Cross-shore sediment transports on a cut profile for large scale land reclamations

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Abstract

When building a large scale land reclamation, the safest way is to shift the existing profile over the required distance of the reclamation project, up to a depth of say 20 m. This way the profile in cross-shore direction does not change and therefore also cross-shore sediment transports will be the same as before the land reclamation was made. A large disadvantage however is that a very large amount of material is needed for realising the reclamation. This makes the reclamation very costly.
To reduce the amount of material a cut profile can be applied. Above a certain depth (say CD -8 m) the cross-shore profile will be the same as the existing profile, but below this depth a relatively steep profile (say 1:50) is constructed. By doing this, material saving up to 40% can be achieved. A disadvantage of this cut profile is that a relatively steep profile has been made, which will effect the sediment transports.
In this study the effect of a cut profile are investigated by using the numerical model UNIBEST-TC of DELFT HYDRAULICS *for the computation of wave energy dissipation and cross-shore sediment transports. As an example the 'Plan Waterman', a plan for a land reclamation between Hook of Holland and Scheveningen, is used in this study. Various different cut profiles have been studied and it is found that especially relatively large waves, which break at the edge of the cut-off, have large influence on the cross-shore sediment transports. It is concluded, that the cut-off should at least be applied at CD-12 m if large changes in the coastal system are not desired.*

Introduction

People often want to live near water and all over the world the areas near the sea get more and more occupied by structures. For this reason there is a trend to reclaim land by making an artificial island near the existing coast or a peninsula against the existing coast. Examples are the recently opened airport in Hong Kong and the 'Plan Waterman', a plan to extend the Dutch coastline between Hook of Holland and Scheveningen. This plan is also known as the 'Plan New Holland'.

In most cases an extension of the coastline is made by dredging material from relatively deep water near the coast and dumping the material in the nearshore section. The safest way is to shift the existing cross-shore profile over the distance of the land

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reclamation. This way large changes in cross-shore sediment transports are avoided because the beach profile keeps the same shape. However, to make a land reclamation this way, a lot of material has to be dredged, which makes the land reclamation project expensive.

There is also another way to construct the land reclamation. On a certain level beneath mean sea level (is Chart Datum; CD) a cut-off can be applied. This means, that the cross-shore profile will not be shifted completely over the distance needed for the reclamation.
In the near shore area the design profile will have the same shape as the existing beach profile. Then, from a certain level beneath CD, the design profile will have a constant and relatively steep slope until it reaches the existing beach profile. By doing this, a lot of material is saved when making the land reclamation. In Figure 1 a cut profile is shown with the definitions as used in this paper..

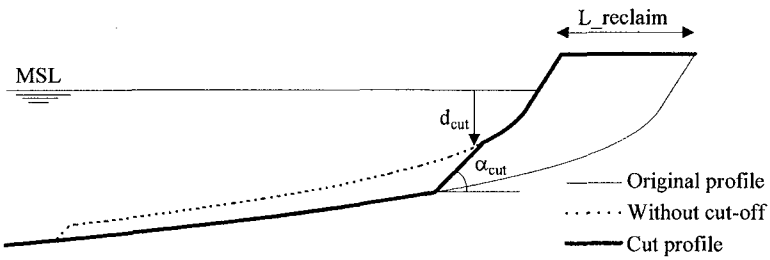

Figure 1. Two methods of making a large scale land reclamation

When a cut profile is applied, wave heights and sediment transports will change in comparison with the situation where no cut profile is applied. When a cut profile is being applied, one of three mechanisms will occur:

- there will be erosion;
- the cross-shore profile will stay stable;
- there will be accretion.

Without any study, the most likely mechanism will be erosion in the nearshore section until a profile shape is reached, which comes close to the profile before the land reclamation. This means eventually a retreat of the waterline, which is, in case of the Dutch policy, not desired.

During this study the numerical model UNIBEST-TC of DELFT HYDRAULICS is used for investigating the influence of a cut profile. To make computations as realistic as possible, the "Plan Waterman" is used as a practical example. In order to get realistic results, the numerical model has been calibrated for the existing situation without the land reclamation before computations on a cut profile are carried out.

