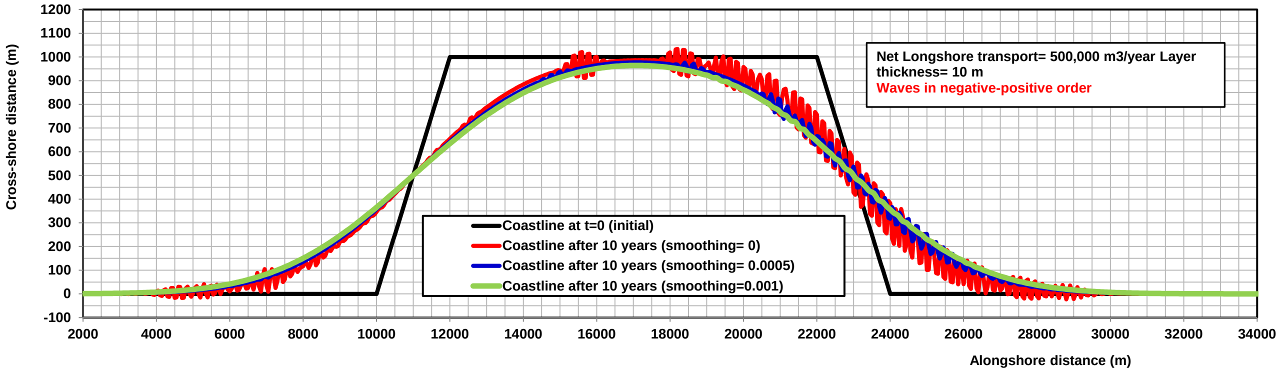

Figure 3.9B *Coastlines; effect of wave order and smoothing parameter; negative-positive wave order*

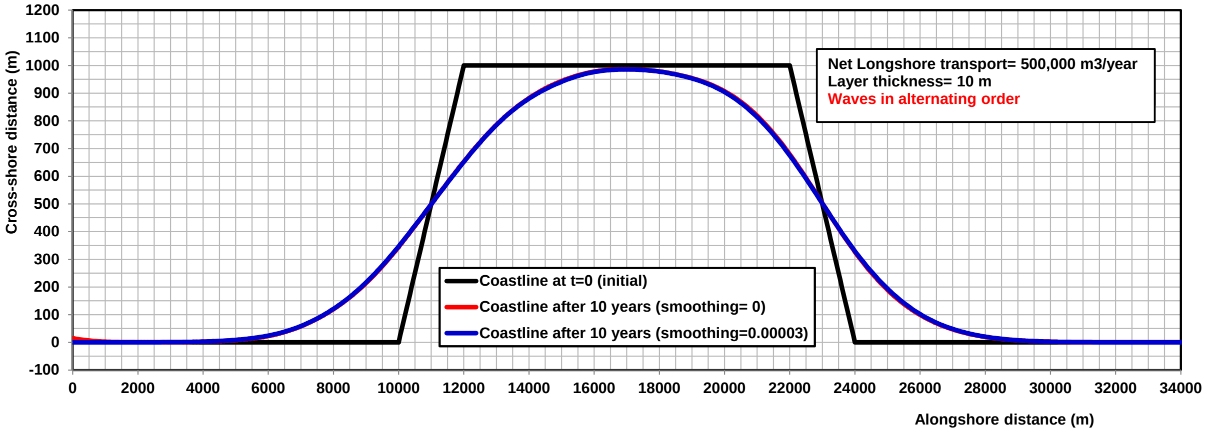

Figure 3.9C *Coastlines; effect of wave order and smoothing parameter; alternating wave order*

Figure 3.9B shows computed coastlines for a coastal extension of 1000 m (Case 20 of **Table 2.1**) and a net longshore transport of 500,000 m^3/year based on waves in (reversed) negative-positive order. The numerical oscillations are relatively large if the smoothing = 0. The oscillations can be suppressed by using smoothing= 0.001. As a result, the computed erosion (total erosion area) increases by about 5%.

Figure 3.9C shows computed coastlines for a coastal extension of 1000 m (Case 20 of **Table 2.1**) and a net longshore transport of 500,000 m^3/year based on waves in alternating order (alternating positive and negative wave angles). The numerical oscillations are absent for smoothing = 0. Minor instabilities are present at the boundary x=0, which can be suppressed by very minor smoothing =0.00003. Both coastlines lines are very close. The computed coastline after 10 years is slighty asymmetric.

These test computations show that for numerical stability it is best to apply a wave table with waves in alternating order (alternating positive and negative wave angles). The wave order slightly influences the accuracy of the long term coastline position (suppression of asymmetry). A smoothing parameter equal to 0.00003 introduces an erosion inaccuracy < 3%.

Calibration of LONGMOR-model using 'sandmotor' data

The LONGMOR-model has been calibrated using the measured coastline changes and erosion volumes of the 'sandmotor' Case. The net longshore transport of sand (d_{50}=0.21 mm) in the situation without 'sandmotor' is assumed to be 200,000 m^3/year based on earlier results (Deltares, 1995a,b).

The model settings are given in **Table 3.6**. Three wave climates have been used (**Tables 3.2, 3.3 and 3.5**). **Table 3.5** is a detailed offshore wave climate consisting of 34 wave conditions (wave angles between 60 and -60 degrees to the coast normal) based on wave measurements in the period 1980-1988 at an offshore depth of 30 m along the coast of South-Holland. Onshore-directed waves > 0.5 m are only present during 108 days. **Tables 3.2, 3.3** and **3.5** are schematized wave climates with 10, 9 and 34 conditions.

PARAMETER	**Values**
Grid size and length	50 m; 12.5 km
Timestep	0.002 day
Grid-'smoothing'	0.00001
Sand d_{50} and d_{90}	0.21 mm; 0.5 mm
Slope surf zone 0 to -7 m NAP	1 to 100
Breakercoefficient	0.6
Wave order	Alternating (positive and negative angles)
Layer thickness of active zone	10 m (between -7 m and +3 m NAP)
Longshore transport formula	Van Rijn (2014)
File name	zandm1.inp; zandm2.inp

Table 3.6 *Model settings LONGMOR for 'sandmotor', South-Holland*

Figure 3.10 shows the computed erosion volumes of the 1D LONGMOR-model as function of time using the same wave climate with 10 conditions (**Table 3.2**) as used in the Delft3D-model runs. The computed erosion volumes are about 30% smaller than those of the Delft3D-model (**Figure 3.6**).

The discrepancies between the Delft3D and the LONGMOR-results are caused by the following effects:

- different wave refraction seaward of the active surf zone (depth contours outside surf zone are almost stationary in Delft3D-model whereas they are rotating in LONGMOR-model similar as the coastline rotation);
- flow contraction resulting in an increase of the tide-driven velocities and transport rates (neglected in LONGMOR);
- wave focusing resulting in enhanced wave heights at both seaward corners (neglected in LONGMOR);
- erosion due to cross-shore transport gradients which may be relatively large during the initial years due to the presence of relativey steep beach profiles (neglected in LONGMOR).

Figure 3.10 also shows the computed erosion volumes based on the detailed wave climate (34 conditions) of the South-Holland coast (**Table 3.5**). The measured initial erosion volumes after 0.5 and 1 year are significantly underestimated. These results show the strong effect of the wave climate on the 1D model results. The 1D model underestimates the measured erosion volumes significantly using this detailed wave climate. The results of the 1D model can only be improved by calibration of the wave climate (adjusting the wave angles and the durations) using measured erosion volumes.

The 1D LONGMOR-model has been calibrated to better represent the measured values by using a schematized wave climate. The calibrated wave climate (9 conditions) is shown in **Table 3.3** and in **Figure 3.5**. The wave climate of **Table 3.3** is slightly more asymmetric than the wave climate of **Table 3.2** used in the Delft3D-model runs, see **Figure 3.5**. **Figure 3.10** shows the computed erosion volumes as function of time based on the applied wave climates (4 to 34 conditions; Tables 3.2 to 3.5). The measured initial erosion volumes after 2 years are reasonably well simulated using calibrated 4 and 9 wave conditions, but the measured erosion after 0.5 and 1 year are significantly underestimated.

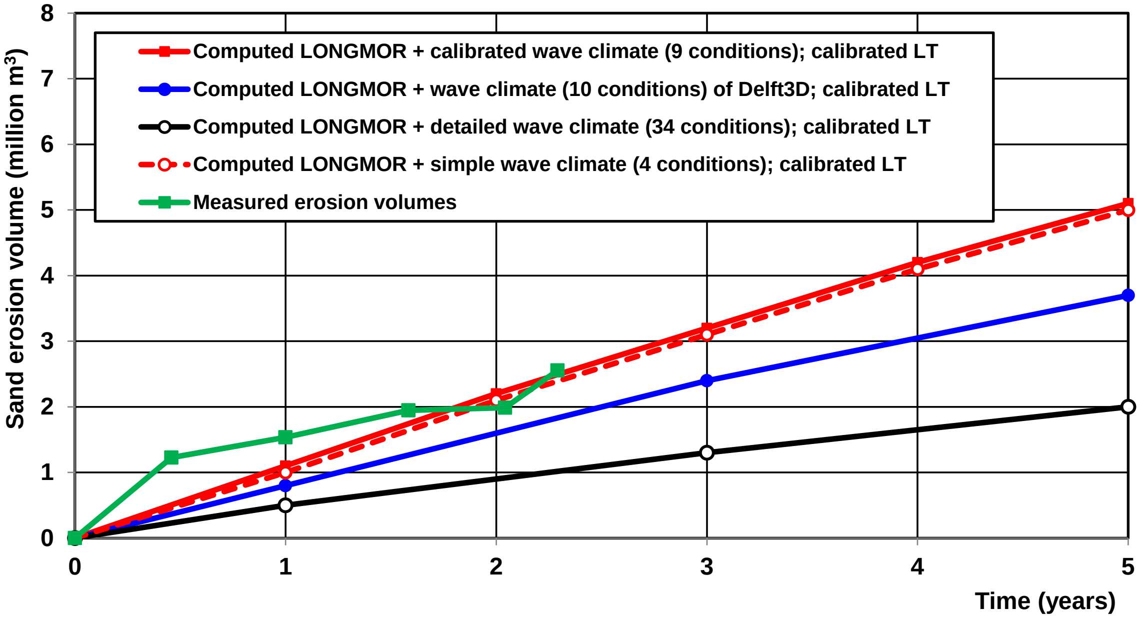

Figure 3.10 *Measured and computed LONGMOR erosion volumes, sandmotor*

Figure 3.11 shows the computed net longshore transport rates after 1 year using the wave tables 3.2, 3.3, 3.4 and 3.5. The net longshore transport rate at both boundaries of the model is about 200,000 m^3/year. The transport curve shows instabilities at the very sharp transition zone near x= 7300 m.

The LONGMOR-model has also been used in combination with a very simple wave climate consisting of four wave conditions, see **Table 3.4**. This wave table was calibrated to give an erosion volume of about 1.1 million m^3 (see **Figure 3.11**) and a net longshore transport of 200,000 m^3/year at the boundary. It is found that less wave conditions lead to more instabilities at the transition zone near x= 7300 m. It is essential to include waves from almost normal directions to the coast, as these waves yield the largest erosion at the flanks of the coastal extension (nourishment).

The maximum transport gradient is approximately:

- 0.8 million m^3/year based on wave table 3.2 (10 conditions),
- 0.5 million m^3 based on the detailed wave table 3.5 (34 conditions),
- 1.1 million m^3/year based on the calibrated wave table 3.3 (9 conditions),
- 1.1 millions m^3/year based on the simple wave table 3.4 (4 conditions).

Sensitivity computations using other model settings yield a variation range of about 0.15 million m^3/year. The computed erosion volumes of 0.5, 0.8 and 1.1 million m^3 after 1 year are considerably smaller (factor 1.5 to 3) than the measured value of 1.5 million m^3.

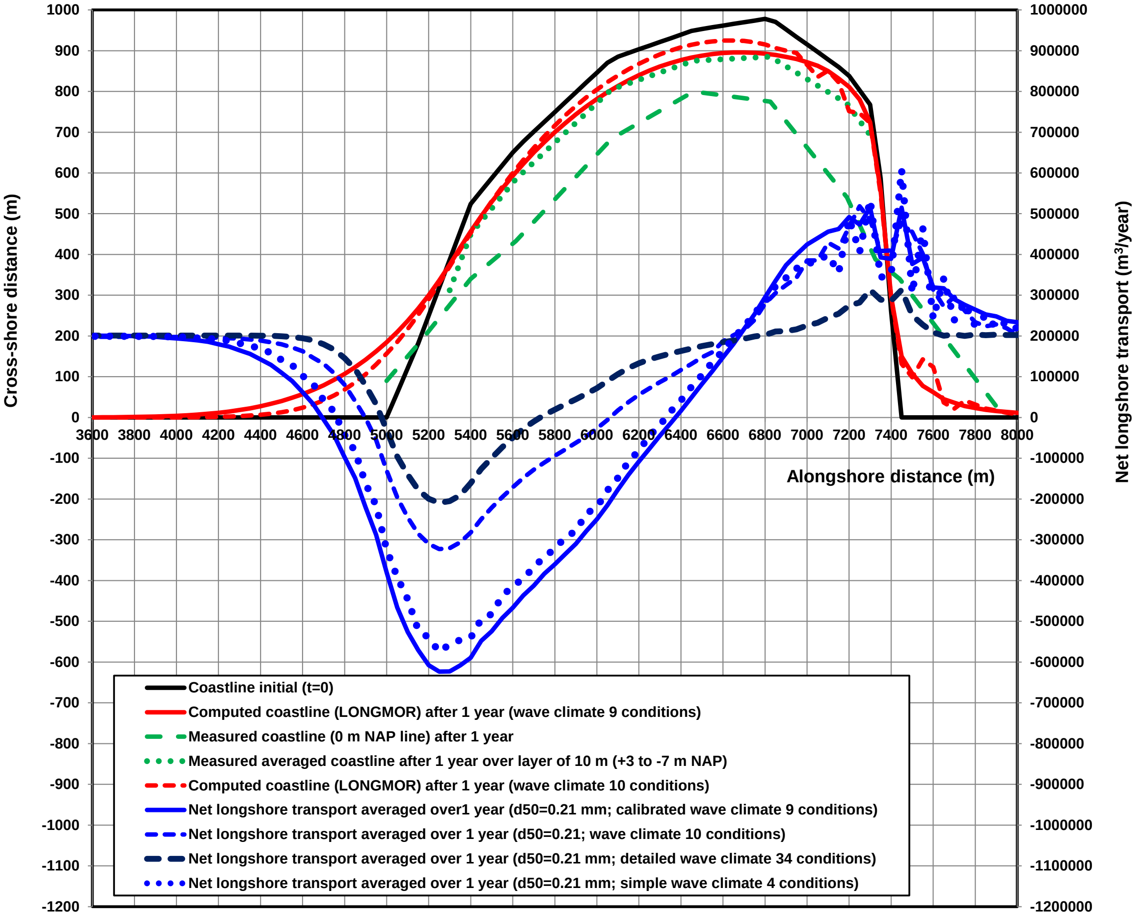

Figure 3.11 *Computed longshore transport rates;*
Computed and and measured coastlines after 1 year, 'sandmotor', South-Holland

The computed coastline recession after 1 year based on wave table 3.3 is also shown in **Figure 3.11**. The computed average coastline recession between x= 5300 m and x= 7000 m is about 60 m. The average 'measured' coastline recession over the length of the central section (x=5300 m to 7300 m; layer thickness= 10 m) of the 'sandmotor' is 1.500,000/(10x2000) = 75 m (**green dotted line in Figure 3.7**). The measured coastline after 1 year (coastline=waterline= 0 m NAP; **green dashed line**) is situated far more landward than the measured average recession line, which points to relatively large erosion near the waterline.

