guide to the assessment of the safety of dunes as a sea defence
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Reproduction of this publication, wholly or in part, is allowed provided that the source is duly acknowledged.
The "Guide to the assessment of the safety of dunes as a sea defence" was published in 1984 (in Dutch) under the auspices of the "Technische Adviescommissie voor de Waterkeringen" (TAW) (= Technical Advisory Committee on Water Defences). The guide is based on extensive laboratory research, including model investigations (at a scale of 1:2), and an analysis of dune erosion which occurred during storms in the not too distant past.

Dikes in the Netherlands have to be designed in such a way that they can withstand a design storm surge. This is a storm surge with a probability of occurrence per year of $10^{-4}$. In such cases the dikes must still have some residual strength.

As to dunes, however, the method presented in this guide does not account for any residual strength. Consequently, dunes designed using this method should be able to withstand a storm surge with a lower probability of occurrence.

Analysis of dikes in the Netherlands has shown that dikes designed to withstand a design storm have a probability of failure per year of approximately $10^{-3}$.

Given the above, dunes will have to be designed on the basis of a probability of failure per year of $10^{-5}$.

In order to calculate the probability of failure, a probabilistic approach, including the standard deviations of the input parameters, is required. However, as a purely probabilistic approach requires considerable computational efforts, the present guide provides an approximation leading to the same result as a probabilistic approach. After publication, the guide has been used to evaluate the safety of all dunes in the Netherlands. The dunes which did not meet the requirements had to be reinforced. The reinforcement programme will be completed in 1990. In the future, all dunes will have to be checked every 5 years against meeting the safety requirements.

The guide was compiled by working group 5 "Dunes as a sea defence" of the Technical Advisory Committee on Water Defences. The composition of this working group at the time of publication of this guide was as follows:

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Provincial Public Works Department of Zeeland
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February 1989

Centre for Civil Engineering Research and Codes
Technical Advisory Committee on Water Defences
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LIST OF SYMBOLS

\( A \) calculated amount of dune erosion above computational level \( (m^3/m) \)

\( CL \) computational level above NAP (Standard Amsterdam Datum) \( (m) \)

\( D_{50} \) \( D_{50} \) of the dune sand \( (m) \)

\( D_{\text{comp}} \) computational value of \( D_{50} \) \( (m) \)

\( d \) distance over which the regression line is shifted to take account of the uncertainty of the profile position \( (m) \)

\( G \) \( g_z \) \( (m^3/m) \)

\( G_0 \) reference value for \( G \) \( (m^3/m) \)

\( g \) distance over which the erosion profile is shifted to take account of a gradient in the longshore transport \( (m) \)

\( \bar{g} \) mean value of \( g \), distance over which the regression line is shifted to take account of a gradient in the longshore transport \( (m) \)

\( H_s \) (expected value of) significant wave height in deep water (or at computational level) \( (m) \)

\( h_0 \) minimum crest level of the limit profile above NAP \( (m) \)

\( P \) point of intersection of the shifted dune front with the storm surge level \( (m^3/m) \)

\( T \) surcharge on \( A \) for - duration of storm surge - gust surges and gust oscillations - inaccuracy of computational model \( (m^3/m) \)

\( \hat{T} \) peak period of the wave spectrum \( (s) \)

\( w \) fall velocity of dune sand in seawater \( (m/s) \)

\( z \) difference in height between the most landward and most seaward point of the total erosion profile of each erosion analysis \( (m) \)

\( \bar{z} \) mean value of \( z \) \( (m) \)

ABBREVIATIONS

COW Centrum voor Onderzoek Waterkeringen (Centre for Flood Defence Research)

CUR Civieltechnisch Centrum Uitvoering Research en Regelgeving (Centre for Civil Engineering Research and Codes)

NAP Normaal Amsterdams Peil (Standard Amsterdam Datum)

RWS Rijkswaterstaat (The Netherlands Public Works Department)

TAW Technische Adviescommissie voor de Waterkeringen (Technical Advisory Committee on Water Defences)
Chapter 1

INTRODUCTION

The „Guide to the assessment of the safety of dunes as a sea defence” replaces the 1972 „Richtlijn voor de berekening van duinafslag ten gevolge van een stormvloed” (Guidelines to the analysis of dune erosion due to a storm surge) [1].

The guide, which is mainly aimed at the assessment of the safety of dunes as a primary sea defence, consists of the following three major elements:

- A computational model for the expected dune erosion during a storm surge. This computational model constitutes an important part of the test method mentioned in Chapter 3, and is therefore already described in Chapter 2.
- A method to test a dune coast against the established safety standards for dunes as a primary sea defence.
- A method to test a dune coast against lower safety standards.

