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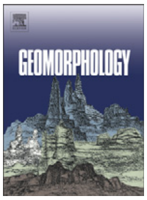

Assessment of dune failure along the Dutch coast using a fully probabilistic approach

C.(Kees) den Heijer [a,b,*], Fedor Baart [a,b], Mark van Koningsveld [c,a]

[a] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA, Delft, The Netherlands*
[b] *Deltares, P.O. Box 177, 2600 MH, Delft, The Netherlands*
[c] *Van Oord, P.O. Box 8574, 3009 AN, Rotterdam, The Netherlands*

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ABSTRACT

This paper describes an investigation into the added value of a fully probabilistic approach to dune resilience assessment over the currently applied deterministic and semi-probabilistic approaches. The method is applied to the Dutch coast but is generically applicable, provided of course the sufficient availability of data. The DUROS+ model in its most basic form was used to quantitatively assess dune resilience. The Monte Carlo method was used for the probabilistic investigation. Important research questions were (1) where can the DUROS+ model in combination with the fully probabilistic approach be applied along the Dutch coast? and (2) what is the alongshore variability of failure probability using this probabilistic approach?

The main conclusion of the work presented in this paper is that the fully probabilistic approach provides valuable added insight with respect to the actual failure probability of transects. At the same time it is noted that the current dune erosion model in its most basic form is not able to cover all of the Dutch coast. Reasons lie in the availability of sufficient quality boundary conditions, applicability limits associated with model assumptions and insufficient quality coastal profile information.

To extend the coverage of the analysis of failure probabilities along the Dutch coast it is recommended (1) to involve more process-based model concepts that can cope with the situations DUROS+ cannot, and (2) to expand currently available data on boundary conditions.

1. Introduction

Many countries in deltaic areas lie below or around sea level and have to be protected from flooding by the sea. Along many coasts natural dunes are the first (and last) line of defence. Research in The Netherlands from 1960 on yielded methods to quantify dune resilience for coastal safety assessments. This enabled coastal managers to engineer the soft and dynamic dune area to be a robust coastal defence of a predetermined resilience.

Current methods to assess the resilience of coastal dunes in The Netherlands are based on a deterministic dune erosion model (Vellinga, 1986; van Gent et al., 2008) and a semi-probabilistic approach based on van de Graaff (1986) and WL | Delft Hydraulics (2007). The DUROS+ dune erosion model (Vellinga, 1986; van Gent et al., 2008) is based on assumptions, such as alongshore uniformity and the absence of hard structures, which are not valid at many locations along the Dutch coast. The semi-probabilistic approach means that for a limited number of locations along the coast representative boundary conditions are derived, using a full probabilistic approach, which are translated to conditions for the areas in between. The actual safety assessment is then performed by applying these boundary conditions along the whole coast in a deterministic way and checking whether the dune cross-sections do not fail. This approach yields a binary result: either the transect fails or it withstands the forcing conditions.

In the meantime many dune erosion models have been developed (Larson and Kraus, 1989; Steetzel, 1993; Sallenger, 2000; Stockdon et al., 2007; Roelvink et al., 2009; van Rijn, 2009). Developments in computing power and also the development of more sophisticated analysis routines and approaches have made a fully probabilistic approach a feasible alternative. Generally, for the application of more advanced dune erosion models, more input, calibration and validation data are required. When applying these models in a probabilistic context and for extreme conditions, availability of data is even more important.

Improved methods for the assessment of the resilience of coastal dunes can either use a more advanced probabilistic approach, a more advanced dune erosion model, or both. The application of a fully probabilistic approach in combination with the presently used DUROS+ model does not only result in probabilities of failure, as opposed to a binary result, but also gives more insight into the applicability of this dune erosion model. For locations where under

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* Corresponding author at: Delft University of Technology, Faculty of Civil Engineering and Geosciences, P.O. Box 5048, 2600 GA, Delft, The Netherlands.
E-mail address: c.denheijer@tudelft.nl (C. den Heijer).

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normative conditions, failure of the first dune row can be expected, the problem becomes 2D, which means that the 1D DUROS+ model is not suitable. Therefore, a clear picture of the applicability of the presently used DUROS+ model can give a better insight in the urgency for the development of an advanced assessment method as well as the data required for that.

This paper presents a resilience map of the first dune row of the Dutch Holland and Wadden coast based on a fully probabilistic approach. To test the applicability of the DUROS+ dune erosion model a selection is made of areas that meet the assumptions. Areas that, according to this first dune row approach do not meet the normative resilience level, indicate a need for detailed inspection. Some of these areas show a need for a more detailed 2D dune erosion modelling approach. Although the method is demonstrated on a Dutch case, the probabilistic approach and the steps to determine where to use a 1D empirical (van Gent et al., 2008) or a 2D process based model (Roelvink et al., 2009) are generic in nature and can be applied elsewhere in a similar manner, provided of course the necessary data are available.

1.1. Design considerations for coastal dunes

Management of coastal dunes involves balancing the interests of the numerous user functions that are provided by dune areas. A dune area provides valuable ecological habitat for a wide range of flora and fauna, it is a popular area for recreation and it provides flood protection for the area that lies behind the dunes. Clearly a dune area preferably provides all of the above-mentioned services simultaneously. Especially for low lying countries (such as The Netherlands), the flood protection function is usually treated with priority.

In order to enable objective decision making on flood protection three things need to be considered (Starr, 1969; Vrijling, 2001). First of all a method is needed to quantitatively assess the resilience of a dune area; in terms of a dune being able to withstand a storm of certain severity. Second, information is needed on the land and property that are protected by that dune area. Third, insight is required in the cost associated with enhancing the level of safety locally as well as regionally (construction as well as maintenance costs). Combining these three things in a cost–benefit analysis enables a rational (political) decision on the desired level of safety given the economic value present in the hinterland.