Then various computations are done for investigating the influence of a cut profile on the sediment transports and the development of the cross-shore profile. These

computations have been subdivided into two parts:

- Initial computations;
- Morphological computations.

Initial computations are used for investigating the effects of a cut profile on the way waves approach the shoreline and the resulting cross-shore sediment transports along the profile.

Morphological computations are done over a period of 10 years. These computations are done by using measured wave conditions from a station near Hook of Holland.

In this study cross-shore transports are only considered; changes in shore parallel sediment transports are not taken into account

The 'Plan Waterman'

In the western part of The Netherlands there is a large need for more land, especially for housing and recreation. Besides the reshuffle of existing areas, also the possibility to create new land in the North Sea is still open. This plan of land reclamation is known as the 'Plan Waterman'.

The 'Plan Waterman' is a plan for extending the Dutch coast between Hook of Holland and Scheveningen over an average distance of about 2 km, varying from 1500 m at Scheveningen to about 3 km at Hook of Holland and with a total area of 3000 hectares (see Figure 2).

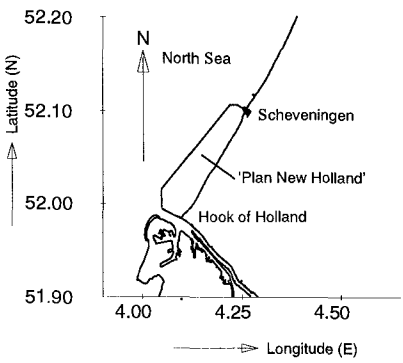

Figure 2. Overview of the 'Plan Wateman'.

The total volume, which has to be nourished for the realisation of the 'Plan Waterman' can roughly be estimated by assuming 25 m^3 necessary for 1 m^2 of the reclamation (from CD -20 m to CD +5 m). For the 'Plan Waterman' the total volume is then estimated at $750*10^6$ m^3.

When applying a cut-off in this situation, a lot of material and therefore money can be

saved. As a reference profile, a shifted profile is chosen, which coincides at a depth of CD -20 m with the existing profile. The beach profile of the land reclamation is continued up to CD +5 m.

In Table 1 is shown how much (in %) is saved by applying a cut profile.

Cut-off depth [m-CD]	Slope of the cut-off			
	1/25	1/50	1/100	1/150
12.0	26%	26%	25%	24%
10.0	32%	31%	30%	28%
8.0	37%	36%	33%	31%
6.0	41%	39%	36%	32%

Table 1. Savings to achieve by applying a cut-off.

From this table it is obvious, that most savings are achieved when the cut-off is made steep and on small depth. On large depths less savings can be achieved by making a steep slope. This is because the slope of the cut-off is shorter at larger depth.

Environmental conditions

To be able to make realistic computations with the UNIBEST model, it is necessary to describe the real situation properly. In this chapter the environmental conditions, as used in the numerical model are discussed shortly.

Cross-shore profiles

Since 1964, every year profile measurements are taken along the Dutch coast to determine the position of beach profiles perpendicular to the shoreline. These profiles are called the 'JARKUS' profiles. The location of these profiles are marked by bench marks along the whole coast of Holland. The area of this study starts near Scheveningen at km 102 and ends at Hook of Holland at km 118.

Grain sizes

For this study, the average value of grain-sizes measured along the coast between Hook of Holland and Scheveningen is used (Table 2).

Parameter	Value
d_{50}	220 μm
d_{90}	290 μm
porosity	0.4

Table 2. Sediment parameters.

Waves

Wave conditions from the nearby EURO-0 platform were used for model

computations. A time series with measured waves and water levels from 1979 to 1991 was analysed and a time series, which represents the average wave climate of these 13 years of measurements was assembled. The measured wave climate from the EURO-0 platform is shown in Figure 3.