The computational model of the 1972 Guidelines has been considerably improved on the basis of extensive model and prototype investigations [2]. The degree of dune erosion due to a random storm surge can be calculated with a certain accuracy by means of the new computational model. The necessary calculation data are the storm surge level, the significant wave height, the grain diameter of the dune sand, and the coastal profile just before the storm surge. The computational model can, apart from test methods, also be used for evaluation and study objectives, such as the calculation of occurred dune erosion.

In order to assess the safety, a test method has been developed on the basis of a probabilistic safety consideration [3]. The accuracy of the computational model and the stochastic nature of the relevant factors that determine dune erosion are taken into account here. These concern, besides the factors already indicated above, the duration of the storm surge and the occurrence of gust surges and gust oscillations.

The probability of collapse in a probabilistic safety consideration is computed on the basis of the calculus of probability, taking into account statistical distributions of the factors that determine dune erosion. Hence a maximum permissible probability of collapse must be indicated as a standard for the safety assessment. This probability of collapse should be in accordance with the Delta Commission Report in order to obtain an equivalent strength for the different types of sea defence. The design levels determined by the Delta Commission serve as a basis for the improvement of sea dikes. A sound dike design must comply with the requirement that „minor exceedance” of the design level will not immediately lead to collapse. Consequently, the frequency of exceedance of the design level may not be interpreted as a frequency of failure. The required safety margin during the occurrence of a water level equal to the design level is
now expressed by a factor with which the frequency of exceedance of the design level must be multiplied so as to arrive at a normative probability per year of collapse for a dune profile. This factor is set at $10^{-1}$ [4]. For Central Holland, for instance, this implies a normative probability of collapse per year of $10^{-5}$.

With the aid of this guide, the largest part of the dune coast can be checked against compliance with the established safety standard. Further investigations are required for a number of coastal sections. This mainly concerns strongly curved coastal sections (see Section 3.1.4), coastal sections protected by hard revetments, and coastal sections that are jointed to structures.

The gradual coastal recession is of great importance in terms of future safety. It is indicated how insight can be gained concerning the point in time when the required safety is at risk.

How the guide should be used is indicated in a fairly direct way. Detailed explanations are omitted where possible. For more background information, reference is made to the indicated literature.
CHAPTER 2

COMPUTATIONAL MODEL FOR THE EXPECTED DUNE EROSION DURING A STORM SURGE

2.1 Introduction

On the basis of extensive model investigations and prototype measurements, a computational model has been developed for the determination of the expected value and the standard deviation of the degree of dune erosion due to a random storm surge. The following factors are assumed to be known: the coastal profile before the storm surge, the grain size of the dune sand ($D_{50}$), the storm surge level, and the significant wave height.

The computational model is applicable to all normal and extreme storm surge conditions and profile shapes along the Dutch dune coast.

2.2 Starting-points

- The coastal profile is transformed into a certain erosion profile during a storm surge with dune erosion.
- The shape of this erosion profile is a function of the significant wave height and fall velocity of the eroded sand in still seawater.
- The shape of the erosion profile is independent of the angle of incidence of the waves, of the coastal profile before the storm surge, and of the storm surge level.
- It is assumed that the eroded sand is transported only in a seaward direction.
- The erosion profile is situated in such a way with regard to the profile before the storm surge that the total area of the eroded sand is equal to the area of the deposited sand (see Fig. 1). It is generally assumed that no net loss of sand occurs in the alongshore direction. Section 3.1.4 is referred to for situations where such net loss does occur.

2.3 The shape of the erosion profile

The erosion profile is built up as follows:

- After erosion has taken place, the dune foot - the point where the steep front of the eroded dune changes into the relatively flat beach profile - is situated at storm surge level. The gradient of the eroded dune slope is 1:1.
- Starting from the dune foot ($x = 0, y = 0$) in the seaward direction, perpendicular to the coast, the profile develops parabolically according to the formula:
storm surge level

$y = \frac{5.717}{7.6} \left( \frac{H_s}{7.6} \right)$

$\approx 0.75 H_s$

erosion profile shifts in landward direction until erosion = sand deposit

Fig. 1. Principle of the computational model for dune erosion.

$$\frac{7.6}{H_s} y = 0.4714 \left( \frac{7.6}{H_s} \right)^{1.28} \left( \frac{w}{0.0268} \right)^{0.56} x + 18 \right)^{0.5} - 2.00$$  \hspace{1cm} (1)

where:

$H_s$ = significant wave height (m) in deep water (water depth of NAP — 20 (m))

$w$ = fall velocity of dune sand in seawater (m/s)

$x$ = distance to the new dune foot (m)

$y$ = depth below storm surge level (m)

to the point with co-ordinates:

$x = 250 \left( \frac{H_s}{7.6} \right)^{1.28} \left( \frac{0.0268}{w} \right)^{0.56}$

$y = 5.717 \left( \frac{H_s}{7.6} \right)$

- Seaward from this point, the profile continues as a straight line with a gradient of 1:12.5 until it intersects the original profile.