A practical application of the above approach is the development of the normative safety level presently used for the Dutch coast. It is based on the evaluation of the probability of failure, the cost of maintenance and the cost of failure in terms of damage to economic value present in the hinterland (van Dantzig, 1956). This normative safety level was proposed by the Delta Committee (1960) following the 1953 storm surge disaster. It is interesting to see how much the economically optimal safety level depends on the cost of failure. The densely populated Holland coast should be able to withstand hydraulic boundary conditions with an exceedance probability of $1 \cdot 10^{-4}$ per year; the Wadden area $5 \cdot 10^{-4}$ per year with the exception of the island Texel ($2.5 \cdot 10^{-4}$ per year); the Delta area $2.5 \cdot 10^{-4}$ per year. In order to establish whether such safety levels are indeed achieved a robust quantitative approach is needed. In The Netherlands this quantitative approach is provided by the DUROS+ model for dunes. The pre-mentioned safety levels are based on an econometric analysis. Inundation of the hinterland is assumed to result in total loss of properties, but fatalities and social disruption are not taken into account. The Delta Committee (1960) explicitly intended the flood defences to be able to (just) withstand the design conditions. The exceedance probabilities of the design conditions are therefore not the failure probabilities of the defence. A study group (Working Group 10; Delta Committee, 1953–1954) recommended to set the maximum failure probability at a factor of 10 smaller than the exceedance probability of the design level.

2. Methods

This section describes the dune erosion model as well as the probabilistic method and discusses the selection method to find the part of the coast that can be modelled with the DUROS+ model given the model's assumptions, and the probability distributions to use in the Monte Carlo analysis. The rather strict limitations of the model, as applied in this study, hold especially for the DUROS+ as such. In the official safety assessment method as prescribed by the Dutch government, several model additions and assumptions enable the assessment of the majority of the coastal transects. Please note that the investigation as presented in this paper is a proof of concept and cannot be considered as a full safety assessment.

2.1. Model for dune resilience assessment: DUROS+

Following the 1953 storm surge disaster and the recommendations by the (first) Delta Committee (1960), important research was done during the 1960s, 1970s and 1980s to better understand the response of dunes to storm surges. Jelgersma (1961) and Jelgersma et al. (1995) studied the geological background of dune behaviour. Vellinga (1982, 1986) carried out a number of experiments on different scales and developed a 1D empirical relation. Van de Graaff (1986) introduced the probabilistic approach. Steetzel (1993) developed a 1D process based DUROSTA model which is also able to account for curved coastlines and alongshore transport. Roelvink et al. (2009) developed the 2D XBeach model which is capable of dealing with dune erosion, overwash and breaching.

The work by Vellinga (1982, 1986) and van de Graaff (1977, 1988), in particular, resulted in the Guideline for Dune Erosion (TAW, 1984, 1995) that provides a relatively simple equilibrium approach (commonly referred to as the DUROS model) to model the very complex processes of dune erosion.

Wave data of actual storms collected during the 1990s indicated that the hydrodynamic boundary conditions had a slightly greater observed peak period than was previously assumed (de Ronde et al., 1995; Roskam and Hoekema, 1996). Because the potential effect of this increased peak period on the estimated dune erosion could not easily be established, additional laboratory tests and studies were performed early in the 21st century (van Gent et al., 2008; van Thiel de Vries et al., 2008). The updated insights were integrated into the previous model leading to the currently applied DUROS+ model.

This section summarises the DUROS+ model of van Gent et al. (2008), which is the current model for dune safety assessment in The Netherlands.

The model assumes an equilibrium profile being developed during a storm, with an average duration. The model does not simulate the profile development in time, it only approximates the post-storm profile shape. The cross-shore position of the post-storm profile is found by assuming conservation of volume in the cross-shore direction. This 1D (cross-shore) approach, implies an underlying assumption of alongshore uniformity. The post-storm profile comprises three elements (Fig. 1):

1. the dry dune front,
2. the parabolic equilibrium post-storm beach profile, and
3. the transition slope connecting the post-storm beach profile with the initial profile.

The dry dune front is described by a 1:1 slope, from the storm surge level upward to the intersection with the pre-storm profile.

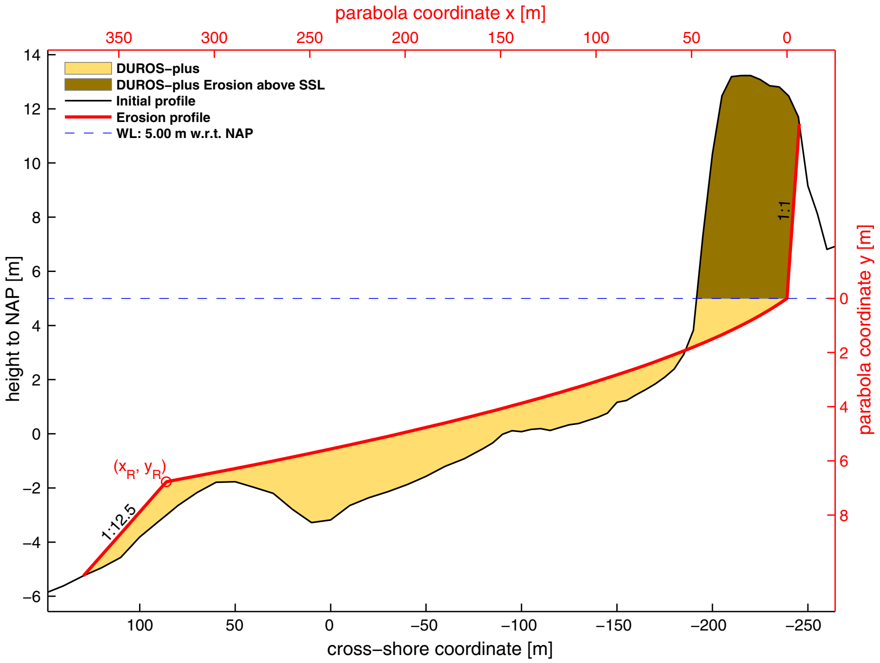

Fig. 1. Example of dune erosion calculation and various sub elements of the method.