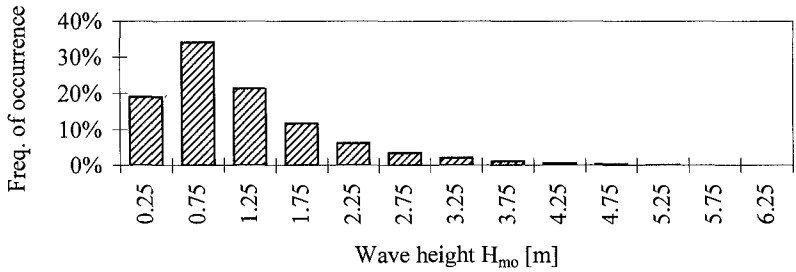

Figure 3. Wave climate as measured at the EURO-0 platform.

Tide levels

The tidal range along the part of the Dutch coast as considered is in the order of 1.5 m during neap tide and 2.0 m during spring tide conditions. Water levels as measured at EURO-0 were taken into account.

At the EURO-0-platform the water level is measured in combination with wave heights. These water levels contain the astronomical tide and also water level changes, caused by wind. Because of storm set up the water level tends to be higher with larger wave heights.

Currents

Because currents are mainly present in the longshore direction and not in cross-shore direction as investigated in this study, currents are not be taken into account during the calculations.

Model calibration

Before any transport computations on a cut profile can be made, the model has to be calibrated. By slightly changing the models parameters, the model is tuned.

For the calibration of the numerical model, the morphological behaviour of an existing beach profile along the coast between Scheveningen and Hook of Holland is used. In this profile a longshore bar is present at about 450 m from the reference point. The bar moves in seaward direction with a speed of approximately 40 m/yr. This bar behaviour is used to compare the outcomes of the numerical model with the measured profiles, because the speed and shape of the bar are easily to be compared. The quality of the calibration is judged by:

- The movement of the sand bar;

- The bed level changes near the waterline;
- Global volume changes along the profile.

By changing parameters such as bed roughness, internal friction angle and wave parameters the model has been adjusted in a way that it represents the existing profile development in a satisfying way. Figure 4 shows the results of the calibration of the profile as chosen.

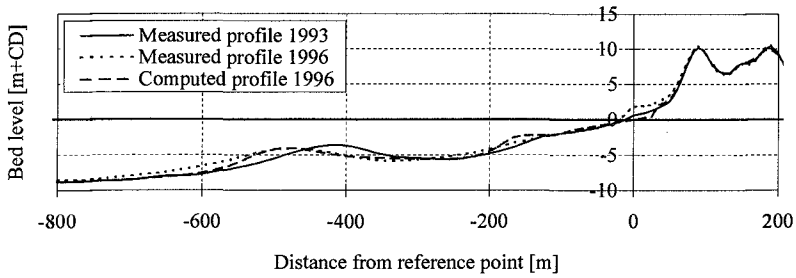

Figure 4. Results of the calibration of the UNIBEST-TC model.

Initial effects of a cut profile

Before the effect of a cut profile on a morphological time scale can be understood, it is worthwhile to investigate the most important processes. Therefore initial computations are performed. For various different wave conditions and cut profiles the distribution of wave height, wave energy dissipation and cross-shore sediment transports are determined. In this chapter some of the results are shown. The results are compared to a profile without a cut-off, which is used as the zero-alternative.

It was found, that especially the location of breaking waves has large effect on the occurring processes. Relatively high waves will suddenly break on the edge of the cut-off, which then leads to large energy dissipation over a small distance. Waves which break onshore of the cut-off, show a more gradual energy dissipation.

For explaining the most important processes in more detail results of computations on a cut profile with d_{cut} = CD -6 m and α_{cut} = 1:50 are discussed. First a wave height distribution with H_{m0} = 1.75 m is discussed, which does hardly result in wave breaking on the edge of the cut-off. Secondly a wave height distribution with H_{m0} = 2.75 m is discussed. This wave height gives breaking on the edge of the cut-off. The results are compared to the zero-alternative.

No breaking waves on the edge of the cut-off

The results of initial computation for deep water wave conditions of H_{m0} =1.75 m are shown in Figure 5. In this figure the wave height, energy dissipation and sediment transport distributions along the cross-shore profile are shown.