The fall velocity $w$ can be calculated with the formula:

$$10\log (1/w) = 0.476 \left(10\log D\right)^2 + 2.180 10\log D + 3.226$$  \hspace{1cm} (2)

where:

$w$ = fall velocity of the dune sand in seawater (m/s)

$D = D_{50}$ of the dune sand (m)
Formula (2) has been derived for seawater with a temperature of 5 °C [6]. The thus computed fall velocities can be used for the entire period during which storm surges (in the Netherlands) can be expected. The influence of wave height and grain diameter (fall velocity) of the dune sand on the erosion profile is illustrated in Figs. 2 and 3.

2.4 Practical application of the computational model for a random storm surge

The degree of dune erosion due to random storm surge conditions for a given coastal profile can be determined as follows:

- The shape of the erosion profile is determined by the significant wave height and the grain diameter (see formula (1)).
- The position of the erosion profile in the vertical sense is determined by the storm surge level (x-axis at storm surge level).
- The position in the horizontal sense is determined by placing the erosion profile over the coastal profile in such a way that an erosion-sedimentation balance is obtained in the direction perpendicular to the coast.
As for the storm surge level, the value which applies just outside the breaker zone must be used. In most cases, the level of gauging stations in deep water can be applied.

If a shoal area is present just off the coast, the significant wave height pertaining to the channel nearest to the breaker zone must be used in the erosion analysis. This wave height can be found from the wave conditions in deep water, whereby, dependent on the local situation, account must be taken of refraction, diffraction, energy dissipation through breaking and friction over the shoal area, as well as of wave growth due to local wind.

The above is illustrated by a number of examples shown in Fig. 4. The left hand side shows the situation before, and the right hand side the situation after the storm surge. The shape of the initial profile and that of the erosion profile determine which case is valid.

Case A: This situation normally occurs during high storm surges.

Case B: This situation may occur in case of a coastal profile with flat slopes. The erosion profile will be partly below the original coastal profile in the final situation. As no account is taken of a landward movement of sand during a storm surge, the original profile is filled with sand from the dune only. The erosion profile does not have the opportunity to develop fully.
before the storm surge  after the storm surge

area = area

- profile before the storm
- profile after the storm

Fig. 4. Analysis of dune erosion; examples of sand movement.
Case C: This situation can be compared to case B. Actually, the sand movements on the seaward side of the bank are of no importance to the recession of the dune. In this case also, the original coastal profile is only partly transformed into the erosion profile.

Case D: In this case, the offshore bank is fully eroded to the erosion profile. The amount of sand further required for the development of the erosion profile comes from the dune.

Case E: In this case, the entire erosion profile is situated below the original coastal profile. This situation will frequently occur during low storm surges. According to the computational model, no dune erosion will take place. In practice, however, a minor amount of dune erosion may occur in many cases due to wave run-up.

2.5 The accuracy of dune erosion calculations with the computational model

In general, the calculated amount of dune erosion will not exactly correspond with the amount of dune erosion actually taking place. The following causes can be mentioned:

- The accuracy of the computational model.
  The computational model is a relatively simple schematization of a complicated natural process. This schematization inevitably entails inaccuracies. The accuracy of the computational model is indicated by means of a deviation from the calculated amount of dune erosion above storm surge level. This deviation has a normal distribution with a mean of zero and a standard deviation

\[
\sigma_A = 0.10A + 20 \text{ (m}^3/\text{m)}
\]  

where

\(A\) = the calculated amount of dune erosion above storm surge level (m\(^3\)/m)

- The accuracy of the input parameters.
  A profile measurement taken just before the storm surge will hardly ever be available. Moreover, there will nearly always be uncertainty as to the exact values of storm surge level, wave height, and grain diameter.

- The effects of gust surges, gust oscillations, and duration of the storm.
  The effects of fluctuations in the water level during the storm surge in consequence of gust surges and gust oscillations are not included in the computational model. The computational model has essentially been developed for relatively high storm surges whereby the storm surge level minus 1.0 m is exceeded for a duration of 4 to 6 hours. Deviations thereof affect the degree of dune erosion.