The formulation for the parabolic profile in the DUROS+ model is given in Eq. (1) (van Gent et al., 2008).

$$\frac{7.6}{H_{0s}}\cdot y = 0.4714\cdot\left[\left(\frac{7.6}{H_{0s}}\right)^{1.28}\cdot\left(\frac{12}{T_p}\right)^{0.45}\cdot\left(\frac{w_s}{0.0268}\right)^{0.56}\cdot x + 18\right]^{0.5} - 2 \qquad (1)$$

Herein y is the vertical coordinate, positive downward with $y=0$ at the storm surge level and x is the cross-shore coordinate which is positive seaward (secondary axes in Fig. 1).

The parabolic profile is cut off at the point described by Eqs. (2) and (3).

$$x_R = 250\cdot\left(\frac{H_{0s}}{7.6}\right)^{1.28}\cdot\left(\frac{0.0268}{w_s}\right)^{0.56} \qquad (2)$$

$$y_R = \left(\frac{H_{0s}}{7.6}\right)\cdot\left[0.4714\cdot\left(250\cdot\left(\frac{12}{T_p}\right)^{0.45} + 18\right)^{0.5} - 2\right] \qquad (3)$$

The transition slope connects the parabolic profile at the seaward end with a 1:12.5 slope to the initial profile. The fall velocity of the sediment in water w_s is defined as a function of the D_{50} grain size (for a water temperature of 5 °C), following (WL | Delft Hydraulics, 1983):

$${}^{10}log\left(\frac{1}{w_s}\right) = 0.476\left({}^{10}logD_{50}\right)^2 + 2.180\,{}^{10}logD_{50} + 3.226. \qquad (4)$$

The total post-storm profile shape is positioned in the cross-shore such that an equilibrium between dune face erosion and foreshore deposition is achieved. The post-storm cross-shore profile as described by Eq. (1) depends on (1) significant wave height, (2) wave peak period and (3) sediment fall velocity; the latter primarily determined by grain size (Eq. (4)). The coefficients in Eq. (1) are calibrated by a range of laboratory experiments for an average storm duration. To account for variations in storm duration, a so-called *additional erosion* is introduced. This is an extra slice of erosion of the dune front (1:1 slope) with a volume which is proportional to the original erosion above storm surge level. The proportionality constant, and so the thickness of the slice, is related to the deviation of the storm duration from the average duration. This means that a longer duration gives extra erosion, but a shorter duration results in a reduction of the initial erosion.

It is important to realise that the DUROS+ model is developed for dune *erosion*. Inundation or overwash processes are not included in the model. In this paper, we devise methods to predict probabilities of inundation of the area behind the first dune row. Here, dune failure is defined as the situation that the dune body above storm surge level is totally eroded.

2.2. Required model input

Crucial input for the DUROS+ model is the shape of the pre-storm cross-shore profile. The details of the profile shape determine the outcome of the erosion-sedimentation balance and hence the landward extent of the storm erosion. Detailed profile information, including foreshore, beach and first dune rows is therefore critical. As a result a well established monitoring programme is crucial to actually enable safety assessment. In the Dutch case the cross-shore profiles are obtained from the JARKUS dataset (Rijkswaterstaat, 2008). The JARKUS data contain in total 2178 cross-shore transects which are measured yearly since 1965. For this study, the transects of 2008 have been used. The transects have an alongshore spacing between 150 m and 250 m. The orientation of the transects is approximately shore normal. The JARKUS data as well as the analysis scripts used in this paper have been provided by OpenEarth (van Koningsveld et al., 2010).

Besides profile information the DUROS+ model requires the following variables as input: the storm surge level, the significant wave height, the wave peak period and the grain size of the local sediment (needed to determine the sediment fall velocity). The first three inputs are commonly derived from time series of (directional) offshore wave buoys. The better the information on the (statistics of the) hydrodynamic boundary conditions, the better the safety assessment. In the Dutch case a number of offshore wave buoys are available with decades of high resolution time series. The final input, grain size, requires sediment sampling. Such a sediment sampling campaign has been executed in The Netherlands and grain size distributions are available at 146 locations along the entire Dutch coast (TAW, 1984). The cross-shore location of these samples is not known.

2.3. A probabilistic approach

To determine the probability of failure, we firstly calculate the probabilities of the relevant forcing combinations along the Dutch coast. The variables that are used for computation of these probabilities are called stochastic variables. The variables that are used as input but that have a fixed value are called deterministic variables. Of the latter it is assumed that they are measured without error. The DUROS+ model contains the following stochastic variables: water level, wave height, wave period, D_{50} grain size and storm duration. The following variables are deterministic: initial (pre-storm) cross-shore profile and wave direction (shore normal).

The Monte Carlo method (Fishman, 1996) is used as a probabilistic model. For each selected transect, random samples are taken from the probability distributions of the boundary and initial conditions. For each of these sampled combinations of conditions the response of the dune is calculated with the dune erosion model (Subsection 2.1). If the model result shows the dune body above storm surge level to be totally eroded, the dune is supposed to fail for these sampled conditions. Otherwise, if the post-storm dune crest is still above storm surge level, the dune is supposed to be able to withstand these conditions. The probability of failure for a transect can be found by dividing the number of failures by the total number of samples.

An advantage of the Monte Carlo method is that it is easy to apply. A disadvantage is that for small probabilities of failure many calculations have to be carried out to get an accurate result, leading to long computation times. To cope with this, the more efficient Monte Carlo Importance sampling technique (Fishman, 1996) is applied. With this technique, the most important stochastic variable (the water level) is scaled to get more failure situations. Afterwards, the resulting failure probability is corrected for the scaling of the stochastic variable. In this way, an accurate result can be found with a limited number of samples. The calculations for this paper have been carried out with 100 samples per transect.