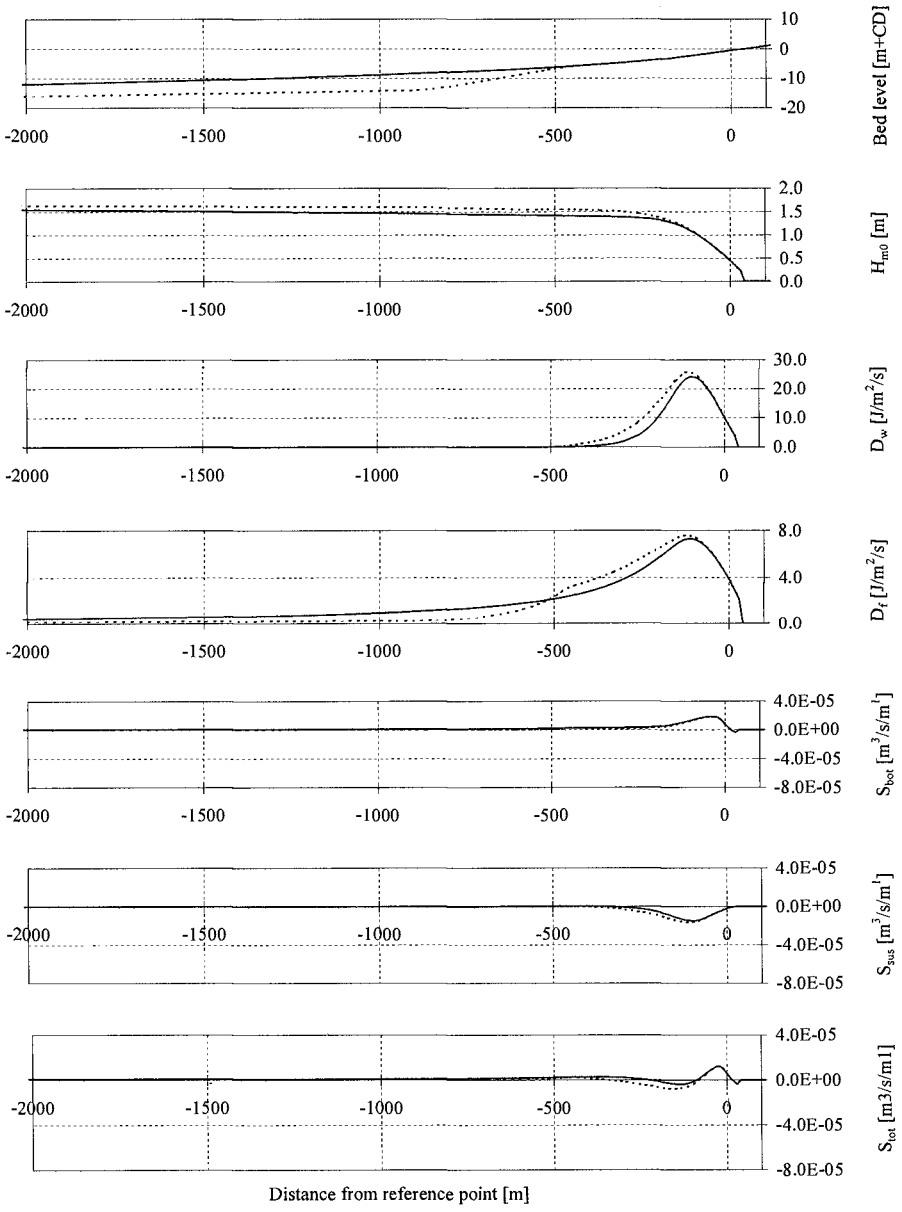

Figure 5. Results of initial computations without wave breaking on the edge of the cut-off.

The wave height H_{m0} distribution

Because the water depth offshore of the cut-off is larger than the depth at the same location along the profile of the zero-alternative, also the wavc height is still larger along the cut-profile. Differences are however small.

In the breaker zone more breaking waves and more dissipation due to bottom friction occur in case of the cut profile. Closer to the shoreline the differences between the wave heights in the two profiles vanish. Notice, that the difference between the two profiles is notable up to approximately 150 from the waterline (that is 350 m onshore of the cut-off).

