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Breaching of dunes

Preliminary quantification of related mechanism and assessment of the probability of occurrence

Report on desk study

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Title

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Preliminary quantification of related mechanism and assessment of the probability of occurrence

Abstract

In order to yield an expression for the probability of breaching, in this desk study the mechanism that play a role in the initiation of breaching of dunes are described and preliminary quantified. In addition a pragmatic description for the assessment of the combined probability of breaching is elaborated. From this it was concluded that although the transition between negligible probability and assured failure is relatively gradual, the present approach using the so-called 'grensprofiel' seems adequate.

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Alkyon
Hydraulic Consultancy & Research

postal address
PO Box 248
8300 AE, Emmeloord
The Netherlands

visiting address
De Deel 21, Emmeloord
tel : +31 527 62 09 09
fax: +31 527 61 00 20

e-mail
info@alkyon.nl
internet
http://www.alkyon.nl

Executive's summary

In order to assess the risk of flooding of a polder, the probability of an individual flooding event has to be determined. The goal of this desk study is to derive a preliminary expression for the assessment of the probability of breaching of a dune.

The critical event, the development of an initial gully which yields further increase of both breach width and depth, could be due to a number of mechanisms. In this report, the most relevant mechanism playing a role in the initiation of breaching are described focusing on the effects of wave-induced overwash, wind-induced sediment transport and geotechnical failure respectively.

For each individual mechanism, the probability of failure has been assessed by development of a conceptual model or interpretation of the results of numerical models assuming a specific initial geometry of the residue of the dune that remains just at the top of the surge (the so-called 'rest dune') and a limited time period for this mechanism to remove this.

Based on this, the conditional probability of breaching has been defined as a function of the driving hydraulic or meteorological conditions and the remaining dune geometry for each individual mechanism.

From mutual comparison it was found that the effects of wave overtopping yielding overwash-related erosion of the dune crest and the erosion due to wind seem to be the most dominant mechanism. Breaching due to local geotechnical failure of the 'rest dune' seems less likely.

For a relative low 'rest dune', the impact of wave overtopping seems rather dramatic. Almost independent of the width of the 'rest dune', the combination of scraping of slices from the dune top by waves overtopping the crest and the backward (seaward) migration and extension of the gully in the landward slope due to concentrated discharge of the overtopping water, yield a fast increasing reduction of the volume of the dune. Consequently, the probability of removing the complete 'rest dune' mainly depends on the initial level of the top of the 'rest dune' relative to the critical water level (storm surge level).

In case of erosion due to wind-induced sediment transport, the characteristic erosion rate of the 'rest dune' is associated with the surge-related wind speeds, this using the combined dependencies between storm surge set-up and offshore wave height and between wave height and wind speed respectively. From further elaboration it was found that at higher surges the probability of eroding a 'rest dune' of fixed dimensions by wind increases.

Using the present so-called 'grensprofiel'-approach, the minimum height of the 'rest dune' with respect to the water level is related to the offshore wave conditions by definition, this in fact assuming a limited wave overtopping rate. Consequently, for locations along the coast with more severe conditions the 'rest dune' must extend higher above the surge level than for locations with less severe conditions. As a consequence, the probability of wash-over related failure of the 'rest dune' reduces significantly for severe conditions.

According to the 'grensprofiel'-approach, the dune geometry is determined by the crest height and a fixed crest width in which the crest height is defined in relation to the significant wave height at open sea.

According to this definition, the dune volume increases with increasing wave heights. However, for severe wave conditions the wind speed increases also. Since sediment transports due to wind are related to the wind speed to the third power, with increasing wave heights the erosion capacity of wind increases more than the dune volume, which makes wind induced erosion more dominant for more severe weather conditions.

Summarising, it is concluded that:

- the transition between negligible probability of failure and assured failure is relatively gradual;
- the probability of failure for a relatively wide 'rest dune' is not always negligible;
- for an adequate description of the probability function the combined effect of wave-induced overwash and wind should be taken into account;
- even for more extreme conditions, the probability of breaching seems to be slightly overestimated by the present 'grensprofiel'-approach.

Consequently, it is recommended to:

- apply a gradual transition for the probability of breaching in order to assess the risk of inundation of a polder;
- formulate a pragmatic relation for this transition taking into account the combined effect of wave-induced overwash and wind effects.

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1 Introduction

1.1 Background

In order to assess the risk of flooding of a polder the probability of an individual flooding event has to be determined. Within this desk study a preliminary expression for the assessment of the probability of breaching of a sandy dune has been formulated.

On behalf of Working group C of the Technical Advisory Committee on Water Defences, Rijkswaterstaat/DWW commissioned Alkyon Hydraulic Consultancy & Research to carry out a desk study to provide information on the processes involved and the probability of occurrence of initial breaching of a sandy dune. This research was carried out within the framework of the DWW-project TAWC-DOORBRAAK.

The major results have been discussed with Prof. Dr. E.W. Bijker (advisor of Alkyon on morphological matters) as well as a commission of Working group C of the Technical Advisory Committee on Water Defences, viz.:

- Dr. J. van de Graaff (Delft University of Technology);
- Mr. W. Leeuwestein (DWW);
- Mr. J.T.M. van der Sande (Waterschap Zeeuwse Eilanden),

in which Mr. W. Leeuwestein acted as the representative of Rijkswaterstaat.

The study was carried out between October 1997 and February 1998 by Mr. M.C. Onderwater and Dr. H.J. Steetzel. In addition Dr. Z. Chen (probability approach) and Mr. D. Hurdle (wave statistics) contributed to parts of the study. Information on geotechnical aspects have been provided by Mrs. B. Lassing (Rijkswaterstaat/DWW).

1.2 Objective

The first objective of the study is to provide quantitative insight in the mechanisms that play a role in the initiation of breaching of a sandy dune or dike and subsequent inundation of a polder. Next the assessment of the probability of breaching using a pragmatic model which takes into account the most important parameters, is studied.

1.3 Scope of work

1.3.1 Description and quantification of related mechanism (Phase A)

Initially, based on a brief literature review on other related mechanism yielding initial breaching, the description and quantification of the three most governing mechanism is elaborated, viz.:

- Description and quantification of dune failure due to wave-induced overwash;
- Description and quantification of dune failure due to wind-induced erosion;
- Description and quantification of geotechnical failure.

1.3.2 Assessment of the probability of breaching (Phase B)

With respect to the assessment of the probability of breaching the following activities are presented in Phase B of this study:

- Mutual comparison between conditional breaching probability for individual mechanism;
- Subsequent assessment of a normative shape of the conditional probability of breaching for given dimensions of the residual profile;
- Assessment of the probability of occurrence of a specific geometry and dimensions of the residual profile based on the application of a dune erosion model;
- Assessment of the combined probability;
- Subsequent comparison with these results with the state-of-the-art approach using the so-called 'grensprofiel';
- Recommendations on the assessment of a pragmatic model for the assessment of the probability of breaching as a function of the most dominant forcing parameters.

2 Basic assumptions and approach

2.1 Introduction

In the process of dune breaching, three different stages can be distinguished:

- The erosion of the actual dune due to continuous, wave-breaking induced erosion of the dune face -> the regular dune erosion process;
- The formation of a small initial gully perpendicular to the dune axis, yielding a continuous inflow of water towards the polder -> the actual breach initialisation;
- The increase of the dimensions of this initial breach yielding a widening breach and influx of large amounts of water -> the process of breach growth and subsequent inundation of the polder.

Based on related research and modelling activities, the available knowledge with respect to former three processes is remarkable different. This hold also for the capability of quantifying the most dominant parameters playing a role in these processes.

With respect to the modelling of the process of dune erosion and the quantification of the expected recession of the dune face a number of well-validated models are available (e.g. DUINAF and DUROSTA) [Steetzel, 1993].

In order to predict the consequences of a dune break-through (the third item), in 1991 a TAW-research-programme was formulated with the objective to enlarge the insight in the process of breach development and to be able to quantify the breach widening rate. The validation of the specially formulated BREACH-model to predict the evolution of a breach is currently being finalised [Steetzel and de Vroeg, 1998].

The basic assumption made in this breach study was that at the start of the actual breaching process an initial (small) gully is present already and consequently a steady flux of water could pass the dune crest in landward direction. The formation of the initial gully was not studied; it just was assumed to exist.

Until now, the second item, the actual breaking-through of the dune has not been studied in any detail. As discussed in Section 1 of this report the assessment of the probability of breaching is of crucial importance in the process of risk analysis since the actual risk of inundation is basically computed from the product of the probability of a breaching and the (financial) consequences of inundation.

2.2 Assumptions

2.2.1 Introduction

In order to quantify the probability of failure, some basic assumptions will be discussed in the following dealing with the initial gully and the limited time interval which is available to deepen and widen the initial gully.

2.2.2 Initial gully

For the further elaboration of the probability of failure of a dune it is assumed that the actual start of the breach widening process will be the direct result of the presence of an initial gully.

This fundamental assumption is based on experiences obtained during the breach-research programme. From these it was found that after an initial gully is 'active', the process of further breach development is unavoidable. Depending on the dimensions of the initial gully and especially the level of the bottom of the gully with respect to the outer water level, the actual start of the predominant widening stage of the breach evolution process (see [Steetzel and de Vroeg, 1998] for more details) takes place within a couple of minutes.

The formation of an initial gully yields failure of the dune by definition. A gully is (in this respect) meant to be a channel in the dunes with a bottom level below mean sea level.

The next problem is to assess the probability of any event (or combination of events) that locally results in a situation where the minimum dune level is well below the outer water level. This probability is in fact the summation of a series of individual chances as elaborated in more detail in Section 2.3.

2.2.3 Time interval

Whether a specific 'rest dune' (say a specific volume) succeeds to withstand the 'acting forces' depends in general terms on:

- the dimensions of the 'rest dune' (volume);
- the forces (erosion rate);
- the available time interval.

The formation of an initial gully must be the result of some kind of erosion process, say wave- or wind-induced transport. In both cases this erosion process can be schematised as a specific erosion rate, momentarily expressed in losses of material from the 'rest dune' per unit of time.
The total integrated amount of erosion will strongly depend on the length of the time interval during which these 'forces' are present.

Since for the present study the impact of extreme storm surges is considered, the shape of the surge close to its maximum has to be taken into account. Based on the experience that for extreme conditions the time-scale of the storm set-up component of the surge (say 1 to 3 days) is relatively long compared to the time-scale of the normal astronomical variation, the shape of the surge near the maximum is more or less invariable (near-triangular) independent of the extremity of the surge itself (see also [De Valk and Steetzel, 1998]).

The erosion processes (viz. 'normal' dune erosion process and erosion of a 'rest dune') near the surge maximum are rather complex, since all acting parameters evolve in time (e.g. the impact of the 'acting forces' will depend strongly on the actual water level). In order to describe and to try to quantify the impact, it is assumed that an adequate estimate of this impact can be obtained using the maximum surge conditions only.

In order to quantify the characteristic duration of such an invariable impact, a number of considerations have to be taken into account, such as:

- Not only the very short period in which the water level is at its very maximum should be taken into account;
- The effect of the erosion processes just before the surge maximum have to be taken into account also;
- Taking into account the typical duration used in the dune erosion test series (about 5 hours) is probably too long since after about 2 hours after the maximum of the surge the outer water level decreases relatively fast and the breach-growth process might not be able to advance (Ref. the second Zwin-test as described in [Steetzel and De Vroeg, 1998]).
- Consequently, the second part of the former interval is not as relevant.

Probably, a sound time interval will be in between two former extremes. A pragmatic, rather safe approach is just to take a 3-hours interval to be adequately characteristic, in which the first two hours refer to the 'prior-top' erosion and the third hour refers to the situation around the maximum.

Consequently, for the present elaboration initially a constant time interval of 3 hours has been used as the characteristic duration in which the maximum 'acting forces' are allowed to erode the 'rest dune', yielding a safe starting point (pessimistic boundary). Since this assumption is rather crucial, an additional elaboration is provided using a 1-hours interval.

The probability of a specific 'rest dune' to withstand the 'acting forces' now only depends on:

- the initial dimensions of the 'rest dune' (say volume);
- the actual 'acting forces'.

For a specific dimension of the 'rest dune' and a specific 'force' (e.g. wave-attack), the probability of failure can now be assessed from the probability of the 'acting force' to erode the 'rest dune' (to remove its volume) within the 3-hour and 1-hour interval as elaborated in more detail in Section 2.3.

2.3 Approach

2.3.1 Introduction

Basically, the probability of failure (or in fact the formation of an initial gully) for a specific condition is assessed from the mutual product of:

- the probability of a specific rate of dune erosion yielding a specific position of the dune face (position R as indicated in Figure 2.1) denoted as p_R, and
- the conditional probability of failure given this dune face position, denoted as $p_{f|R}$

The related equation is:

$$p_{f,R} = p_R \cdot p_{f|R}$$

in which the two right-hand probabilities will be elaborated in the following.

2.3.2 Probability of dune face regression

The probability of the actual dune face regression refers to the position of R as shown in Figure 2.1.
The critical position R_{cr} refers to the location of the dune face for which the so-called 'grensprofiel' just fits in the landward part of the 'rest dune'. The probability of a specific position to be reached reduces in landward direction and depends on both the acting hydraulic conditions as on the strength of the dune in terms of volume, height and sediment characteristics. In Figure 2.1 a qualitative example of this probability function is shown.

The position $R = R_{\max}$ refers to the situation in which landward no dune material above storm surge level is present anymore. The probability for which this position is achieved equals the lowest minimum probability of failure, in which the effect of additional failure mechanism are not taken into account.

2.3.3 Conditional probability

The probability for the erosion of the total 'rest dune' reduces with increasing distance from the back of the dune, say increasing distance between R and $R_{\max}$.
A quantitative example of this conditional probability is presented in Figure 2.2.

The actual shape of this function depends on the failure mechanisms taken into account. For large distances ΔR this conditional probability reduces towards $p_{f,R} \downarrow 0$, whereas for $\Delta R \downarrow 0$ failure becomes unavoidable, thus $p_{f|R} \uparrow 1$ by definition.

2.3.4 Combined probabilities

The total probability of failure P_F (the erosion of the 'rest dune' within a fixed time interval assuming invariable hydraulic/meteorological conditions) can be assessed from the summation of individual failure contributions according to:

$$P_F = \int_{R='d'}^{\infty} p_R \cdot p_{f|R} \, dR$$

In this expression all possible positions of R have to be taken into account in between the front of the dune $R = 'd'$ and the back of the dune and even beyond the most landward position $R = R_{\max}$.
Subdivision of former integral into two contributions for $R < R_{\max}$ and $R > R_{\max}$ according to:

$$P_F = P_{F(R<R_{\max})} + P_{F(R \geq R_{\max})}$$

yields:

$$P_F = \int_{R='d'}^{R_{\max}} p_R \cdot p_{f|R} \, dR + \int_{R=R_{\max}}^{\infty} p_R \cdot p_{f|R_{\max}} \, dR$$

Since the conditional probability of failure equals 1 for $R \geq R_{\max}$:

$$p_{f|R_{\max}} = 1$$

the former expression can be simplified to:

$$P_F = \int_{R='d'}^{R_{\max}} p_R \cdot p_{f|R} \, dR + \int_{R=R_{\max}}^{\infty} p_R \, dR$$

Figure 2.3 provides a schematic representation of former expression. The integrated probability of failure refers to the shaded area in the lower panel.

Since the conditional probability of failure for $R \geq R_{\max}$ (the second part of the expression) equals 1 by definition:

$$p_{f,R_{\max}} \equiv 1$$

the second contribution can be simplified to:

$$P_{F(R \geq R_{\max})} = \int_{R=R_{\max}}^{\infty} p_R \, dR$$

In fact this expression denotes the probability of exceedance of the maximum position $R = R_{\max}$:

$$P_{F(R \geq R_{\max})} = P_{o\,(R=R_{\max})}$$

and is only a part of the total probability of failure.
The objective of this study is to enlarge the insight in the first contribution.

2.3.5 Pragmatic formulation

Within this study a pragmatic approach is aimed for in which the actual probability of failure can be assessed from the second contribution directly.
So starting with:

$$P_F = \int_{R='d'}^{R_{\max}} p_R \cdot p_{f|R} \, dR + P_{o\,(R=R_{\max})}$$

or in modified form:

$$P_F = \left(\frac{\int_{R='d'}^{R_{\max}} p_R \cdot p_{f|R} \, dR + P_{o\,(R=R_{\max})}}{P_{o\,(R=R_{\max})}} \right) P_{o\,(R=R_{\max})}$$

yielding a simplified expression according to:

$$P_F = C_F \; P_{o\,(R=R_{\max})}$$

in which the C_F-factor refers to the relative magnitude of the total and the minimum probability of failure.

$$C_F = \frac{\int_{R='d'}^{R_{\max}} p_R \cdot p_{f|R} \, dR + P_{o\,(R=R_{\max})}}{P_{o\,(R=R_{\max})}}$$

This factor will depend on the shape of the dune as well as the hydraulic and meteorological conditions, say:

$$C_F = F\{\ldots\}$$

It should be noted that in the present 'grensprofiel'-approach the probability of failure is computed from the probability of exceedance of the critical position landward of the most landward situated 'grensprofiel'.

$$P_F^* = P_{o\,(R=R_{cr})}$$

If the definition of the 'grensprofiel' would be correct and thus

$$P_F^* = P_F$$

a first estimate of the actual magnitude of the failure correction factor can be assessed from:

$$C_F = \frac{P_{o\,(R=R_{cr})}}{P_{o\,(R=R_{\max})}}$$

Based on experience achieved with the use of the DUROS-model a change in the frequency of exceedance of the position of point R with a factor 0.1 yields a landward shift of about 10 to 15 m. Given the width of a typical 'grensprofiel' of about 10 m, the magnitude of the failure correction factor is about 10 in this case.