3.3.4 CROSMOR computations

The 2 dimensional-vertical CROSMOR-model has been used to compute the erosion of sand in the cross-shore profile zone between +3 and -7 m NAP. The effect of longshore transport gradients is neglected. The model settings are given in **Table 3.7**. The mean annual wave climate of **Table 3.3** has been used for reasons of simplicity. A storm with a deep-water wave height of $H_{s,o}$= 5 m and a duration of 5 hours (once in 5 years) and storm surge level of 1 m has been added. The median sand particle diameter is set to d_{50}= 0.21 mm. The maximum tidal velocities during flood and ebb are assumed to be relatively large (factor 2 increase) to simulate the flow contraction effect (**Table 3.7**). To simulate the relatively steep beach profile, the 'entrainment' of sand at the beach by the waves has been increased by 30% (sef=1.3).

Figure 3.12 shows the results of the CROSMOR-model for cross-shore Profile 108.41 km.
The computed erosion after 1 year is about 400 tot 450 m^3/m (about 50% of the measured value of 900 m^3/m after 1 year). A sef-value of 1.3 yields about 10% more erosion at the beach. The increase of the tidal velocities (factor 2) yields a 10%-increase of the erosion. The CROSMOR-model underestimates the measured erosion because only cross-shore transport processes are simulated; the longshore transport gradients are neglected.

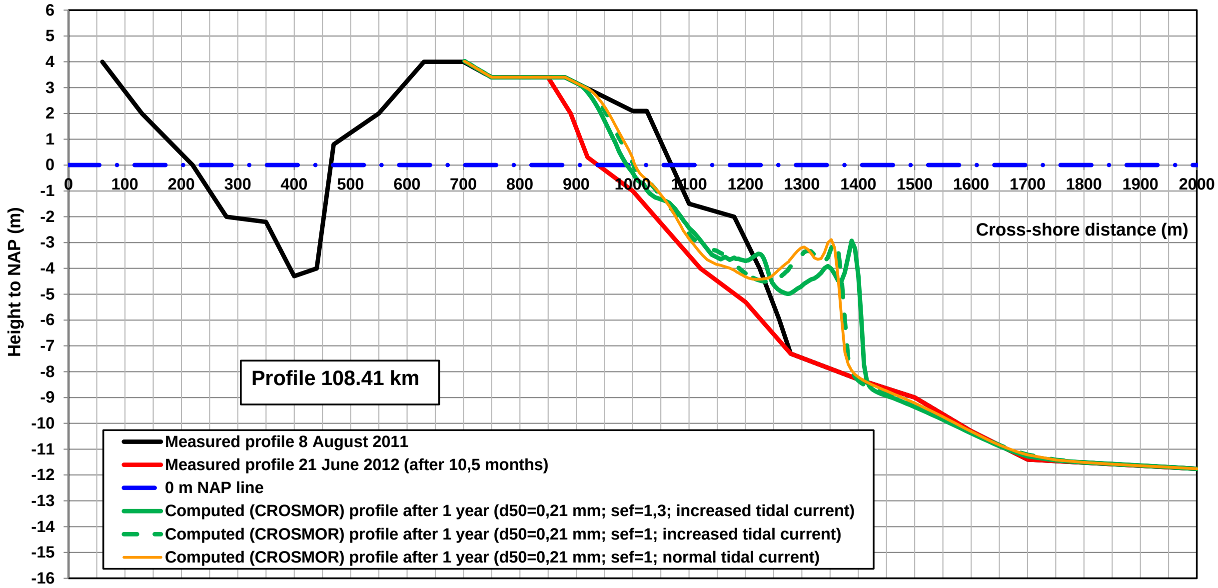

Figure 3.12 *Measured and computed cross-shore profiles, 'sandmotor',108.41 km; d_{50}=0.21 mm*

PARAMETERS	VALUES		
Tidal conditions	Time (sec)	Flow velocities (m/s)	Water levels (m)
	0	0	0
	3600	0.8	0.5
	10800	1.2	1.0
	18000	0.8	0.5
	21600	0	0
	25200	-0.7	-0.4
	32400	-1.1	-0.8
	39600	-0.7	-0.4
	43200	0	0
Limiting depth = water depth in last grid point	0.5 m		
Grid size; total length	50 m (deep water) to 2 m (beachzone); 5000 m		
Number of wave classes per wave height	1		
Wave asymmetry	based on Isobe-Horikawa		
Coefficient Longuet-Higgins streaming; roller effect	0.5 (default=1); 0.5 (default=1)		
Grain size sand d_{50}	0.21 mm		
Coefficients sandtransportformulas	1 (default= 1)		
Coefficient sandtransport due to wave asymmetry	0.2 (default= 1)		
Coefficient sand entrainment beachzone	1.0 (default) and 1.3		
Bed roughness	automatic		
Temperature and salinity	10 degrees and 30 promille		

Table 3.7 *Model settings CROSMOR for 'sandmotor'*

If it is assumed that Profile 108.41 km is representative for the central section (length of 2000 m) of the 'sandmotor', then the total erosion after 1 year due to cross-shore transport gradients is about 800,000 (±150,000) m^3. Sensitivity computations using other model settings yields a variation range of 150,000 m^3/year. The total annual erosion volume due to cross-shore transport gradients will decrease to about 100,000 m^3 during later years (after 3 to 5 years) when the beach profile is smoothed into a quasi-equilibrium profile.
The computed erosion at the waterline after 1 year is about 90 m. The computed mean recession over the height of the active zone between +3 m en -7 m NAP is about 450/10= 45 m.
The eroded sand is deposited as a sand bar in the deeper part of the profile. In reality, the formation of a sand bar will be suppressed during the first years due to the presence of relatively large longshore transport gradients. This latter effect cannot be simulated by the CROSMOR-model.

3.3.5 Best estimate of computed erosion after 1 year based on LONGMOR and CROSMOR results

The computed erosion values due to longshore transport gradients (LONGMOR) and due to cross-shore transport gradients (CROSMOR) have been computed separately, while these processes in reality occur simultaneously. Both model results have to be combined in a balanced way to obtain a realistic estimate of the total erosion after 1 year along the central section of the 'sandmotor'.
The **upper limit** can be obtained by linear addition of both values resulting in 1.1+0.8=1.9 million m^3 after 1 year.
The **lower limit** can be obtained by only using the erosion due to longshore transport gradients resulting in 1.1 million m^3 after 1 year.
The **most realistic** estimate can be obtained by vectorial addition of both results resulting in $(1.1^2+0.8^2)^{0.5}$= 1.35 (±0.4) million m^3 after 1 year, see **Table 3.8**.
The measured erosion after 1 year along the central section of the 'Sandmotor' (length of 2000 m) is about 1.5 million m^3.
The LONGMOR-model gives a recession of 70 m (average value over height of active zone of 10 m).
The CROSMOR-model gives an average recession of about 45 m. The computed recession of CROSMOR at the waterline (0 m NAP) is about 90 m.
The computed average recession based on both models (LONGMOR and CROSMOR) is about $(70^2+45^2)^{0.5}$= 85 m (±15 m). The 'measured' average recession is about 75 m.
The computed recession at the waterline after 1 year based on both models is about $(70^2+90^2)^{0.5}$= 115 m. The measured recession at the waterline after 1 year is in the range of 140 to 350 m. Thus, the measured recession at the waterline after 1 year is significantly (20% to 70%) underestimated by the models.
The initial erosion volumes computed by both models (vectorial summation of LONGMOR and CROSMOR results, see **Table 3.8**) are shown in **Figure 3.13**. The results show reasonable agreement after year, but the erosion after 0.5 years is still largely (50%) underestimated.

Time (years)	**Cumulative erosion due to longshore transport gradients (million m^3/year)**	**Cumulative erosion due to cross-shore transport gradients (million m^3/year)**	**Cumulative erosion due to longshore and cross-shore transport gradients (million m^3/year)**
0	0	0	0
1	1.1	0.8	1.35
2	2.2	1.0	2.4
3	3.2	1.1	3.4
4	4.2	1.2	4.4
5	5.1	1.3	5.3
10	8.1	1.8	8.3

Table 3.8 *Computed erosion volumes for 'sandmotor' based on LONGMOR and CROSMOR results*

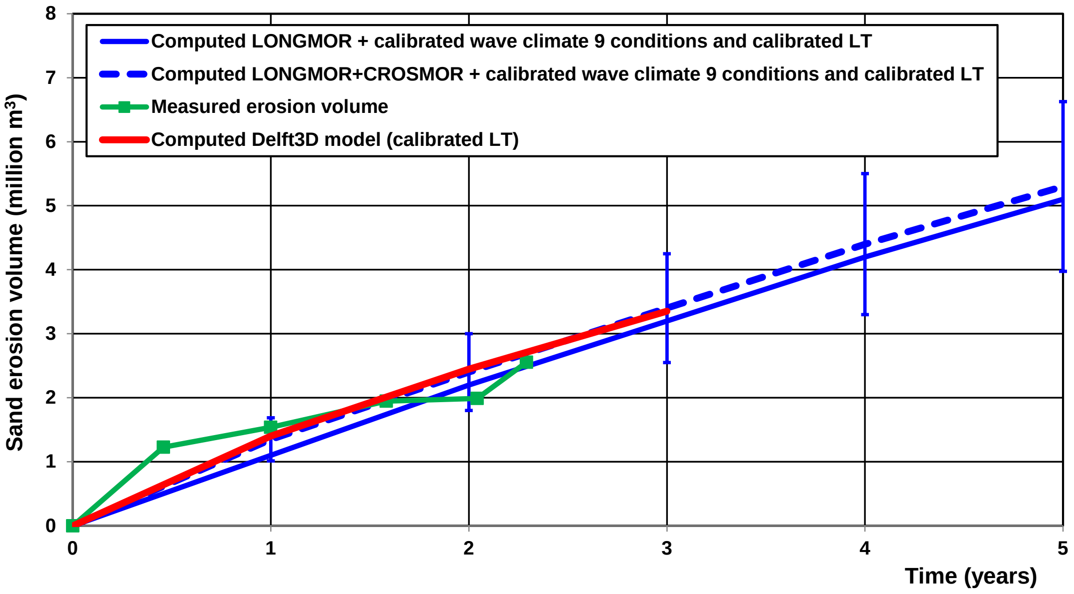

Figure 3.13 *Measured and computed erosion volumes as function of time, 'sandmotor'*

3.3.6 Comparison of all model results

The computed erosion volumes over 5 years based on the Delft3D-model (applied in 2DH mode) of Deltares, the 1D UNIBEST-CL of Deltares and the 1D LONGMOR-model are shown in **Figure 3.14**. All models have been calibrated to produce a net annual longshore transport of about 200,000 m^3/year in the undisturbed situation (first calibration step). It is assumed that the results of the most sophisticated Delft3D-model represents the 'best' results. The 1D UNIBEST-model yields almost the same results using the dynamic boundary conditions at a depth of 6.3 m (see Section 3.3.2) with 269 wave conditions to simulate the annual wave table. Using only 10 wave conditions in UNBEST-CL, yields slightly smaller erosion volumes. Hence, the number of wave conditions is much less important than the type of boundary condition. In Section 3.3.2 it is shown that the type of boundary condition is crucial to obtain accurate results using a 1 D model approach. It is remarkable that the 1D UNIBEST-CL model can produce rather accurate results for a complicated large-scale coastal extension over a short distance (strong perturbation of the coastline) in comparison to the more sophisticated Delft3D-model. Important phenomena such as tidal flow, flow contraction and cross-shore transport are not represented by the 1D model. This seems to suggest that these latter phenomena are not that important compared to the wave angle effect (shift of the coastline).

The LONGMOR-model does not include the dynamic boundary condition as used in the UNIBEST-CL-model. The simplified LONGMOR-model can produce the same results as the other models by calibrating the wave conditions. However, this involves an additional calibration step. Thus, two calibration steps are required: 1) the net annual longshore transport rate and 2) the wave table. The second calibration step is difficult to achieve as the results of more sophisticated models are often not available. Neglecting the second calibration step, the computed erosion volumes of the LONGMOR-model are about 30% too small.

Figure 3.15 shows the net annual longshore transport rates of the UNIBEST-CL and the LONGMOR-model. The initial coastline used in the LONGMOR-model is different from that used in the UNIBEST-model. The initial coastline used in the LONGMOR-model has a rather steep coastline in the region x=7200 m to x=7500 m (see Figure 3.15). This introduces instabilities of the longshore transport rate in this region, see Figure 3.15. The initial coastline of the UNIBEST-model is much smoother to prevent intstabilities.

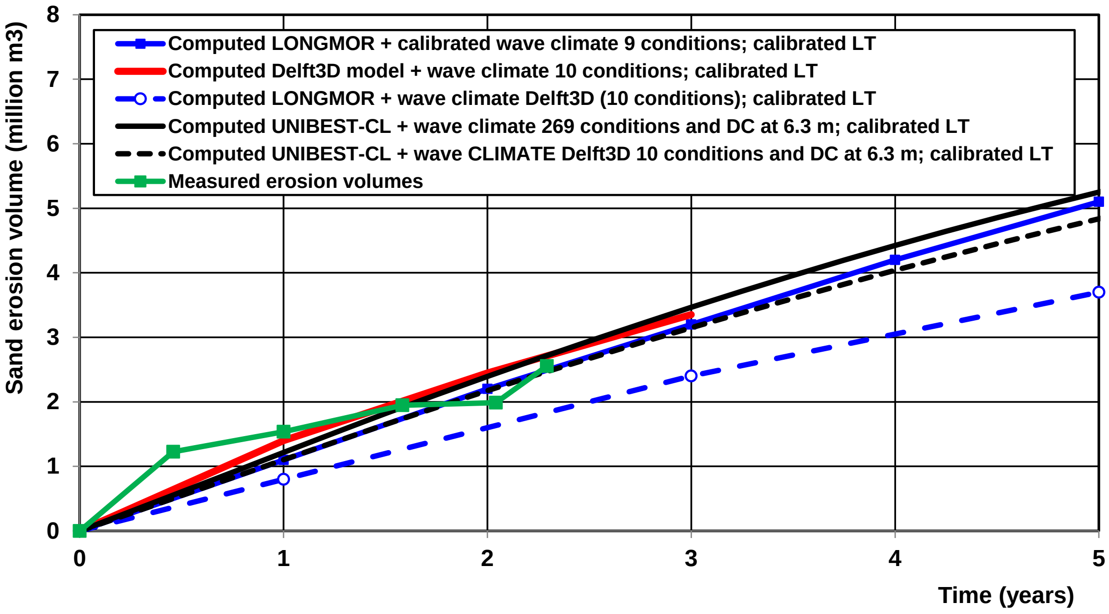

Figure 3.14 *Measured and computed erosion volumes as function of time, 'sandmotor' (comparison of models)*