Energy dissipation

Wave energy dissipation as used in the UNIBEST-TC model is based on Battjes & Janssen (1978).

Offshore of the cut-off water depths are still relatively large in both cases and energy dissipation due to wave breaking hardly occurs here. Onshore of the cut-off larger wave heights are present in case of the cut profile. This leads to larger energy dissipation for the same water depth. Wave breaking also starts at larger distance from the shoreline.

Also the dissipation due to bottom friction, D_f, is affected by the cut-off. Because of the larger depth offshore of the cut-off the energy dissipation due to bottom friction is smaller here. Along the slope of the cut-off the water depth decreases relatively fast. Together with larger wave heights this leads to an increased dissipation due to bottom friction onshore of the cut-off.

Bottom sediment transport

For bed-load transport computations thc formula of Ribberink (see Van Rijn et al., 1995) is used in the UNIBEST-TC model.

Only a very small increase in wave energy dissipation occurs and therefore also the difference in bottom transport along both profiles is very small. Just onshore of the cut-off the onshore directed bottom transport tends to be slightly smaller in case of the cut profile.

Suspended sediment transport

Suspended transport is formulated with the velocity times concentration concept. Sediment concentrations are modelled following Van Rijn, 1993.

In case of the cut profile energy dissipation because of breaking waves is slightly higher than if the zero-alternative profile is applied. This yields a larger sediment concentration. Because of the higher waves also the offshore directed flow velocities increase. This results in an increased offshore directed suspended transport.

Differences in wave heights and energy dissipation are however small, so also the increase of the suspended transport is small.

Total sediment transport

Because of the smaller onshore directed bottom transport and the larger offshore directed suspended transport, the total sediment transport in case of a cut profile is more offshore directed. Even in this case, where hardly any wave breaking on the edge of the cut-off takes, the difference with the zero-alternative is relatively large.

Breaking waves on the edge of the cut-off

When waves break due to the sudden change of the depth at the edge of the cut-off, other effects occur than described in the previous section. In Figure 6 results are shown from computations with a cut profile where large wave breaking occurs at the edge of the cut-off (H_{m0} = 2.75 m).

The wave height H_{m0} distribution

Offshore of the cut-off the water depth is larger than at the same location in the zero-alternative profile. Because of smaller bottom influence, wave heights are here also slightly larger. At the edge of the cut-off the wave height suddenly decreases. In case of the cut profile the wave height at this location is significantly larger and wave breaking occurs. Onshore of the cut-off the wave height further decreases up to approximately 150 m from the waterline. Here wave heights are the same in both cases.

Energy dissipation

Where the wave height along the profile increases, the energy dissipation due to breaking, D_w, suddenly increases as well and D_w is relatively high along the whole profile onshore of the cut-off. Along this part of the profile a large amount of breaking occurs and finally the wave height decreases to a height which is similar to the wave height distribution in case of the zero-alternative.

Offshore of the cut-off the water depth is still relatively large in relation to the wave height. Therefore also energy dissipation is much smaller in case of the cut profile. Along the slope of the cut-off the energy dissipation due to bottom friction, D_f, suddenly increases. Compared to the local water depth the waves are relatively high and this results in a large energy dissipation. Also onshore of the cut-off waves are higher than in the zero-alternative. This also results in larger D_f values

Bottom sediment transport

Along the profile the bottom transports are more or less similar in both cases. In case of the cut profile the onshore directed bottom transports are slightly smaller. Seaward of the cut-off this is because of smaller bottom friction (or larger water depth). At the edge of the cut-off large energy dissipation due to wave breaking causes a near bottom velocity which is offshore directed. Because of this, also the bottom transport becomes