3 Mechanism

3.1 Introduction

Based on an additional literature review three of the most dominant processes have been described in more detail, viz.:

- Wave-induced overwash;
- Wind-induced erosion;
- Geotechnical failure.

Based on a preliminary assessment of the related mechanism, it was concluded that the first process, erosion due to overwash processes appeared to be one of the most dominant mechanism. Since this process has not been extensively described in literature (see e.g. [Kobayashi et al. 1996]), some attention has been paid to the formulation of a simple overwash model as described in more detail in Appendix A, based on [Steetzel, 1987].

Since this elaboration 'needs' wave conditions as an input parameter, firstly a fixed relation between a surge event (with a specific surge level and an accompanying yearly frequency of exceedance) and the offshore wave conditions has been defined. From this surge level related offshore wave climate, a series of characteristic wave conditions has been elaborated. Next, every individual offshore mean wave condition is translated to a nearshore location and split up in a distinct number of individual waves, yielding a series of individual overtopping events.

In case of the erosion due to overwash, the characteristic erosion rate is assessed from the summation of individual overtopping events, taking into account the frequency of occurrence of individual waves.

For the assessment of the wind-induced erosion use has been made of the research activities carried out for the SCOPE/SAFE-model as described in [Steetzel, 1995] and [Van Boxel and Arens, 1997]. In order to define the characteristic wind velocity, a relation between wind velocity and wave height have been defined.

Specific information on the geotechnical failure was provided by Rijkswaterstaat/DWW. They applied a numerical model to assess the probability of failure for a series of specific 'rest dune' shapes.

3.2 Wave uprush/overwash

3.2.1 Introduction

When waves approach the shore the wave height reduces due to wave breaking and bottom friction. However, on a small rest dune these waves might yield significant overtopping and consequent erosion due to overwash.

3.2.2 Approach

In this section overwash of waves over a small dune is investigated by developing a conceptual model for simulating overwash and the resulting sediment transports for a small dune (for details see Appendix A).
Since overwash due to overtopping waves has not been described in literature, the process of overtopping is described by investigating the relevant processes of importance for overtopping. These processes are:

- approach of offshore waves over a typical erosion profile;
- wave run-up on a steep slope;
- mechanism of overtopping waves;
- erosion due to overtopping waves.

When the processes of importance during overwash are known better, a conceptual model is formulated for giving an indication of the amount of erosion, which is caused by overtopping waves. Here, the mechanisms of importance are discussed shortly. In Appendix A the model is described in more detail.

For giving an indication of the probability of breaching due to overwash, a probability distribution for offshore wave heights is used. Both mechanisms and probability distributions are then combined for deriving the probability of breaching due to overwash.

3.2.3 Wave transition

When a wave approaches from deep water, it will reduce in height because of bottom friction and breaking. At the toe of the dune the wave height will then be reduced significantly. For computing the overwash, caused by a specific wave condition, the local wave height at the toe of the dune is used. This local significant wave height is assumed to be a fraction of the offshore significant wave height.

3.2.4 Wave run-up

For waves approaching a beach with a vertical dune, the Shore Protection Manual gives an indication of the run-up. In this formulation a beach slope in front of the dune of 1:10 is used (see Figure 7-9 in [CERC, 1984]).

The local wave height at the toe of the dune together with the resulting run-up are calibrated by using measurement data from experiments reported in M1819-II [Delft Hydraulics,1983].

3.2.5 Wave overtopping

When the run-up of a wave is larger than the crest height, it means that a volume of water will continue its way over the dune crest. When passing the dune, this volume of water will also take sediment particles with it and this will result in erosion and thus a reduction of the crest height. When the complete dune has been eroded, this will lead to breaching.

3.2.6 Results from computations

The above described mechanisms are used for developing an indicative model for describing the process of breaching due to overwash. The model simulates the process from the approaching waves until the resulting erosion, caused by this wave.
The model continues its computations until the dune has been completely eroded. The model is described in more detail in Appendix A.

As an example in Figure 3.1 the resulting crest height and width are shown as a function of time. At time t= 0 the dune has the following geometries:

- crest height $H_{crest} = 4$ m;
- crest width $B_{crest} = 12$ m
- offshore wave height $H_{sig,0} = 8$ m.

As can be seen from this figure, near the end of the simulation the crest height reduces very fast. Because of the low crest, large amounts of water flow over the dune crest which yield to accelerated erosion. The crest width increases in time, this because of the trapezium-shaped dune; when H_{crest} decreases, B_{crest} will increase.

3.2.7 Probability of offshore wave heights

The model as presented in the previous section is based on the offshore significant wave height. For giving an indication of the probability of breaching because of overwash, the probability of occurring wave heights on deep water has to be known for severe storm surges. Here, this probability distribution is discussed.

Probability of wave heights during storm surges

During surge levels between NAP +3m and NAP +7m, expected wave heights can be fitted into a conditional normal probability distribution [Van de Graaff,1986]. For example for Hook of Holland the normal conditional probability distributions is described by (see also Figure 3.2):

$$\mu H_{sig} = 4.82 + 0.6h - 0.0063(7.0-h)^{3.13}$$
$$\sigma H_{sig} = 0.60 \text{ m}$$

where h is the storm surge level above NAP.

Probability distribution of individual maximum surge levels

Based on extrapolation of historical data the Deltacommittee (1960) presented curves for frequency of exceedance of maximum storm surge levels for several stations along the Dutch coast following an exponential distribution:

$$P(\underline{h} > h) = \alpha \exp(-\beta h)$$

As an example the frequency of exceedance of surge levels for Hook of Holland is given in Table 3.1.1 (see also Figure 3.2).

Surge level [m+NAP]	Frequency of exceedance per year	Return period [years]
3	$1 \cdot 10^{-1}$	10
4	$4 \cdot 10^{-3}$	250
5	$2 \cdot 10^{-4}$	5.000
6	$1 \cdot 10^{-5}$	100.000
7	$5 \cdot 10^{-7}$	2.000.000

Table 3.2.1 Probabilities of storm surge levels at Hook of Holland.

3.2.8 Probability of breaching due to overwash

Breaching will have to take place in a short period of time, where there is a maximum water level. It is assumed, that this maximum water level will have a duration of 3 hours. After this period of time it is assumed that the water level has decreased so far, that there will be no critical situation for breaching anymore. This means, that breaching will occur if a small rest dune is eroded by overwash within a time period of 3 hours. As for example can be seen from Figure 3.1, an offshore wave height of 8 m needs approximately 8 hours for eroding a rest dune with dimensions H_{crest} = 4m and B_{crest} = 12m. This means that breaching will not take place in this case. However, smaller rest dune geometries may show breaching during these wave conditions.

For giving an indication of the probability of breaching during a storm surge with level h, the following method has been used:

- The time, needed for eroding a rest dune, has been computed for various values for H_{crest}, B_{crest} and $H_{sig,0}$;
- For each combination of H_{crest} and B_{crest} the wave height H_{sig0}, which leads to breaching in 3 hours time, has been extracted from the computational data;
- Given a storm surge level h, the probability of exceedance of this specific wave height $H_{sig,0}$ is derived following Section 3.2.7 (see also Figure 3.2);
- The probability of exceedance of this specific wave height $H_{sig,0}$, which leads to breaching of a rest dune with dimensions H_{crest} and B_{crest}, is also the probability of breaching of the rest dune.

In Figure 3.3 the significant wave height on deep water, which is needed for eroding a rest dune with a specific dune geometry in a period of 3 hours, is shown as a function of H_{crest} and B_{crest}. When for example assuming a rest dune with H_{crest} = 3 m and B_{crest} = 3 m, from Figure 3.3 it can be seen that a significant wave height of 7.5 m is needed for eroding this rest dune in 3 hours time.

As can be seen from this figure, for low crest heights the influence of the crest width is limited. Because of the large amount of water flowing over the rest dune, it does not matter whether there is a large crest width or not. For large crest heights however the influence of the crest width is much larger.

Given a surge level h, the wave heights as presented in Figure 3.3 all have a specific probability of exceedance. This probability distribution is given in Figure 3.2. When the wave height $H_{sig,0}$, appertain to a rest dune with dimensions H_{crest} and B_{crest}, is exceeded, it means there will be breaching of this specific rest dune. This means, that the probability of breaching due to overwash equals the probability of exceedance of $H_{sig,0}$. In Figure 3.4 this probability of breaching is shown by multiplying the wave heights of Figure 3.3 with the probability of exceedance from Figure 3.2. This is done for surge levels from NAP +3 m to NAP +7 m.

As already indicated, a time period of 3 hours for breaching can be seen as a upper limit and the peak of the storm surge where breaching will take place will probably be shorter. As a lower limit the same computations as described above are done for a time period of 1 hour. The resulting probability of breaching is shown in Figure 3.5.

3.3 Wind-induced erosion

3.3.1 Introduction

When wind blows over an erodable bed, due to shear stresses near the bed sediment particles will be displaced by the wind. Because of this erosion the dune volume will decrease and eventually this could lead to breaching. In this section an elaboration of the probability of breaching due to wind transport will be given.

3.3.2 Approach

The wind model HILL_MDL is used for computing the wind field over a small dune and the eroding capacity of wind is derived from the SCOPE-model for sediment transports. The probability of exceedance of specific wind speeds is obtained from available storm data and probability distributions of surge levels and occurring wave heights as mentioned in Section 3.2.7

3.3.3 Transport capacity

When a wind flows along a dune cross section, the wind field will not be constant. Due to changing bed roughness and bed level, the flow distribution near the surface will change. In order to elaborate the influence of a small dune on the wind flow distribution, the HILL_MDL-model is used.
The transport capacity due to wind is then calculated by using the transport formulation used in the SCOPE/SAFE-model.

The HILL_MDL model

When wind flows over a flat surface, the lower part of the wind field can be schematised using a logarithmic function:

$$u(\hat{z}) = \frac{u_*}{\kappa} \ln\left(\frac{\hat{z}}{Z_0}\right)$$

However, because of obstacles as dunes and varying bed roughness, this wind field will not be constant over a dune cross section. Also near the bed, where transports will take place, the wind field will differ and can therefore not be assumed constant. This changing wind field is modelled in the numerical model HILL_MDL.

For a given wind field, set by U_{10}, the HILL_MDL model computes the wind field along a cross section for several levels above the surface. Also the shear stress velocity u_*, which is used for transport computations, is computed along the dune cross section.

The SCOPE/SAFE-model

The SCOPE-model computes the sediment transports due to wind along a cross section. An important parameter during these computations is the shear stress velocity u_*. When a wind field approaches a dune formation, the vertical distribution of the wind profile will change because of changing bed roughness and changing bed levels along the dune cross section. Within SCOPE-model the shear stress velocity u_* is derived from the bed roughness only and the effect of changing bed levels is not taken into account.

Assuming a reference-value for the shear stress velocity above sea, $U_{*,ref}$, the amplification factor A_{u*} is defined as:

$$A_{u_*} = \frac{u_*(x)}{u_{*,ref}}, \text{ where } \quad u_{*,ref} = u_*(x_0)$$

This factor gives a measure of the shear stress velocity along the cross-shore profile and is independent of the actual magnitude of the wind speed. In Figure 3.6 a comparison is provided between the amplification factor of the computed shear stress velocity of HILL_MDL and SCOPE for a typical residual profile. As can be seen from this figure, contraction of flow lines, as described by HILL_MDL, on top of the dune results in an average shear stress velocity, which is about 25% higher than the shear stress velocity for a spatially invariant wind field as used in the present version of the SCOPE-model. Since the sediment transports are proportional to the third power of this shear stress velocity, it means that transports will be a factor 2 higher when using the computed shear stress velocity from HILL_MDL.

In Figure 3.7 occurring transports as function of the wind speed are shown. For computing these transport two factors have been applied:

- a factor 2 has been applied for the effect of contraction of flow lines over a small dune;
- the transport capacity of wet sand is lower than that of dry sand. Therefore a factor 1.35 is applied on the threshold velocity where transports by wind start to occur [Arens, 1994].

As can be seen from this figure, gusts with very high wind speeds will probably give large transports. However, because these gusts have a relative small time scale, the effect on the total amount of transport will be limited.

3.3.4 Wind velocity probability distribution

Because not very much is known of occurring wind speeds, probability distributions for occurring wave heights and storm surges are used for investigating the probability distribution for wind speeds.

Relation wind speed -wave height

Not very much is known of occurring wind speeds during severe storm conditions. For giving an indication of wind speeds during a storm, 132 storms from NESS-data for ELD have been analysed. When a comparison is made between occurring wind speeds and hourly-averaged wave heights, there seems to be some relation, as can be seen in Figure 3.8.

Occurring wind speeds are assumed to be distributed following a two-parameter Weibull-distribution:

$$p(U_{10} > \overline{U} | H_{sig}) = 1 - \exp\left(-\left(\overline{U} - a\right)^{b}\right)$$

where:

U_{10}	hourly-averaged wind speed at 10 m above the surface expressed in m/s
H_{sig}	significant wave height in m
a, b	additional parameters

Both a and b have been introduced in order to introduce the effect of the significant wave height. From curve fitting the following descriptions for a and b were elaborated:

$$a = 4.8 + 3.3\,H_{sig}$$
$$b = 1.7 + 1.3\,H_{sig}$$

Probability distribution for wave heights during storm surges

The same probability distribution as mentioned in Section 3.2.7 is used.

Probability distribution for storm surges

The same probability distribution as mentioned in Section 3.2.7 is used.

Total probability distribution for wind speed U_{10}

The wind speed U_{10} is given for each wave height H_{sig} at deep water following a Weibull-distribution. This probability distribution is valid for a specific wave height and storm surge level. The following steps lead to a probability distribution of wind speeds during a given storm surge level:

- Multiply the conditional Weibull-distribution for wind speeds by the probability of exceedance of wave height H_{sig} (Section 3.2.7);
- The probability of exceeding wind speed U_{10} during a storm surge with level h is then obtained by integrating this multiplication for all values of H_{sig}.

The total probability distribution of occurring wind speeds during a storm event with surge level h is then given by:

$$p(U_{10} > \overline{U} | h) = \int_{H_{sig}=0}^{\infty} p(U_{10} > \overline{U} | H_{sig} | h) \cdot p(H_{sig} > \overline{H} | h)\, dH_{sig}$$

3.3.5 Probability of breaching due to wind-induced erosion

In the previous section the probability of exceedance of wind speeds have been obtained. The probability distribution of dune erosion due to wind induced transport is then obtained by multiplying this probability distribution by the transport capacity as a function of the wind speed U_{10} (see Figure 3.7).

By doing this a probability distribution is obtained, which gives the probability of exceedance of wind induced transport during a storm surge with level h. This is shown in Figure 3.9.

From this figure the probability of breaching can be obtained. This is illustrated with an example:

The following case is assumed:
- a crest height H_{crest} of 4 m;
- a crest width Bcrest = 3 m;
- storm surge level h = NAP +6 m.

For breaching of this dune a volume of 30 m^3 per metre dune has to be eroded. If this volume is eroded in 3 hours, the transport capacity of wind will be 10 m^3/hr. From Figure 3.7 it can be seen that a wind speed of 35 m/s will give such transport capacity. Given a surge level of NAP +6 m, the probability of a transport capacity of 10 m^3/hr (and therefor the probability of breaching) is approximately 5% (see Figure 3.9).

In Figure 3.10 the probability of breaching is shown for all combinations of H_{crest}, B_{crest} and h. This is done by summarising the information from Figure 3.7 and 3.9.

As already indicated, a time period of 3 hours for breaching can be seen as a upper limit and the peak of the storm surge where breaching will take place will probably be shorter. As a lower limit the same computations as described above have been carried out for a time period of 1 hour. The resulting probability of breaching is shown in Figure 3.11.

3.4 Geotechnical failure

3.4.1 Introduction

In addition to the erosion processes, described in the previous sections, there is also a possibility that the small rest dune will fail because of geotechnical instabilities. This means, the forces on the dune cannot be resisted by shear stresses inside the dune. The dune will then breach by sliding off along a circle. In this section the mechanism will be explained and the probability of failure due to geotechnical instabilities will be discussed.

3.4.2 Approach

Unlike the failure mechanisms in the previous two sections, geotechnical failure of a dune is not set by the weather conditions at sea. Failure will occur when friction inside the dune is smaller than the forces along a slide circle. For Dutch dikes a common criteria for safety is the ratio between resisting forces and forces which yield failure. When this safety factor is higher than 1.7 for all possible slide circles through the dike cross section, the dike is assumed to be stable.

For different rest dune geometries, the critical slide circle has been assessed with the computer program MPROSTAB and on basis of the safety factors of these slide circles an indication is given of the possibility of breaching due to geotechnical failure.

3.4.3 Probability of geotechnical failure

For 4 different dune geometries (see Table 3.4.1) the probability of breaching due to geotechnical failure is obtained by computing the safety factor for the specific dune geometry. Within these computations it is assumed, that the cross-section of the rest dune is full of water. This is justified since there will be probably wave overwash and rainfall during a storm surge.

Case	Description	Hcrest [m]	Bcrest [m]	Level hinter-land [m-wl]
1	Steep dune with low hinterland	5	3	6
2	Low dune with low hinterland	3	3	6
3	Low dune with high hinterland	3	3	3
4	High an wide rest dune	5	10	6

Table 3.4.1 Dune geometries for probability of geotechnical failure.

In Figure 3.12 the definition of the dune parameters are shown. Only slide circles are taken into account, which result in instantaneous breaching. A few examples of slide circles are shown in Figure 3.12. A slide circle through points B and D will probably give the largest probability of failure. This slide circle is relative steep in comparison to a slide circle through for example B and C and has no support of material at the landward side of the dune as in case of a slide circle through A and E.

The safety factor of the rest dunes with a slide circle through B and D is shown in Figure 3.13 and Table 3.4.2.

Case	Safety factor
1	2.017
2	1.565
3	2.152
4	2.385

Table 3.4.2 Probability of failure due to geotechnical failure.

As can be seen from this Figure 3.13, a relative steep dune with a short base (distance B-D) will give the smallest safety factor and therefore the largest probability of failure. However, the safety factor is still 1.565, which is just slightly smaller than the value 1.7. This dune is still presumed to be stable.

If the length of the base of the dune increases, also the total friction force along the slide circle will increase and the slide circle will be less steep, yielding an increasing safety factor.

A higher level of the hinterland will give a much larger dune stability. Because the slopes in the slide circle decrease for a higher level of the hinterland, the driving forces for geotechnical failure will decrease. This means the safety factor will increase.

4 Probability assessment

4.1 Introduction

In order to assess the probability of breaching the following steps have been distinguished:

- Mutual comparison between conditional breaching probability for distinguished individual mechanism;
- Subsequent assessment of a normative shape of the conditional probability of breaching for given dimensions of the rest dune;
- Assessment of the probability of occurrence of a specific geometry and dimensions of the residual profile based on the application of a dune erosion model;
- Assessment of the combined probability;
- Subsequent comparison with these results with the state-of-the-art approach using the so-called grensprofiel;
- Proposal of a pragmatic model for the assessment of the probability of breaching as a function of the most dominant forcing parameters;

A detailed elaboration of these aspects is presented in Chapters 4 and 5.

In Chapter 3 mechanisms of three different breaching mechanisms are described.

From the mutually linked probability distributions of surge levels, wave heights and wind speeds, the probability of breaching for each individual mechanism has been estimated.

In the following sections the results are compared and an attempt is given to describe the joint probability of breaching.

4.2 Individual conditional probability

In Chapter 3 the probability of breaching due to a specific failing mechanism is given for several different geometric shapes of the 'rest dune'. As can be seen from the results, breaching due to geotechnical failure has a very low probability of occurrence (almost all geometries have safety factors above 1.7) compared to breaching due to overwash or wind induced erosion. Consequently, this failure mechanism will not be taken into account when discussing the probability distribution of breaching.

When comparing Figures 3.4 and 3.5 with Figure 3.10 and 3.11 respectively, it can be seen, that the probability breaching due to overwash and wind-induced erosion are of the same order of magnitude. As function of the 'rest dune' geometry, the required offshore wave condition to erode this dune in 3 hours time by overwash can be assessed from (curve fit of Figure 3.3):

$$H_{sig,overwash} = 5 - 4 \cdot \ln\left(1 - \frac{H_{crest}}{6.5 - 0.033 \cdot (\Delta - 3H_{crest})}\right)$$

in which H_{crest} denotes the initial height of the 'rest dune' in relation to the surge level and Δ is the width of the 'rest dune' at the surge level. With a front slope of 1:1 and a back slope of 1:2 to be computed from:

$$\Delta = B_{crest} + 3 \cdot H_{crest}$$

The wind speed U_{10}, which is needed for eroding a rest dune in a period of 3 hours is computed as follows:

- the transport capacity, which is needed is set by the volume of sand in a cross shore section;
- the relation between the transport capacity and the wind speed U_{10} is given by the SCOPE-model (factors are applied for contraction of flow lines and wet sand). With the formulations for wind induced transport, the required wind speed U_{10} can be derived;
- the probability of exceedance of the required wind speed is given in Section 3.3.4.

From the formulations as given above, the probability of breaching due to wave-induced overwash and wind-induced erosion is given by the probability of exceedance of a specific wave height and wind speed during a storm surge with level h.

For a few arbitrary storm surges and crest heights the probability of breaching in 3 and 1 hours is shown in Figure 4.1 and 4.2 respectively.
As can be seen from this figure, wind-induced erosion is dominant for small values of Δ and large crest heights. For larger rest dune geometries wave induced erosion becomes dominant, because the wind has not sufficient transport capacity for eroding the large volume of sand.

However, processes will occur simultaneously during a storm and the probability distribution of both processes will have to be taken into account. This is discussed in the next section.

4.3 Joint conditional probability

Since wind induced erosion and wave induced overwash occur simultaneously, both probability distribution have to taken into account when describing the joint conditional probability of breaching during a storm surge.

Example:
For large crest heights where hardly any overtopping will occur, erosion will be mainly caused by wind. However, after some time the crest height will be decreased and also overtopping waves will give erosion, which means the erosion process will accelerate.

This process cannot be described by combining the results from separate computations of the processes caused by wind and waves. For giving the probability distribution of breaching due to both waves and wind, the processes have to be modelled in a combined simulation model.

4.4 Summary and conclusions

4.4.1 Summary

Three mechanism which could yield to breaching have been studied in some detail, viz.:

- Wave uprush and overwash;
- Wind erosion;
- Geotechnical failure.

Based on the analysis presented, the wind induced erosion and wave induced overwash seem to be the most relevant mechanisms for breaching.

4.4.2 Conclusions

The probability of breaching due to geotechnical failure of the dune is estimated very low compared to the probability of breaching due to overwash and wind induced erosion and will therefore probably not occur.

Because erosion mechanisms of wave induced overwash and wind induced erosion occur simultaneously and have the same order of magnitude, these processes will have to be combined in order to give a probability of breaching during a storm surge. When describing these processes separately, an accurate estimation cannot be given.

4.4.3 Recommendations

Wind induced erosion and wave induced overwash are most likely the predominant processes and these erosion mechanisms cannot be dealt with separately. Therefore it is recommended to develop a simulation model, which contains both wave induced overwash and wind induced erosion.

5 Comparison with the 'grensprofiel'

5.1 Introduction

From previous studies dealing with the probability of breaching, the so-called 'grensprofiel' approach has been formulated. In this chapter a comparison is made between this method and the description of erosion mechanisms derived from the previous chapters.

5.2 Formulation

The 'grensprofiel'-approach is based on the assumption, that during a storm surge there is a certain dune geometry, which is assumed to be stable. It will be able to withstand the 'last' waves at the maximum level of the storm surge. After the maximum surge level is reached, the water level will decrease and there will not be a critical situation anymore.

This dune geometry is assumed to have a crest width of 3 m and a height which depends on the offshore wave conditions following:

$$H_{crest} = 0.12 \cdot T_p \cdot \sqrt{H_{0,sig}}$$

where:

T_p	peak period [s];
$H_{0,sig}$	offshore significant wave height [m].

When the dune geometry is smaller, the dune is assumed to fail. When the dune dimensions are larger, the dune is expected to provide enough resistance. This means, this approach will give a block function for the probability of breaching.

5.3 Comparison

Because a combined probability distribution for both wave-induced overwash and wind-induced erosion cannot be given in this stage, an accurate comparison with the 'grensprofiel'-approach cannot be given. However, an preliminary indication can be given by comparing the individual probability distributions of wave induced overwash and wind induced erosion.
For a number of storm surges this is shown in Figure 5.1 and Figure 5.2 for respectively a duration of 3 and 1 hours.

From this it can be observed that the impact of wind erosion seems to be dominant, since the contribution of the impact of overwash is small due to the pre-defined relation between wave height and the height of the crest of the 'grensprofiel'.

For small storm surges the results of computations for a critical duration of 3 hours, show approximately the same results as the 'grensprofiel'-approach. For larger storm surges the approach as described in this report gives a larger probability of breaching.

When comparing the results of computations for a critical duration of 1 hour, it can be seen that the 'grensprofiel'-approach is conservative compared to the approach as described in this report.

Since the 1-hour interval is probably a better estimate of the actual characteristic duration, it can be concluded from Figure 5.2 that the present approach is conservative.

However, as already indicated in Chapter 4, when assuming wave induced overwash and wind induced erosion to occur simultaneously, breaching will probably occur for larger values of Δ. This means that the 'grensprofiel'-approach is somewhat less conservative as resulted from this study.

5.4 Conclusions

When comparing the 'grensprofiel'-approach to the mechanisms as described in this study, the 'grensprofiel'-approach seems conservative. However, when modelling both wave induced overwash and wind induced erosion simultaneously, the 'grensprofiel'-approach might be somewhat less conservative.

6 Summary and conclusions

6.1 Summary

A study has been carried out to elaborate the three processes for causing breaching of a 'rest dune'. These processes are:
- Wave induced overwash;
- Wind induced erosion;
- Geotechnical failure.

Based on available knowledge of the processes and probability distributions of occurring wave heights and wind speeds during storm surges, these processes have been described and a model has been developed in order to estimate the probability of breaching.

6.2 Conclusions

The probability of breaching due to geotechnical failure of the dune is estimated to be very low compared to the probability of breaching due to overwash and wind-induced erosion. From this it is concluded that based on the present knowledge failure due to geotechnical mechanism is considered to be negligible.

For 'rest dunes' with a relatively large height (say 5m above water level) wind-induced erosion will be the dominant process, because wave overtopping does not occur often for these elevations. However, if the remaining dune height is less (to say 2.5m above water level), wave overtopping will be more serious and consequently wave-induced overwash will then be the most important process for erosion.

Because erosion mechanisms of wave induced overwash and wind induced erosion occur simultaneously and have the same order of magnitude, these processes will have to be combined in order to give a probability of breaching during a storm surge. When describing these processes separately, an accurate estimation cannot be given.

From a comparison with the present 'grensprofiel'-approach it was concluded that the probability of failure is adequately described (that is yielding a safe result) by the present formulations.

6.3 Recommendations

Both wave-induced overwash and wind -induced erosion seem to have the same order of magnitude for the probability of breaching. Therefore these processes should be dealt with simultaneously in order to assess the combined probability of breaching.
It is recommended to develop a simulating model, which contains both wave-induced overwash and wind-induced erosion. From this elaboration a general applicable formulation for the gradual transition between negligible probability of failure and assured failure can be determined.

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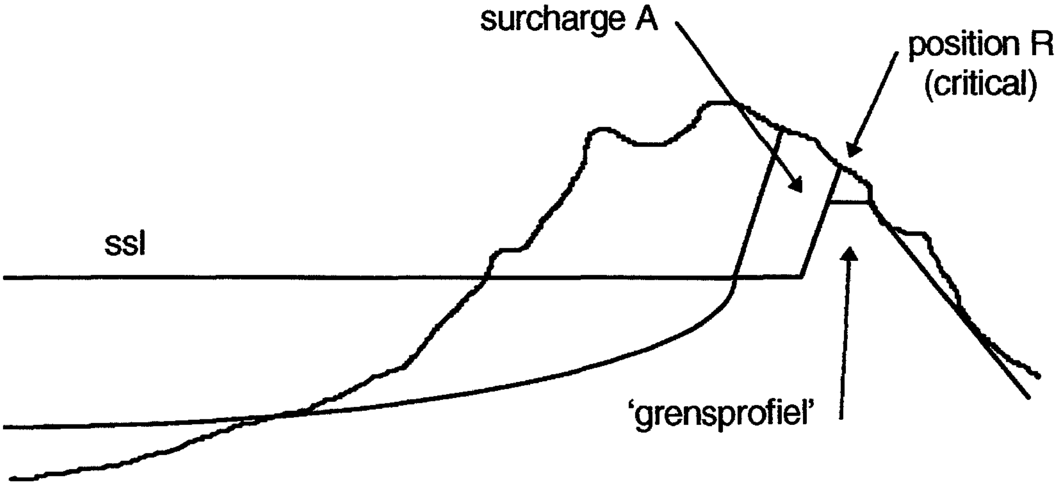
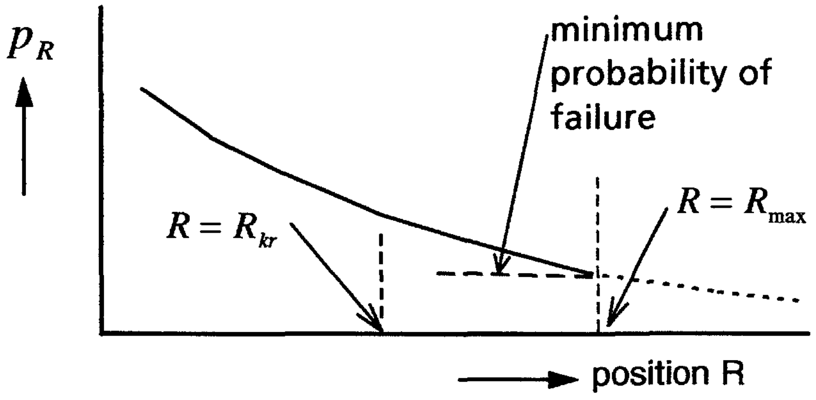
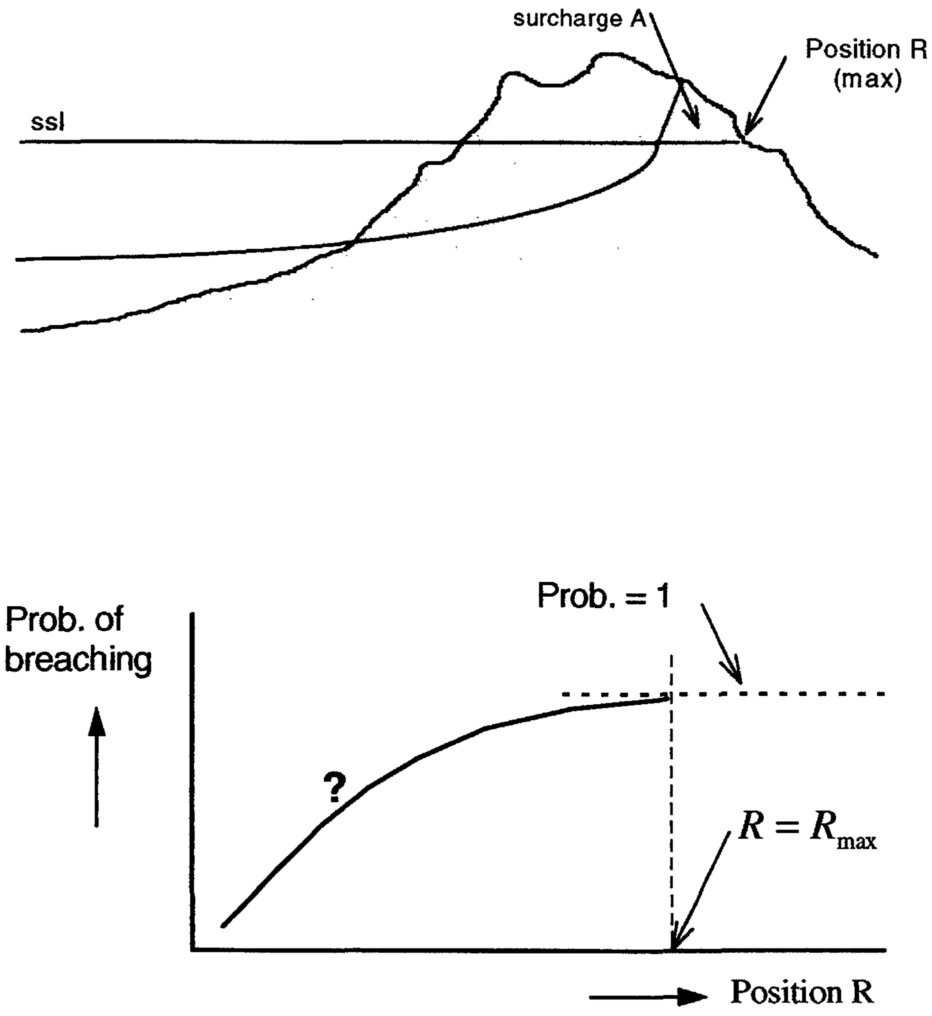
Figures





Dune erosion and probability functions

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 2.1



Conditional probability of failure

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 2.2

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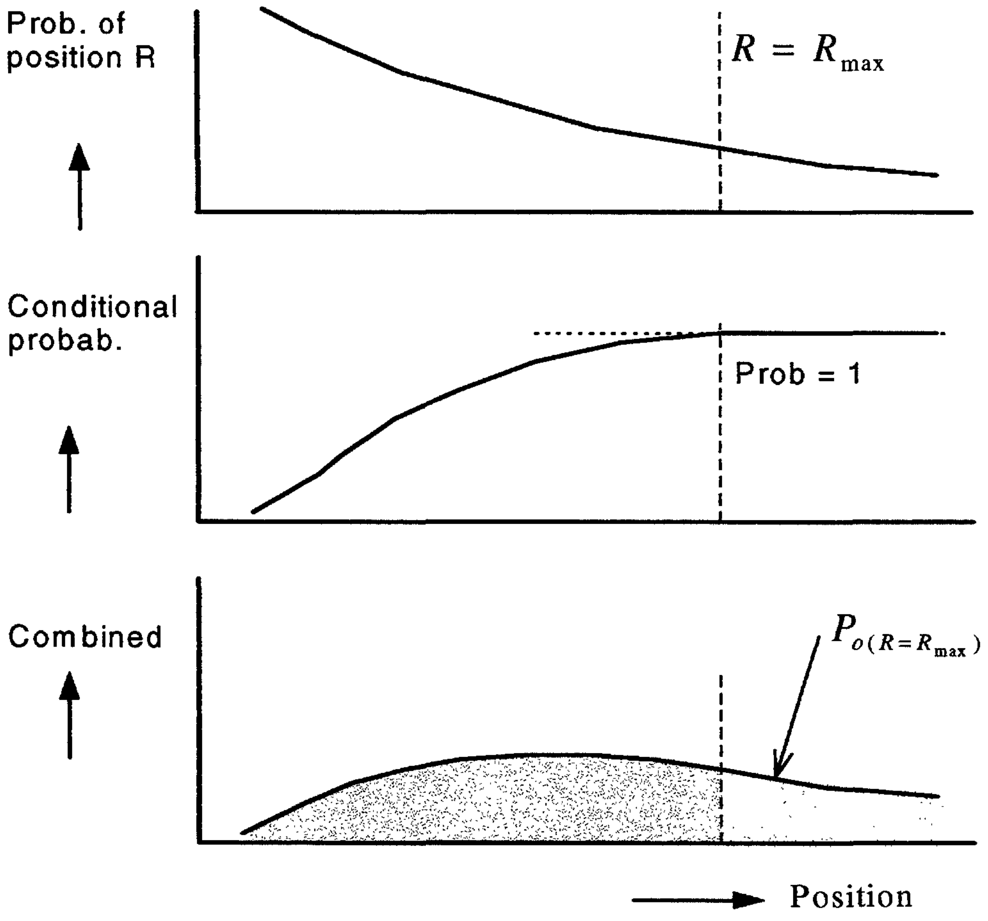

Combined probability of failure

Fig. 2.3

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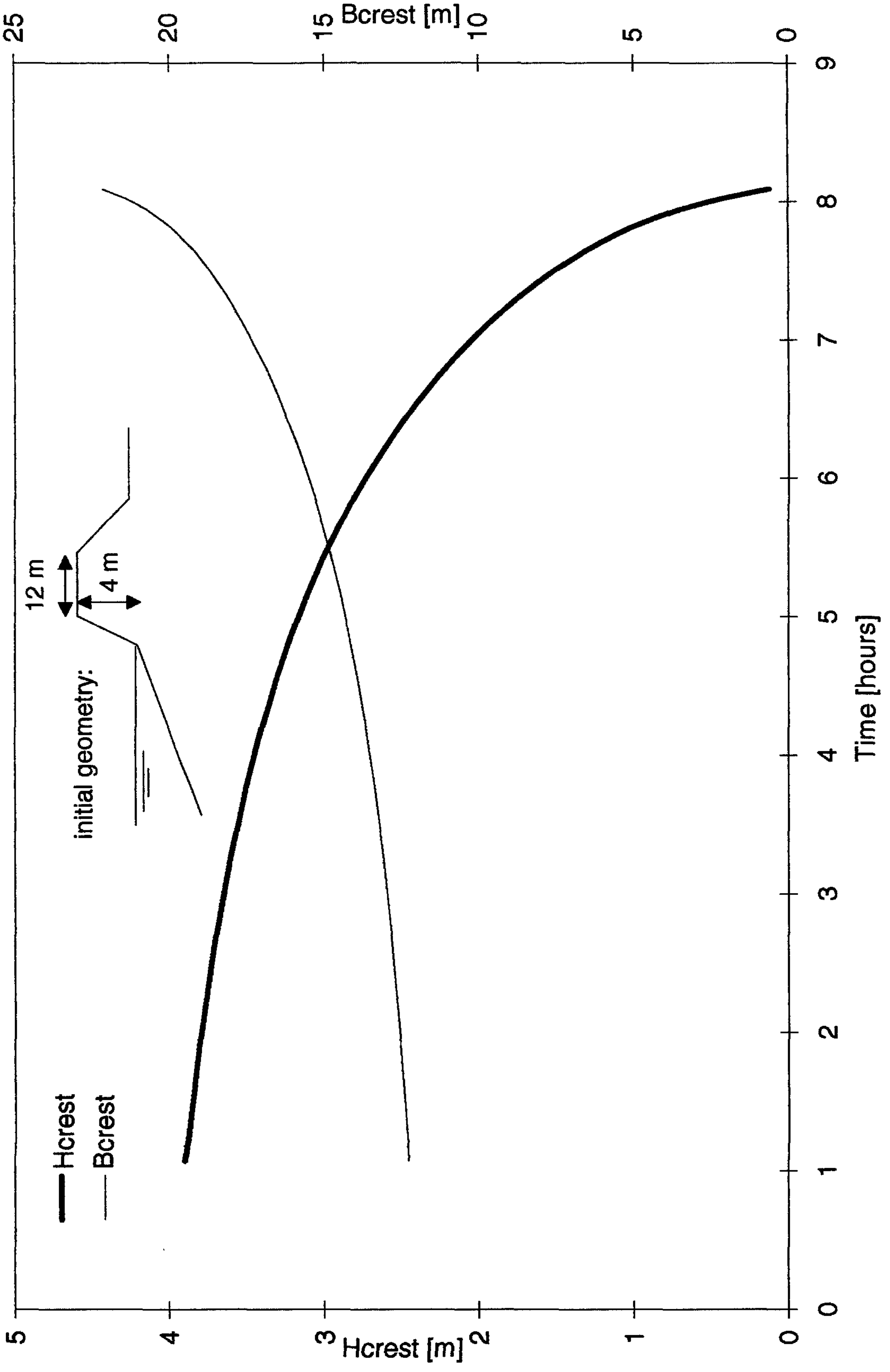
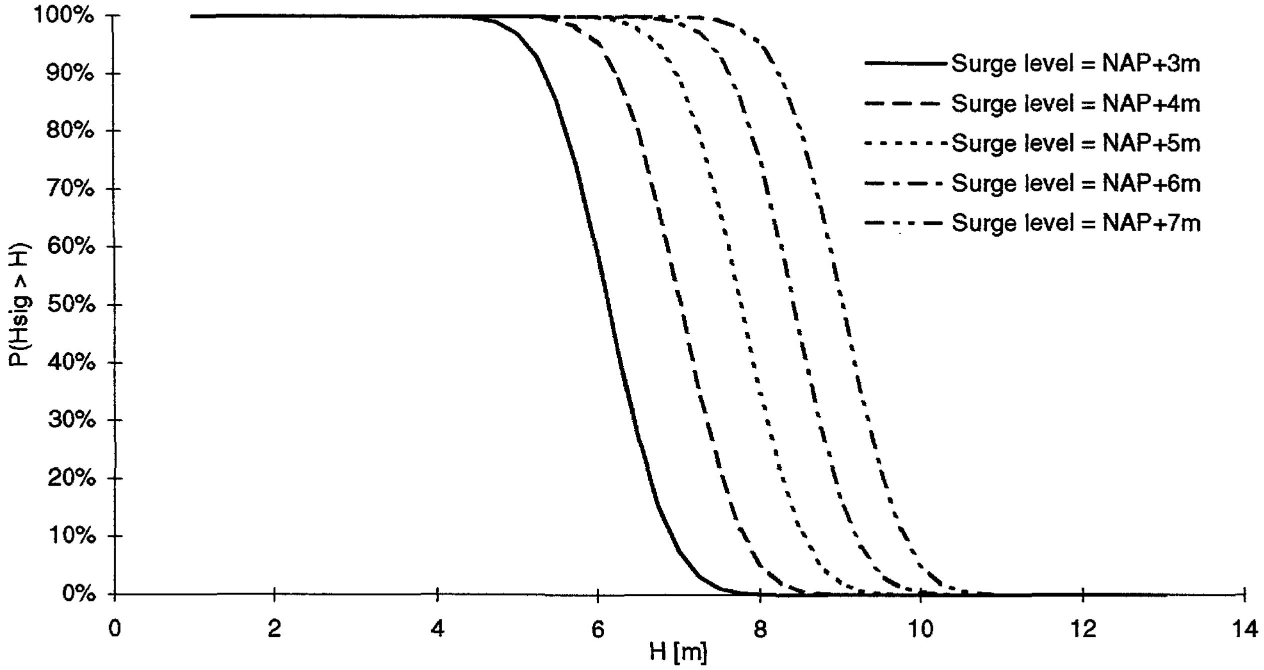
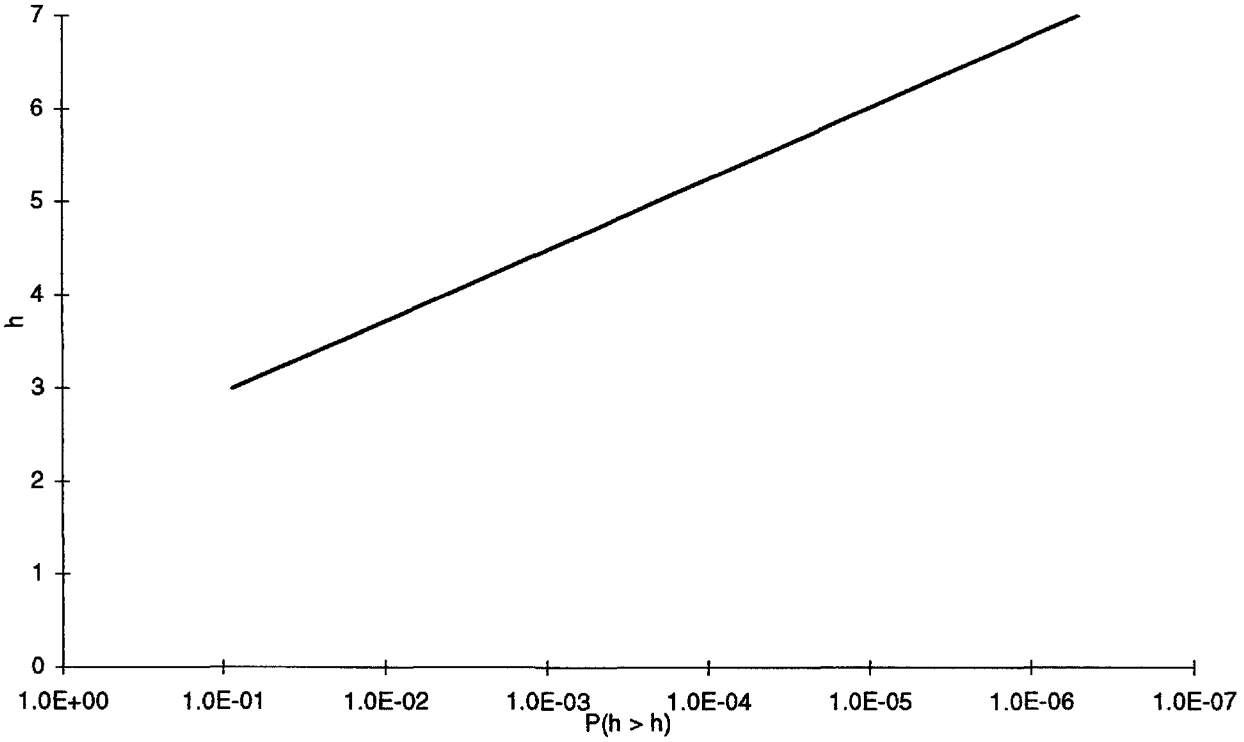


Process of breaching as function of time

t=0 : Hcrest = 4m, Bcrest = 12m, Hsig = 8 m

BREACHING OF DUNES - Related mechanism and probability A158 **Alkyon** Fig. 3.01





Probability of wave heights and storm surges

a) Probability of wave heights during storm surge

b) Probability of storm surges

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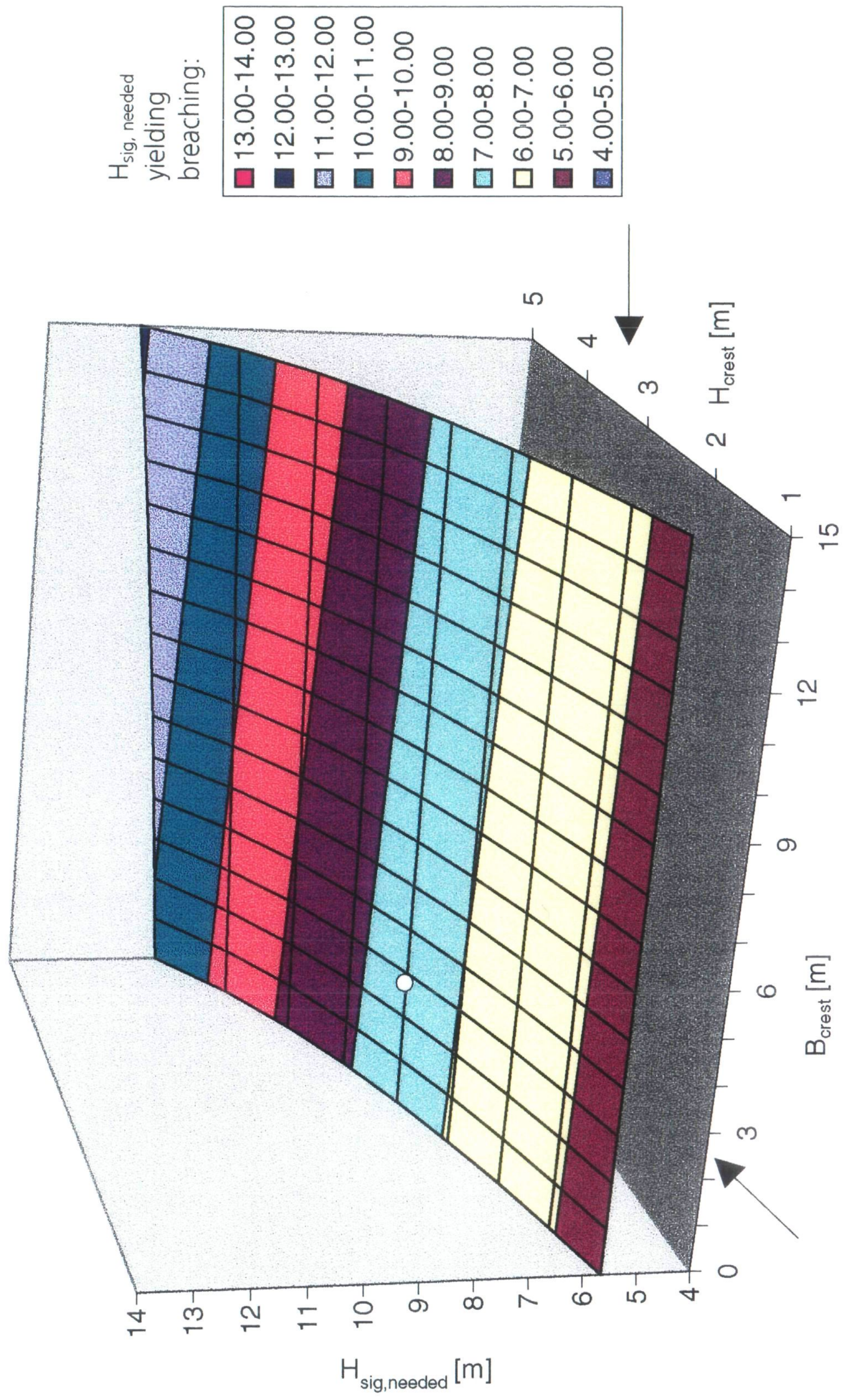

Hsig,0 needed for eroding rest dune in 3 hours time

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.03

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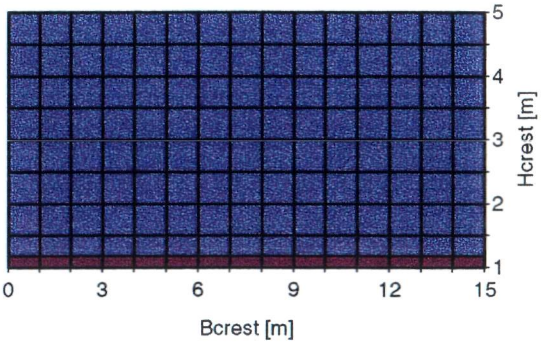
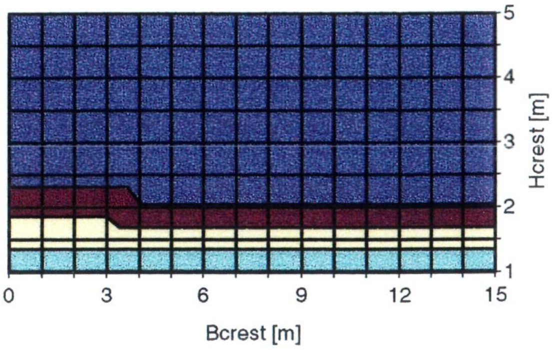
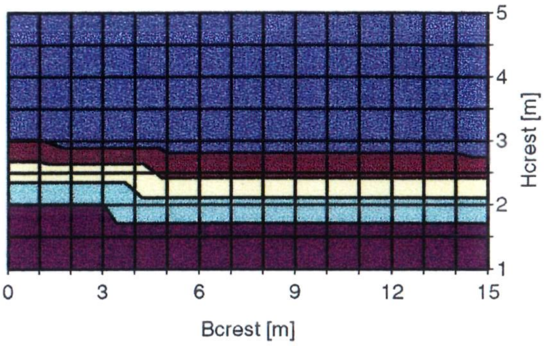


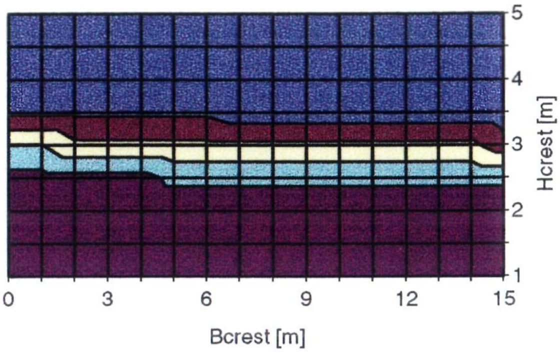
Surge level = NAP +3m



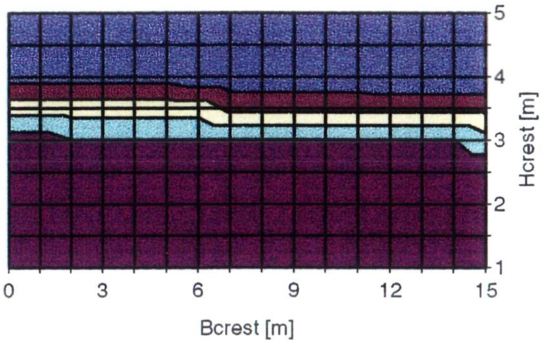
Surge level = NAP +4m



Surge level = NAP +5m



Surge level = NAP +6m



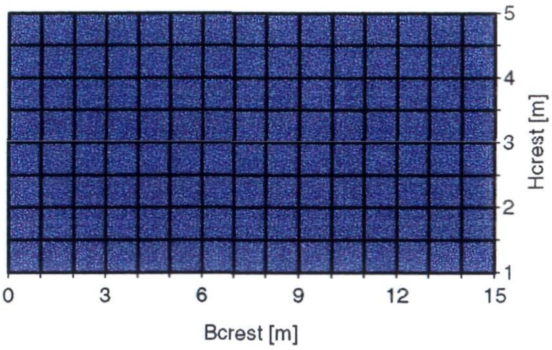
Surge level = NAP +7m

Probability of breaching:

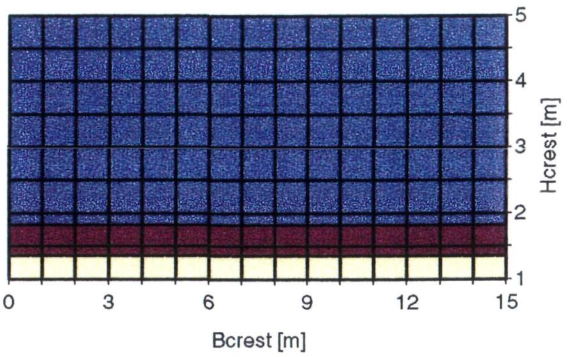
▨	0% - 20%
▨	20% - 40%
▨	40% - 60%
▨	60% - 80%
▨	80% - 100%

Probability of breaching due to overwash
for surge levels from NAP +3m to NAP +7m
Critical period of time = 3 hours

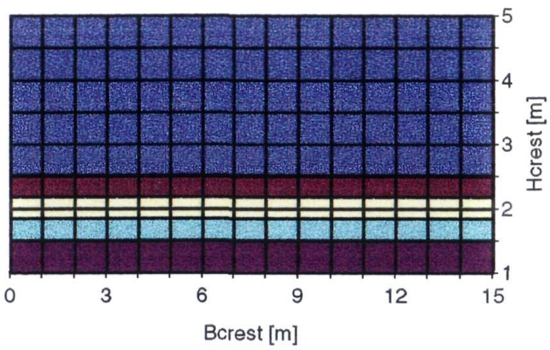
BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.04



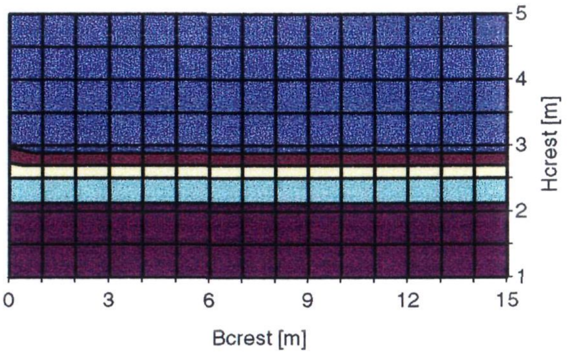
Surge level = NAP +3m



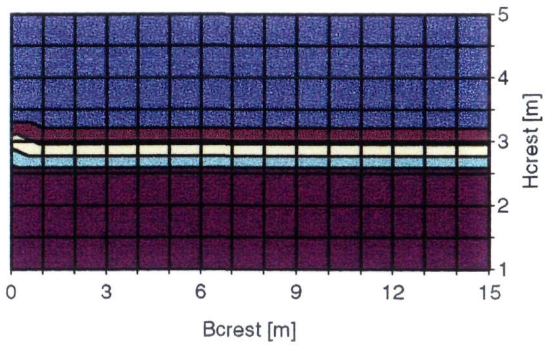
Surge level = NAP +4m



Surge level = NAP +5m



Surge level = NAP +6m



Surge level = NAP +7m

Probability of breaching:
- 🟦 0% - 20%
- 🟥 20% - 40%
- ⬜ 40% - 60%
- 🟦 60% - 80%
- 🟪 80% - 100%

Probability of breaching due to overwash
for surge levels from NAP +3m to NAP +7m
Critical period of time = 1 hour

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.05

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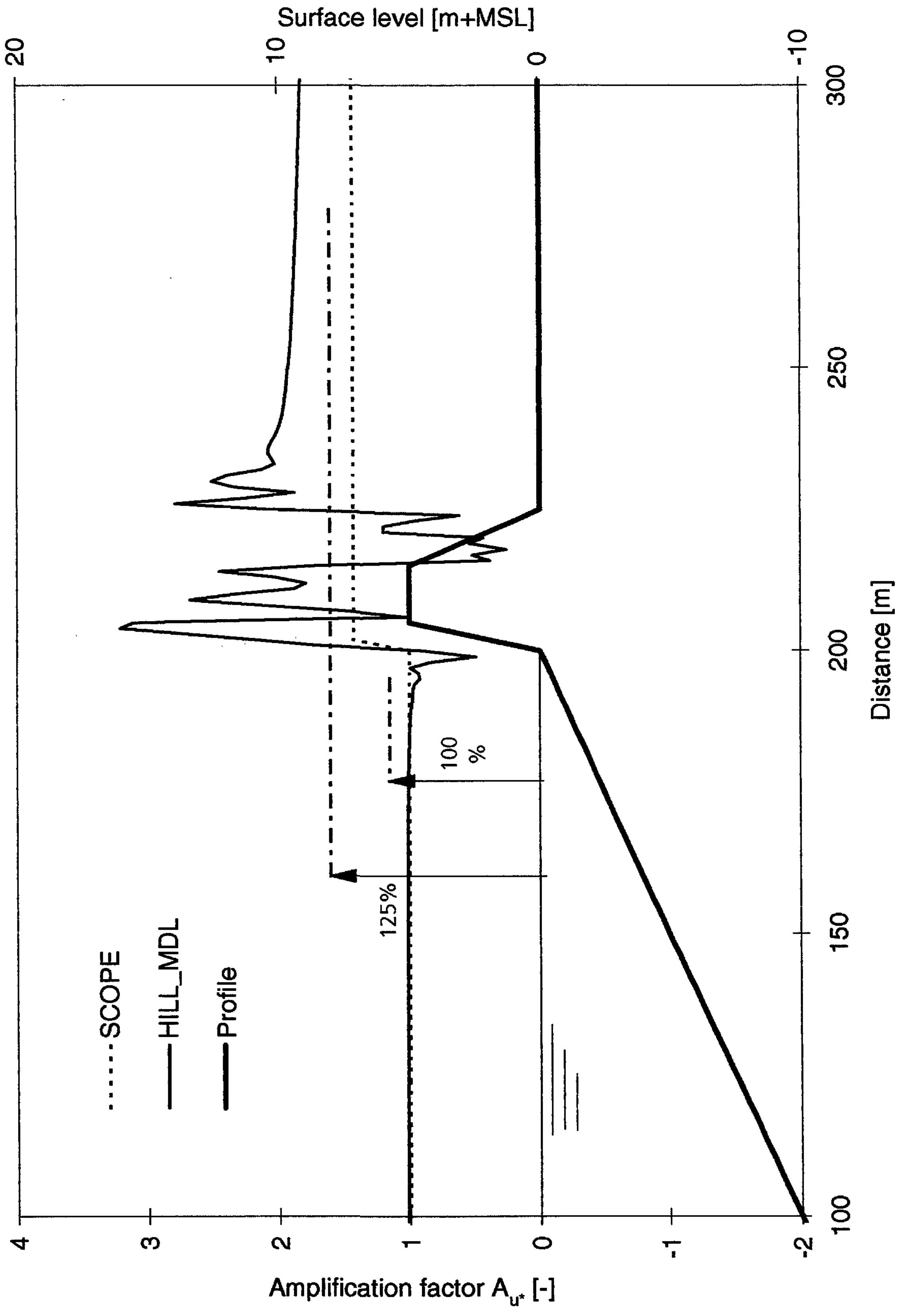

Amplification factors for shear stress velocities
following SCOPE and HILL_MDL

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.06

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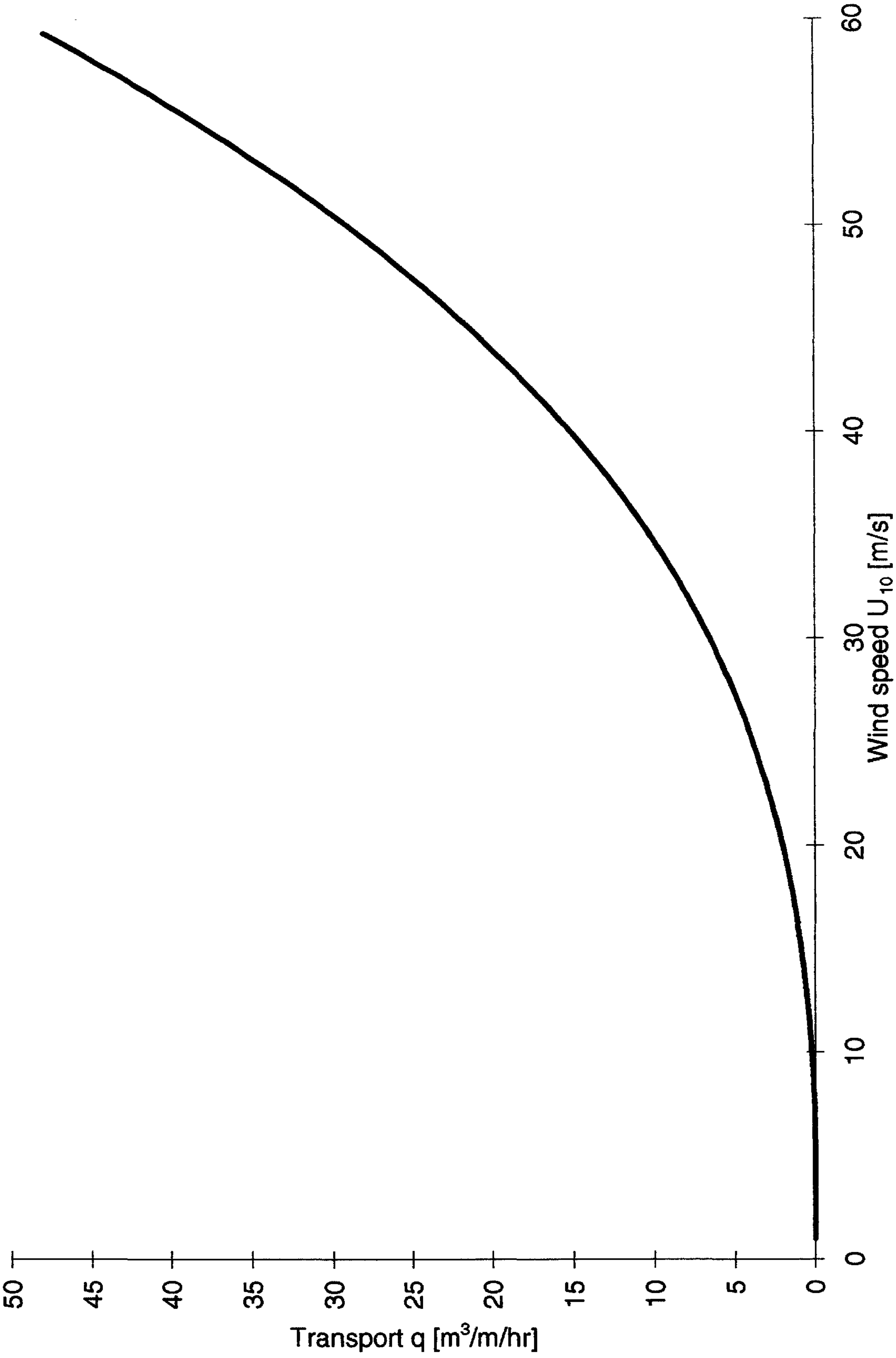

Transport capacity as function of U10

BREACHING OF DUNES - Related mechanism and probability A158 **Alkyon** Fig. 3.07

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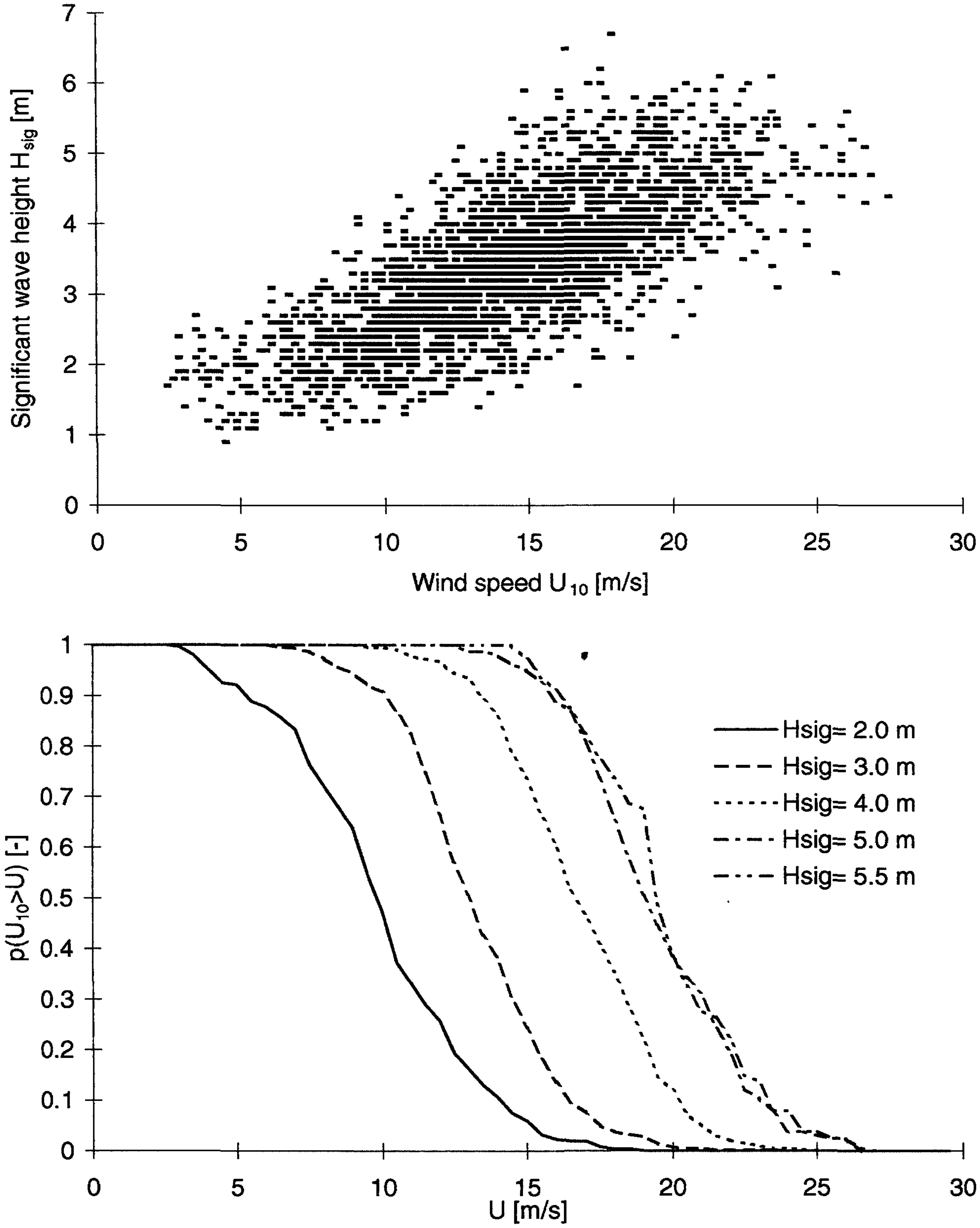
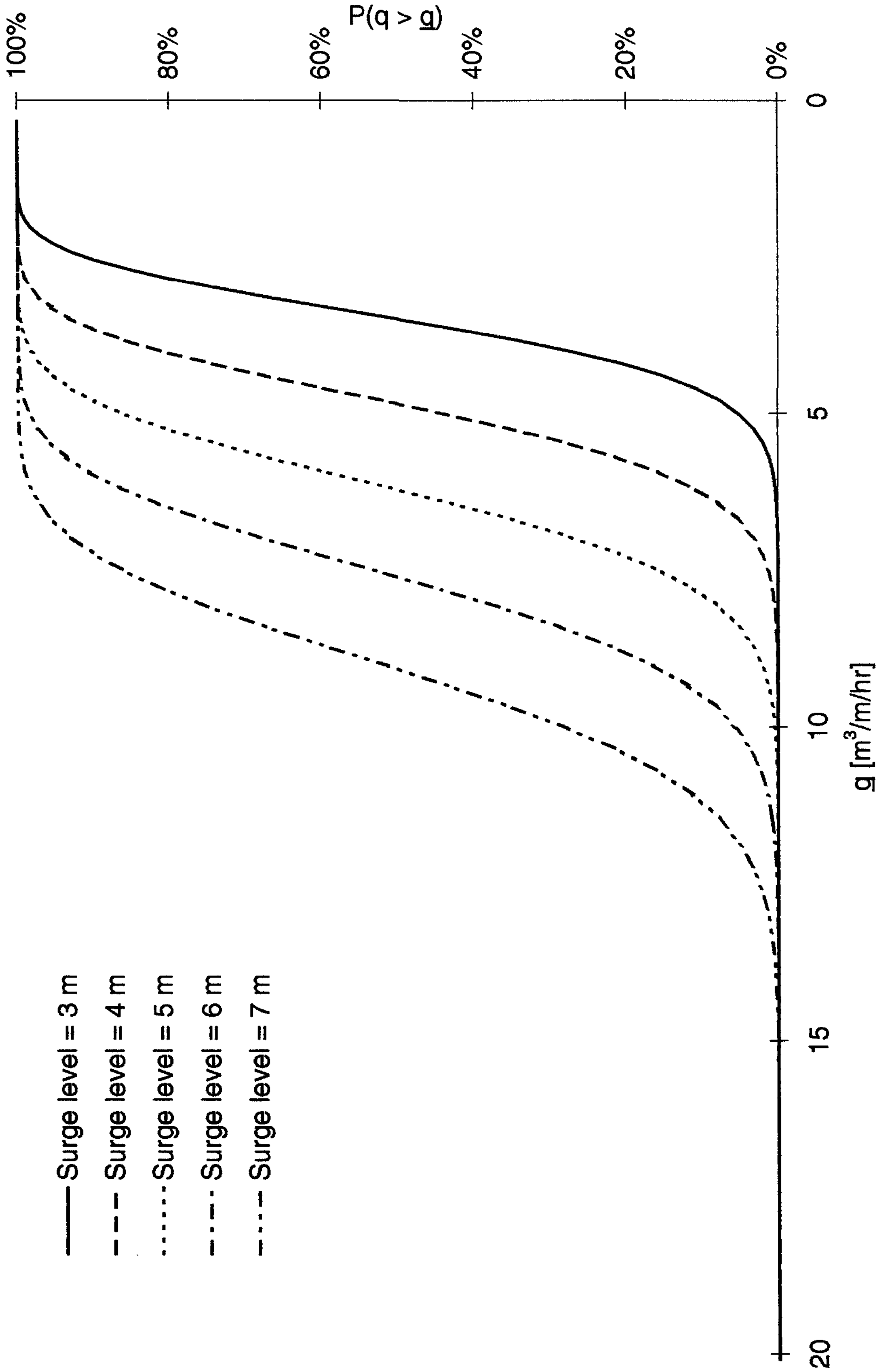