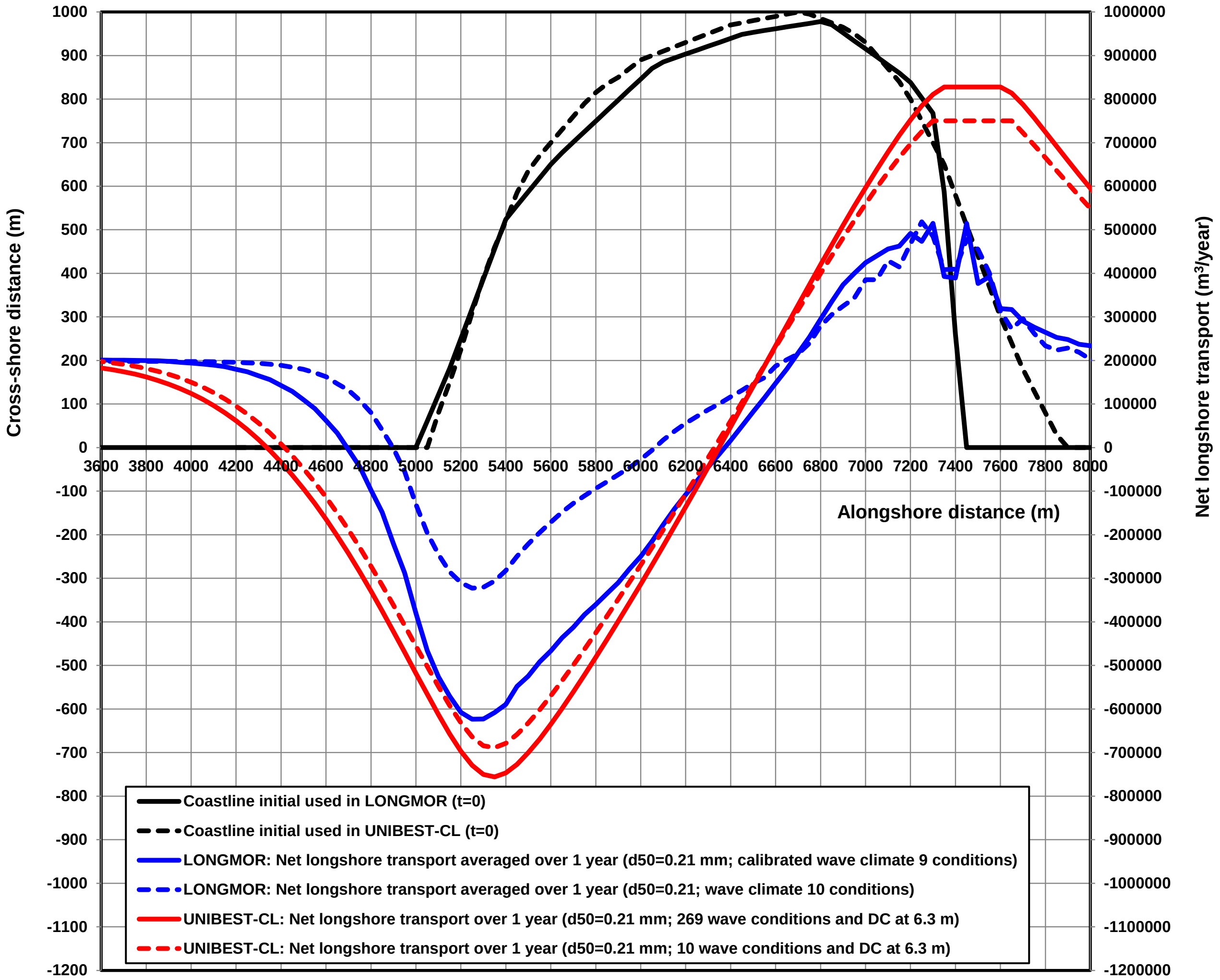

Figure 3.15 *Computed net longshore transport, 'sandmotor'*

4 Erosion of sand along land reclamations and required maintenance nourishments

4.1 Introduction

A land reclamation protected by a sandy beach-dune system will suffer from enhanced erosion as result of the protrusion of the land reclamation into the sea. The erosion will be maximum during the first 3 to 5 years after construction and then gradually reduce to a quasi-equilibrium value.
During (normal) conditions with average winter storms, the erosion will occur mainly in the zone between the -6 m and +3 m NAP lines. Erosion above the dunefoot line (+3 m) will only occur during extreme storms with high surge levels.
Without regular maintenance (beach nourishments) to compensate for the annual sand losses due to erosion, the new land reclamation of sand will disappear on the long term.

4.2 Erosion due to longshore transport gradients based on LONGMOR-model

The 1D LONGMOR-model has been used to simulate the longshore transport and erosion in the new situation with land reclamation. The dimensions of the land reclamations considered are given in **Table 2.1**. In all, the initial erosion has been computed for 20 cases. The general settings of the LONGMOR-model are given in **Table 4.1**.

PARAMETER	**VALUE**
Grid size and model length	50 m; 35 km
Time step	0.0025-0.005 day
grid-'smoothing'	0.0001-0.0003
Sand d_{50} and d_{90}	0.25 mm; 0.5 mm
Slope surf zone +3 to -7 m NAP	1 to 50
Breakercoefficient	0.6
Layer thickness of active zone	10 m (between -7 m and +3 m NAP)
Longshore transport formula	Van Rijn 2014
File name	beachs1.inp

Table 4.1 *Settings LONGMOR-model*

4.2.1 Effect of wave climate and wave order

Various types of wave climates have been used to determine the effect on the erosion of a land reclamation:

- wave climate of Table 3.2 (10 wave conditions),
- wave climate of Table 3.3 (9 wave conditions),
- simple wave climate of Table 3.4 (4 wave conditions).

Each of these three wave tables yields a net annual longshore transport rate of about 200,000 m^3/year using Eq. (1).
Wave Table 3.2 is somewhat more symmetric compared to wave Table 3.3 (see **Figure 3.5**)

Figure 4.1 shows the net annual longshore transport along the land reclamation of Case 18 (**Table 2.1**) with seaward length of 2500 m and landward length of 6500 m during the first year (initial situation) based on wave Table 3.3.

The net annual longshore transport (LT) in the undisturbed situation far away from the land reclamation is approximately 200,000 m^3/year.

The computed net transport is slightly unstable at the downwave transition zone (x= 15-16 km), if the waves are applied in the positive-negative order of Table 3.3. These instabilities are caused by the sharp transition (corner points) in the initial situation and will die out rapidly in later years when a more smooth coastline is present.

The instabilities are absent, if the waves are applied in alternating order with alternating positive and negative wave angles of **Table 3.3**.

The erosion volume is maximum during the initial situation (first year) and can be computed as (**Figure 4.1**):

$$V_e = LT_{maximum}-LT_{miminum} = 600,000 - (-400,000)= 1.000,000 \text{ m}^3/\text{year}.$$

Figure 4.2 shows the land reclamation after 1 year and 10 years based on wave **Table 3.3**. The initial erosion volume is about 1 million m^3 after 1 year (layer thickness = 10 m). The wave order has a small effect on the coastline. Alternating wave conditions yield a more symmetrical coastline.

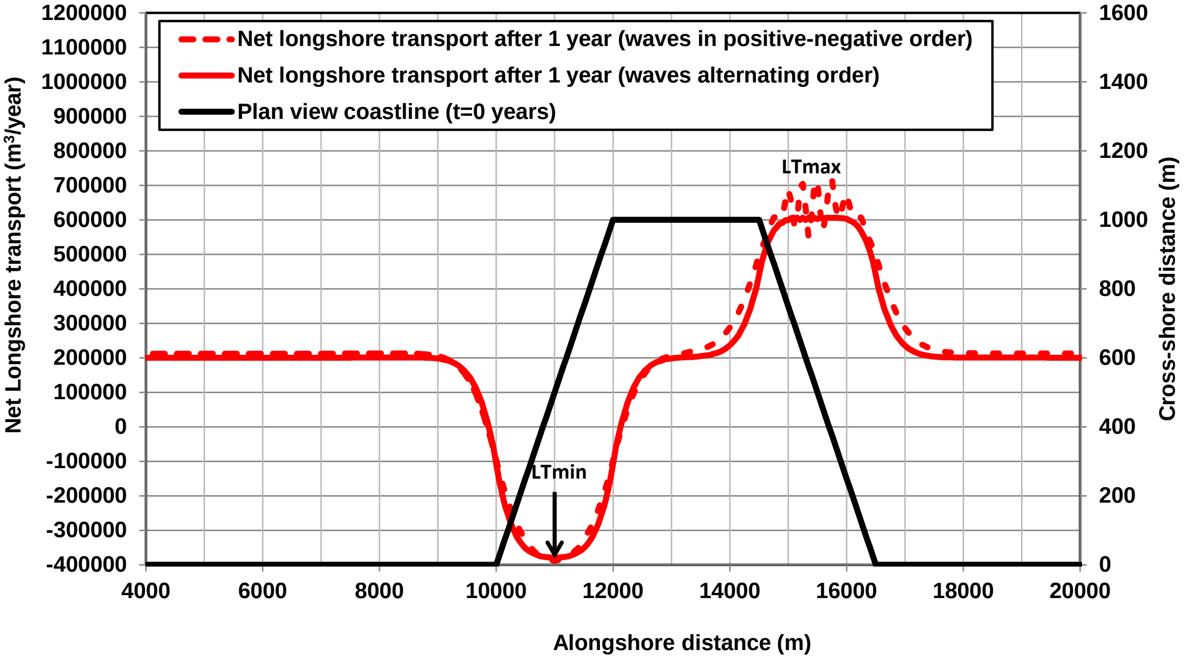

Figure 4.1 *CASE 18: Longshore transport gradient averaged over 1 year;*
Net longshore transport = 200,000 m^3/year (Wave Table 3.3)

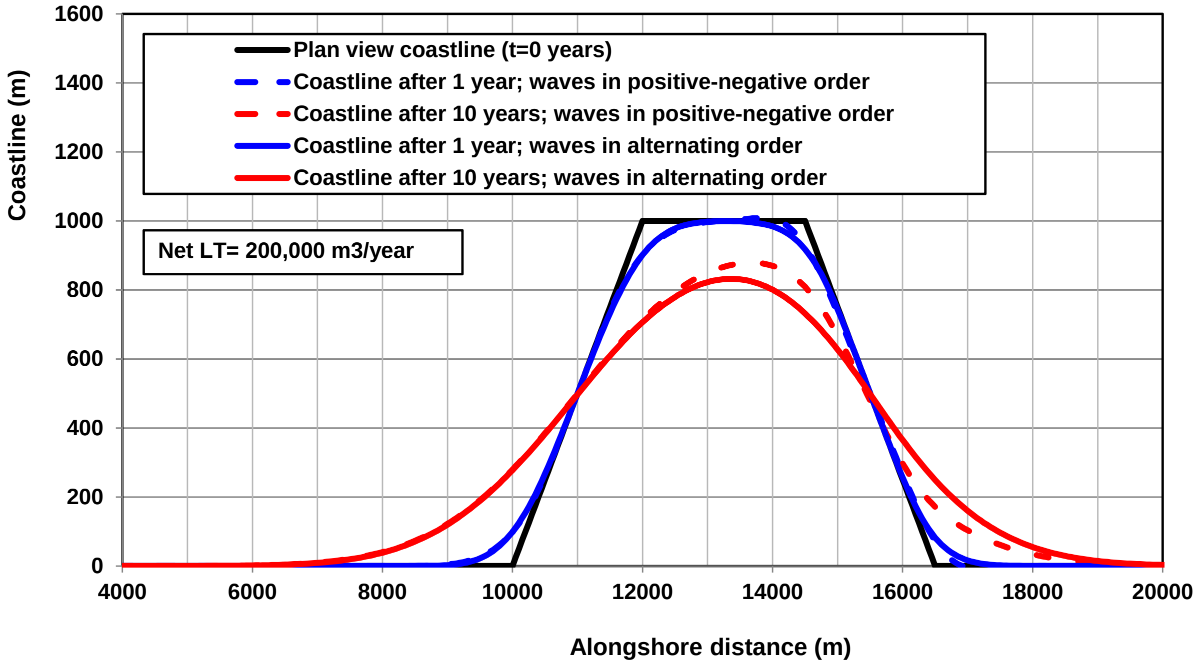

Figure 4.2 *CASE 18: Computed coastlines after 1 and 10 years (Wave Table 3.3)*

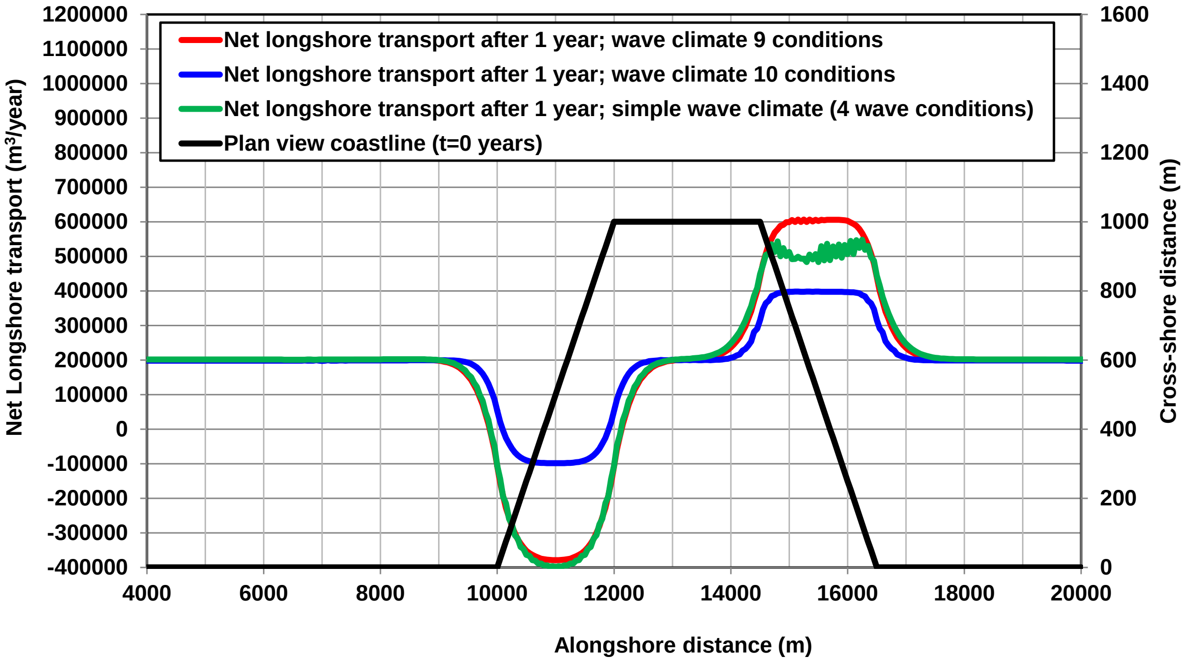

Figure 4.3 *CASE 18: Longshore transport gradient averaged over 1 year;*
three wave climates (Tables 3.2, 3.3 and 3.4); net longshore transport= 200,000 m^3/year

Figure 4.3 shows the effect of the three wave climate (**Tables 3.2, 3.3 and 3.4**) on the initial net longshore transport for land reclamation Case 18 (see **Table 2.1**). The net annual longshore transport (LT) far away from the land reclamation is approximately 200,000 m^3/year for all three wave climates.

The maximum longshore transport gradient is approximately 1.000.000 m^3/year for wave Table 3.3.

The maximum longshore transport gradient is approximately 500,000 m^3/year for wave Table 3.2.

The maximum longshore transport gradient is approximately 900,000 m^3/year for wave Table 3.4.
Based on these results, the wave climate of Delft3D yields a 50% reduction of the longshore transport gradient and hence initial erosion volume.

Figure 4.4 and **4.5** show the effect of the wave climates on the computed coastlines after 1 and 10 years. Wave Table 3.2 (Delft3D) yields considerably smaller erosion than wave Table 3.3 (Van Rijn; 9 conditions).
Wave Table 3.4 (simple wave climate; 4 conditions) yields almost the same results as that of wave Table 3.3.