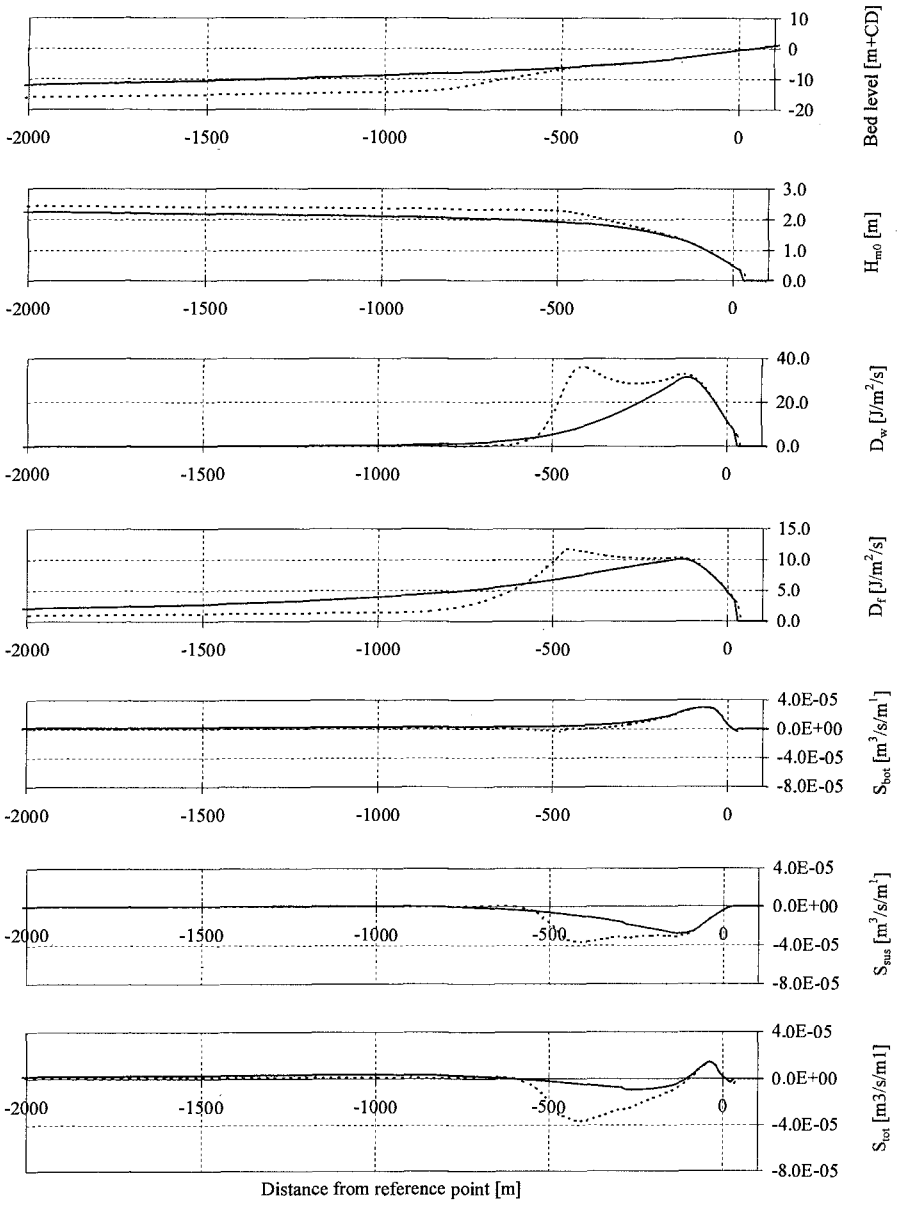

Figure 6. Results of initial computations with large wave breaking on the edge of the cut-off.

offshore directed along the edge of the cut-off.

Suspended sediment transport

The effect of the sudden breaking of waves at the edge of the cut-off can also be seen in the suspended transport along the profile. At this point large turbulence because of breaking causes larger sediment concentrations and with a larger offshore directed flow this results in a larger offshore suspended transport.

Total sediment transport

Especially the suspended transport is largely influenced by the cut-off. This can also be seen in the total sediment transport distribution. Up to approximately 150 m from the waterline the difference in offshore directed transport is relatively large compared to the zero-alternative.

Morphological effects of a cut profile

In order to investigate the morphological effects of a cut profile close to the coast, computations were carried out over a period of 10 years. For these computations a wave scenario based on measured waves at the EURO-0 platform are used. Computations were performed for various cut-off depths and cut-off slopes and the results are again compared with the zero-alternative. As an example the profile changes of a cut profile with a cut-off at CD -6 m is shown in Figure 7.

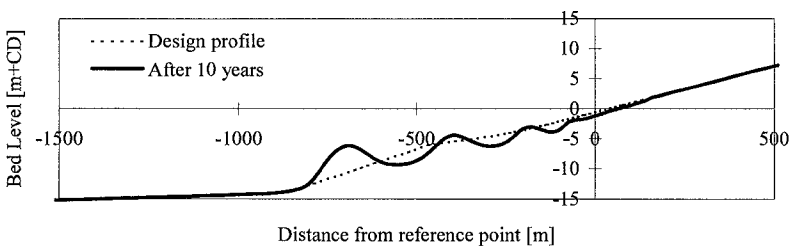

Figure 7. Computed profile with d_{cut} = CD -6 m after 10 years.

As can be seen, large erosion occurs in the nearshore area and the waterline retreats.

If the cut-off is placed at larger depth, less waves break because of the sudden change of depth and therefore also the amount of erosion is smaller. In Figure 8 profile changes after 10 years are shown for a design profile with d_{cut} = CD -14 m. As can be seen, the profile is quite stable and there is even some accretion near the waterline.

In order to make a quantitative comparison between different cut profiles, the yearly averaged transports through depth contours is computed. This is discussed in the next sections.

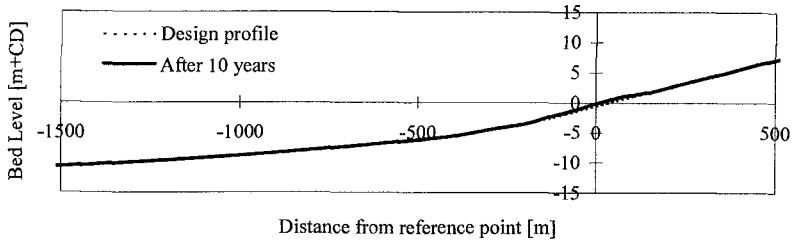

Figure 8. Computed profile with d_{cut} = CD -14 m after 10 years.

Influence of the cut-off depth d_{cut}

As can be seen in the results of the initial computations especially the application of relatively high waves, which lead to wave breaking on the edge of the cut-off, results in a large effect on the sediment transports. It is obvious that the effect of the cut-off will decrease when the cut-off is applied at larger depth. Wave breaking on the edge of the cut-off then hardly occurs and therefore also differences in the sediment transports in comparison with the zero-alternative will be smaller. For investigating the influence of the cut-off depth on a morphological time scale, computations over a period of 10 years are made. The yearly average cross-shore transports are shown in Figure 9. In this figure the horizontal axis shows the depth contours along the profile and the vertical axis gives the yearly amount of sediment which is transported through that depth contour. This is done for cut-profiles with d_{cut} = CD -6 m, -10 m and -14 m Results are compared with the zero-alternative. As can be seen from this figure, a cut-off at CD -6 m results in large offshore directed transport up to large depth.

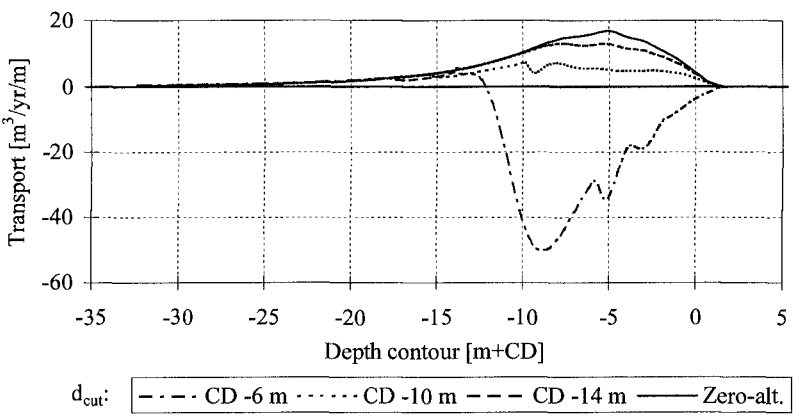

Figure 9. Influence of the cut-off depth on the yearly average cross-shore transports.

From Figure 9 it can also be seen that the initial cross-shore profile of the zero-alternative as applied is apparently not a fully stable (equilibrium) profile

Influence of the cut-off slope d_{cut}

From the previous section it was seen that the cut-off depth has large influence on the yearly average transports along the profile. In Figure 9 however a very steep slope of 1:50 was used. A more gentle slope will result in a more gradual wave breaking. This will then result in smaller offshore directed transports. As an example results of morphological computations on a cut profile with d_{cut} = CD - 8 m are done for various cut-off slopes. Results are shown in Figure 10. As it can be seen from this figure, the cut-off slope indeed affects the yearly average transports in the nearshore section. However, even with a cut-off slope of 1:150 differences are still large compared to the zero-alternative.

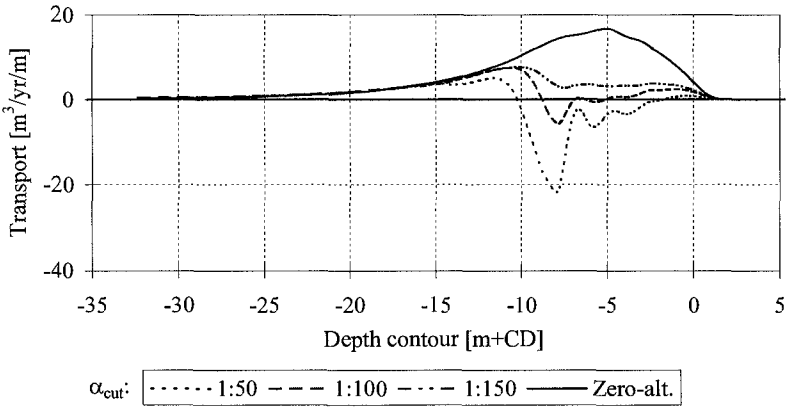

Figure 10. Influence of the cut-off slope on the yearly average transports.

Conclusions

For a large scale land reclamation project as the 'Plan Waterman' a huge amount of material is needed, which makes a project like this very expensive. When applying a cut-profile instead of shifting the whole beach profile over the distance needed for the reclamation, a lot of material can be saved. Material savings up to 40 % are possible.

During this study computations are made with the numerical model UNIBEST-TC, developed by DELFT HYDRAULICS. Especially the effects of a cut profile in cross-shore direction are investigated. Before computations on cut profiles were made, the model has been calibrated for the situation along the coast of between Hook of Holland and Scheveningen.

Computations have been subdivided in initial and morphological computations. From the initial computations it is concluded, that especially the location where waves break is of large influence on the energy dissipation and sediment transports. If waves start breaking onshore of the cut-off the processes are similar to the processes as occur on a profile without a cut-off. Relatively large waves start breaking due to the sudden

change of depth at the edge of the cut-off. This sudden breaking of waves results in large energy dissipation over a small distance which results in large offshore directed suspended transports.

From morphological computations it is concluded, that even a cut-off at large depth still has influence on the sediment transports in the nearshore section of the beach profile. During normal wave conditions differences in sediment transports along a cut profile are very small in comparison with a profile where no cut-off has been applied. When however looking at the yearly average cross-shore transports through specific depth contours, it can be seen that these small differences still have large influence on the coastal development in cross-shore direction. When applying a cut-off at relatively small depth (CD -8 m) a less steep cut-off slope can reduce the seaward directed transports. On the more gentle slope waves break more gradual and the more gradual energy dissipation leads to small offshore directed suspended transports.

In case of the Dutch policy for the coastline protection the coastline is not allowed to retreat due to erosion. In that case there are mainly two options:

- Placing the cut-off at large depth (at least CD -12 m) and do small extra maintenance nourishments;
- Placing the cut-off at small depth and do a lot of extra maintenance nourishments in order to prevent ongoing erosion.

Since the cross-shore profile will eventually develop to an equilibrium profile. At the end the volumes needed for the zero-alternative and the volumes, needed for a cut profile and maintenance nourishments together, are the same. In the first case this volume is already needed during construction. In the latter case the volume is spread over time. This might result in economical advantages.

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