- Redistribution of sand in the along-shore direction.
  Based on the starting-point that no net loss of sand from the cross-sectional profile occurs, a different degree of dune recession can be calculated for adjacent cross-sectional profiles. In that case, redistribution of sand will occur in the along-shore
direction. The degree to which this will take place depends on the local situation. The starting-point of an erosion-sedimentation balance in the cross-shore direction applies neither to coastal sections with a strong coastline curvature nor to coastal sections with an interruption in the beach or dune profile. For such coastal sections, an additional amount of dune erosion must be taken into account due to a gradient in the longshore transport (see Section 3.1.4).
CHAPTER 3

SAFETY ASSESSMENT OF A CROSS SECTION
OF A DUNE COAST

3.1 The test method for the safety assessment

A relatively simple test method for the assessment of the safety of a cross section of a dune coast has been developed in such a way that the result corresponds with that of the more complicated probabilistic calculations. The test method comprises a number of computational rules for the determination of that degree of dune erosion just before collapse. The values, to be used in the calculations, for the considered factors which determine the dune erosion (Chapter 1) are determined in such a way by probabilistic numerical techniques, that the thus calculated degree of dune erosion has a probability of exceedance equal to the required maximum permissible probability of collapse.

For some coastal sections, an additional amount of dune erosion, due to a gradient in the longshore transport, is still to be taken into account. In what way this is taken into account is not derived from the probabilistic calculations on which the test method is based, where this aspect was left aside.

The long-term development of a dune profile is of great importance, especially in case of an eroding coast. The test method has been developed in such a way that also a good impression can be obtained of the point in time when loss of the required safety of the dune profile might occur. Hence measures can be taken in time.

It is assumed that a series of profile measurements over the past 15 years or more is available. In this connection, the yearly coastal measurements included in the data files of the automated processing system (Jarkus software) of the Rijkswaterstaat (The Netherlands Public Works Department) can be advantageously used. The availability of such a time series is not only imperative for assessing the safety in the future, but also for the processing of the influence of the profile fluctuations on the safety. These fluctuations must be taken into account because it is not exactly known which profile is present just before the storm surge.

The procedure of the test method is as follows:

- An erosion analysis is made for each profile from the series of profile measurements with the aid of the computational model described in Chapter 2. Specific computational values need to be included here for the remaining input parameters (storm surge level, significant wave height, and grain diameter).
- For each erosion analysis, the calculated amount of dune erosion above storm surge level is augmented with a surcharge to take account of the influences of the inaccuracy of the computational model, the gust oscillations and gust surges and the uncertainty about the time during which the water level remains at about maximum
level. The effect of this surcharge is expressed in an additional recession of the steep dune front. Point P is the intersection of this shifted dune front with the storm surge level (see Fig. 5).

- The above calculations yield a time series for the position of point P. These positions can be plotted in a diagram as a function of time (see Fig. 6). It can be easily induced from the position whether there is question of a stable, eroding, or progressing coast. The trend of the position of point P as a function of time can be estimated by means of regression analysis. A linear approximation will usually do. The profile fluctuations are expressed in the scattered position of the points P around this regression line (see Fig. 6).

- The influence of the uncertainty of the profile position is now taken into account by shifting the regression line over a certain distance ($d$), dependent on the magnitude of the profile fluctuations, in a landward direction. The shifted regression line, the design erosion line, yields the position of the design erosion point as a function of time. The design erosion point is the intersection of the steep dune front and the storm surge level here, the position of which has a probability of exceedance which is equal to the considered maximum permissible probability of collapse. In case of the straight coast of Central Holland, for instance, this probability is $10^{-5}$ per year. So far, the influence of a gradient in the longshore transport on the dune erosion has not been taken into consideration.

- For coastal profiles whereby account must be taken of the net loss of sand from the profile due to a gradient in the longshore transport, the final design erosion line is obtained by shifting the in the foregoing obtained shifted regression line over an additional distance ($\bar{d}$) in landward direction.
- In case a minimum profile, the limit profile, no longer exists landwards of the design erosion line, the remaining profile no longer satisfies the established safety standard. Hence this limit profile does not offer a safety margin, but represents the situation just before collapse (limit state).

The following sections will discuss the foregoing in more detail.

3.1.1 *The erosion analysis*

With the aid of the computational model described in Chapter 2, an erosion analysis is carried out for each profile from the available series of profile measurements. The following values must be used for the storm surge level, the significant wave height, and the grain diameter of the dune sand:

- The storm surge level.
  When assessing the safety in view of the function as a primary sea defence, the computational value for the storm surge level equals the design level*, as established by the Delta Commission [5], plus a two third part of the decimation height. This level is called the computational level.
  Computational level = design level + 2/3 decimation height.
  The decimation height is the difference in height between the water level with a probability of exceedance 10 times smaller than that of the design level, and the design level.