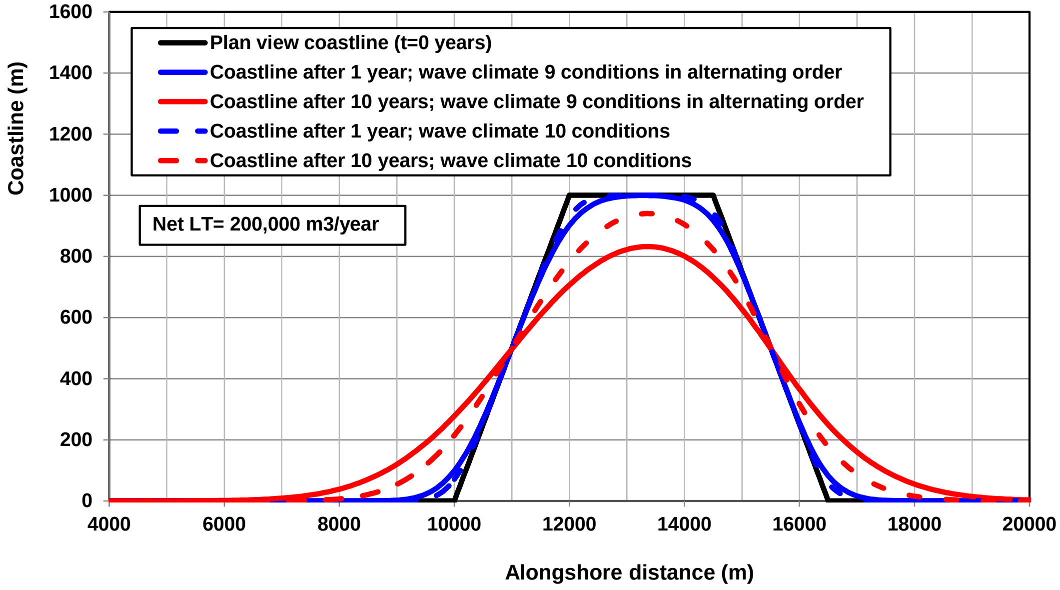

Figure 4.4 *CASE 18: Computed coastlines after 1 and 10 years (Wave Tables 3.2 and 3.3)*

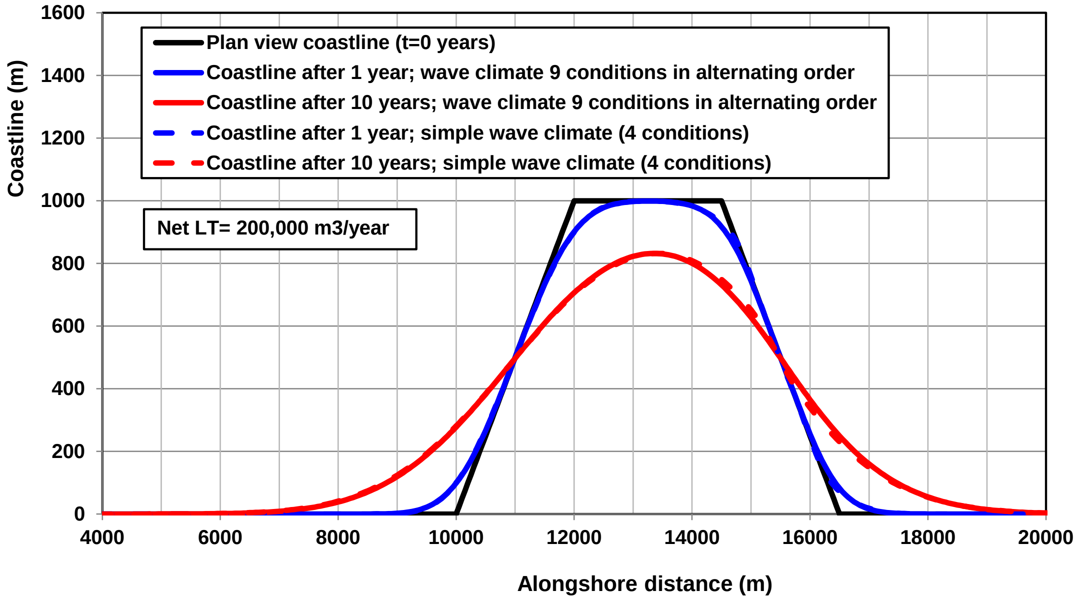

Figure 4.5 *CASE 18: Computed coastlines after 1 and 10 years (Wave Tables 3.3 and 3.4)*

Figures 4.6A and **4.6B** show the computed longshore transport rates for each wave condition of **Table 3.2** and **Table 3.3**. The time-averaged longshore transport rates are also shown.

Figure 4.6A shows that the two wave conditions: H_s=2.43 m and angle=56.6 and H_s=2.24 m and angle=-55 of wave Table 3.2 yield a relatively strong reduction of the time-averaged longshore transport gradient and hence erosion. The time-averaged longshore transport gradient reduces from 2500 m^3/day (=900,000 m^3/year; Figure 4.6B) to 1300 m^3/day (470,000 m^3/year; Figure 4.6A).

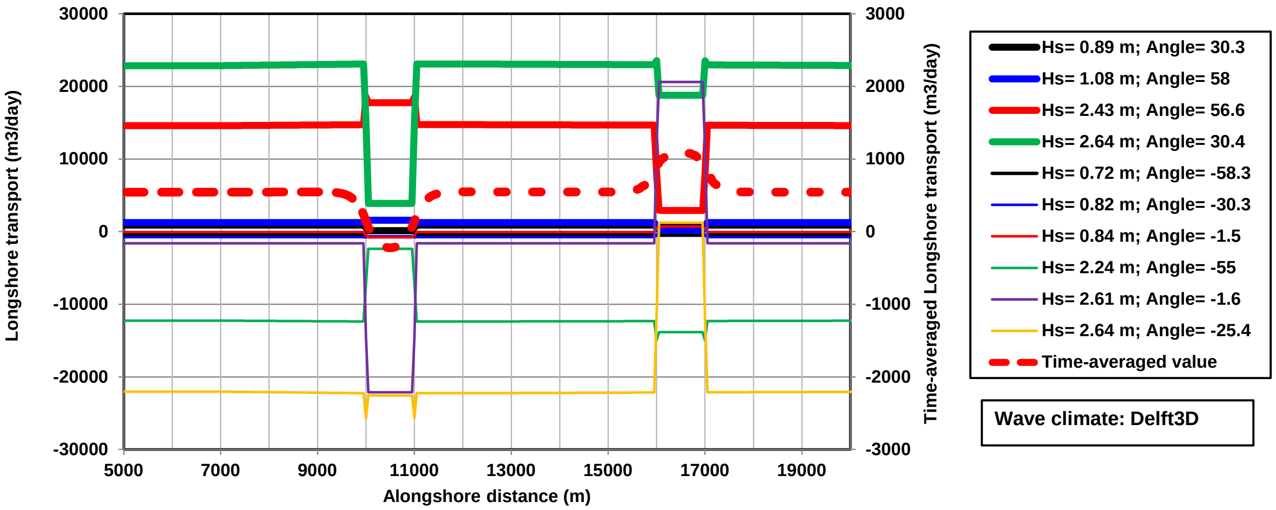

Figure 4.6A *CASE 18: Computed longshore transport rates for each wave condition; wave climate Delft3D 10 conditions (Table 3.2)*

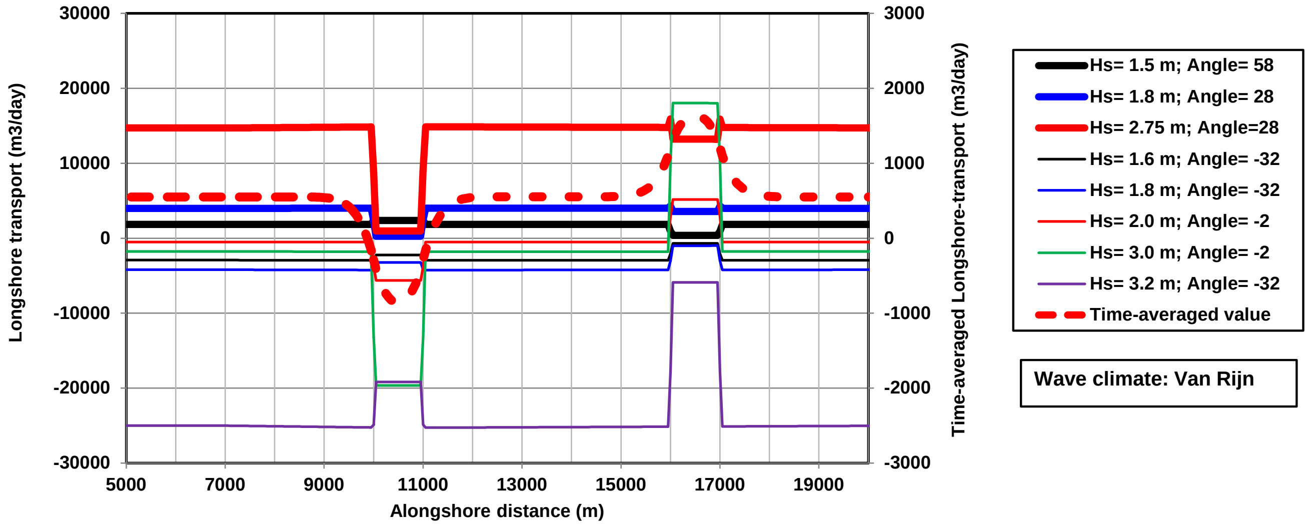

Figure 4.6B *CASE 18: Computed longshore transport rates for each wave condition; wave climate Van Rijn 9 conditions (Table 3.3)*

4.2.2 Initial erosion volumes for various land reclamation designs

The LONGMOR-model has been applied to compute the erosion volumes (after 1 and 3 years) for all 20 cases (using the calibrated wave Table 3.3) and net longshore transport rates in the range of 100,000 to 500,000 m^3/year. The longshore transport formula was calibrated to give a net longshore transport of respectively 100,000; 200,000; 300,000; 400,000 and 500,000 m^3/year at the upwave boundary (left to right in Figure 4.1). Results are shown in **Figures 4.7A,B** and in **Table 4.2**.

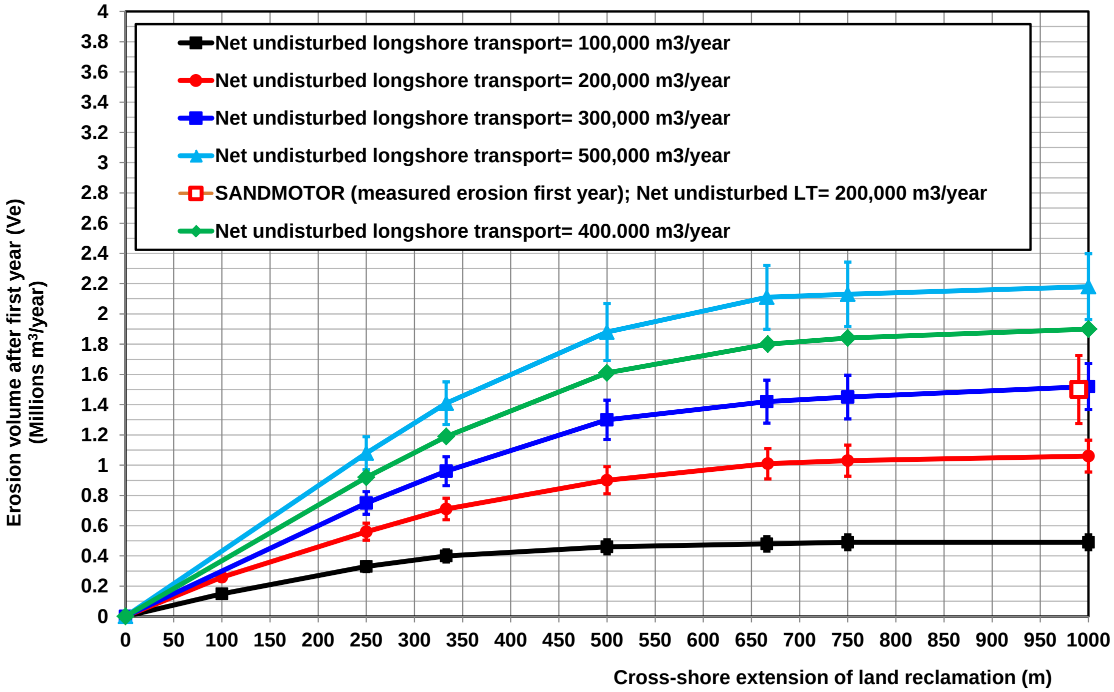

Figure 4.7A *Computed erosion volume (first year) as function of cross-shore extension; LONGMOR*

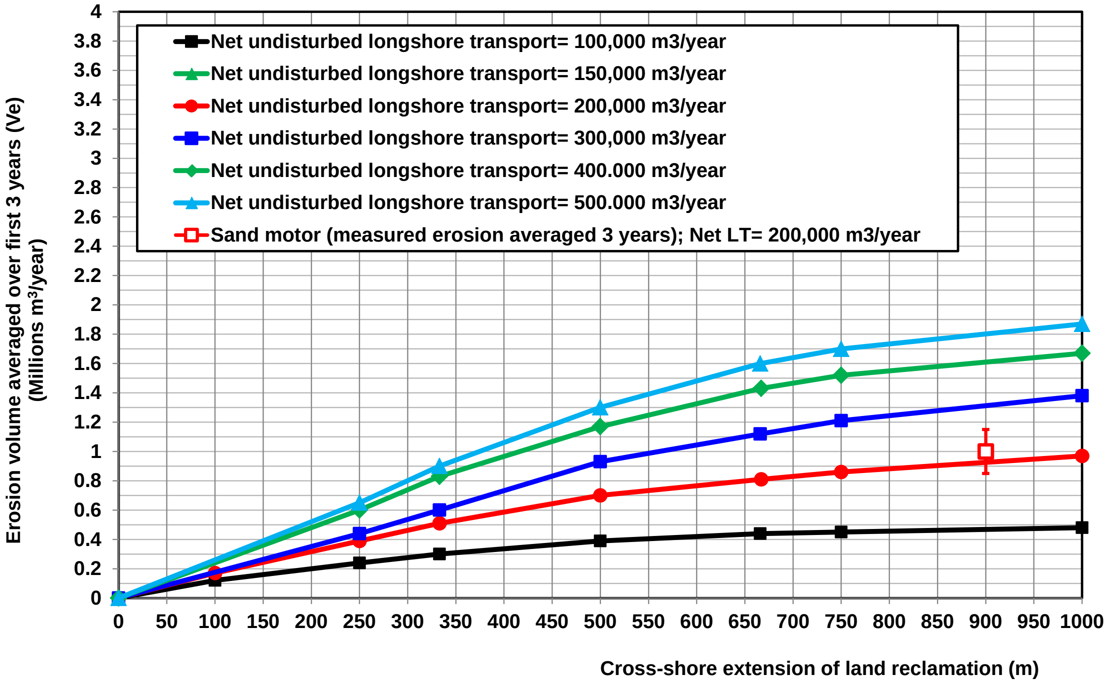

Figure 4.7B *Computed erosion (average 3 years) as function of cross-shore extension; LONGMOR*

Case	Cross-shore extension; horizontal shift of mean waterline (m)	Longshore length (at seaward and landward side) (m)	Net LT= 100,000 m^3/year Maximum erosion loss averaged over 1 year and 3 years (m^3/year)	Net LT= 200,000 m^3/year Maximum erosion loss averaged over 1 year and 3 years (m^3/year)	Net LT= 300,000 m^3/year Maximum erosion loss averaged over 1 year and 3 years (m^3/year)	Net LT= 400,000 m^3/year Maximum erosion loss averaged over 1 year and 3 years (m^3/year	Net LT = 500,000 m^3/year Maximum erosion loss averaged over 1 year and 3 years (m^3/year)
1	250	625; 1625	305,000 195,000	485,000 305,000	690,000 370,000	830,000 430,000	940,000 470,000
2	250	1250; 2250	350,000 250,000	600,000 400,000	800,000 500,000	990,000 580,000	1,140,000 650,000
3	250	2500; 3500	350,000 250,000	600,000 400,000	790,000 510,000	980,000 570,000	1,170,000 690,000
4	250	7500; 8500	350,000 250,000	590,000 400,000	790,000 520,000	980,000 570,000	1,160,000 700,000
5	333	833; 2166	400,000 300,000	710,000 480,000	960,000 600,000	1,180,000 700,000	1,390,000 780,000
6	333	1666; 3000	400,000 300,000	710,000 510,000	970,000 610,000	1,200,000 810,000	1,450,000 910,000
7	333	3333; 4663	410,000 310,000	710,000 520,000	970,000 610,000	1,200,000 830,000	1,450,000 910,000
8	500	1250; 3250	460,000 390,000	870,000 680,000	1,290,000 940,000	1,620,000 1,180,000	1,870,000 1,330,000
9	500	2500; 4500	450,000 380,000	920,000 710,000	1,290,000 950,000	1,630,000 1.190,000	1,940,000 1,380,000
10	500	5000; 7000	470,000 400,000	920,000 710,000	1,300,000 950,000	1,610,000 1.160,000	1,900,000 1,360,000
11	500	15000;17000	460,000 390,000	910,000 700,000	1,310,000 960,000	1,600,000 1,150,000	1,900,000 1,350,000
12	666	1666; 4330	480,000 440,000	1,000,000 810,000	1,440,000 1,100,000	1,650,000 1,300,000	2,110,000 1,660,000
13	666	3333; 6000	480,000 440,000	1,010,000 810,000	1,420,000 1,140,000	1,820,000 1,380,000	2,110,000 1,680,000
14	666	6666; 9333	480,000 440,000	1,020,000 815,000	1,430,000 1,130,000	1,820,000 1,370,000	2,110,000 1,670,000
15	750	1875; 4875	490,000 450,000	1,030,000 860,000	1,470,000 1,230,000	1,840,000 1,530,000	2,160,000 1,730,000
16	750	3750; 6750	490,000 450,000	1,040,000 860,000	1,420,000 1,200,000	1,850,000 1,520,000	2,110,000 1,690,000
17	750	7500; 10500	490,000 450,000	1,040,000 870,000	1,430,000 1,200,000	1,850,000 1,520,000	2,140,000 1,700,00
18	1000	2500; 6500	500,000 470,000	1,020,000 980,000	1,550,000 1,400,000	1,870,000 1,660,000	2,190,000 1,900,000
19	1000	5000; 9000	490,,000 460,000	1,060,000 970,000	1,510,000 1,360,000	1,950,000 1,690,000	2,100,000 1,850,000
20	1000	10000; 14000	490,000 470,000	1,050,000 960,000	1,500,000 1,350,000	1,950,000 1,690,000	2,100,000 1,850,000

Table 4.2 *Computed initial erosion volumes due to longshore transport gradients; LONGMOR*

Figure 4.7A shows the computed initial erosion volume (based on LONGMOR-model) as function of the cross-shore extension for various values of the net longshore transport rate in the undisturbed situation (at the boundaries far away). For most cases the alongshore length of the land reclamation (see Table 2.1) has a minor effect (<20%) on the computed erosion volumes, because the initial erosion is concentrated around the seaward corner points (see also **Figure 4.8**).
The erosion volume increases significantly with increasing cross-shore extension. The measured initial erosion volume of the 'sandmotor' over the first year (about 1.5 million m^3/year) and averaged over the first three years (about 1 million m^3/year) are also shown in **Figures 4.7A,B**. The net longshore transport in the undisturbed situation at the 'sandmotor' location is about 200,000 m^3/year (Van Rijn 1997; Deltares 1995a,b). The measured initial erosion volume of about 1.5 million m^3 after 1 year at the 'sandmotor' is considerably underestimated (about 30%) by the LONGMOR-model. This discrepancy is primarily caused by the erosion due to cross-shore transport gradients which may be relatively large during the initial years due to the presence of relativey steep beach profiles.

Figure 4.7B shows the computed erosion volume averaged over the first 3 years (based on LONGMOR-model) as function of the cross-shore extension for various values of the net longshore transport rate in the undisturbed situation. The erosion volume of sand increases significantly with increasing cross-shore extension. The effect of the alongshore length of the land reclamations on the erosion values is minor (10% to 20%) for most cases and somewhat larger (30%) for a net longshore transport of 500,000 m^3/year, see **Table 4.2**. The measured erosion volume averaged over 3 years of the 'Sandmotor' is slightly (10%) underestimated by the LONGMOR-results (see **Figure 4.7B**).

Figures 4.7C and **4.7D** show similar results for LT = 200,000 and 400,000 m^3/year based the results of three models: LONGMOR (present study), UNIBEST (Stam, 2014) and DELFT3D (Stam, 2014). UNIBEST and DELFT3D were only run for coastal extensions of 333, 666 and 1000 m. The erosion volumes measured after 1 and 3 years at the 'sandmotor' are also shown. The models underpredict the 1year-'sandmotor' results: 15% for UNIBEST and DELFT3D and 30% for LONGMOR (**Figure 4.7C**). The model results are in good agreement with the 3 year-'sandmotor' results (**Figure 4.7D**).
Intercomparison of the model results show that the LONGMOR-model yields somewhat smaller values (about 20% for most cases) than the other two models UNIBEST and DELFT3D for LT=200,000 m^3/year. The maximum difference (30%) occurs for the largest coastal extension of 1000 and the largest LT= 400,000 m^3/year, see **Figure 4.7D**.
The differences between both 1D models (LONGMOR and UNIBEST) may be caused by:

- small differences in the applied wave climates;
- different longshore transport equations and offshore boundary conditions (Section 3.3.2);
- different numerical solution methods.

The 1D models (UNIBEST and LONGMOR) yield almost the same results for LT=200,000 m^3/year as the much more sophisticated DELFT3D model, which is a very surprising result as important phenomena (tidal flow, flow contraction effect, wave focussing effect; cross-shore transport gradients) are neglected using a 1 D model approach. It may be concluded that these phenomena are less important than the wave angle effect. (see also Section 3.3.6). Further studies are required to analyse the performance of the 1D models.

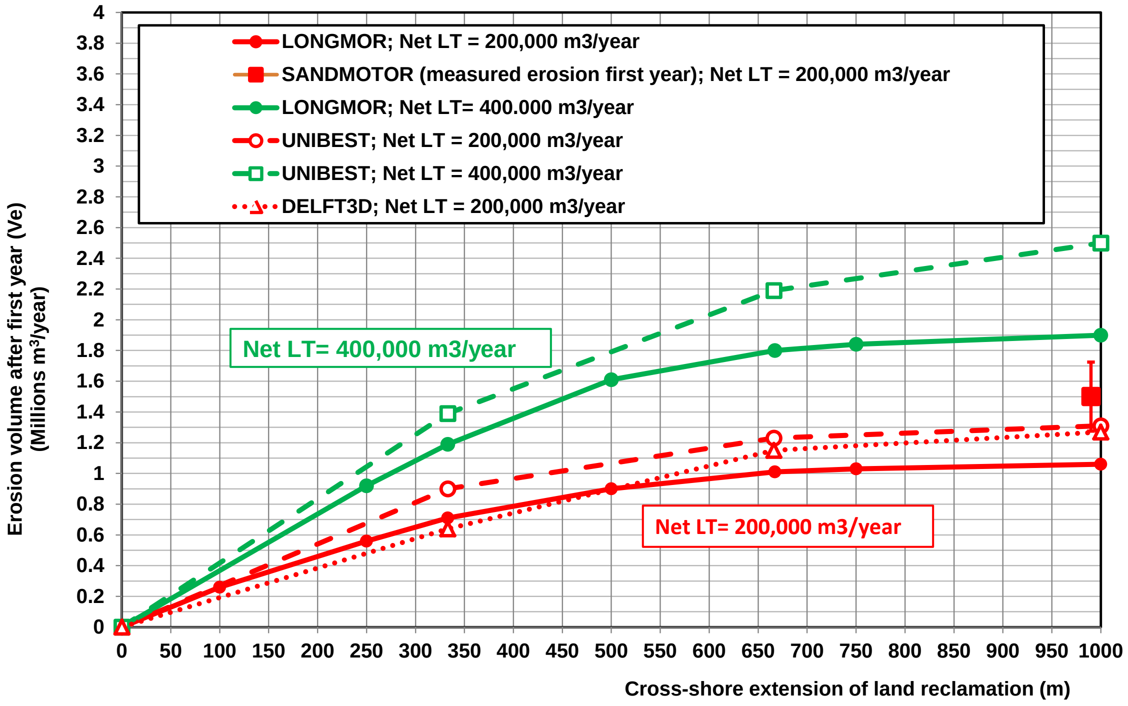

Figure 4.7C *Computed initial erosion volume (first year) as function of cross-shore extension of land reclamation and net longshore transport; LONGMOR, UNIBEST and DELFT3D results*

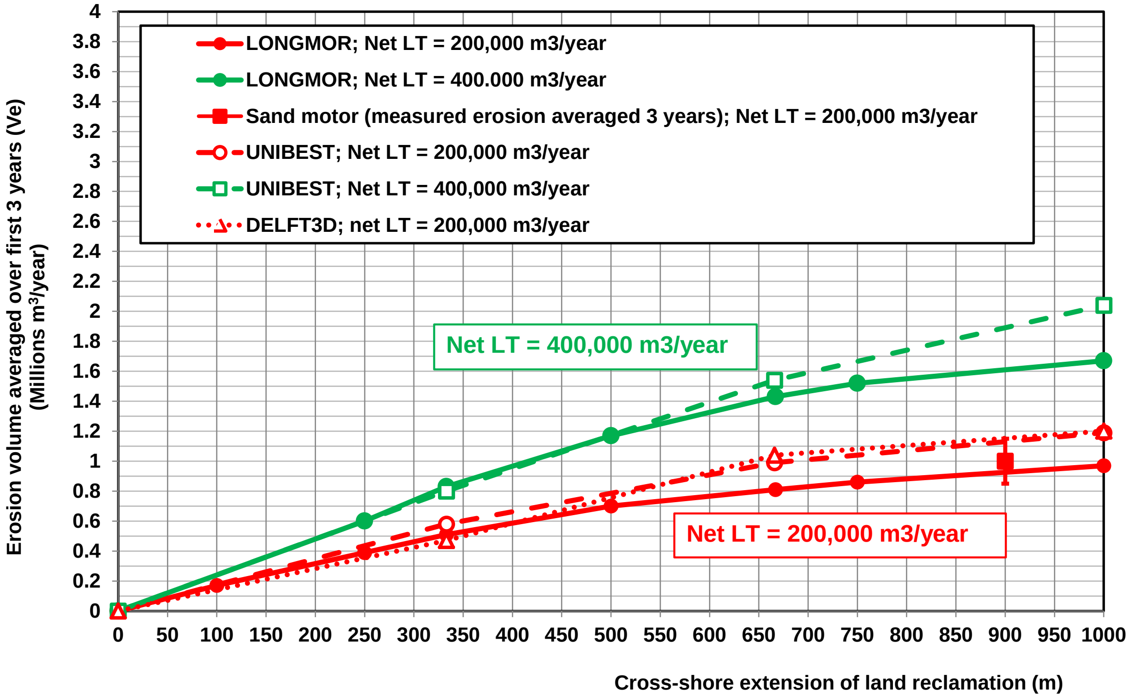

Figure 4.7D *Computed initial erosion volume (average value of first 3 years) as function of cross-shore extension of land reclamation and net longshore transport; LONGMOR, UNIBEST and DELFT3D results*

Figure 4.8 shows the computed coastline changes (based on LONGMOR-model) after 1 year for extensions of 250, 500, 750 and 1000 m. It can be seen that the initial erosion is primarily determined by the coastal angles around the seaward corner points. The erosion volumes after 1 year are almost constant for extensions larger than 500 m, see also **Figure 4.7A**.

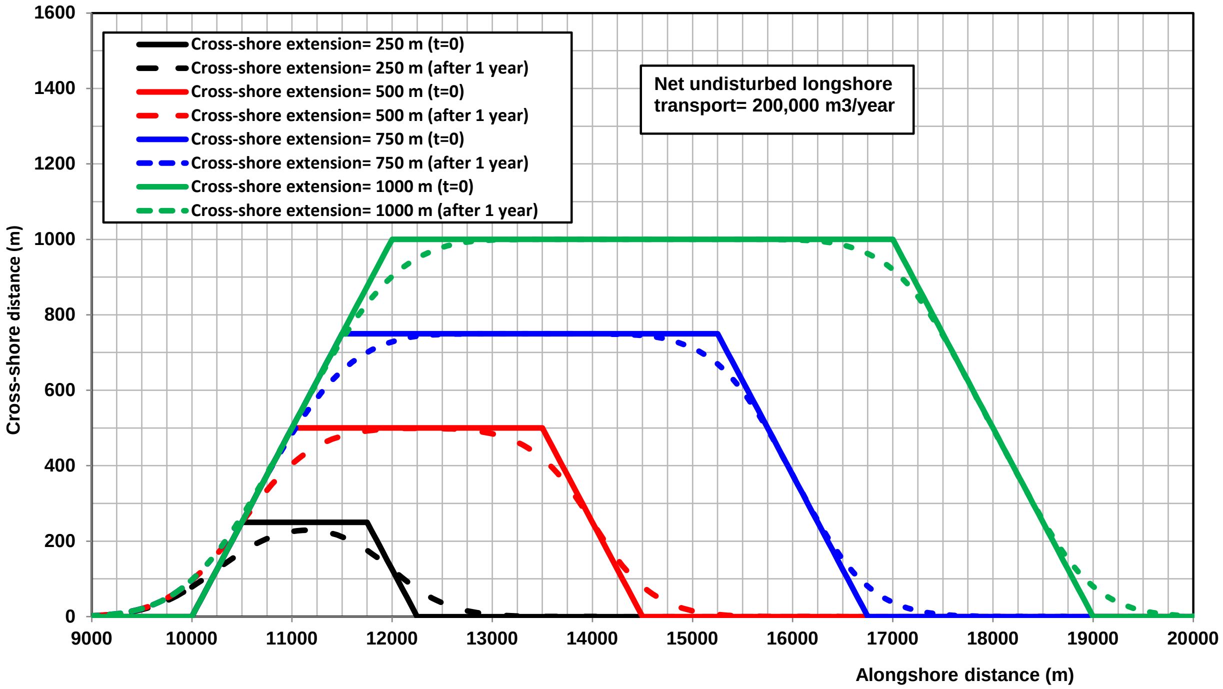

Figure 4.8 *Computed coastline changes after 1 year for Cases 3, 9, 16 and 19*

4.3 Erosion due to cross-shore gradients based on CROSMOR-model

The cross-shore profiles along land reclamations are not natural 'equilibrium' profiles. The initial profiles will be transformed into more natural profiles with sand bars and troughs by cross-shore transport processes. This can be simulated by the 2DV CROSMOR-model. Model computations have been made over a period of 5 years to quantify the erosion of the relatively steep, initial beach near the water line. Model settings are given in **Table 4.3**.

The applied wave climate is a yearly-averaged wave climate based on observations in the period 1980-1988 along the exposed Dutch coast (Deltares 1995a,b) and has 9wave height classes ($H_{significant}$) between 0.5 and 3.2 m, see **Table 3.3**. A storm with a deep-water wave height of $H_{s,o}$= 5 m and a duration of 5 hours (once in 5 years) and storm surge level of 2 m has been added. The Dutch coast is an exposed coast along the North Sea.