Probability of occurrence of wind speeds during storms
a) Relation between Hsig and U10
b) Probability distribution per Hsig

BREACHING OF DUNES - Related mechanism and probability A158 **Alkyon** Fig. 3.08

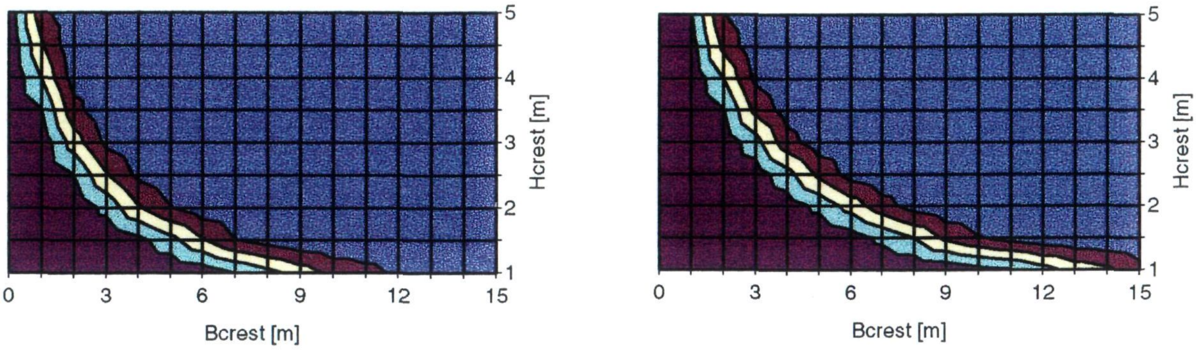
file: A158F1r2.xls; Apr 1998



Probability of transports during storm surge

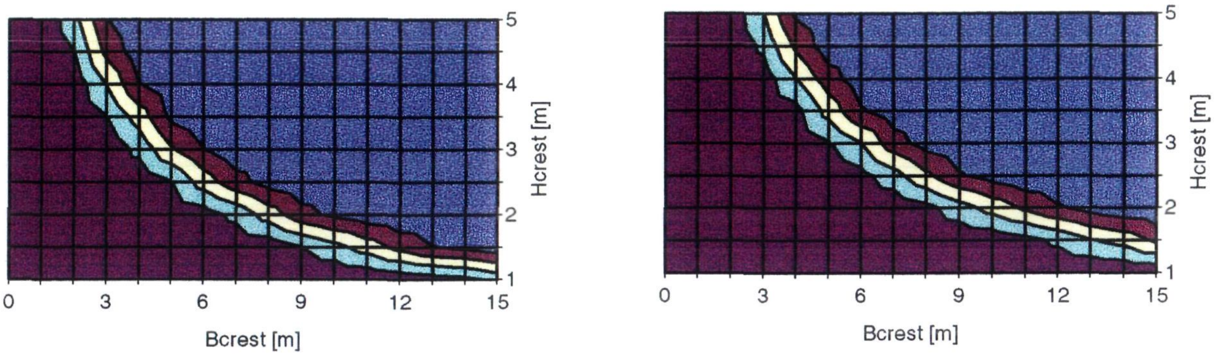
BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.09

file: A158F1r2.xls; Apr 1998



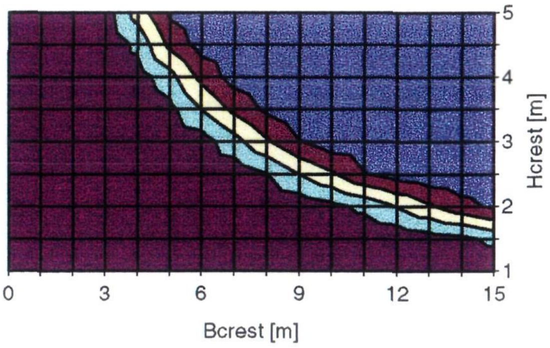
Surge level = NAP +3m

Surge level = NAP +4m



Surge level = NAP +5m

Surge level = NAP +6m



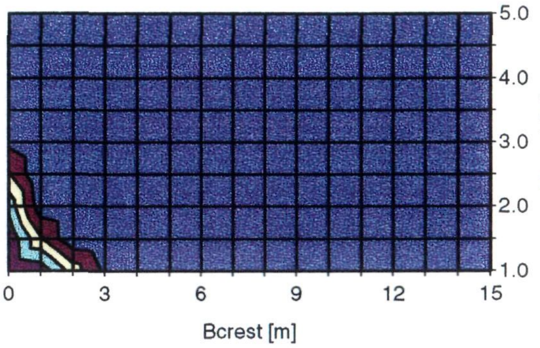
Surge level = NAP +7m

Probability of breaching:

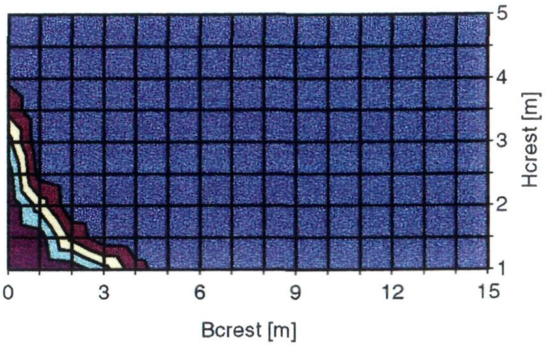
▨ 0% - 20%
▨ 20% - 40%
▨ 40% - 60%
▨ 60% - 80%
▨ 80% - 100%

Probability of breaching due to wind-induced erosion
for surge levels from NAP +3m to NAP +7m
Critical period of time = 3 hours

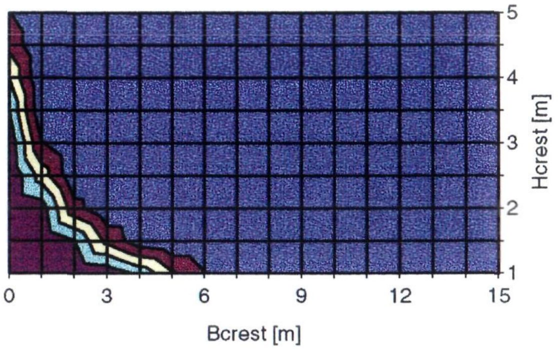
BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.10



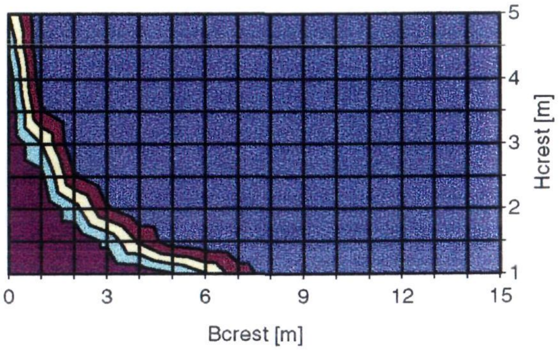
Surge level = NAP +3m



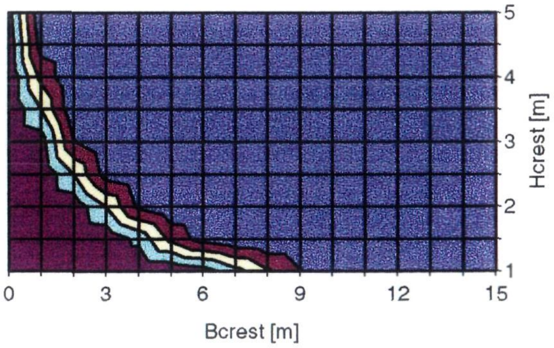
Surge level = NAP +4m



Surge level = NAP +5m



Surge level = NAP +6m

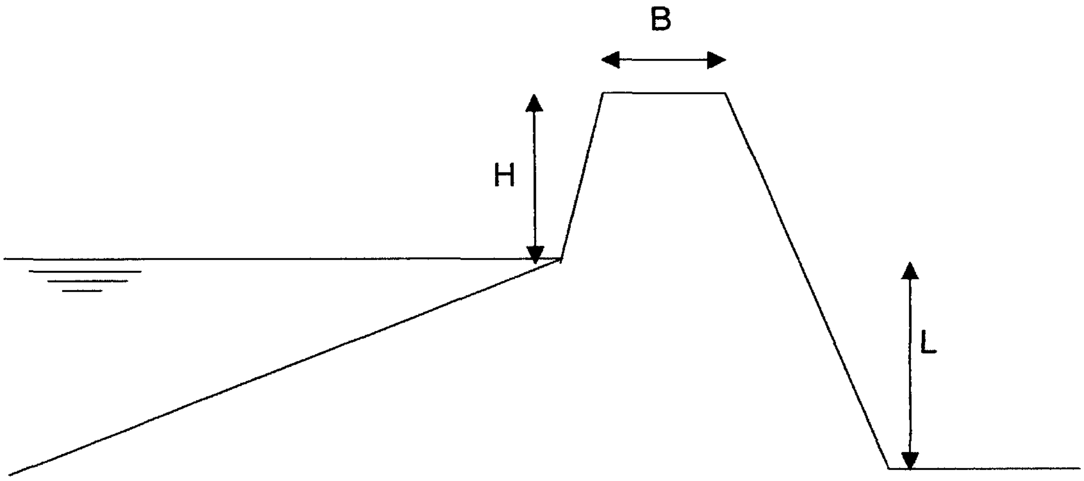


Surge level = NAP +7m

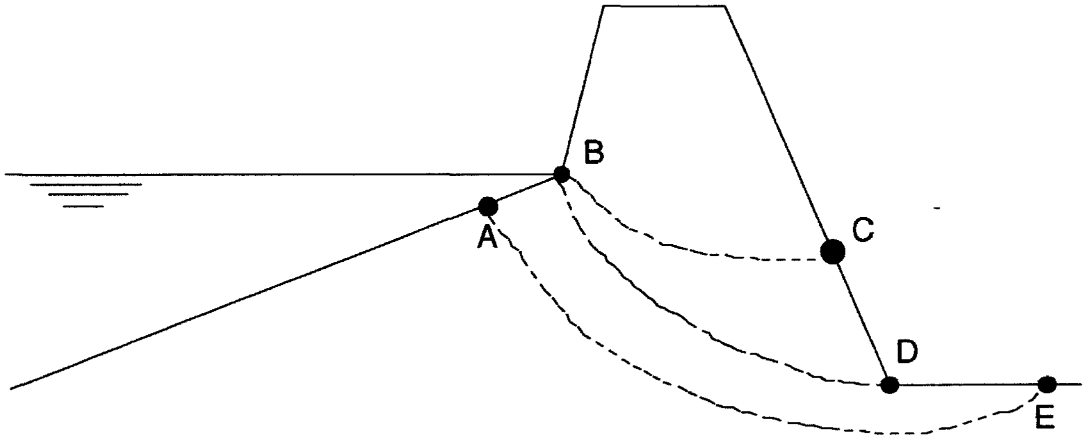
Probability of breaching:

- 🟦 0% - 20%
- 🟥 20% - 40%
- ⬜ 40% - 60%
- 🔷 60% - 80%
- 🟪 80% - 100%

Probability of breaching due to wind-induced erosion
for surge levels from NAP +3m to NAP +7m
Critical period of time = 1 hour



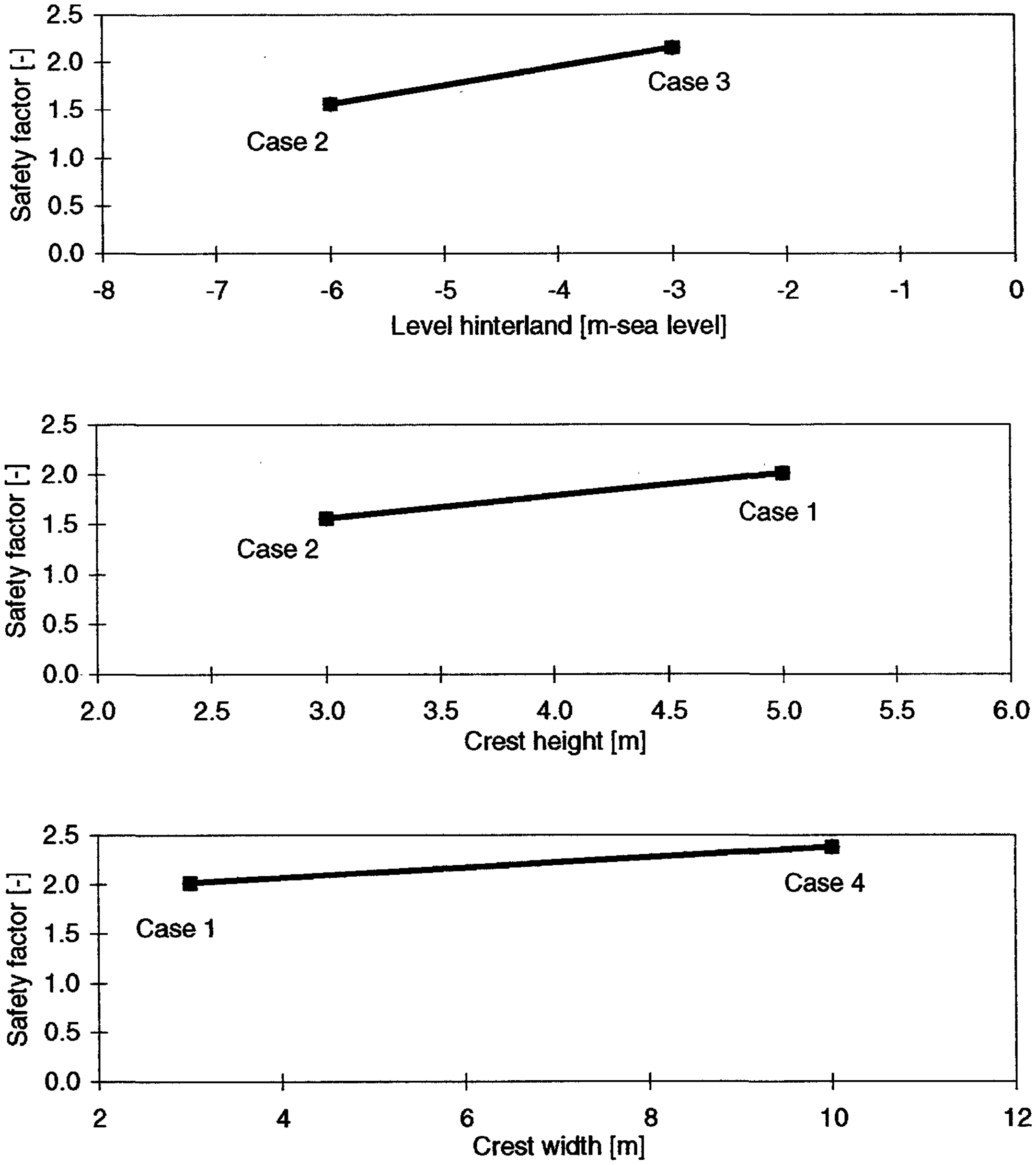
b) Definition of dune geometry's



a) Possible slide circles, which result in instantaneous breaching

Principle sketch of dune geometries and possible slide circles

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 3.12

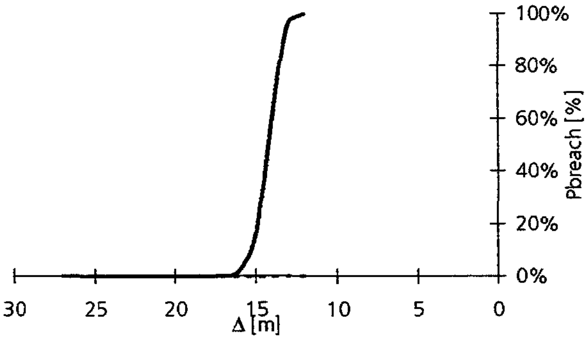


Case	Hcrest [m]	Bcrest [m]	Hinterland [m+sea level]
1	5	3	6
2	3	3	6
3	3	3	3
4	5	10	6

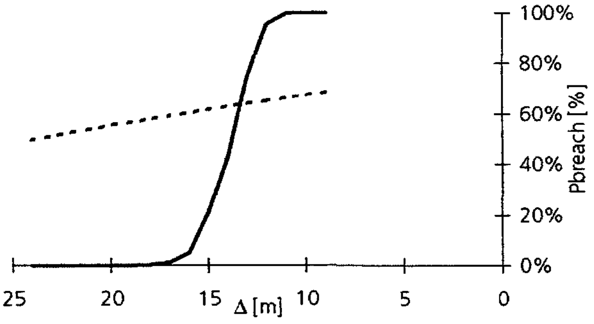
Computed safety factor for different dune geometries.

BREACHING OF DUNES - Related mechanism and probability A158 **Alkyon** Fig. 3.13

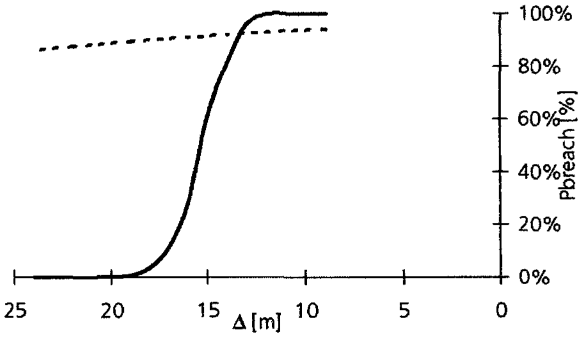
file: A158F1r2.xls; Apr 1998



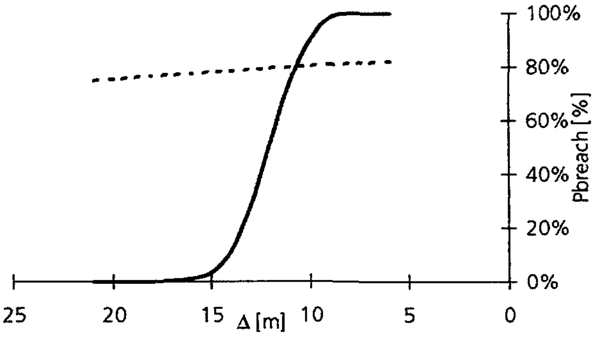
Surge level = NAP +4m
Hcrest = 4.0 m



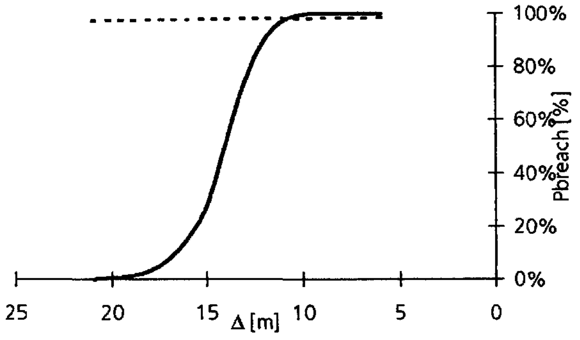
Surge level = NAP +5m
Hcrest = 3.00 m



Surge level = NAP +6m
Hcrest = 3.00 m



Surge level = NAP +4m
Hcrest = 2.00 m



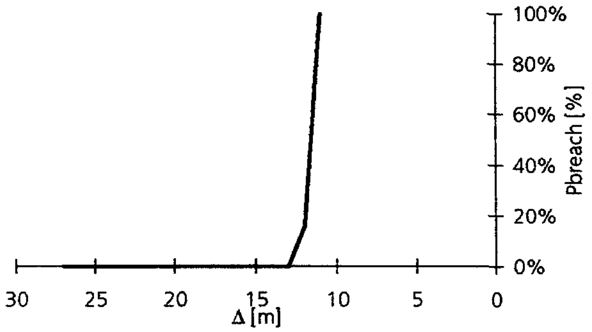
Surge level = NAP +5m
Hcrest = 2.00 m

—— Wind induced erosion
- - - - Wave induced overwash

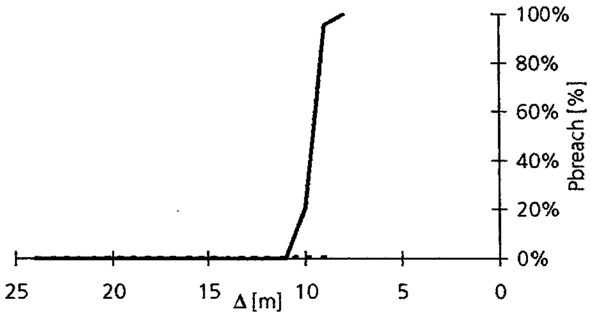
Probability of breaching due to wind induced transport
and wave induced overwash
Critical period of time = 3 hours

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 4.1

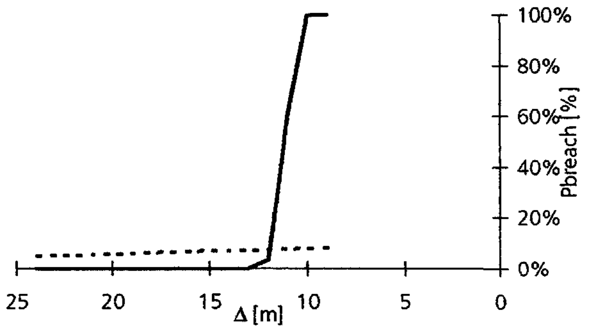
file: A158F1r2.xls; Apr 1998



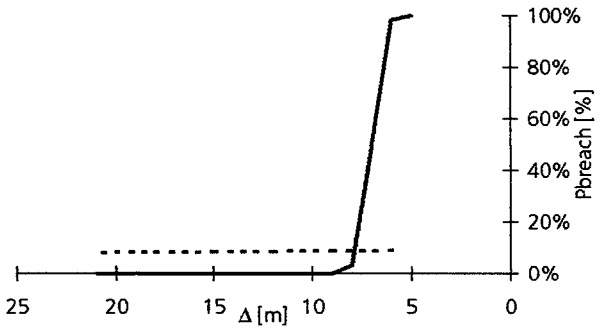
Surge level = NAP +4m
Hcrest = 4.0 m



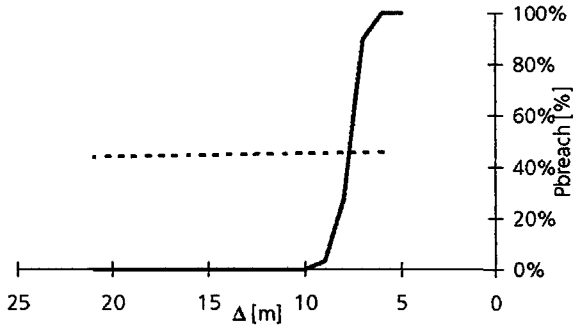
Surge level = NAP +5m
Hcrest = 3.00 m



Surge level = NAP +6m
Hcrest = 3.00 m



Surge level = NAP +4m
Hcrest = 2.00 m

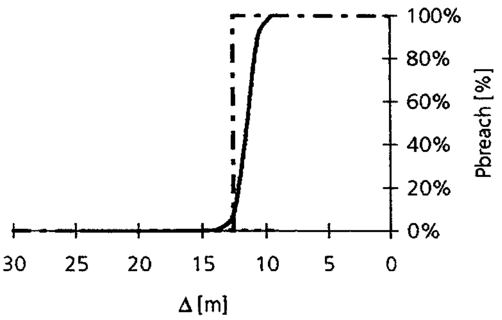


Surge level = NAP +5m
Hcrest = 2.00 m

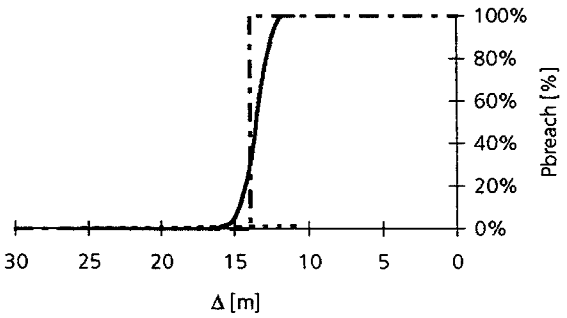
——— Wind induced erosion
- - - - - - - Wave induced overwash

Probability of breaching due to wind induced transport
and wave induced overwash
Critical period of time = 1 hour

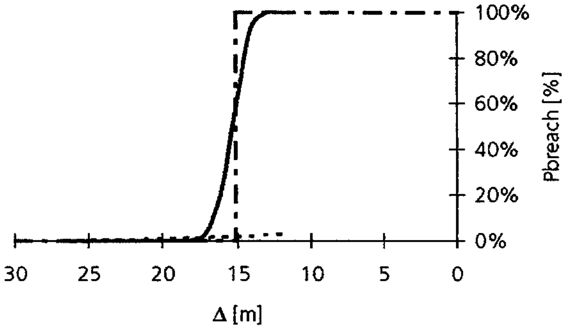
BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. 4.2



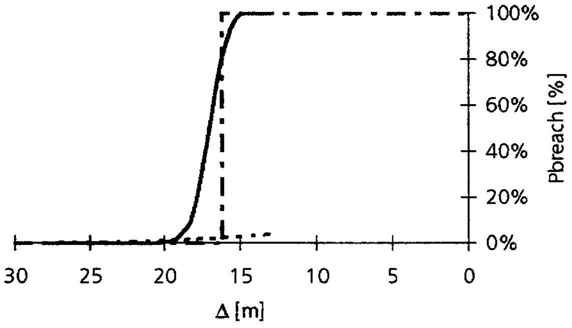
Surge level = NAP +3m
Hcrest = 3.20 m



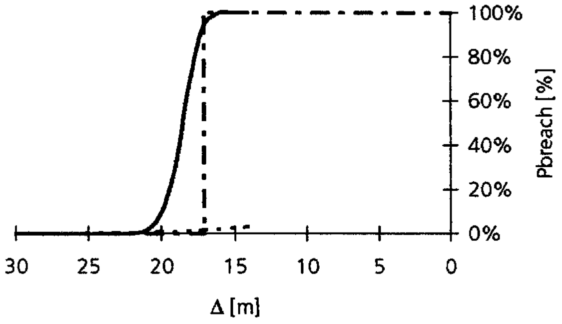
Surge level = NAP +4m
Hcrest = 3.66 m



Surge level = NAP +5m
Hcrest = 4.04 m



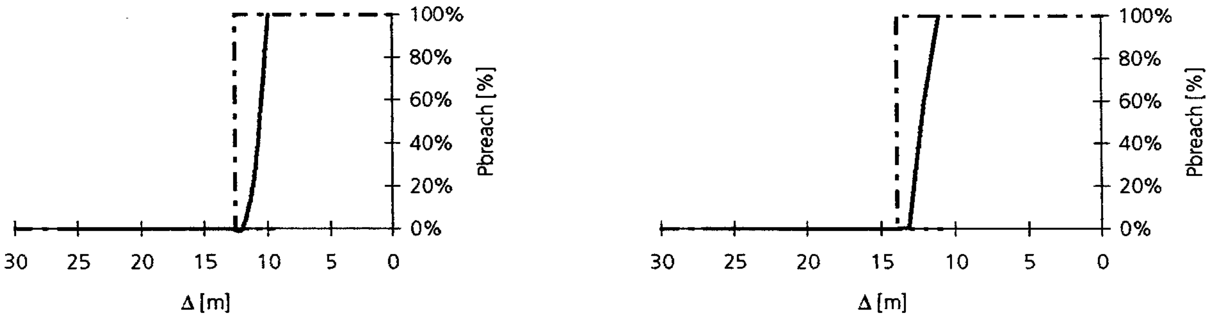
Surge level = NAP +6m
Hcrest = 4.38 m



Surge level = NAP +7m
Hcrest = 4.70 m

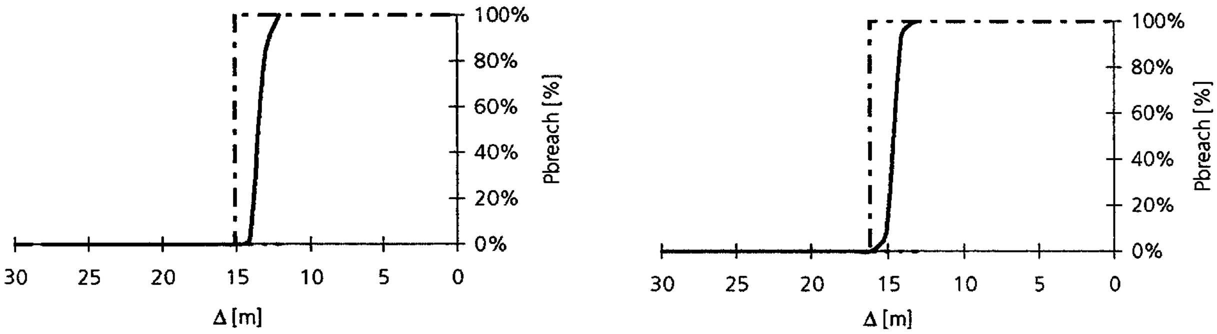
·········· Wave induced erosion
———— Wind induced erosion
–·–·–·– "Grensprofiel" approach

Probability of breaching due to wind induced transport
compared to "Grensprofiel" approach
Critical period of time = 3 hours



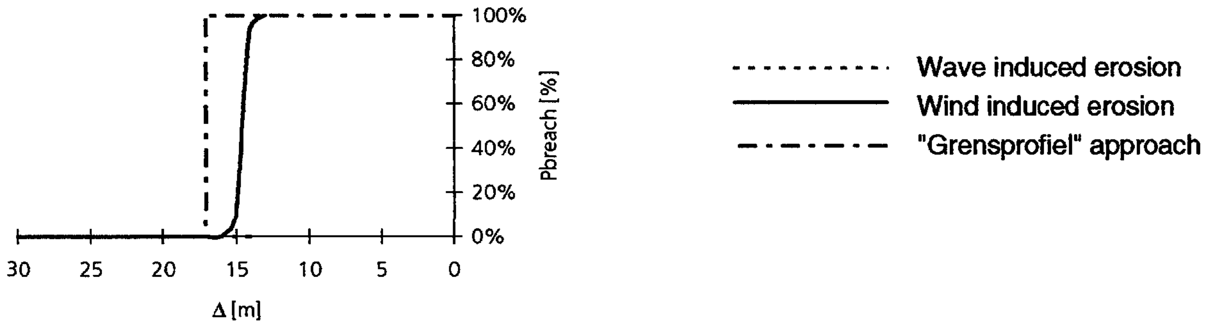
Surge level = NAP +3m
Hcrest = 3.20 m

Surge level = NAP +4m
Hcrest = 3.66 m



Surge level = NAP +5m
Hcrest = 4.04 m

Surge level = NAP +6m
Hcrest = 4.38 m



Surge level = NAP +7m
Hcrest = 4.70 m

Probability of breaching due to wind induced transport
compared to "Grensprofiel" approach
Critical period of time = 1 hour

BREACHING OF DUNES - Related mechanism and probability A158 **Alkyon** Fig. 5.2

Appendix A

Description of a conceptual wave-induced overwash model

Description of a conceptual overwash model

Within the framework of this study a preliminary version of a conceptual model for simulating overwash and overwash-induced erosion over a small dune crest has been developed.
It should be noted that erosion of the front side of the dune due to run-up and wave breaking, say the normal dune erosion mechanism, has not been taken into account.

Started is with the description of the wave-scenario and the accompanying wave run-up based on the offshore wave conditions.

Wave-scenario

A wave-scenario following a Rayleigh distribution is used for a wave height H_{sig} at deep water, in which the offshore wave height is multiplied by a factor f_{wave} in order to take into account the effect of decreasing wave height due to wave breaking and bottom friction. This factor is assessed by comparing the results of the conceptual model with the measurements from flume experiment M1819-II as described in [Delft Hydraulics, 1983]. The modified Rayleigh distribution is given by:

$$p(H \geq \overline{H}) = \exp(-2\left(\frac{\overline{H}}{(H_{sig} \cdot f_{wave})}\right)^2$$

The accompanying wave period for each individual wave is given by:

$$T = \sqrt{\frac{2\pi}{g \cdot s} \cdot H}$$

thus assuming that each individual wave at deep water has the same wave steepness s.

Wave run-up

The amount of wave run-up on a smooth slope for breaking waves is modelled following Figure 7-9 of the Shore Protection Manual. [CERC, 1984].
It is assumed there is a front slope with slope 1:10 and small depth in front of the dune (d_s/H_0' approx. 0.45), where d_s is the water depth in front of the rest dune and H_0' is the unrefracted wave height on deep water.

Re-shaping of waves

When there is overtopping over the dune crest, the wave will change shape along the crest of the dune. This re-shaping is modelled following Steetzel [Steetzel, 1987]. The wave is modelled as a half of a clock-form. Along the dune crest this clock-form will change shape and position because of diffusion and convection:

$$d(X,t) = \frac{A_0}{\sqrt{\pi D(t+t')}\,\exp\left(\frac{-(X - Xr(t))^2}{4D(t+t')}\right)}$$

Where:
d(X,t) : Water height as function of X and t [m];
A_0 : Overtopping volume [m^2];

D : Diffusion coefficient [m^2/s];
t : Time [sec];
t' : $= \dfrac{\left(R\dfrac{(1-Rh)^2}{(2\tan(\alpha)}(Rh'-Rh)\right)^2}{\pi D}$ [sec]
Rh : Relative run-up ($=H_{crest}/R$) [-];
Rh' : $=(Rh+\sqrt{8+Rh^2})/4$ [-];
X : Distance from dune front [m];
Xr(t) : Wave translation from dune front
$= U_{q\max}\cdot Tr\cdot\left(1-\exp(-\dfrac{t}{Tr})\right)$ [m];
Tr : characteristic inertia time [sec];
$U_{q\max}$: Flow velocity in time of maximum discharge
$= \dfrac{2\pi R}{T_p}/\tan(\alpha)\cdot\sqrt{1-Rh'^2}$ [m/s]

More details on these formulations is provided in [Steetzel, 1987].

As an example this transformation of a water volume is shown in Figure A-1

Along the dune crest the volume of overtopping water is assumed to be constant. This means, that the effect of infiltration of water into the dune is neglected. This seems a reasonable assumption since wave overtopping will take place in a very short time interval. Secondly, the dune will probably be saturated by water because of severe weather conditions during a storm surge.

Contraction on top of the dune crest

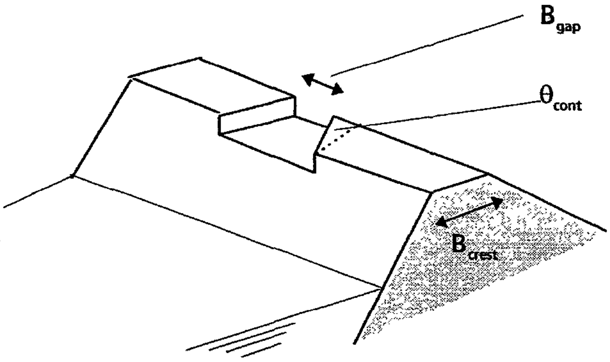
When there is overtopping over a dune crest, the water flow will not always flow perpendicular over the crest. When, at a certain location, there is a small scour channel on top of the dune crest, water tends to flow through that small channel. When more water flows through this small channel, this will also mean more crest erosion at this specific location along the dune crest. This increase in dune erosion near the channel is implemented by assuming a factor for the height of the wave on top of the dune crest.

For example, when a dune with gap B_{gap} width is assumed on top of the dune crest and a contraction of θ_{cont} degrees, then the factor for increasing wave height on top of the dune crest will be (see sketch):

$$f_{cont}(x) = 1 + x\cdot\frac{B_{gap}}{2\cdot(B_{crest}\cdot\tan(\theta_{cont}))}$$

Where:

$f_{cont}(x)$: Contraction factor as function of distance x from dune front [-];
B_{gap} : Gap width [m];
B_{crest} : Crest width [m];
θ_{cont} : Degree of contraction [°].



This contraction factor will give an increasing water volume along the dune crest, which will give more sediment transport. It is assumed, that B_{gap} and θ_{cont} will be constant in time, which mean no erosion occurs along the sides of this gap. For contraction values of 2m and 20° for resp. B_{gap} and θ_{cont} seem reasonable.

On the landward side of the dune no contraction has been taken into account. The water which flows through the gap on top of the dune is assumed to flow straight down on the landward side of the dune.

Sediment transports on top of the dune crest

Along the dune crest the water volume picks up sediment . The amount of sediment, which can be transported during one time step is defined by the transport capacity S_{cap}. This capacity is limited by the amount of material, which already is in suspension in the wave volume. When sediment concentrations in the water volume are low, sediment particles will be picked up more easily as when the water volume has almost reached its maximum sediment concentration. This limitation is implemented by a factor, which equals 1 for a water volume without sediment and 0 for a water volume which has reached its maximum sediment concentration c_{∞}:

$$K_c = (1 - \frac{c}{c_{\infty}})$$

Because of turbulence inside the water volume, the sediment concentration is assumed to be homogenous again after one time step.

The amount of sediment, which is transported from the dune crest by a single wave can then be used for computing the crest height reduction. Here, it is assumed, that the dune crest will always be horizontal. Every time a wave passes the dune crest, a small horizontal slice is transported from the dune crest.

Sediment transports on the landward side slope of the dune

It is assumed, that the water volume will continue its way on the dunes backside. If the maximum sediment concentration has not been reached at that time, the water volume will also pick up sediment particles on the dunes backside

Conform to the reduction of H_c, also the reduction of the landward side slope is assumed to take place along the entire length of the slope. This means that the landside of the dune will always be straight and the slope will not change. From erosion on the backside of the dune the new crest width is calculated.

Using wave scenarios

In the above only a single wave is used for computations. The effect of N waves following the Rayleigh-distribution is then calculated by summarising all separate conditions following:

$$S_{total} = \sum_{i=1}^{N} S(H_i) \cdot p(H_i)$$

After each passing wave the dune crest will be reduced in height and the landward side slope of the dune is translated seaward. Because of this, also the wave run-up and sediment transports will be different. Wave run-up and sediment transports will be updated for the new dune dimensions after a time t_{update} or when the reduction of the crest height is more the $dH_{c,max}$. These values are inserted as standard values during computations

Default model values

Based on experience the following default values are used:

Parameter	Value	Unit
inertia time	10	sec
diffusion rate	1	m²/sec
transport capacity	10	kg/sec
max. sed. concentration	5	%

Table 1 Default model values.

It should be noted that the maximum sediment concentration appeared to be one of the most important parameters. The magnitude used for the computations (5%) is in accordance to the results of small-scale model tests carried out by Yukiko Tega, who conducted seven tests consisting of 72 runs to measure wave reflection, overtopping and overwash of dunes. She found a simple relation between overwash and overtopping yielding a constant ratio of 0.04 (4%) as reported in [Kobayashi et. al., 1997].

Model validation

The model as described above is, with respect to the overtopping volume, validated by using measurement data from experiment M1819-II in the Scheldeflume. During this experiment the time average overtopping rate is measured for several crest heights. Using this data, the formulation for wave run-up and overtopping is validated.

Figure A-2 provides the results of this validation and it can be seen that the model represents wave overtopping in a satisfying way for crest heights lower than 5 m. Here, the significant wave height on deep water (wave steepness s = 0.03) has been multiplied by 0.15 to yield a good estimate of the wave action at the toe of the structure.

Since no measurement data is available for the transformation of the water volume on top of the dune crest, no validation has been done here.

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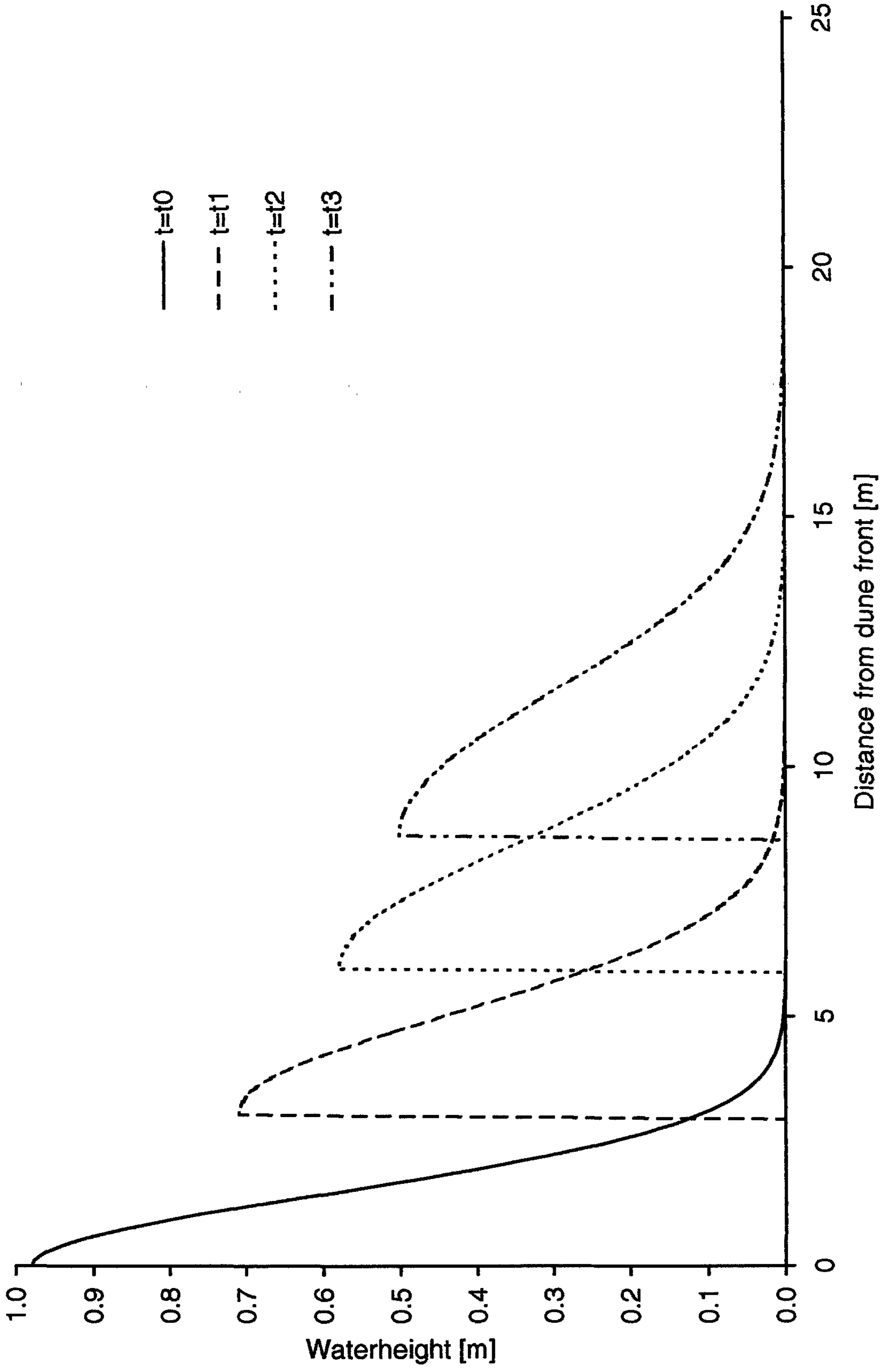

Wave transformation over a dune crest
Examples of instantaneous profiles

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. A-1

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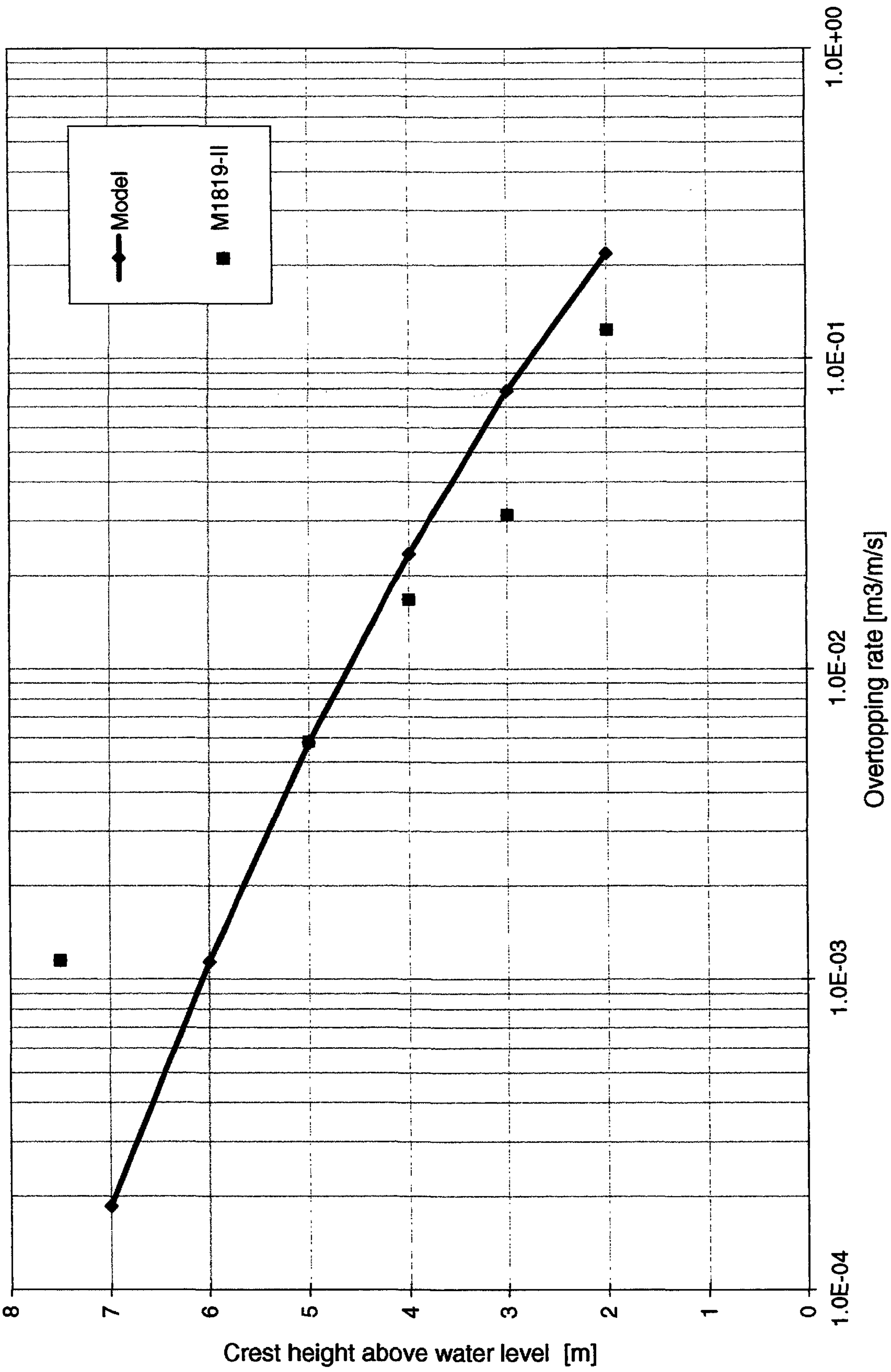

Validation of the wave overtopping model

Comparison between measured and computed rates

BREACHING OF DUNES - Related mechanism and probability A158 Alkyon Fig. A-2

Ministerie van Verkeer en Waterstaat

Ministerie van Verkeer en Waterstaat

Dienst Weg- en Waterbouwkunde

Aan
RWS Dienst Weg-en Waterbouwkunde
T.a.v. mw. drs. S.J. Fraikin
Postbus 5044
2600 GA Delft

C.c.
Mw. ir. M. Jak (RWS DWW)
dr. ir. H.J. Steetzel (Alkyon)

Contactpersoon Sandra Fraikin	Doorkiesnummer 015 - 2518 330
Datum 21 juni 1998	Bijlage(n) rapport
Ons kenmerk TAW-c/DOORBRAAK, project 3100/0310	Uw kenmerk -

Onderwerp
Aanbieding rapport 'Breaching of dunes; preliminary quantification of related mechanism and assessment of the probability of occurence'

Geachte leden van de TAW-c,

Met genoegen zend ik u hierbij een exemplaar van het rapport 'Breaching of dunes; preliminary quantification of related mechanism and assessment of the probability of occurence'.

Dit rapport vormt het produkt van de studie naar de mechanismen en de kans van optreden van een duindoorbraak, en is onder begeleiding van de TAW-c tot stand gekomen.

Met vriendelijke groet,

Mw. drs. S.J. Fraikin
Projectleider afdeling Waterkeren

Postbus 5044, 2600 GA Delft
Van der Burghweg 1

Telefoon (015) 251 85 18
Telefax 015 - 2518 555
E-mail s.j.fraikin@dww.rws.minvenw.nl

Bereikbaar vanaf NS-station Delft Centrum met buslijn 63 (halte Oudelaan) en buslijn 129 (halte Balth. v d. Polweg)