* The design level has been defined as the (storm surge) level with (for Central Holland) a probability of exceedance 10^-4 per year. For Zeeland it is 2.5 \cdot 10^{-4} and for the Wadden Islands it is 5 \cdot 10^{-4}.

---

**Fig. 6. Principle of the test method for the safety assessment.**
Hence the frequency of exceedance of the computational level is 0.215 times the frequency of exceedance of the design level and, consequently, 2.15 times larger than the concerned maximum permissible probability of collapse (see also Section 3.3). Table 1 represents the design level, the decimation height, and the computational level for a number of locations along the Dutch coast.

- The significant wave height.

The expected value of the wave height at computational level has to be used as the significant wave height $H_s$. The probability density functions for the significant wave height as a function of the water level have been determined for a number of locations along the Dutch coast [10]. The expected values of the significant wave height for these locations can be read from the diagram in Fig. 7. The given values hold for deep water conditions.

For a particular dune section, the expected value of the significant wave height at computational level can be found by means of this diagram.

The influence of possibly present shoal areas off the coast still has to be accounted for (see also Section 2.4).

Fig. 7. Expected value of the significant wave height as a function of the storm surge level at a number of locations along the Dutch coast [10].
Table 1. Design levels, decimation heights, and computational levels along the Dutch coast.

<table>
<thead>
<tr>
<th>location</th>
<th>design level (m above NAP)</th>
<th>decimation height (m)</th>
<th>computational level** (m above NAP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vlissingen</td>
<td>5.40</td>
<td>0.72</td>
<td>5.90</td>
</tr>
<tr>
<td>Hoek van Holland*</td>
<td>5.25</td>
<td>0.72</td>
<td>5.75</td>
</tr>
<tr>
<td>Scheveningen</td>
<td>5.40</td>
<td>0.70</td>
<td>5.85</td>
</tr>
<tr>
<td>Katwijk</td>
<td>5.40</td>
<td>0.70</td>
<td>5.85</td>
</tr>
<tr>
<td>IJmuiden</td>
<td>5.15</td>
<td>0.67</td>
<td>5.60</td>
</tr>
<tr>
<td>Den Helder</td>
<td>5.05</td>
<td>0.66</td>
<td>5.50</td>
</tr>
<tr>
<td>Texel</td>
<td>4.90</td>
<td>0.68</td>
<td>5.35</td>
</tr>
<tr>
<td>Vlieland</td>
<td>4.70</td>
<td>0.68</td>
<td>5.15</td>
</tr>
<tr>
<td>Terschelling</td>
<td>4.80</td>
<td>0.68</td>
<td>5.25</td>
</tr>
<tr>
<td>Ameland</td>
<td>5.10</td>
<td>0.68</td>
<td>5.55</td>
</tr>
<tr>
<td>Schiermonnikoog</td>
<td>5.15</td>
<td>0.68</td>
<td>5.60</td>
</tr>
</tbody>
</table>

* outside the breakwaters  
** The computational levels are rounded off to a multiple of 5 cm

- The grain diameter.
  The computational value \(D_{\text{comp}}\) for the grain diameter is:

\[
D_{\text{comp}} = \mu_{D_{50}} - 5 \left( \frac{\sigma_{D_{50}}}{\mu_{D_{50}}} \right)^2
\]  (4)

where:
\[
\mu_{D_{50}} = \text{the expected value of the } D_{50}
\]
\[
\sigma_{D_{50}} = \text{the standard deviation of the } D_{50}
\]

Representative values for a part of the sea strip along the Dutch coast are listed in Table 2.

3.1.2 The surcharge on the amount of erosion above computational level

Three surcharges on the amount of dune erosion \(A\) (m\(^3\)/m) above the computational level are to be included in the analysis specified in Section 3.1.1:

- A surcharge of 0.10 \(A\) (m\(^3\)/m) to take into account the uncertainty about the time during which the water remains at about maximum level. This time span is the most determinative factor for the amount of dune erosion in the entire development of the water level during the storm surge.
- A surcharge of 0.05 \(A\) (m\(^3\)/m) to take into account the effect of gust surges and gust oscillations.
- A surcharge of 0.10 \(A + 20\) (m\(^3\)/m) to take into account the inaccuracy of the computational model for the expected dune erosion.

The sum of the surcharges on the amount of dune erosion \(A\) above computational level consequently amounts to 0.25 \(A + 20\) (m\(^3\)/m). This surcharge is expressed as a landward shift of the originally calculated dune foot (Fig. 5).
Table 2. Mean, standard deviation, and computational value of the grain size for a part of the sea strip along the Dutch coast.