2.4. Research questions

Major assumptions involved in applying the DUROS+ model are alongshore uniformity and absence of hard structures. Other models for the effect of storms on the coast, that can deal with alongshore non-uniformity and hard structures, have become available (Steetzel, 1993; Lesser et al., 2004; Roelvink et al., 2009). Therefore we evaluate what part of the Dutch coast can be modelled using the empirical DUROS+ model.

The current approach to safety assessment is to perform probabilistic calculations on a limited number of selected locations along the coast. The resulting design conditions are interpolated along the coast and as such used as input for deterministic calculations for each transect, leading to a binary result: safe or not safe. This paper describes the use of a fully probabilistic approach to each transect along the whole coast, to examine the probability of failure of the first dune row. This gives insight in the resilience of the first dune row along the Dutch coast. Locations where the failure probability of the first dune row is higher than the local normative safety level have to be considered in more detail with a more advanced dune erosion model.

2.5. Selection of transects

One of the most important assumptions in DUROS+ is the sediment balance in the cross-shore, implying the assumption of along shore uniformity. The model is therefore only applicable to reasonably straight coasts. Furthermore DUROS+ is validated for experiments with sand only. Therefore we will not apply the model at locations with hard layers or structures. Another assumption is that the pre-storm cross-shore profile is known at least in the vertical range where the profile is likely to change during the storm. Finally information about the wave conditions has to be available. These assumptions lead to the following inclusion criteria for JARKUS transects where the model is deemed applicable:

- the angle between the extended transect and the connection line between the two relevant boundary condition locations must be between 70 and 110°. This requirement implies in practice that the strongly curved Wadden island heads are left out of consideration.
- sections of the coastline containing hard structures (*Hondsbossche* and *Pettemer Zeewering*) and harbours are left out.
- the transect must at least reach from NAP − 5 m to NAP + 5 m (NAP is the Dutch vertical datum, approximately mean sea level). With this requirement transects that only contain the underwater profile up to the beach, or only contain part of the beach and the dune are excluded.
- Wave measurement data of sufficient quality, that useful probability distributions may be derived, are only readily available near Hoek van Holland and northwards. Therefore, the southern part of The Netherlands, the Delta region, is left out of consideration.

The remaining transects are cropped at the landward side if more than one dune row is present in the data. This means that the failure probability of only the most seaward dune row is calculated. Two main reasons have led to this choice. Firstly, this gives the best comparable results. Secondly, after failure of the first dune row, any further erosion or overwash processes should be considered in 2D.

2.6. Probability distributions

The probability distributions that were used for the development of the safety assessment method for the Dutch dune coast (WL | Delft Hydraulics, 2007) have been reused in this paper (see Table 1 for a summary of the distributions used).

2.6.1. Water level

The stochastic properties of the water level are described by a conditional Weibull distribution:

$$F_e(H>h) = \rho\, exp\left[-\left(\frac{h}{\sigma}\right)^{\alpha} + \left(\frac{\omega}{\sigma}\right)^{\alpha}\right] \tag{5}$$

where:

h	the highest water level during a storm surge [m] above NAP
F_e	the probability of exceedance of the highest level h during a storm surge [year^{-1}]
α	a shape parameter that depends on the location along the coast
ω	a threshold above which the function is valid [m] above NAP
σ	a scale parameter that depends on the location along the coast
ρ	the frequency of exceedance of the threshold level ω.

Rewriting Eq. (5) to isolate h yields:

$$h = \sigma\left[log(\rho) + \left(\frac{\omega}{\sigma}\right)^{\alpha} - log(F_e(H>h))\right]^{\frac{1}{\alpha}}. \tag{6}$$

Table 1
Probability distributions.

Variable	Mean	Standard deviation	Distribution type
Water level (h)	$f(P_{exc})$ Eq. (6)	–	Conditional Weibull
Wave height (H_s)	$f(h)$ Fig. 2	0.6 m	Normal
Wave period (T_p)	$f(H_s)$ Fig. 2	1 s	Normal
Grain size (D_{50})	159 μm–277 μm	8 μm–37 μm	Normal
Surge duration	0	$0.1*A$	Normal

2.6.2. Wave height

The wave height is correlated to the water level because during storms their main driving force is wind. The stochastic properties of the wave height are described by a normal distribution. The mean value is related to the water level by a relation obtained from Stijnen et al. (2005). Stijnen et al. (2005) describe the relation between water level and wave height for 5 locations along the Dutch coast, as presented in Fig. 2 panel a. The standard deviation is a constant value of 0.6 m. In Fig. 3 the measurement locations for the boundary conditions along the Dutch coast are depicted. One of those, *Steunpunt Waddenzee*, is an artificial station in the sense that the data for that location are interpolated between the two neighbouring locations.

2.6.3. Wave period

The wave period is correlated to the wave height, and thus indirectly to the water level. Also the wave period's stochastic properties are described by a normal distribution. Again the mean value is obtained according to a relation from Stijnen et al. (2005), as shown in Fig. 2 panel b. The standard deviation is set to 1 s.

2.6.4. Grain size

Grain size distributions have been derived from sediment samples at 146 locations along the Dutch coast (TAW, 1984). 105 out of these are located in the area of the selected transects. Although it is not known where in the cross-shore these samples have been taken, they are assumed to be representative for the entire cross-shore profile. The D_{50} grain sizes that can be derived from these samples are assumed to be normally distributed. Mean D_{50} grain sizes vary between 159 and 277 μm. Standard deviations of the D_{50} grain sizes vary between 8 and 37 μm. The finer sediment mainly occurs in the Wadden area in the northern part of The Netherlands. This is also related to the fact that the profile slope is relatively mild there.