The wave asymmetry of the near-bed velocities is computed by the method of Isobe-Horikawa (Van Rijn 1993, 2011). The net streaming near the bed is computed by the method of Longuet-Higgins (Van Rijn 1993, 2011). The vertical tide lies between +1 and -0.8 m NAP. The maximum flood velocity in deep water is set to 0.6 m/s; the maximum ebb velocity is set to 0.5 m/s. The particle size is 0.25 mm.

Figure 4.9 shows the initial bottom and the computed bed levels after 1 and 5 years for d_{50} = 0.25 mm and a large maintenance layer of 650 m^3/m. The maintenance layer serves as sand supply layer to compensate the erosion of sand at the beach and inner surf zone (see also **Figure 2.2**).

In the first year a new sand bar with a width of about 200 m and a height of about 4 m is generated between x= 3150 m and x= 3350 m. Most of the erosion takes place at the lower beach.

Figure 4.10 shows similar results for d_{50} = 0.25 mm and a small maintenance layer of 450 m^3/m.

PARAMETERS	VALUES		
Tidal conditions	Time (sec)	Velocity (m/s)	Water level (m)
	0	0	0
	3600	0.3	0.5
	10800	0.6	1.0
	18000	0.3	0.5
	21600	0	0
	25200	-0.2	-0.4
	32400	-0.5	-0.8
	39600	-0.2	-0.4
	43200	0	0
Depth landward boundary (last grid point)	0.5 m		
Grid size and total length	30 m (deep water) to 5 m (beachzone); 4000 m		
Number of wave classes per condition	1		
Wave asymmetry	According to Isobe-Horikawa		
Coefficient Longuet-Higgins streaming; roller effect	0.5 (default=1); 0. (default=1)		
Median grain size d_{50}	0.25 mm		
Coefficients sand transport formulas	1 (default= 1)		
Coefficient sand transport by wave asymmetry	0.2 (default= 1)		
Coefficient sand entrainment beach zone	1 (default)		
Coefficient return flow (undertow)	1 (default)		
Bed roughness	Automatic		
Temperature and salinity	10 degrees and 30 promille		
File name	landr1.inp and landr2.inp		

Table 4.3 *Settings CROSMOR-model for land reclamation*

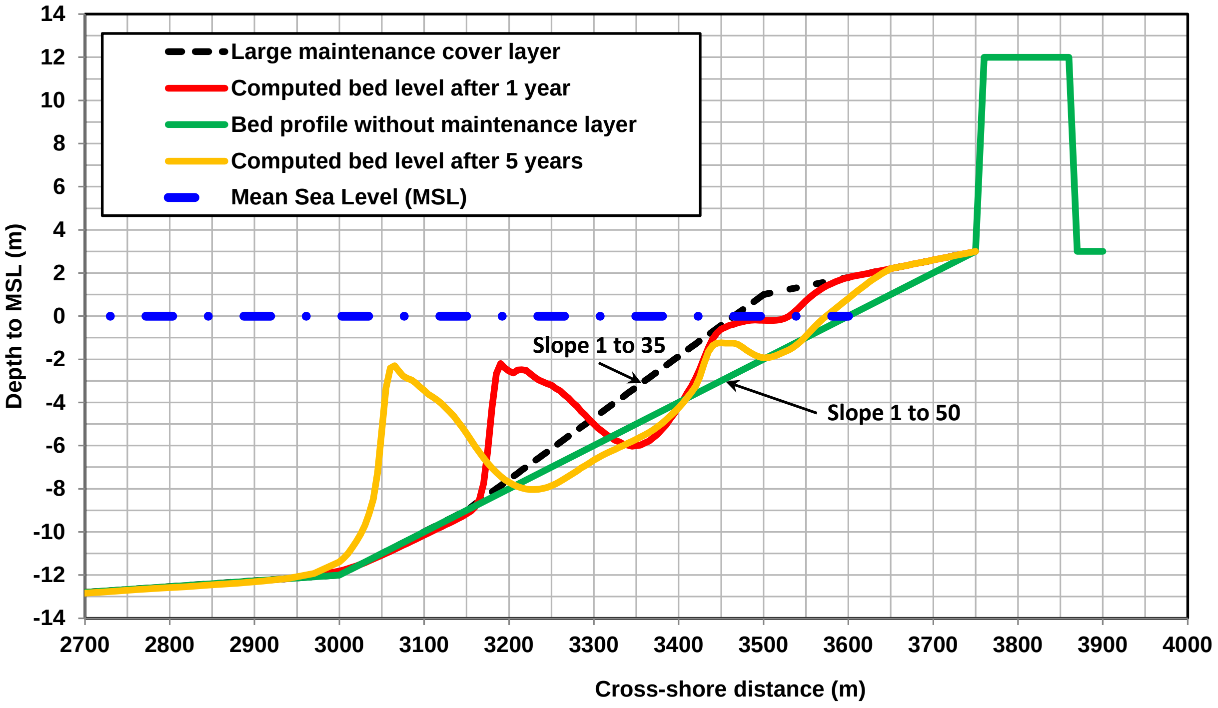

Figure 4.9 *Computed bed levels of cross-shore profile of land reclamation; large maintenance layer*

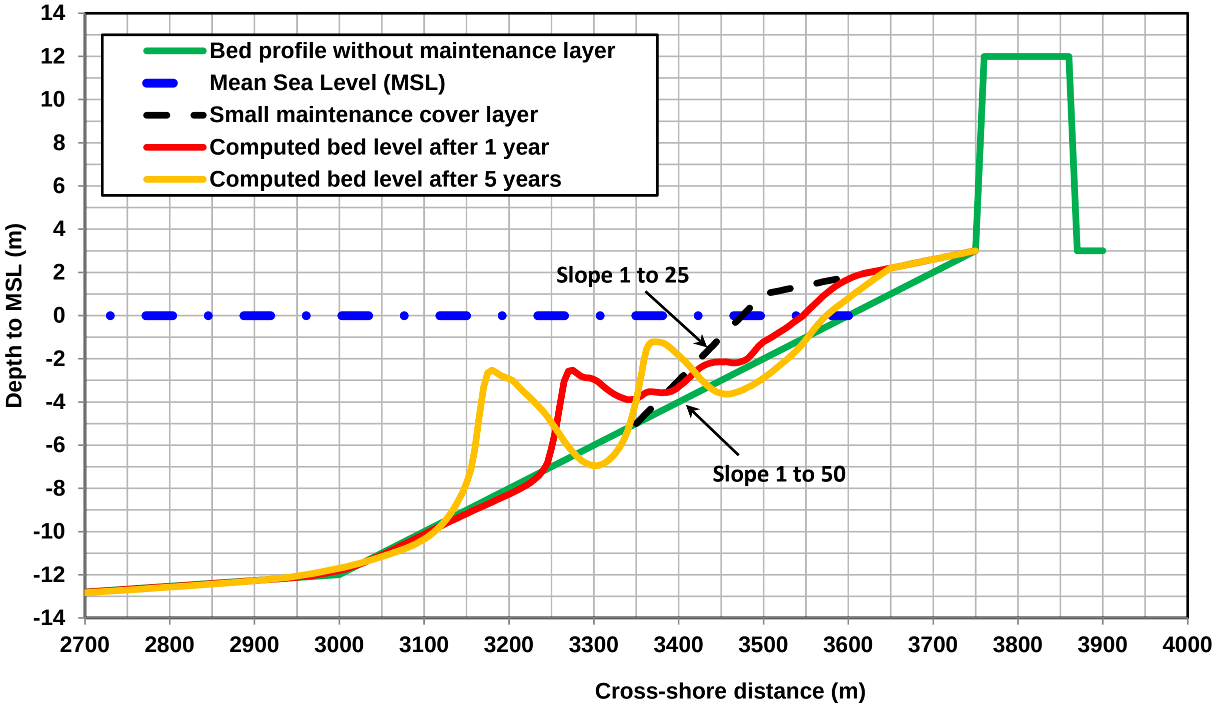

Figure 4.10 *Computed bed levels of cross-shore profile of land reclamation; small maintenance layer*

Coastal erosion (above the -2 m level) **and** **Recession at the mean water line**	**Large maintenance layer of 650 m^3/m with slope of 1 to 35** **d$_{50}$=0.25 mm** **(File: landr1.inp)**	**Small maintenance layer of 450 m^3/m with slope of 1 to 25** **d$_{50}$=0.25 mm** **(File: landr2.inp)**
Erosion volume after 1 year Coastal recession after 1 year	75 m^3/m 70 m	200 m^3/m 70 m
Erosion volume after 5 year Coastal recession after 5 year	275 m^3/m 120 m	350 m^3/m 120 m
Average erosion volume (5 years)	55 m^3/m	70 m^3/m

Table 4.4 *Erosion volumes (above -2 m line) and coastline recession due to cross-shore transport gradients*

Table 4.4 shows the erosion results of all computations. Based on these results for an exposed coast, the average annual erosion volume during the initial stage of about 5 years after construction is estimated to be in the range of 55 tot 70 m^3/m/year. The sand material is eroded from the beach zone and deposited in the surf zone beyond the -2 m NAP-line.

The maximum recession at the mean waterline due to cross-shore transport processes after 5 years is estimated to be about 120 m.

Table 4.5 shows the computed total erosion volumes due to cross-shore transport gradients (70 m^3/m/year) for all cases, taking into account the alongshore length of the land reclamations.

Case	Cross-shore extension (m)	Effective alongshore length (m)	Maximum erosion loss volume (average value of first 3 years) (m^3/year)
1	250	0.5x(625+1625) = 1125	80,000
2	250	0.5x(1250+2250) = 1750	125,000
3	250	0.5x(2500+3500) = 3000	210,000
4	250	0.5x(7500+8500) = 8000	560,000
8	500	0.5x(1250+3250) = 2250	160,000
9	500	0.5x(2500+4500) = 3500	245,000
10	500	0.5x(5000+7000) = 6000	420,000
11	500	0.5x(15000+17000) = 16000	1,120,000
15	750	0.5x(1875+4875) = 3375	235,000
16	750	0.5x(3750+6750) = 5250	370,000
17	750	0.5x(7500+10500) = 9000	630,000
18	1000	0.5x(2500+6500) = 4500	315,000
19	1000	0.5x(5000+9000) = 7000	490,000
20	1000	0.5x(10000+14000) = 12000	840,000

Table 4.5 *Computed initial erosion losses due to cross-shore transport gradients*

4.4 Initial erosion volume due to combined longshore and cross-shore gradients

The total erosion volume during the first 3 years of the land reclamations can be obtained by combining the results from Sections 4.2 and 4.3.

It is proposed to determine the total erosion loss due to both longshore and cross-shore transport gradients by vectorial summation of both values (from **Table 4.2** and **4.5**). The total erosion volume for Case 1 with net longshore transport of 100,000 m^3/year then becomes $(195{,}000^2+80{,}000^2)^{0.5}$= 210,000 m^3/year, see **Table 4.6**. The other values are given in **Table 4.6.**

Figures 4.11A to 4.11E show the computed erosion volume (average value of first 3 years) as function of the alongshore length, the cross-shore extension and the net longshore transport rate. The alongshore length is defined as the average of the most landward length and the most seaward length (see **Table 4.5**) of the land reclamationds. The erosion volume increases with increasing length of the land reclamations.

This effect is mainly caused by erosion losses due to cross-shore transport gradients (assumed to be 70 m^3/m/year). These results represent the annual erosion during the first 3 years. The erosion has to be compensated by regular maintenance nourishments, otherwise the land reclamation will gradually disappear on the long term. If, regular nourishments are carried out, the erosion on the longer term will gradually reduce to a quasi-equilibrium value.

The nourishment volume can be placed on the beach of the land reclamation as a maintenance cover layer and needs to be replaced every 3 to 5 years, depending on conditions.

CASE	Cross-shore extension; horizontal shift of mean waterline (m)	Effective along shore length (m)	Net LT= 100,000 m^3/year Maximum erosion loss averaged over first 3 years (m^3/year)	Net LT= 200,000 m^3/year Maximum erosion loss averaged over first 3 years (m^3/year	Net LT= 300,000 m^3/year Maximum erosion loss averaged over first 3 years (m^3/year)	Net LT= 400,000 m^3/year Maximum erosion loss averaged over first 3 years (m^3/year)	Net LT = 500,000 m^3/year Maximum erosion loss averaged over first 3 years (m^3/year)
1	250	1125	210,000	325,000	380,000	440,000	475,000
2	250	1750	295,000	430,000	525,000	605,000	670,000
3	250	3000	325,000	450,000	550,000	610,000	720,000
4	250	8000	615,000	690,000	765,000	800,000	895,000
8	500	2250	420,000	700,000	955,000	1,190,000	1,340,000
9	500	3500	450,000	750,000	980,000	1,215,000	1,400,000
10	500	6000	580,000	825,000	1,040,000	1,235,000	1,425,000
11	500	16000	1,185,000	1,320,000	1,475,000	1,605,000	1,755,000
15	750	3375	505,000	890,000	1,250,000	1,545,000	1,745,000
16	750	5250	580,000	935,000	1,255,000	1,565,000	1,730,000
17	750	9000	775,000	1,075,000	1,355,000	1,645,000	1,810,000
18	1000	4500	565,000	1,030,000	1,435,000	1,690,000	1,925,000
19	1000	7000	670,000	1,085,000	1,445,000	1,760,000	1,915,000
20	1000	12000	960,000	1,275,000	1,590,000	1,885,000	2,030,000

Table 4.6 *Computed total erosion volumes (average of first 3 years) due to combined longshore and cross-shore transport gradients along land reclamations*

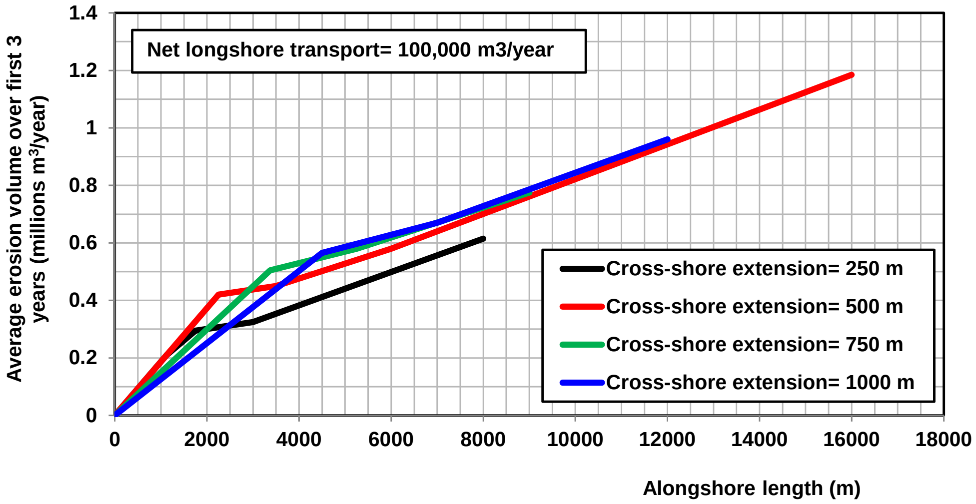

Figure 4.11A *Computed erosion volume as function of alongshore length, cross-shore extension and net longshore transport; LT= 100,000 m^3/year*

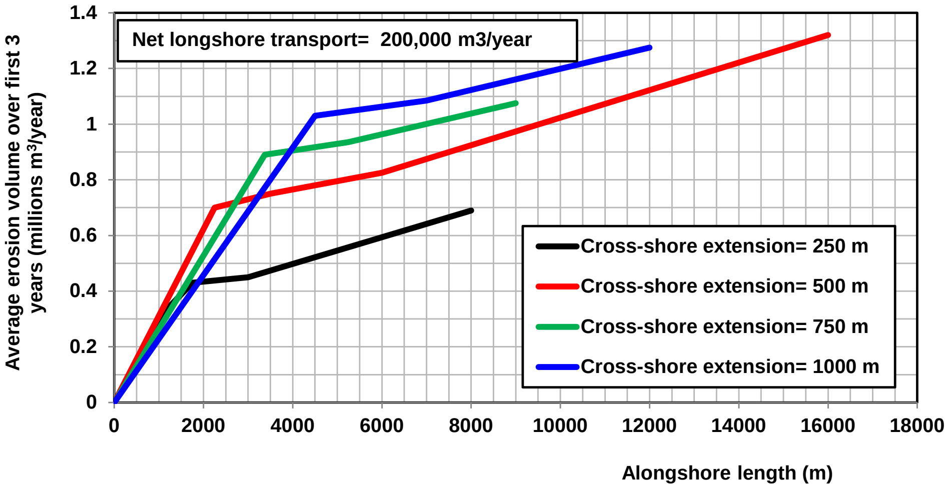

Figure 4.11B *Computed erosion volume as function of alongshore length, cross-shore extension and net longshore transport; LT= 200,000 m^3/year*

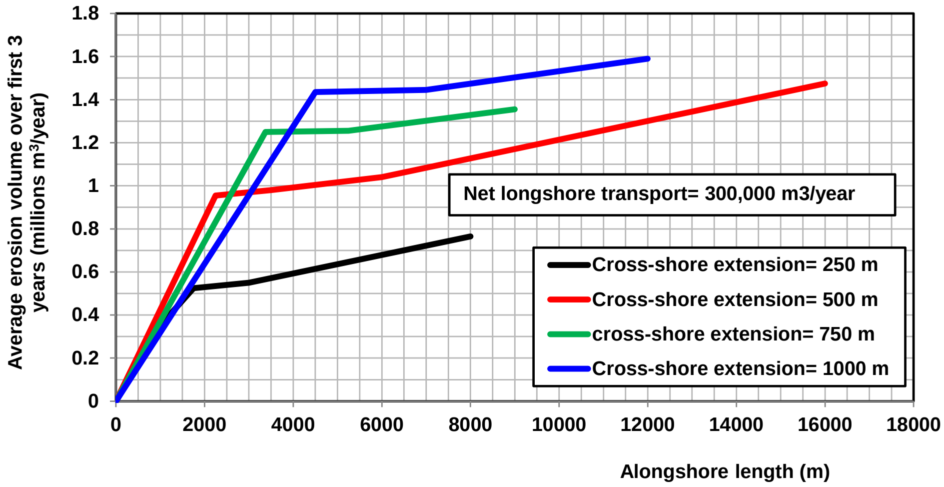

Figure 4.11C *Computed erosion volume as function of alongshore length, cross-shore extension and net longshore transport; LT= 300,000 m^3/year*

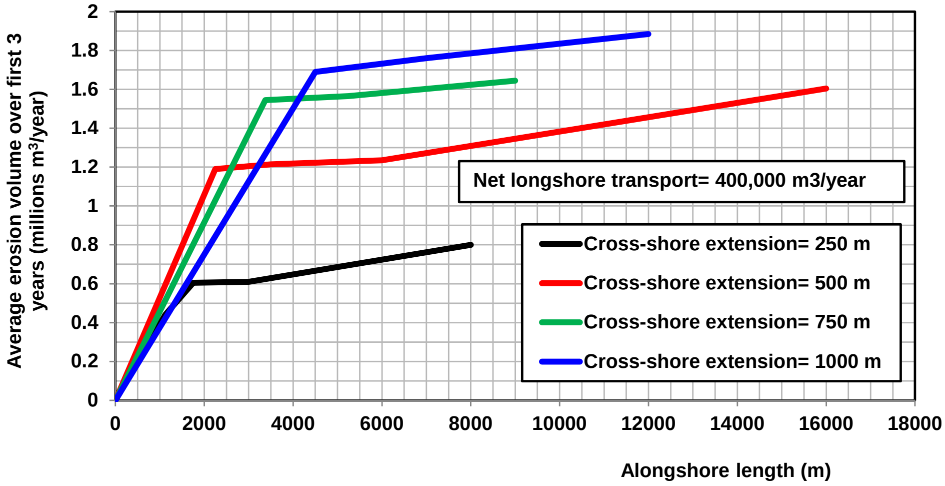

Figure 4.11D *Computed erosion volume as function of alongshore length, cross-shore extension and net longshore transport; LT= 400,000 m^3/year*

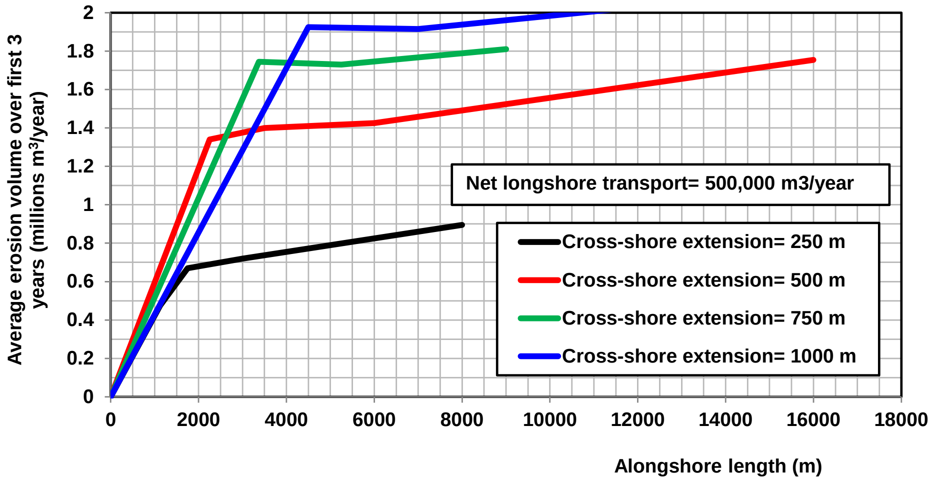

Figure 4.11E *Computed erosion volume as function of alongshore length, cross-shore extension and net longshore transport; LT= 500,000 m^3/year*

4.5 Long term effects

The long term effects are explored for two cases: land reclamation 10 (Beachs1.inp) and 13 (Beachs3.inp), see **Table 2.1**.

The basic data are:

Case 10
- Alongshore length at beach = 7000 m (see **Figure 4.12**);
- Alongshore length at seaward boundary = 5000 m (see **Figure 4.12**);
- Effective length= 6000 m;
- Cross-shore extension = 500 anm;
- Net longshore transport = 300,000 m^3/year.

Case 13
- Alongshore length at beach = 6000 m (see **Figure 4.16**);
- Alongshore length at seaward boundary = 3333 m (see **Figure 4.16**);
- Effective length= 4666 m;
- Cross-shore extension = 666 m;
- Net longshore transport = 200,000 m^3/year.

Case 10

Figure 4.13 shows the computed coastlines after 1, 3, 5, 10, 15 and 20 years (smoothing=0.00003). Erosion occurs at the seaward side of the land reclamation. The erosion is largest at both seaward corner points of the land reclamation. The total erosion volume after 20 years is about 9 million m^3, see **Figure 4.14**. Without nourishment the land reclamation will gradually disappear.

The sand nourishment volume required to keep the land reclamation as much as possible in place over a period of 20 years has been determined by trial and error resulting in a value of 15 million m^3.

Two nourishment schemes have been applied (see **Figure 4.14**):

A) Continuous: the nourishment volume is 0.7 m^3/m/day in the zone between x = 10500 and 12000 m (length=1500 m) and between x = 15000 and 16500 m (see **Figure 4.12).** Thus, the total nourishment volume is 0.7x1500x2x7300 = 15 million m^3 over 20 years or 7300 days. No nourishment is done in the central section of the land reclamation.

B) Every 5 years: nourishment scheme with an interval of 5 years. The total volume is 15 millions m^3 over 20 years.

Figure 4.15 shows the computed coastlines after 20 years with and without nourishment. The total erosion volume after 20 years is about 9 million m^3. Both nourishment schemes are just sufficient to keep the land reclamation free of erosion. Minor seaward growth at both corner points can be observed. The nourishment volume over 20 years is about 15 million m^3, which is a factor of 1.7 larger than the total erosion volume of 9 million m^3. The excess volume of sand is accumulated at the flanks and seaward of the land reclamation (zones A, see **Figure 4.15**).

Thus, the required nourishment volume (15 million m^3) is about ***1.7 times*** larger than the total erosion volume (9 million m^3) after 20 years.

Using the average erosion volumes after 1 and 3 years (see **Figure 4.14** or **Figures 4.7A,B**), the total nourishment volume for 20 years can be computed as (see **Table 4.7**):

$$V_{N,20\ years} = 20\ f_{cor1}\ V_{e,1\ year}$$

$$V_{N,20\ years} = 20\ f_{cor3}\ V_{e,3\ year}$$

with:

$V_{N,20\ years}$ = nourishment volume for 20 years = 15 million m^3;

$V_{e,1\ year}$ = erosion volume after first year based on Figure 4.14 =1.3 million m^3/year;

$V_{e,3\ year}$ = average erosion volume over first 3 years based on Figure 4.14 = 2.85 million m^3 = 2.85/3 = 0.95 million m^3/year;

f_{cor1}, f_{cor3}= correction factors, see **Table 4.7**.

Time period	**Erosion volume based on Figures 4,7A,B**		**Erosion volume over 20 years**		**Required nourishment volume over 20 years**		**Correction factors**	
	Case 10	**Case 13**	**Case 10**	**Case 13**	**Case 10**	**Case 13**	**Case 10**	**Case 13**
1 (first year)	1.3 million m^3/year	1.0 million m^3/year	26 millions m^3	20 millions m^3	15 millions m^3	15.6 million m^3	f_{cor1} =15/26= 0.58	f_{cor1} =15.6/20= 0.78
3 (first 3 years)	0.95 million m^3/year	0.85 million m^3/year	19 millions m^3	17 millions m^3			f_{cor3} =15/19= 0.79	f_{cor3} =15.6/17= 0.92

Table 4.7 *Correction factors*

<u>**Case 13**</u>

Figure 4.16 shows the computed coastlines after 20 years with and without nourishment.

The sand nourishment volume required to keep the land reclamation as much as possible in place over a period of 20 years has been determined by trial and error resulting in a value of 15.6 million m^3.

The nourishment value applied is 0.8 m^3/m/day (continuous) in the zone between x = 10666 and 12000 m (length=1333 m) and between x = 14000 and 15333 m (see **Figure 4.16).** Thus, the total nourishment volume is

0.8x1333x2x7300 = 15.6 million m^3 over 20 years or 7300 days. No nourishment is done in the central section of the land reclamation.

A nourishment scheme with an interval of 5 years has also been applied (total of 15.6 millions m^3 over 20 years).

The correction factors are given in **Table 4.7**.

Summarizing, the total nourishment volume can be computed based on the erosion volume after the frist year. The correction factor to compute the total nourishment volume for 20 years is about $f_{cor1} \cong 0.7 \pm 0.1$ based on the results of both cases of **Table 4.7**.

Using the average erosion volume over the first 3 years, the correction factor to compute the total nourishment volume for 20 years is about $f_{cor3} \cong 0.85 \pm 0.05$.

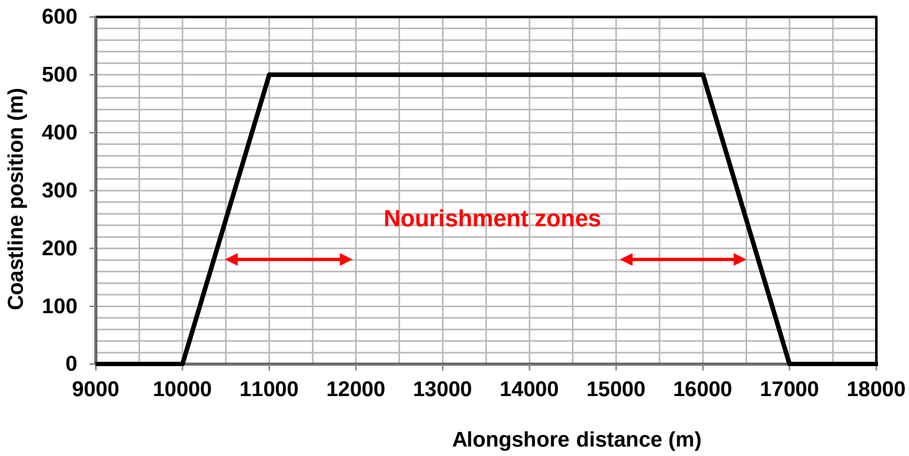

Figure 4.12 *Planform of Land reclamation Case 10*

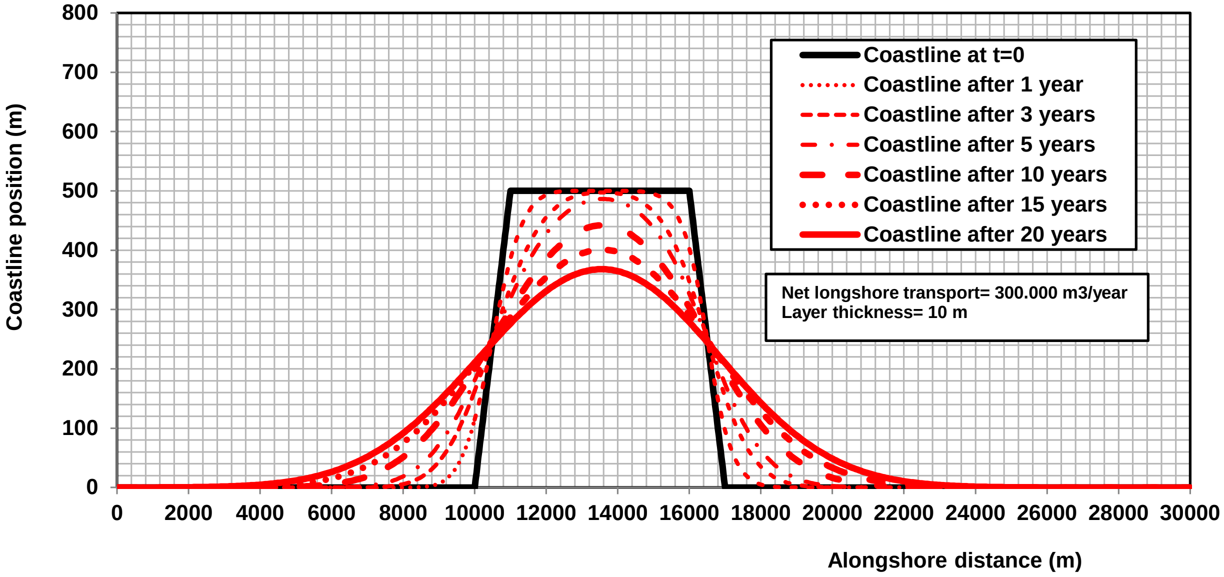

Figure 4.13 *Computed coastlines of Land reclamation Case 10*

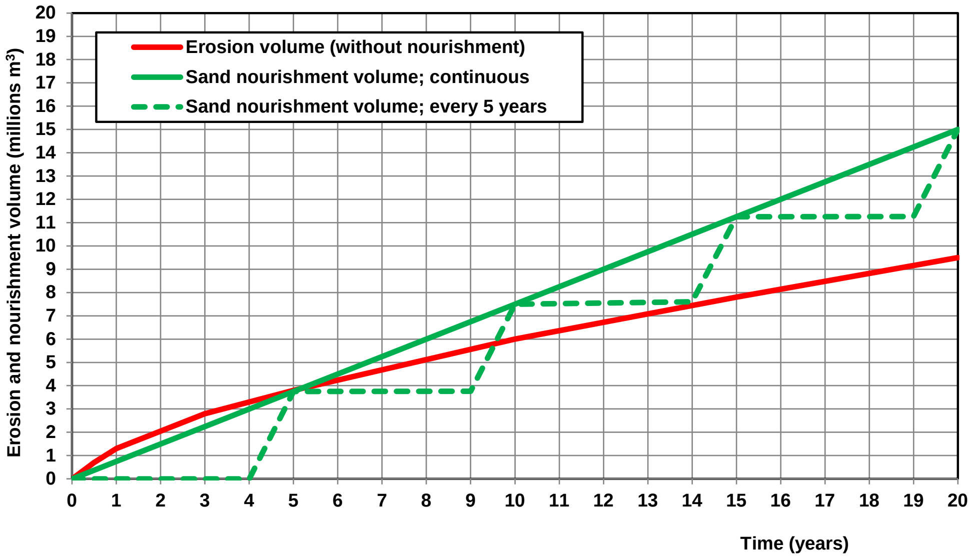

Figure 4.14 *Cumulated erosion volume and nourishment schemes; Case 10*

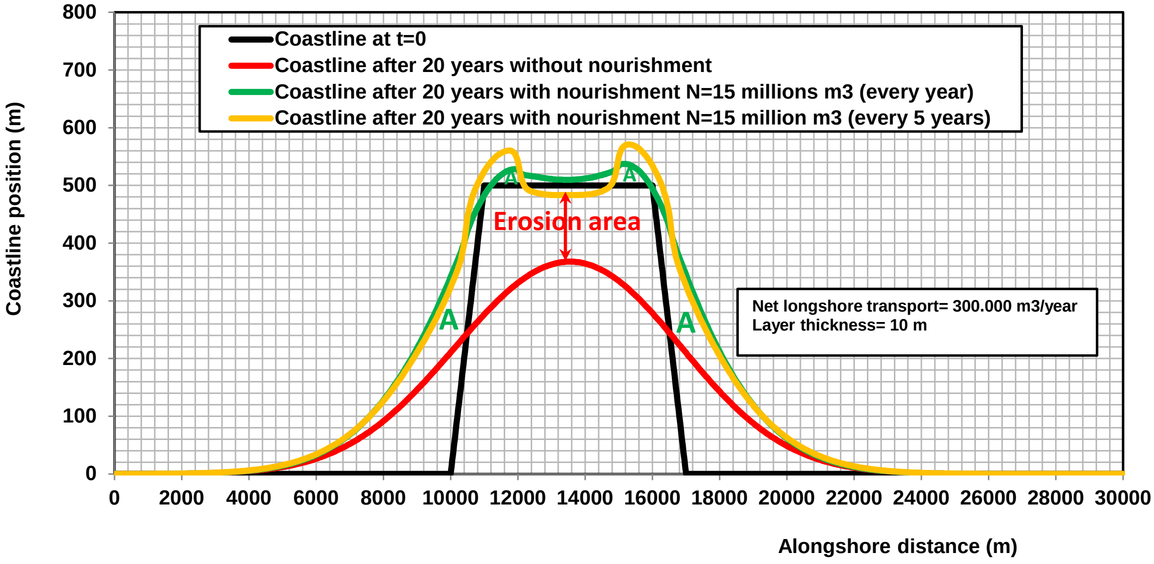

Figure 4.15 *Computed coastlines after 20 years with and without nourishment; Case 10*

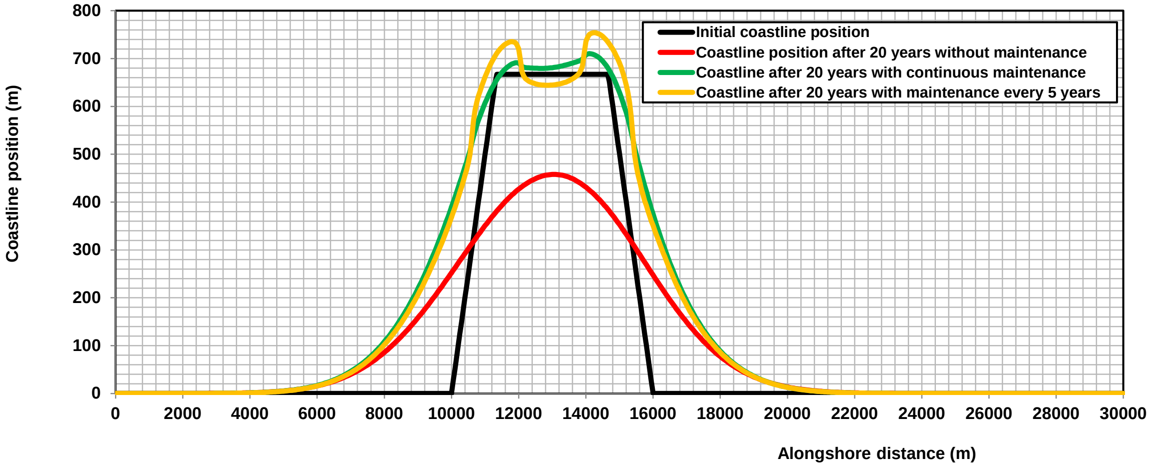

Figure 4.16 *Computed coastlines after 20 years with and without nourishment; Case 13*

5. Application of results

The results of Section 4 have been used to estimate the initial erosion volume of a new coastal extension (made in 2014/2015) between the beach villages of Camperduin and Petten along the coast of North-Holland. This coastal section is protected by a seadike and groins, known as the 'Hondbossche and Pettemer' Seadike (HBPZ) with a length of about 6 km (Profile 22 to 28 km). The seadike section protrudes into the sea over a distance of about 200 m with respect to the surrounding coastline, see **Figure 5.1** and **5.2A**. Beaches are minor or absent along this part of the coast.

As the dimensions of the seadike are not sufficient to withstand a super (design) storm with a recurrence interval of 10000 years (storm surge level of about 5.5 m above mean sea level, offshore wave height of about 10 m), it was decided to reinforce this coastal section with a new beach-dune system of sand, which implies an additional cross-shore coastal extension of about 300 m (**Figure 5.2B**). The crest width of the new sand dune is about 100 m and the crest level is about 10 m above mean sea level. The new beach has a width of about 200 m between the mean waterline and the dune foot level.

In all, the new coastline will protrude about 500 m into the sea with respect to the surrounding coastline (**Figure 5.2A**).

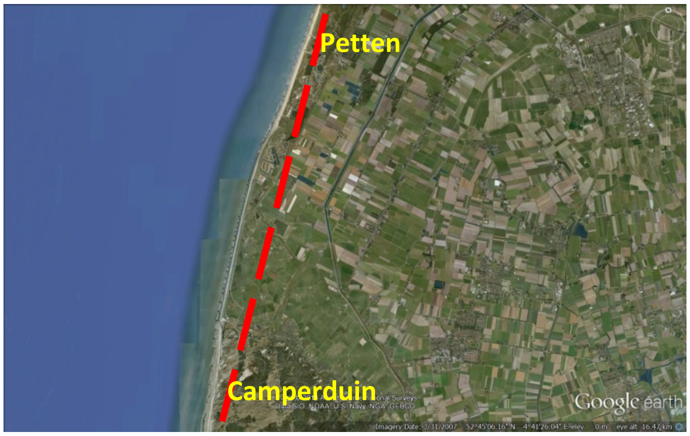

Figure 5.1 *Coastal section Petten-Camperduin along Holland coast protected by seadike and groins (old situation); HBPZ case*

The coastline of the protruding section between Petten (x=12000 m, see **Figure 5.2**) and Camperduin (x=7000 m) is shown in **Figure 5.2A**. The beaches north and south of the seadike consist of medium sand with d_{50} in the range of 0.2 to 0.25 mm. These beaches are backed by a single row of sand dunes with crest level at about 10 m above mean sea level (NAP).

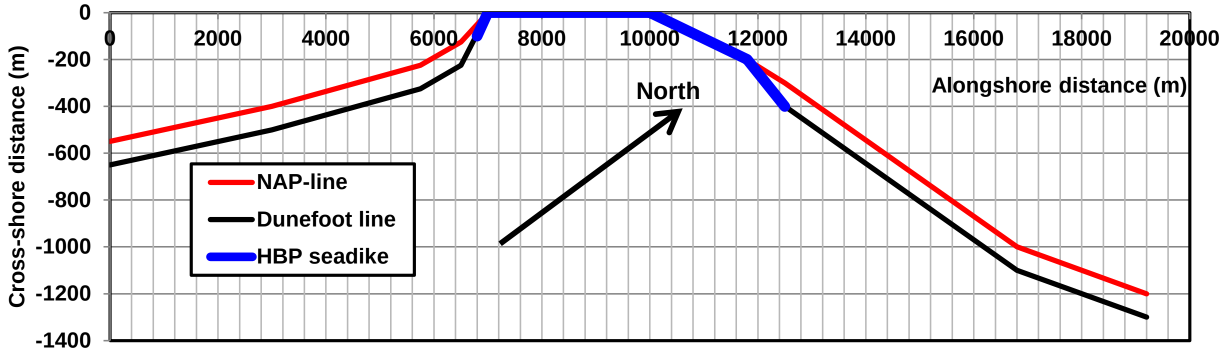

Figure 5.2A *Coastline of seadike and surroundings in existing (old) situation; HBPZ case*

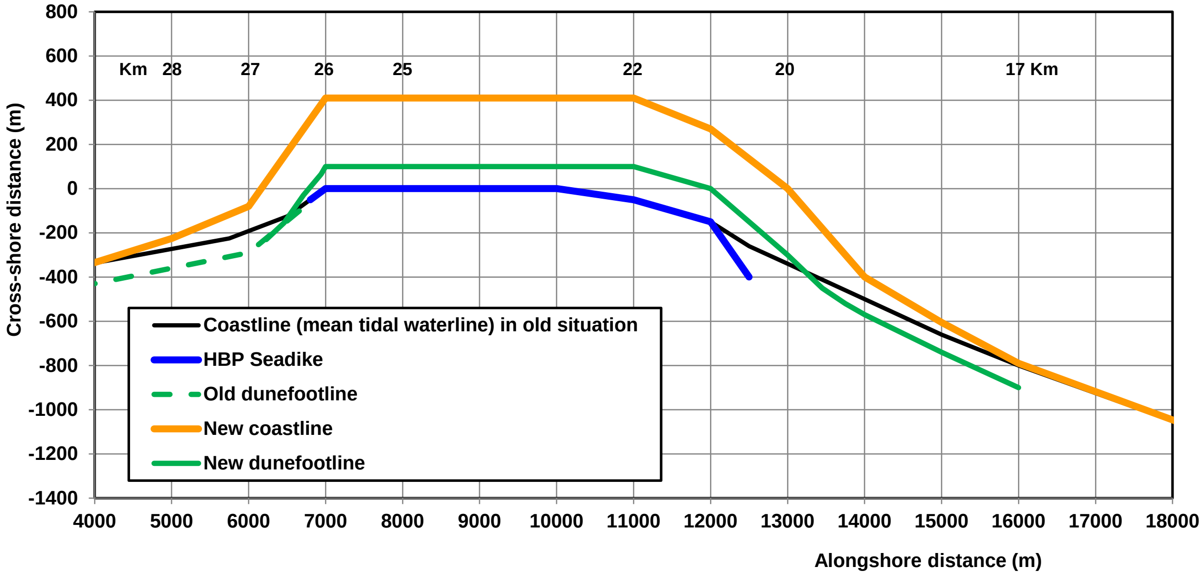

Figure 5.2B *Coastline in new situation; HBPZ case*

The vertical tide has a tidal range of about 1.2 m during neaptide and 1.8 m during springtide. The maximum tidal flow velocity to the north (flood) is about 0.5 m/s in deep water and about 0.4 m/s to the south (ebb). The dominant waves come from south-west directions.

Earlier studies (Deltares, 1995a,b) have shown that the net (northgoing) longshore sand transport is of the order of 100.000 m^3 per year at the south side of the seadike and about 300.000 m^3 per year at the north side. Hence, the longshore transport gradient along this coastal section is of the order of 200.000 m^3/year (±50%).

Since 1990, many beach and shoreface nourishment programmes have been executed along this part of the coast. The mean nourishment volume (per unit length) in the period 1990 to 2006 was about 25 m^3 per m coastline per year resulting in a value of 250.000 m^3 per year over the project length of 10 km.

Summarizing, the characteristics are:

- cross-shore coastal extension = 400 to 600 m; Alongshore length = 6000 m;
- net longshore transport = 200,000 to 250,000 m^3/year; alongshore transport gradient = 200,000 m^3/year.

Based on **Figures 4.7A and 4.7C**, the erosion values after 1 year due to longshore transport gradients have been interpolated resulting in the values given in **Table 5.1**. The computed erosion values are in the range of 0.7 to 1.3 million m^3 (1.0 ±0.3) after 1 year for a net longshore transport of 200,000 to 250,000 m^3/year.

Type of model	**Erosion volume after 1 year**	**due to longshore transport gradient**
	coastal extension= 400 m	**coastal extension= 600 m**
1D LONGMOR-model	Erosion= 0.80 to 0.95 million m^3	Erosion= 0.95 to 1.15 million m^3
1D UNIBEST-model	Erosion= 0.95 to 1.10 million m^3	Erosion= 1.15 to 1.30 million m^3
2DH DELFT-model	Erosion= 0.7 million m^3	Erosion= 1.05 million m^3

Table 5.1 *Erosion volumes after 1 year with net longshore transport= 200,000 to 250,000 m^3/year*

Based on **Table 4.5** (case 10), the initial erosion volume after 1 year due to cross-shore transport gradients is about 0.42 million m^3/year for a length of 6000 m.

Combining both results, the total erosion loss due to both longshore and cross-shore transport gradients after 1 year is estimated to be about $(1^2 + 0.42^2)^{0.5}$= 1.1 million m^3/year.

Assuming a correction factor of about 0.7 (see **Table 4.7**) , the total required nourishment volume over 20 years is estimated to be about 0.7 x 20 years x1.1 millions m^3/year = 15.4 million m^3 ($\pm$30%).

In practice, the total nourishment volume of 15.4 million m^3 can be supplied in a 5 cycles (every 4 to 5 years) of 3.1 million m^3. Each volume of 3.1 million m^3 can be placed as a maintenance cover layer on the beach. Initially, a maintenance volume of 3.1 million m^3 layer should be present.

Assuming a total beach length of 6000 m and a cross-shore width of 300 m, the maintenance layer thickness is about 1.7 m. This layer is sufficient for a period of about 4 to 5 years.

It should be realized that a maintenance layer thickness of 2 m and a beach slope of 1 to 30 will result in an additional seaward shift of the waterline of about 30x1.7 = 50 m, which may cause additional erosion as it leads to a larger total seaward extension of the land reclamation (larger protrusion).

6. Summary and Conclusions

In this paper it is explored to protect land reclamations by natural sand dunes and beaches. As the land reclamations are protruding into the sea, they will suffer from erosion due to longshore and cross-shore transport gradients. Regular sand maintenance nourishments will be required to compensate the erosion of sand along the dynamic coastline of the land reclamations. The dimensions of the land reclamations have been varied: cross-shore lengths upto 1000 m and alongshore lengths upto 14000 m.

Various models (Delft3D area model, UNIBEST-CL and LONGMOR coastline model and CROSMOR profile-model) have been used to estimate the erosion of sand along the land reclamations. The erosion values have been plotted as function of the cross-shore extension and the alongshore length of the land reclamations. These values can be used to estimate the maintenance volumes.

To verify the models applied, they have been used to simulate the erosion of sand along the mega-nourishment (19 million m^3 of sand in 2011) known as the ‘sandmotor’, at the coast of South-Holland (10 km south of the city of the Hague, The Netherlands).

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