<table>
<thead>
<tr>
<th>location</th>
<th>point of reference (km)</th>
<th>$\mu_{D_{50}}$ (μm)</th>
<th>$\sigma_{D_{50}}^*$ (μm)</th>
<th>$D_{comp}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiermonnikoog</td>
<td>1.04</td>
<td>150</td>
<td>8</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>3.02</td>
<td>169</td>
<td>8</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>5.01</td>
<td>165</td>
<td>8</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>7.00</td>
<td>164</td>
<td>8</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>9.20</td>
<td>163</td>
<td>8</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>11.00</td>
<td>164</td>
<td>8</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>13.00</td>
<td>159</td>
<td>8</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
<td>159</td>
<td>8</td>
<td>157</td>
</tr>
<tr>
<td>Ameland</td>
<td>4.01</td>
<td>187</td>
<td>10</td>
<td>184</td>
</tr>
<tr>
<td></td>
<td>6.00</td>
<td>178</td>
<td>9</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>8.00</td>
<td>172</td>
<td>9</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>10.00</td>
<td>176</td>
<td>18</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>12.00</td>
<td>161</td>
<td>8</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>14.00</td>
<td>164</td>
<td>15</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>16.00</td>
<td>170</td>
<td>9</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>18.00</td>
<td>163</td>
<td>8</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>21.40</td>
<td>170</td>
<td>9</td>
<td>168</td>
</tr>
<tr>
<td></td>
<td>24.00</td>
<td>170</td>
<td>9</td>
<td>168</td>
</tr>
<tr>
<td>Terschelling</td>
<td>1.00</td>
<td>210</td>
<td>11</td>
<td>207</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
<td>202</td>
<td>10</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>5.00</td>
<td>206</td>
<td>11</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td>7.00</td>
<td>189</td>
<td>9</td>
<td>187</td>
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<tr>
<td></td>
<td>9.00</td>
<td>187</td>
<td>9</td>
<td>185</td>
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<tr>
<td></td>
<td>11.00</td>
<td>178</td>
<td>9</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>13.00</td>
<td>183</td>
<td>9</td>
<td>181</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
<td>181</td>
<td>9</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
<td>188</td>
<td>9</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>19.00</td>
<td>187</td>
<td>9</td>
<td>185</td>
</tr>
<tr>
<td></td>
<td>21.00</td>
<td>188</td>
<td>9</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>23.00</td>
<td>190</td>
<td>10</td>
<td>188</td>
</tr>
<tr>
<td></td>
<td>25.00</td>
<td>191</td>
<td>10</td>
<td>189</td>
</tr>
<tr>
<td></td>
<td>27.00</td>
<td>189</td>
<td>9</td>
<td>187</td>
</tr>
<tr>
<td></td>
<td>29.00</td>
<td>192</td>
<td>10</td>
<td>190</td>
</tr>
</tbody>
</table>

* From Ref. [9]. However, for $\sigma_{D_{50}}$, a minimum value of 5% of $\mu_{D_{50}}$ was assumed here.

3.1.3 Processing the profile fluctuations

The results of the calculations of Sections 3.1.1 and 3.1.2 can be incorporated in a location-time diagram of the obtained point P (see Fig. 6). A linear regression line for the position of point P in time can be determined from this diagram, as well as the standard deviation of the position of the calculated points P from this line. The design erosion line is obtained by shifting this regression line landwards over a distance $d$.

$$d = \frac{\sigma_P^2 \bar{x}}{275} \quad (m) \quad (5)$$

21
where:

\[ \sigma_p = \text{the standard deviation of the position of the calculated points P from the regression line (m)} \]

\[ \bar{z} = \text{mean value of the differences in height } z \text{ between the most landward and the most seaward point of the total erosion profile of each erosion analysis (m) (see Fig. 5)} \]

The constant in the denominator of the right term in equation (5), \( (m^2) \), is determined in such a way that, using the test method, the desired outcome is obtained.

### 3.1.4 Processing a gradient in the longshore transport

In case of a varying longshore transport of sand along the coast (gradient in the longshore transport), for instance caused by obliquely approaching waves, an erosion-sedimentation balance for a particular coastal section does not exist. For safety reasons, those coastal sections are of importance where the erosion-sedimentation balance has a negative outcome (total outgoing longshore transport exceeds the total incoming longshore transport).

The result is an additional landward shift of the erosion profile over such a distance that the (cross-sectional) area of the shift corresponds with the difference in longshore transport (see Fig. 8).

A value of the gradient in the longshore transport due to a (not too strong) curvature of the coastline will be indicated in this section [7]. Further investigations are required for strongly curved coastal sections, such as at the heads of islands. This also holds for other

![Fig. 8. The influence of a gradient in the longshore transport on dune erosion.](image-url)
situations where a gradient in the longshore transport can be expected, such as at the transition between a dune and a structure (e.g. a breakwater, a dike, or a dune foot protection) and during strong variations in wave height in the along-shore direction (for instance behind sand-banks). The guide is, therefore, inadequate for assessing the safety of such coastal sections.