2.6.5. Storm duration

The DUROS+ model (see Subsection 2.1) is based on an average storm duration and does not include the storm duration as a separate variable. To additionally include a variety of storm durations in the probabilistic calculation, a normally distributed additional erosion (with respect to the original erosion “A” as computed with DUROS+, indicated as “DUROS-plus Erosion above SSL” in Fig. 1) is introduced. The mean value is zero and the standard deviation is 10% of the original erosion above the water level. Please note that this approach allows for the additional erosion to also become negative, resulting in a reduction of the erosion with respect to the original DUROS+ result.

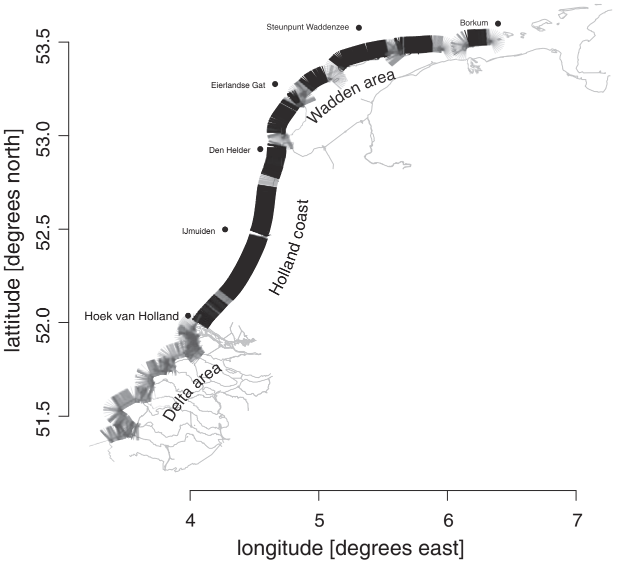

Fig. 3. Overview of transects that were selected as suitable for DUROS+ (black). The remaining, not selected, transects are showed in grey.

2.6.6. Other influences

In the method described by WL | Delft Hydraulics (2007) contributions for the uncertainty of the model and for the variation in cross-shore profile volume are also proposed. In this paper these variables are left out of consideration. The contribution of the profile variation could be taken into account but appears to have a minor influence only. The contribution of the uncertainty of the model is mainly relevant for design or assessment purposes and therefore considered to be outside of the scope of this paper.

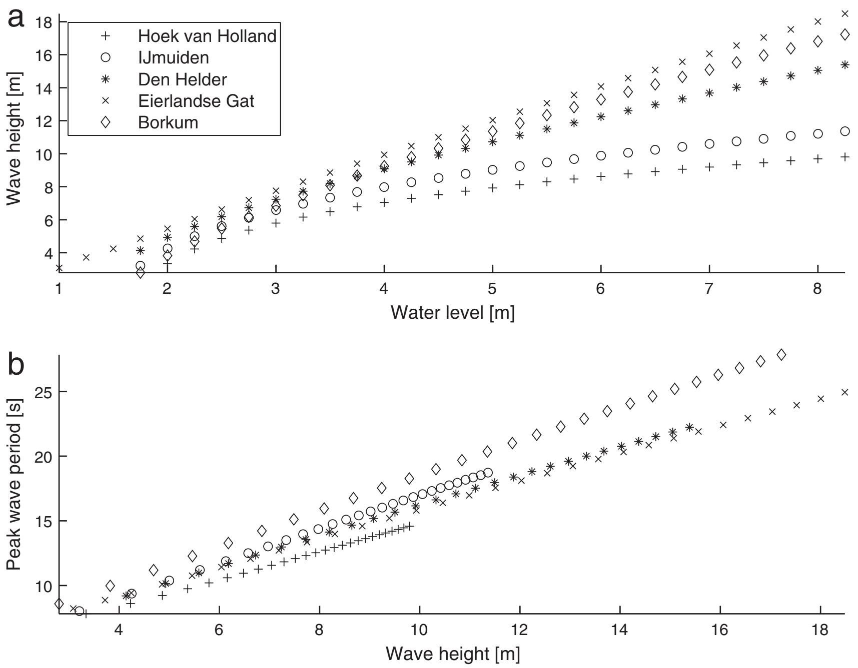

Fig. 2. (a) Mean wave height as function of water level. (b) Mean peak wave period as function of wave height.

3. Results

In this section the DUROS+ model is applied in a fully probabilistic manner using the information available at the Dutch coast: JARKUS transects, offshore wavebuoys, grain size and storm duration estimates.

3.1. Transects included in the probabilistic analysis

The Dutch coast is commonly divided in three areas: (1) the *Wadden area* in the north with a series of islands and inlets in between (848 transects), (2) the central *Holland coast* (593 transects) and (3) the *Delta area* in the south with several inlets most of which have been closed with dams and barriers as part of the Delta plan (737 transects) (see Table 2).

In the Wadden area only 429 transects, out of the 848, are selected (51%). The main reason for excluding transects in this area is the occurrence of coastal curvatures at the island heads. In these areas the DUROS+ model, in its basic form, is not applicable for two main reasons. Firstly, the model is not developed for the strongly curved coastlines as what occurred here. Secondly, in these areas near the inlets high current velocities can occur, which are also not included in the current model setup. The 2D XBeach model (Roelvink et al., 2009) is not based on these assumptions and should be applicable here.

At the Holland coast 448 out of the 593 transects have been selected (76%). Exclusions in this area are mainly due to some dikes and hard structures. In addition, in the south of the Holland coast area, some transects have been excluded because they only cover the shallow water part and the beach. The 2D XBeach model (Roelvink et al., 2009) does have an option to model hard structures in a beach (van Dongeren et al., 2009).

The Delta area is excluded as a whole because of the lack of readily available wave boundary conditions. In this area with its dams barriers and inlets a more advanced model like XBeach (Roelvink et al., 2009) is needed, provided that the right data are available. Fig. 3 shows the distribution of the selected transects for the year 2008. Table 2 gives an overview of the numbers of available and selected transects per area.