The value of the to be accounted for gradient in the longshore transport $G$ (m$^3$/m) for not too strongly curved coastal sections, can be calculated with the formula:

$$G = \frac{A^*}{300} \left( \frac{H_s}{7.6} \right)^{0.72} \left( \frac{w}{0.0268} \right)^{0.56} G_0 \quad \text{(m$^3$/m)}$$

where:

- $A^*$ = calculated amount of dune erosion above the computational level including the surcharge (m$^3$/m) (see Sections 3.1.1 and 3.1.2)
- Note: $A^*$ is also a function of $H_s$ and $w$
- $H_s$ = significant wave height at computational level (m) (see Section 3.1.1)
- $w$ = fall velocity (m/s) calculated with formula (2) (Section 2.3) with $D=D_{\text{comp}}$ (Section 3.1.1)
- $G_0$ = reference value for $G$ (m$^3$/m) (see Table 3)

Coastal sections with a curvature according to class 1 are considered as straight coasts (see Table 3). The entire coast from Hoek van Holland to Den Helder is considered to fall within class 1.

As for curvature, the following coastal sections fall within class 5 (further investigations are required):

- **Walcheren**: point of reference (km) $5^{40}-8^{00}$
- **Schouwen**: point of reference (km) $8^{00}-12^{00}$
- **Goeree**: point of reference (km) $2^{00}-5^{00}$
- **Voorne**: point of reference (km) $9^{00}-11^{00}$
- **Texel**: point of reference (km) $4^{00}-8^{00}$
- **Vlieland**: point of reference (km) $31^{00}-32^{00}$
- **Terschelling**: point of reference (km) $51^{00}-54^{00}$
- **Ameland**: point of reference (km) $59^{00}-2^{00}$
- **Schippermonnikoog**: point of reference (km) $5^{00}-6^{50}$

The coastal curvature must be determined over stretches of at least several hundreds of metres.

The final design erosion line for the concerned cross sections is obtained by shifting the line determined in Section 3.1.3 landwards over an additional distance of $\bar{g}$ (m). The
Table 3. Reference value for the difference in longshore transport for different classes of coastal curvature [7].

<table>
<thead>
<tr>
<th>class</th>
<th>curvature interval degrees/1000 m</th>
<th>$G_0$ (m$^3$/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-6</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>6-12</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>12-18</td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>18-24</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 24</td>
<td>further invest.</td>
</tr>
</tbody>
</table>

distance $\bar{g}$ is the mean value of the additional recession $g$, due to a gradient in the longshore transport, of the erosion point of each profile of the considered series of profile measurements (see Figs. 6 and 8).

3.1.5 The limit profile

The critical erosion point indicates the degree of dune erosion just before collapse. A minimum, yet stable profile (limit profile) must still be present landwards of the critical erosion point. The dune is supposed to collapse in case of a minor increase of dune erosion.

The dimensions of the limit profile are determined as follows [8]:

- The minimum crest level $h_0$ is calculated with the formula:

$$h_0 = CL + 0.12\hat{T}\sqrt{H_s} \quad \text{(m) above NAP}$$

(7)

however,

$$h_0 \geq CL + 2.5 \quad \text{(m)}$$

where:

$CL = \text{the computational level (m) above NAP (see Section 3.1.1)}$

$\hat{T} = \text{peak period of the wave spectrum (s)}$

$H_s = \text{expected value of the significant wave height (m) at computational level (see Section 3.1.1)}$

- In general, $\hat{T} = 12s$ may be applied. In case of a shoal area just off the coast, the peak period pertaining to the significant wave height must be used in the analysis.

- The minimum width of the limit profile at crest level $h_0$ is 3 m.

- The gradient of the inner slope must be flatter than or equal to 1:2.

The above is illustrated in Fig. 9.
Remark
The shape of the dune profile can be such that the required crest level of the limit profile according to formula (7) is just not fully attained on the landward side of the design erosion line, even though excess width is indeed available. This is the object of further research in terms of possible compensation for insufficient crest level. If the dune improvement were confined to the realization of the limit profile in such a case, it is as yet recommended to wait for the results of this research* before starting the improvement.

3.2 The influence of gradual coastal recession on the safety

The cross section complies with the safety standard as long as the design erosion line is situated seawards of the line which indicates the critical erosion point as a function of time.

In case of a gradual coastal recession, insight can be gained concerning the point in time when the required safety appears to be at risk by extrapolation in time of the design erosion line (see Fig. 6).