Applying the selection criteria, described in Subsection 2.5, 877 transects out of 2178 transects (40%) are considered suitable to include in the fully probabilistic approach. Without the Delta area the percentage of included transects is 61%. For 753 out of these 877 profiles a failure probability could be determined using the probabilistic approach. For the other 124 profiles, the probability can be considered lower than $1 \cdot 10^{-17}$ per year. As an estimate for these we use $1 \cdot 10^{-17}$ per year.

3.2. Alongshore distribution of failure probability

The expected failure probability along the Holland coast is at most $1 \cdot 10^{-5}$ per year as this is the normative safety level for dunes as primary sea defences. The calculated failure probabilities are summarised in Fig. 4, that shows that about 10% of the selected transects have a higher failure probability than $1 \cdot 10^{-5}$ per year.

As can be seen in Fig. 5, most of the locations with the highest failure probability can be found in the Wadden area. The Wadden islands have a required safety level of $5 \cdot 10^{-5}$ per year (with the exception of Texel, where it is $2.5 \cdot 10^{-5}$) and part of the islands are outside the primary sea defences.

Table 2
Overview of total available and selected transects as well as transects where the first dune row does not meet the requirements.

Area	Available transects	Selected transects	Normative safety level [year^{-1}]	Transects not meeting safety level
Wadden area	848	429	$5 \cdot 10^{-5}$	45
Holland coast	593	448	$1 \cdot 10^{-5}$	23
Delta area	737	0	$4 \cdot 10^{-5}$	–
Total	2178	877	–	68

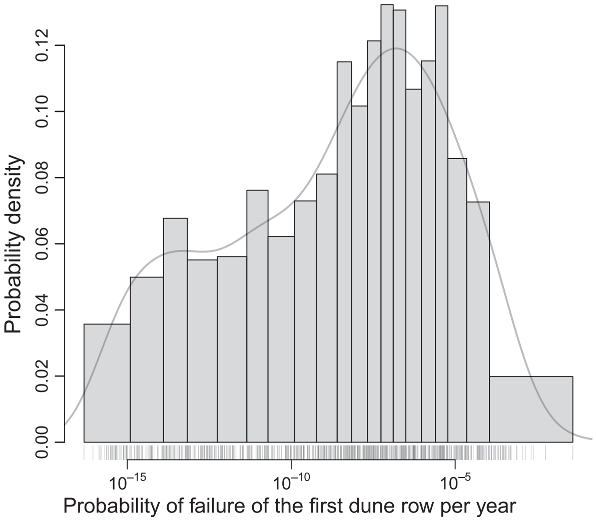

Fig. 4. Histogram of the probabilities ($p > 10^{-17}$ per year) of failure of the first dune row (all calculated transects). The bin-width is variable and each bin contains an equal number of observations. The graded line is the Kernel density function. In the rug plot along the horizontal axis the individual data points are indicated.

As an example we will look at four locations in detail. From north to south, a transect with the largest failure probability ($p = 1/26$ year^{-1}) at the tail of the Wadden island Terschelling (Fig. 6 panel a), a transect just North of the *Pettemer Zeewering* (Pettemer Sea defence) (Fig. 6 panel b), a transect near Bergen with a probability of failure of about the normative value of 10^{-5} year^{-1} (Fig. 6 panel c) and finally a transect just North of the harbour entrance of IJmuiden (Fig. 6 panel d).

An example of a dune with a high failure probability is the tail of the Wadden island Terschelling (Fig. 6 panel a). The crest of the first dune row of this profile is only 8 m above mean sea level and the dune is narrow. Behind a dune valley of about 400 m wide, there is a second low dune row. The high failure probability of the first dune row of this transect is not expected to lead to any safety problems because this transect is outside the protected area.

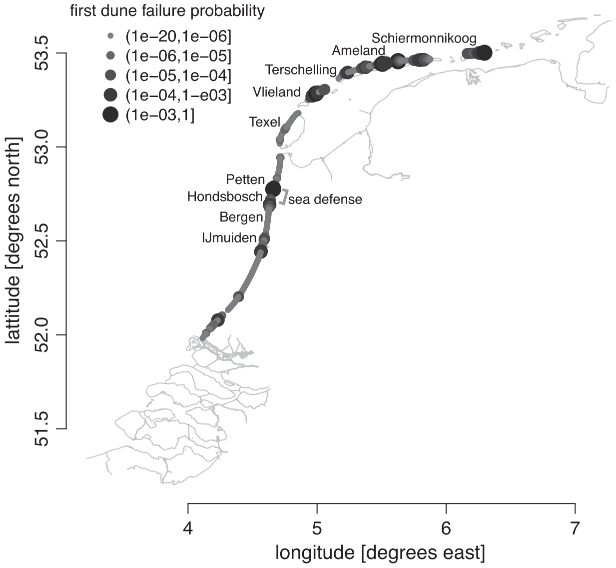

Fig. 5. Map of the locations with the probability of failure of the first dune row.

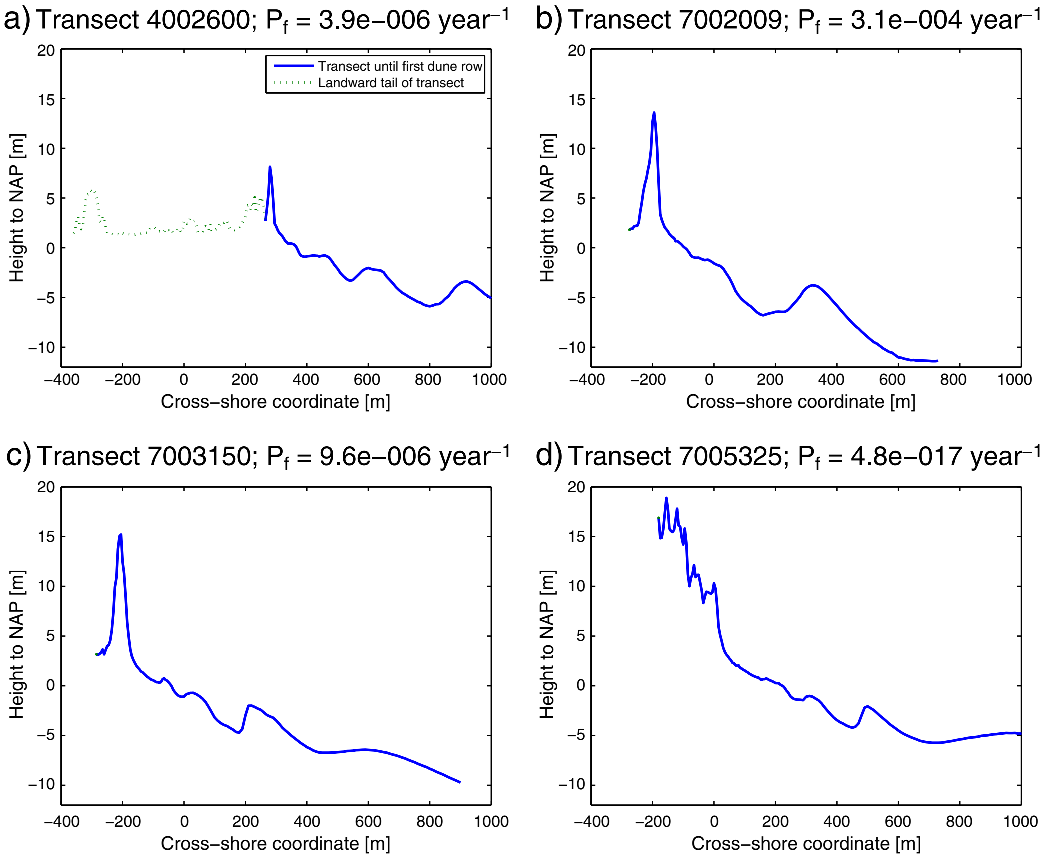

Fig. 6. Four examples of profiles with the calculated probability of failure (P_f) of the first dune row.

Just north of the Pettemer Sea defence are nine transects where the first dune row does not meet the normative safety level. One of these is depicted in panel b of Fig. 6. Fig. 7 shows the surrounding area in Google Earth, including the nine transects and an elevation map based on LIDAR data. The LIDAR data show that there are some relatively low areas in the second dune row. A proper assessment of the failure probability of this dune area is only possible with a 2D process-based model. The Pettemer Sea defence is one of the known weak spots of the Dutch coast (Ministeries VROM et al., 2006). The last big storm that affected the area was the storm of November

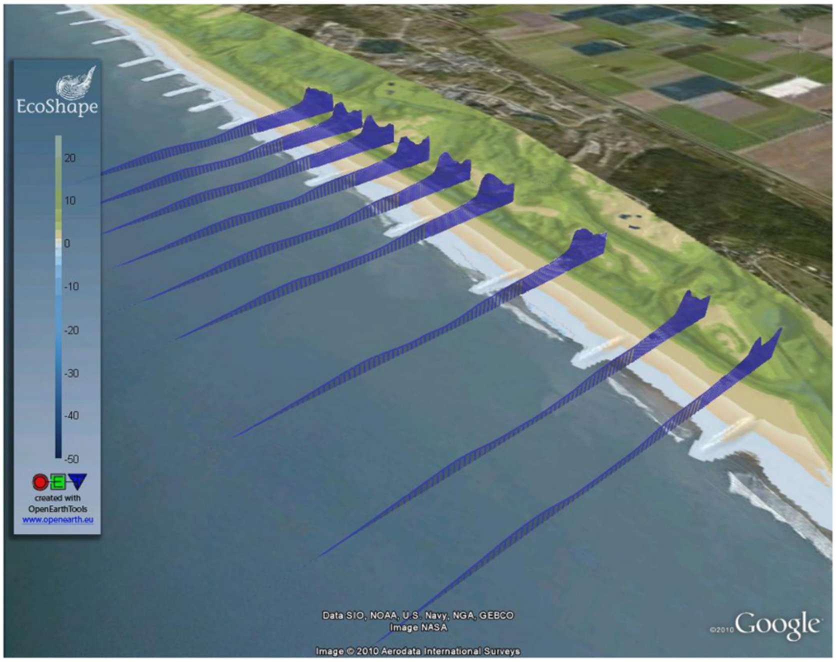

Fig. 7. A Google Earth view of the area just north of Petten. The transects (measured in 2008) where the first dune row does not meet the requirements are indicated.

2007, when the dunes were severely eroded. There are plans to increase the safety level by nourishments across the whole sea defence ranging from Petten to 6 km southwards.

A transect with a probability of failure of the first dune row around the normative safety level is located near Bergen. This dune reaches about 15 m above sea level but is relatively narrow. A relatively wide dune area is present at this location. For more insight in the situation after failure of this first dune row, detailed 2D process-based modelling is required.

The last example is a transect just North of the harbour entrance of IJmuiden where the first dune row is very wide and high (almost 20 m asl) and therefore it results in the smallest probability of failure.

4. Discussion

The research in this paper was done with the basic form of the computer model for safety calculations and the assumptions on probabilities of boundary conditions, as presently used in The Netherlands. The model has some limitations that need to be discussed.

4.1. Limitations of the method

4.1.1. Extreme boundary conditions

Failure is only possible when extreme conditions are imposed. The boundary conditions in this study are extrapolated further than for the regular safety evaluation. This decreases the precision of the boundary conditions and could also lead to conditions that are physically not realistic. This, however, plays mainly a role for relatively safe transects that “need” very extreme conditions to induce failure.

4.1.2. DUROS+ for extremer conditions

As mentioned in Section 1, the applied model is only developed for dune erosion. However, when inundation occurs due to erosion, at some stage also overwash starts to play a role. Also some extreme conditions for the occurrence probabilities are out of the validation range of the model, which has been validated for conditions around 1/100,000 per year storms.

4.1.3. DUROS+ for non-standard dunes

The DUROS+ model has been developed for the so-called reference profile. This is a cross-shore profile that is considered as more or less representative for the Dutch coast. The reference profile corresponds best with the transects at the Holland coast. It is not clear whether application of DUROS+ in the Wadden area, where the grain size is smaller and the profile slopes are milder, leads to realistic results (Deltares, 2008). Deltares is carrying out laboratory experiments to get more insight into dune erosion processes for mild sloped profiles.

The DUROS+ model is limited to the process of erosion. The dune erosion model does not account for some aspects like vegetation or hard structures. The safety calculations are carried out with a 1D model, using measured cross-shore transects with an alongshore spacing between 150 and 250 m. In areas which are non-uniform alongshore, the alongshore position of the transect could influence the failure probability. If the weakest location in a coastal section is in between two transects, the failure probability will be underestimated.

4.1.4. Limitations of the first dune row approach

The calculations presented in this paper are based on the JARKUS dataset. A transect is considered as failed when no dune body above the storm surge level is left in the first dune row. However, this does not automatically mean that the hinterland will flood, because there may be more dune rows, which were not included in the analysis. After the first dune row has failed other processes have to be taken into account. The problem becomes two dimensional behind the failed dune and should be modelled by a combined morphological and inundation model in at least 2 dimensions.

4.2. Selection of transects

As appears from Table 2, many of the available transects have not been included in the investigation. Two main reasons for not selecting these transects can be given. Firstly, the model used in its basic form is not developed for dealing with alongshore non-uniform coastal sections and hard structures. Secondly, boundary conditions in the southern part of The Netherlands are not readily available. To solve the first item, application of a process based morphodynamic model (such as Delft3D: Lesser et al., 2004; or XBeach: Roelvink et al., 2009) is a possible solution. The second item could be resolved by applying hydrodynamic models to simulate the boundary conditions for the dune erosion model and using Belgian measurement data for validation.

4.3. Failing transects

The islands that form the Wadden area are only partially defended by the primary sea defence. Of the 68 transects that have a first dune row failure probability higher than the normative safety level, 25 out of 45 of the Wadden transects are located in the area outside the primary sea defence. The 20 locations that are inside or very close to the primary defence area are located on the Wadden islands Schiermonnikoog, Ameland and Terschelling. Along the Holland coast 5 areas have been pinpointed as priority weak spots (Ministeries VROM et al., 2006) when accounting for sea-level changes and climate scenarios. Out of these 5 areas, only the Hondsbossche and Pettemer sea defences are near (just south) the area where nine transects are found of which the first dune row does not meet the normative safety level.

4.4. Validation

Since the majority of the failure probabilities are extremely low, validation with field data is difficult. The dune erosion model is calibrated and validated for a large number of laboratory experiments at different scales. Only for the largest probabilities of failure can the order of magnitude be related to observations in recent history. The largest probability of failure is 1/26 per year and is found at the tail of the island of Terschelling. In recent decades, overwash has been observed at the tails of some of the Wadden islands, so in this respect the order of magnitude of this probability of failure seems realistic. The largest failure probability along the Holland coast is of O(1e-3) per year. The fact that no failure of dunes has been observed on the Holland coast in the last century is from this viewpoint also realistic.

5. Conclusions

The aim of this paper was to present a resilience map of the first dune row of the Dutch Holland and Wadden coast using a fully probabilistic approach and to test the applicability of the DUROS+ model (van Gent et al., 2008).

The DUROS+ model in its most basic form was used to quantitatively assess dune resilience. The Monte Carlo method was used for the probabilistic investigation. Important research questions were (1) where can the DUROS+ model in combination with the fully probabilistic approach be applied along the Dutch coast? and (2) what is the alongshore variability of failure probability using this probabilistic approach?

Regarding the applicability of the method it can be concluded that the assumptions that underly the DUROS+ model in its most basic form result in the exclusion of a significant amount of transects from a fully probabilistic analysis. The Delta area was not considered because of insufficient information on boundary conditions for that area. About 50% of the transects in the Wadden area and 75% of the transects along the Holland coast passed the inclusion criteria for analysis. The excluded transects are found in areas with highly curved coastlines and coastlines containing hard layers or structures. Further analysis of the transects that were thus far excluded requires modification of the basic DUROS+ concept or the use of other more suitable model concepts. To enable broader coverage of failure probability assessment the use of a more generally applicable model for the remaining 40% of the coast is recommended.

Regarding the alongshore variability of dune resilience it can be concluded that at 45 transects of the Wadden area, the first dune row does not meet the normative safety level of $5 \cdot 10^{-5}$ per year. Twenty of these are not part of the primary sea defence and reflect the natural process of fresh dune rows building after nourishment. At 23 transects of the Holland coast the first dune row does not meet the normative safety level of $1 \cdot 10^{-5}$ per year. In all of these cases, however, more dune bodies are present landward of the first dune row. Proper safety assessment of these areas is only possible by applying a 2D process-based model.

Regarding the usefulness of the fully probabilistic approach, firstly, it can be concluded that this is the first time that actual failure probabilities for each of the transects along the Dutch coast have been calculated. This provides important additional information to the presently applied approaches (binary result: fail or safe). Secondly, it was demonstrated that developments in computing power and also the development of more sophisticated analysis routines and approaches indeed have made a fully probabilistic approach a feasible alternative to current deterministic and semi-probabilistic approaches. Thirdly, the main conclusion of the work presented in this paper is that the fully probabilistic approach provides valuable added insight with respect to the actual failure probability of transects. At the same time it is noted that the current dune erosion model in its most basic form is not able to cover all of the Dutch coast. To extend the coverage of the analysis of failure probabilities along the Dutch coast it is recommended to (1) involve more process-based model concepts that can cope with the situations DUROS+ cannot, and (2) to expand the currently available data on boundary conditions.

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