Taking into account the time necessary for preliminary design, approval, and execution, as well as the inaccuracy of the prediction of the above-mentioned point in time, it can be determined when the preliminary design must start.

---

* The results of this research were published in 1987. A lower limit profile is allowed, provided enough width is present in the remaining profile. The relation between the crest width \( c_w \) and the crest level \( c_i \) is \( c_w > (36/c_i) - 1.5 c_i \); but at any time \( c_w > 3 \) and \( c_i > 0. c_i \) is the height above computational level \( CL \) [Ref. 11].
3.3 Testing against lower safety standards

The test method for the safety assessment of dunes as a primary sea defence, as described in the previous sections, can also be applied to the determination of the position of the design erosion point as a function of time with a larger probability of exceedance. This may be of importance for reasons of management.

To this end, the following computational values for the storm surge level and the significant wave height need to be used in the calculation:

- Storm surge level.
  A water level with a probability of exceedance 2.15 times larger than the probability of exceedance of the position of the design erosion point must be introduced for the storm surge level (see also Section 3.1.1).

- Significant wave height.
  The expected value at this water level must be introduced as the significant wave height. This value can be derived from Fig. 7.

The remaining computational values and steps in the procedure for the determination of the design erosion line, pertaining to the safety standard, remain unchanged.

This method can be applied for probabilities of exceedance per year of the position of the design erosion point between $10^{-3}$ and $10^{-5}$. 
CHAPTER 4

REMARKS

4.1 Longshore redistribution

The test method described in this guide always applies to only one cross section of a range of dunes. A certain degree of longshore redistribution of the sand will take place in case of short-spaced section lines with large differences in dune erosion (see also Section 2.5). In addition, the maximum permissible limit of the position of the design erosion line (limit profile) may show an erratic pattern along the coast. These three-dimensional effects may be of importance to the safety assessment. No generally valid rules are given for including these effects into the calculation. Matters need to be assessed on the basis of the local situation.

4.2 Groynes and rows of piles

Coastal sections with groynes or rows of piles can also be tested using the guide. The presence of such structures is supposed to exert no direct influence on the degree of dune erosion.

4.3 Dune foot protections

Dune sections that are protected by hard revetments can, for the time being, be assessed with this guide by assuming the absence of the protection. Model investigations may be carried out in such cases.

4.4 Relative sea level rise

In view of the relatively short period after which a dune coast will undergo another safety check, especially in case of eroding coasts, and the more frequent execution of necessary improvement works (mostly beach nourishment) as compared to dikes, the relative sea level rise has not been taken into account in the test method. For every verification and possible adaptation, the prevailing design levels must be used in the calculation.

4.5 Non-linear regression

The determination of the expected future position of the erosion point with the aid of a linear regression line through the calculated erosion points as a function of time does not always give reliable results.
Possible causes are:

- Human interference on the considered coastal section or on an adjacent coastal section in the period in which the profile measurements were carried out, as well as an occurred trend break during that period.
- The to be expected trend break in the future due to a sandbank or channel which is moving towards the coast.
- The influence of the dune height, decreasing in the landward direction, on the regression line.
- A clearly noticeable non-linear trend.

Should the case arise, an alternative for the linear regression approximation will have to provide a prognosis for the future position of the erosion point.
CHAPTER 5

SUMMARY

A method is presented to evaluate the safety of dunes as a sea defence. The method is based on the dune erosion profile according to VELLINGA combined with a probabilistic approach. Every dune can be tested with this method and it is possible to determine the probability of collapse of a dune whereby the polders are flooded.
REFERENCES

The references 1 up to and including 11 are all in Dutch and will be difficult to obtain abroad.

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2. Waterloopkundig Laboratorium, Rekenmodel voor de verwachting van duinafslag tijdens stormvloed (Computational model for the expected dune erosion during a storm surge), M 1263 IV, November 1982.
6. Waterloopkundig Laboratorium, De valsnelheid van zand in zeewater van 5°C (The fall velocity of sand in seawater at 5°C), M 1263 IVb, September 1983.
7. Centrum voor Onderzoek Waterkeringen, Rekenmodel voor extra duinafslag ten gevolge van een gradiënt in het langstransport als gevolg van een kromming van de kustlijn (Computational model for additional dune erosion as a result of a gradient in the longshore transport due to a curvature of the coastline), S-81.040, April 1984.
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10. Rijkswaterstaat, Deltadienst, Golfhoogte - waterstand relaties t.p.v. de NAP — 20 m lijn langs de Nederlandse kunst (wave height - water level relations at the NAP — 20 line along the Dutch coast), Notitie WWKZ-83 G.218, March 1983.

Further background information can be found in:
