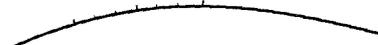


Modelling statistics of storm duration to assess  
the reliability of dunes as flood protection -  
preliminary investigation

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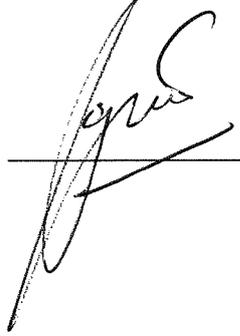
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## List of symbols

Symbol:	Description:	First appears in Section:
$h$	sea level = still water level	3.2
$h_s$	surge	3.2
$\hat{h}_s$	surge maximum	3.2
$T_s$	surge duration at the base level	3.2
$t$	time	3.2
$H_s$	significant wave height	3.2
$T_p$	peak period	3.2
$h_a$	astronomical tide, approximated by a sinusoid	3.2
$\hat{h}_a$	amplitude of astronomical tide	3.2
$T_a$	period of astronomical tide	3.2
$t_{sm}$	time-shift of the tidal wave relative to the surge maximum	3.2 3.2
$\beta$	ratio of time-shift $t_{sm}$ to one half of a tidal period	3.2
$R$	characteristic dune regression between NAP +5m and NAP +12m	3.2
$V_5$	amount of dune erosion above NAP+5 m	3.2
$d_r$	dimension of the duneface above NAP+5m	3.2
$f$	frequency of exceedance	3.3
$p_f$	conditional probability of exceedance of an $f$ -quantile	4.2

# 1 Introduction

Dune erosion during storm is a dynamical process. Failure of a dune to protect the hinterland against flooding not only depends on the levels of the loads (sea level, wave height) reached, but also on the *persistence*, or duration of these loads.

At present, estimates of the reliability of dunes as a flood-retaining structure are based on a model for the shore profile left after a storm which has lasted sufficiently long [TAW, 1996]. This profile is a function of the initial shore profile and of surge, astronomical tide and waves. It is based on the assumption that sand eroded from the dune is deposited in the surfzone and on the beach, which causes enough wave breaking to stop further erosion. If a dune of a certain size is left during such an event, no flooding will occur.

It is expected that most storms do not last long enough to produce the limiting shore profile. This can be taken into account by incorporating a model of the evolution of the shore profile during a storm into the reliability analysis. For that purpose, the numerical model DUROSTA was developed [Steetzel, 1993], which simulates the shore profile based on an initial profile and time-series of sea level, significant wave height, peak wave period and mean wave direction at an offshore location.

To estimate a frequency of failure of a dune, a description of the statistics of the load histories during extreme storms is needed, the so-called *load model*. It should include the aspect of storm duration and the variability of different parameters such as sea level and peak period during a storm. To arrive at a model which is useful in practice, we need to reduce the total number of random variables involved to a few which really matter and determine their joint distribution function. This can be done in two ways:

- **Starting from the process:** identify a limited number of characteristics of a load history which determine dune regression. Such characteristics could be variables such as (for example) the duration of the excursion of the still sea level above a certain height. The statistical modelling can then focus entirely on these variables, without having to deal with the complexities of modelling an entire load history.
- **Starting from the load history:** analyze data to determine a model which approximates the load history during an arbitrary storm in terms of a few parameters, and which includes the aspect of storm duration to a sufficient degree.

The present study investigates the prospects of both approaches using results from the literature and some exploratory data-analyses and model simulations. Some relevant information about modelling of storm duration or *persistence* as it is usually called is summarized in Chapter 2. In Chapter 3, the sensitivity of dune regression to the duration and height of storm surges is assessed in order to get an idea of the relative importance of duration.

## 2 Review of some previous work on storm duration

Time-profiles of surges are generally modelled by coastal engineers as functions of some fixed shape with only two variable parameters, a height and a length scale. In the Netherlands, the heights and durations of storm surges at a.o. Hoek van Holland were investigated by [Van Weerden et al., 1987]. They fitted trapezoidal and  $\cos^2$ -functions to 125 surges with peaks above 1.50 m and determined for each fitted surge profile the length of time spent above the 0 m level. Plots of this duration against the surge height showed a wide scatter; an example is shown below. This lead the authors to conclude that duration and height are independent random variables. In chapter 4, we will discuss this work in more detail in conjunction with our own data analysis.

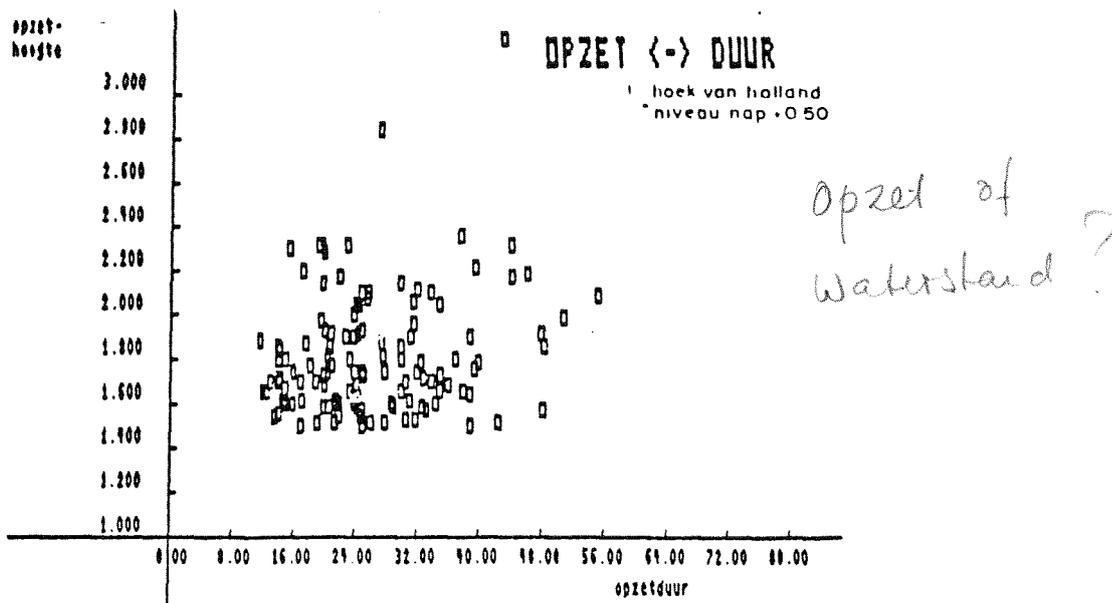


Figure 2.1 Scatter plot of surge maximum and duration above the 0.5 m + NAP level at Hoek van Holland from [Van Weerden et al., 1987].

Modelling individual surges using time-profiles of a prescribed shape is simple but not very general. In the literature, alternative approaches have been proposed to describe the time-variation of environmental parameters.

For extremes, examples are FBC models [Ditlevsen and Madsen, 1996]. These simplify the time-history of a variable by dividing the time-axis up into discrete intervals during which the variable is constant. In the standard version, the intervals are of equal length and values in different intervals are considered mutually independent. Different variables are assumed to be independent and to vary on sufficiently different time-scales (measured by the lengths of the intervals). These assumptions make it easy to combine the distribution functions of maxima of different variables to derive the distribution of the maximum load over a long time-interval such as a year.

In principle, there should be no objection against models such as FBC models which regard variables as constant over discrete time-intervals. The available wave, wind and sea level measurements have been sampled no more frequently than three-hourly or hourly. Only for wind and waves (including infragravity waves), shorter time-scales may be relevant but information about the variability on these shorter time scales is normally derived from spectra assuming stationarity over 1-3 hours.

However, one might object to the simplification of regarding values in successive intervals of a certain fixed length as mutually independent. Therefore, more refined models have been proposed to represent time-dependence more accurately, at the expense of complicating the computation of failure probabilities of structures when the load depends on more than one variable. Numerous possibilities exist.

A frequently applied approach (e.g. [Vrouwenvelder et al, 1997]) is to transform all variables individually to make the distribution functions of their instantaneous values Gaussian, and then assumes that the sequence is a Gaussian process of some particular simple form, e.g. a first-order Markov process. In the context of modelling of storm duration, using a Gaussian process is not likely to be successful: statistics of the lengths of excursions of a Gaussian process above and below a level are symmetrical around the mean, which has been shown to be invalid for e.g. significant wave height [Jenkins, 1987]. A crude but simple way to overcome this may be to model the *values* in consecutive intervals as a discrete Gaussian process, but let the *length* of an interval depend on the value (e.g. lower values persisting for a longer time). However, this will definitely complicate the description of dependence between different variables.

beeteld  
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Another possible alternative to parametric modelling of surges is to determine in what ways extreme surges differ from more commonly occurring surges. This may lead to rules for scaling up and/or dilating measured surge histories to simulate histories of extreme surges, which are then used to assess the frequencies of occurrence of extreme loads. Such an approach might be useful for modelling loads determined by different variables. However, it has so far only been applied to problems in which only the peak load but not the duration of the load matters, such as in wave overtopping of a seawall [de Haan and de Ronde, 1997; de Valk et al., 1997].

Finally, instead of trying to mimic the behaviour of environmental variables during storms, one might ask which information about the behaviour is really needed in order to model loads for a particular type of structure and failure mechanism. For example, there could be problems in which only the duration of an excursion above a certain high threshold matters. Describing the problem with fewer variables could simplify the problem considerably. In particular, if it could be reduced to a problem which was studied before, explicit solutions might be available. Most examples in the literature of problems studied apply in fact to Gaussian processes, e.g. [Cramer and Leadbetter, 1967; Leadbetter, Lindgren and Rootzen, 1987]. However, L. de Haan of Erasmus University Rotterdam concluded that dune erosion appears already too complex to be reduced to one of these well-studied problems.

?

### 3 Shore profile behaviour and its consequences for load modelling

#### 3.1 Objectives

This chapter deals with the following questions:

- How sensitive is dune erosion to extreme durations en heights of surges? This insight is valuable for determining how much effort should be invested in modelling of the statistics of storm duration.
- How sensitive is the dune erosion for variability within a storm, and in particular for the tidal variation and the phase difference between maxima of tide and surge?
- Is it possible to simplify for a given shore profile the description of its response to an arbitrary storm?

#### 3.2 Sensitivity of dune regression to the parameters of a schematized storm history

##### Introduction

In order to obtain a crude picture of the relative influence of duration and height of surges on dune regression, DUROSTA computations have been carried out for a large number of schematized storms with different surge maxima and duration.

##### Surge schematisation

For these computations, the shape of a surge is assumed to be cosine squared with the basis at zero, according to:

$$h_s(t) = \hat{h}_s \cdot \cos^2\left(\frac{\pi t}{T_s}\right) \quad (1)$$

where  $\hat{h}_s$  denotes the surge amplitude and  $T_s$  the surge duration at the base level. DUROSTA computations were carried out for 81 basic combinations of surge maximum  $\hat{h}_s$  and surge duration  $T_s$ .

##### Surge formulations

For the vertical astronomical tide a tidal amplitude (difference of top and mean) of 0.68 m has been used, whereas three specific shifts between tidal and surge maxima are elaborated.

For simplicity, a fixed relationship between surge, significant wave height and peak period was assumed. It was determined from exceedance frequency curves of the storm maxima of these variables. The curve used for surge height is described in Section 3.3. Curves for significant wave height and peak period were taken from [De Ronde et al., 1995] and [Roskam and Hoekema, 1996]. The mutual relation between surge  $h_s$ , significant wave height  $H_s$  and peak period  $T_p$  is schematised as follows:

$$H_s = 3.832 (1.119 - \ln(f / 7.47))^{0.382} \quad (2)$$

$$T_p = 7.206 (2.424 - \ln(f / 10.3))^{0.333} \quad (3)$$

with  $f$  given by

$$f = 10.74 (1 + 0.1 (0.50 - h_s) / 0.5131)^{10} \quad (4)$$

*Wie heeft dit bedacht?*

It is assumed that waves approach normal to the coastline.

An example of the combined variations of surge level, wave height and wave period according to the relationships given above is shown in the next figure.

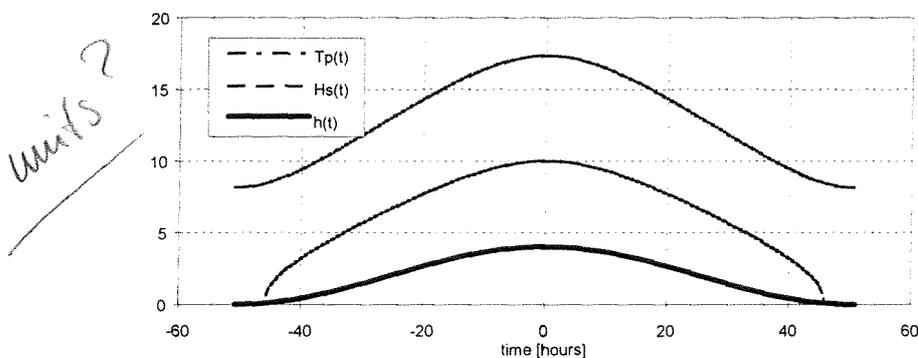


Figure 3.3 Example of combine variations of surge level, wave height and wave period.

### Tide schematization

The astronomical tide variation  $h_a(t)$  is described according to:

$$h_a(t) = \hat{h}_a \cdot \cos\left(\frac{2\pi}{T_a}(t - t_{sm})\right) \quad (7)$$

where  $\hat{h}_a$  denotes the amplitude (= 0.68m), the astronomical period  $T_a$  (12.41 hours) and  $t_{sm}$  the shift of the tidal wave with respect to the surge maximum. This tidal shift is expressed in relation to the astronomical period  $T_a$  according to:

$$t_{sm} = \frac{\beta \cdot T_a}{2} \quad (8)$$

Computations have been performed for  $\beta = 0, \beta = 0.5$  and  $\beta = 1.0$ . When  $\beta = 0$ , the maxima of both the tidal wave as the storm surge occur at the same time, whereas for  $\beta = 1.0$  the maximum of the storm surge coincides with the low water of the tidal wave.

### Combined formulation

The resulting sea level is now assessed from:

$$h(t) = h_a(t) + h_s(t) \tag{9}$$

An example of the composition of these levels for  $\beta = 0$  and  $\beta = 1.0$  are show in figure 3.4 and 3.5 respectively.

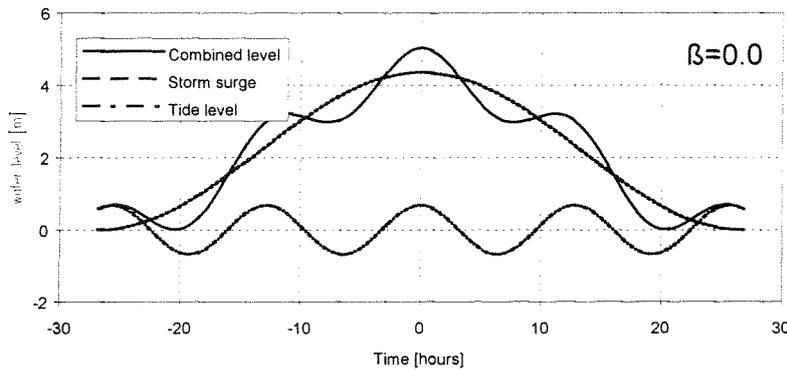


Figure 3.4 Example of individual and combined waterlevel variation for a surge with coinciding peaks.

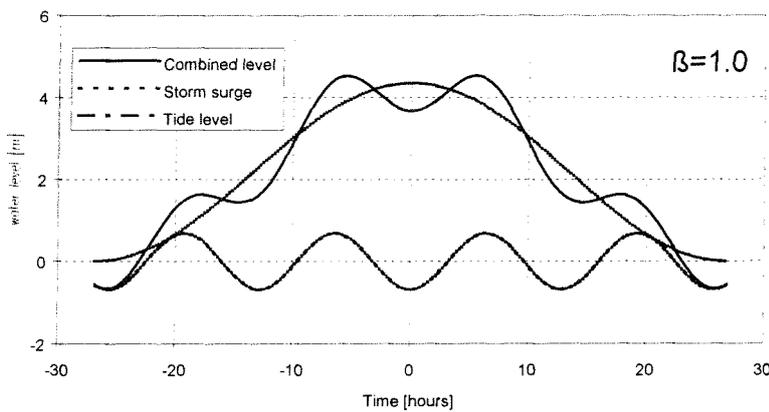


Figure 3.5 Example of individual and combined waterlevel variation for a surge maximum coinciding with low water.

The values of surge maximum  $\hat{h}_s$  and surge duration  $T_s$  used in the computations are summarised in the next table:

$\hat{h}_s$ [m]	$T_s$ [hours]
2.42	30.3
2.77	53.7
3.08	70.7
3.36	86.3
3.60	101.6
3.82	117.0
4.02	132.6
4.20	148.6
4.35	165.1

Waarom deze waarden?

Table 3.1 Values of surge maximum and surge duration used in computations

These magnitudes are chosen in such a way that the relevant part of the possible combinations is taken into account (see Section 3.3 also). All individual combinations are taken into account, which makes a total of 81 computations.

### Cross-shore profile

A schematised beach profile as shown in figure 3.6 has been used for the actual DUROSTA-computations, having a horizontal dune at +12m above reference. Offshore, the slope of the seabed is 1:200.

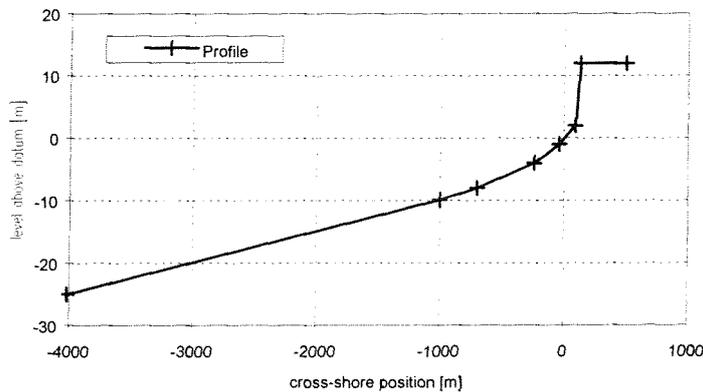


Figure 3.6 Schematized cross-shore profile used for DUROSTA-computations.

### Regression definition

To be able to compare results from the numerous DUROSTA-computations, a special parameter is introduced, which gives a clear view of the effects of the storm on the dune erosion. For this, a

regression estimate  $R$  has been defined as the characteristic dune regression between NAP +5m and NAP +12m (see figure 3.7).

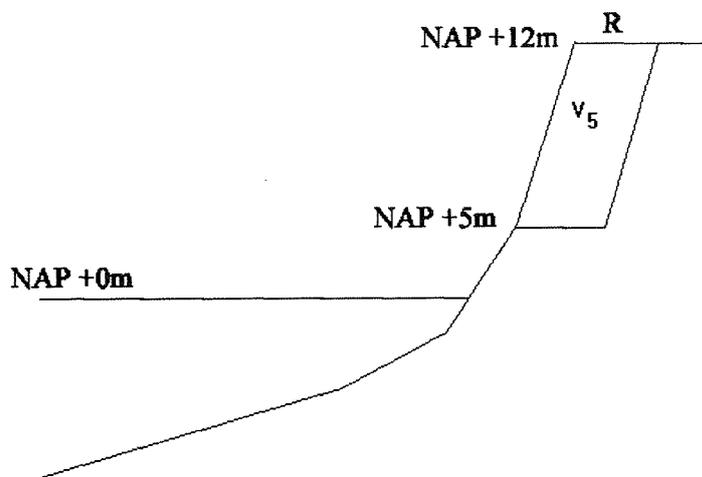


Figure 3.7 Schematized representation of characteristic recession estimate.

The  $R$ -estimate for each computation is assessed from amount of dune erosion above the NAP+5 m level  $V_5$  according to:

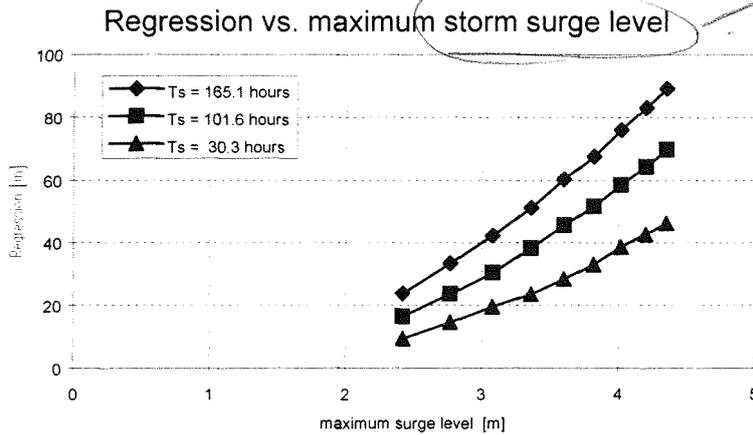
$$R = V_5 / d_r \quad (10)$$

where  $d_r$  denotes the dimension of the duneface above the NAP+5m-level, with  $d_r = 7$  m.

General results from computations are described in this section. Firstly the case with  $\beta = 0$  will be discussed.

### Effect of maximum surge level

A larger storm surge also means a larger wave height. It is obvious, that this larger wave attack will yield more regression. In figure 3.8 results are shown from computations for a storm of  $T_s = 30.3$ , 101.6 and 165.1 hours respectively.



*Inidelyker  
maken wat  
wordt bedoeld!*

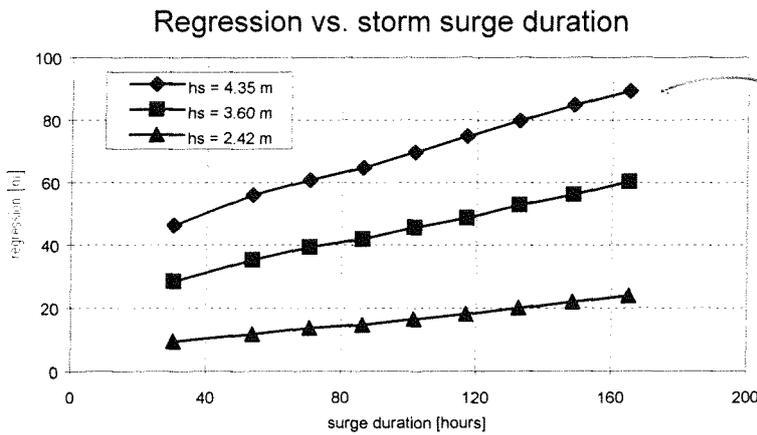
Figure 3.8 Regression as a function of the maximum surge level for three different surge durations.

From the results the following can be concluded that:

- The amount of regression  $R$  increases with increasing storm surge level  $\hat{h}_s$  and thus increasing  $H_s$ . The regression increases strongly with increasing maximum surge level;
- All lines of constant  $T_s$  seem to yield  $R = 0$  at  $\hat{h}_s = 0$  m. This is obvious, because for a storm with  $\hat{h}_s \downarrow 0$  the wave height will be zero during the whole storm.

**Effect of maximum surge duration**

It is obvious, that a larger storm duration  $T_s$  will yield more dune regression also.



*te kort  
door  
badit.  
is dit reëd?  
geen einde?*

Figure 3.9 Regression as a function of the surge duration for three different maximum surge levels.

From results shown in figure 3.9, it can be concluded that.

- The regression rate seems to decrease slightly for increasing  $T_s$ . This is probably caused by the fact that the cross-shore profile tends to reach an equilibrium.
- With increasing surge level  $\hat{h}_s$  the gradient of  $R - T_s$ -curves increases slightly also, probably because of the related increase of the wave height.

*Wat wordt  
bedoeld?*

**Combined effect of surge level and duration**

For elaboration of the combined influence of  $\hat{h}_s$  and  $T_s$ , a new parameter has been defined viz.  $T_3$ : the duration, for which the level NAP +3m is exceeded by the sea level (surge including tide). Results are shown in figure 3.10.

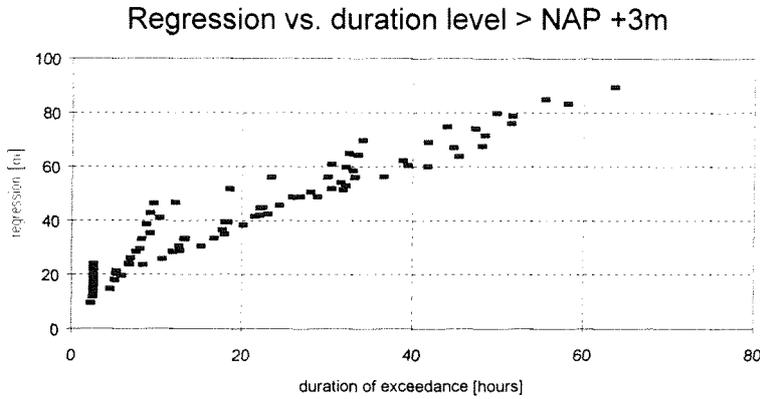


Figure 3.10 Regression as a function of the duration of exceedance of the NAP+3 m level for all computations performed.

From this figure it can be seen, that a more severe storm (longer exceeding NAP +3m) yields a larger dune regression. It can be seen also that even this specific duration does not show a clear relation with the regression, especially for the less severe storms.

Another method may be to define a relation between regression and both storm duration and maximum surge level. From a fit-procedure it was found that for the case  $\beta = 0$ , the best relation was:

$$R = 0.308 \cdot \hat{h}_s^{2.34} \cdot T_s^{0.44} \tag{11}$$

In figure 3.11 and 3.12 a comparison between computed and estimated regression is presented.

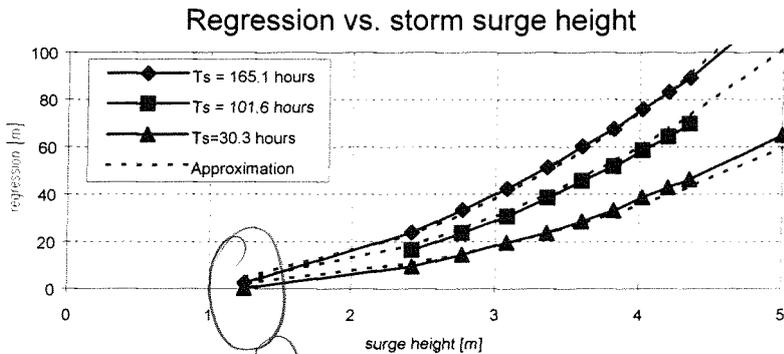


Figure 3.11 Comparison between computed and estimated regression as a function of the maximum surge height for three different surge durations.

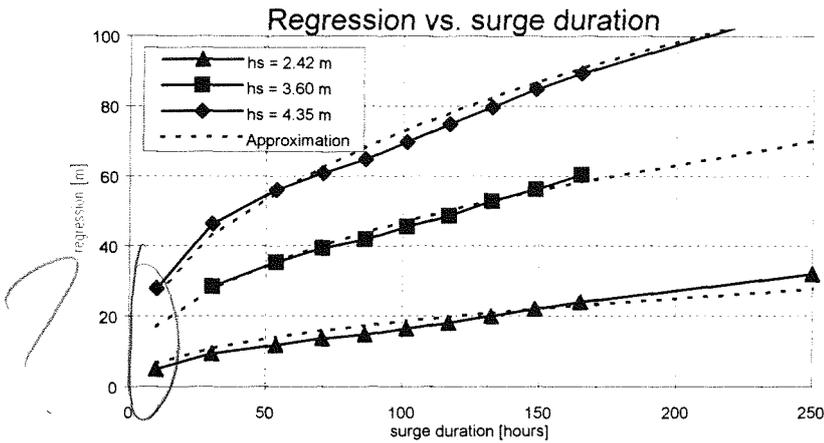


Figure 3.12 Comparison between computed and estimated regression as a function of surge duration for three different maximum surge heights.

### Effect of the tidal shift

The maximum storm surge level during a storm is related to the phase shift between the tidal fluctuation and the moment at which the maximum surge occurs, as defined using the  $\beta$ -coefficient. Some characteristic results are presented in figures 3.13 to 3.15.

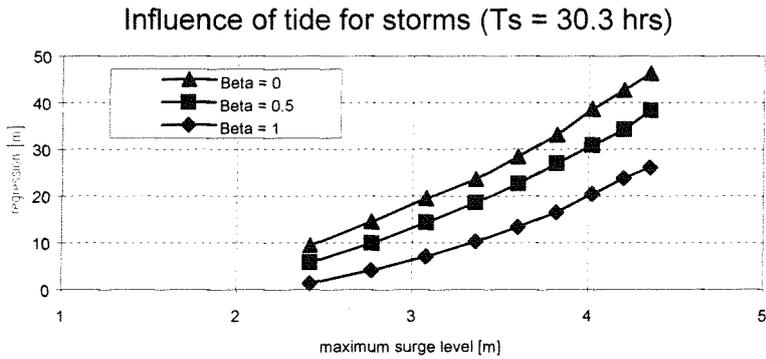


Figure 3.13 Effect of the mutual shift index between surge maximum and tidal maximum for a short surge of 30.3 hours.

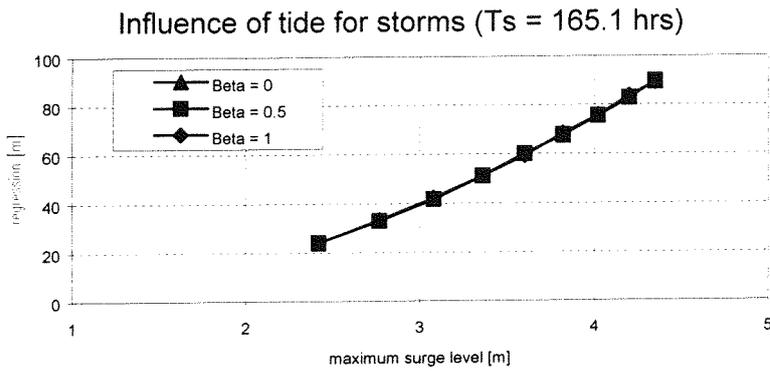


Figure 3.14 Effect of the mutual shift index between surge maximum and tidal maximum for a long surge of 165.1 hours.

As can be seen from figures 3.13 and 3.14, especially storm surges with small  $T_s$  are influenced by the tidal shift. When  $T_s$  becomes larger, more tide cycles are present around the maximum storm surge (see figure 3.15 and 3.16). Because of this, the average maximum storm surge will not be influenced by  $\beta$  and effect of the tidal shift on the regression decreases.

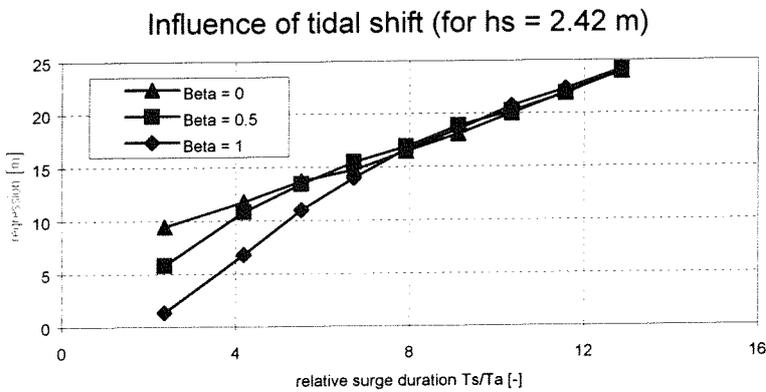


Figure 3.15 Effect of the mutual shift index between surge maximum and tidal maximum as a function of the relative surge duration for a surge of 2.42 m.

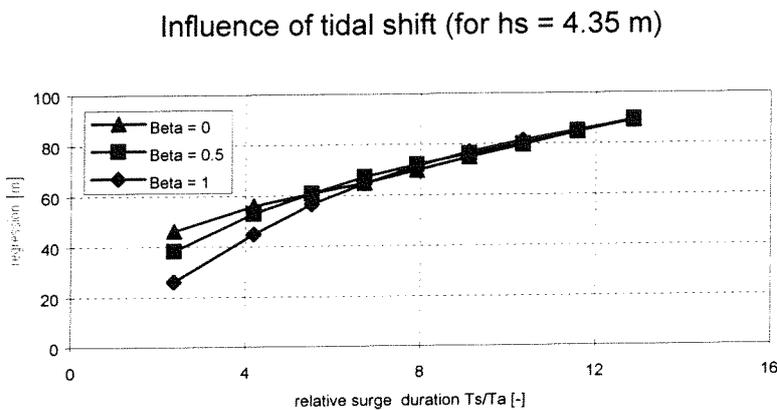


Figure 3.16 Effect of the mutual shift index between surge maximum and tidal maximum as a function of the relative surge duration for a surge of 4.35 m.

For a storm with  $T_s = 30.3$  hours the dune regression with  $\beta = 0$  is about twice as much as in the case with  $\beta = 1$ . When  $T_s$  increases, the influence of  $\beta$  decreases. When  $T_s$  about  $8T_a$ , the influence of  $\beta$  can be neglected (see figure 3.16).

## Conclusions

From the results of the computations performed, the following conclusions can be drawn:

- Increasing maximum storm surge levels (and thus increasing wave attack) will give an exponential increase of dune regression;
- Increasing storm surge duration will give an inverted-exponential increase of dune regression. This is probably caused because an equilibrium profile is almost reached;
- Only for storms shorter than about 8 tidal phases the timing of the surge in relation to the tidal fluctuations has influence on dune regression. When high tide and maximum storm surge occur on the same time, a large dune regression will be found in relation to a case where low tide occurs with maximum storm surge.

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## 3.3 Consequences of sensitivities for reliability analysis

An important question is how important it really is to obtain accurate statistics of extremes of surge duration for the purpose of assessing the reliability of dunes for flood protection, because this determines how much effort should be invested in determining these statistics. Stated more precisely, the question is to what extent the frequency of failure of a dune profile is determined by the frequency of occurrence of extreme surge durations. In this section, we try to find a preliminary answer by combining the computations of dune regression presented in section 3.2 with assumptions on the statistics of surge height and duration.

These statistics were taken from different sources and places and combined, so they are at best indicative. Exceedance frequencies of surge at Petten were derived from preliminary estimates in [Dillingh et al., 1993] (which were presented in a comparison of methodologies and were not used to derive exceedance frequencies of sea level):

- First, exceedance frequencies of high-tide surge levels at Den Helder were taken from table 6.5 of [Dillingh et al., 1993]; this is a Generalized Pareto distribution (GPD);
- Exceedance frequencies of high-tide surge levels at nearby Petten were estimated from this curve by first estimating the  $10^{-4}$  /yr quantile of high-tide surge level at Petten, and then adjusting the scale parameter of the GPD;
- This  $10^{-4}$  /yr quantile was determined by assuming that the  $10^{-4}$  /yr quantiles of sea level maxima and high-tide surge maxima at Den Helder and Petten differ by the same amount, and the difference between the  $10^{-4}$  /yr quantiles of sea level maxima at Den Helder and Petten was obtained from.[Phillippart et al., 1995].

?

Wat gebeurt hier

- It was assumed that the statistics of surge maxima are identical to the statistics of high-tide surge levels. This actually underestimates quantiles of surge maxima somewhat, because high-tide surge levels are sampled only every 12 hours.

The resulting exceedance frequencies used for surge maxima at Petten are:

$$f = 10.74 (1 + 0.1(0.50 - \hat{h}_s) / 0.5131)^{10} \quad (12)$$

with  $f$  the exceedance frequency and  $\hat{h}_s$  the surge maximum. It must be noted that despite the attempt to incorporate a number of corrections into this curve, it remains at best a crude approximation. Accurate estimates of exceedance frequencies of surge maxima are simply not available at present.

A distribution function of duration of surge above the 0 m +NAP level could be obtained from [Van Weerden at al., 1987]. It is actually determined for Hoek van Holland but we simply combined it with the distribution of surge maxima determined for Petten. The distribution function is of the lognormal type, assumes a cosine<sup>2</sup> type surge profile and applies to the population of surges above 1.5 m. We converted probabilities of exceedance (during an arbitrary surge with peak above 1.5 m) to exceedance frequencies by multiplying with the frequency of exceedance of 1.5 m by the surge maximum. For the values of surge height and duration used in the dune regression computations presented in Section 3.2, the following table summarizes the return periods, which are reciprocals of the frequencies of exceedance.

*Over-  
gripe-  
type*

Surge height [m]	2.42	2.77	3.08	3.36	3.60	3.82	4.02	4.20	4.35
return period of exceedance [yr]	10	32	100	320	10 <sup>3</sup>	3.2 10 <sup>3</sup>	10 <sup>4</sup>	3.2 10 <sup>4</sup>	10 <sup>5</sup>

Table 3.2 Return periods of surge peak height used in the sensitivity analysis.

Duration [hours]	30.3	53.7	70.7	86.3	101.6	117.0	132.6	148.6	165.1
return period of exceedance [yr]	0.89	2.8	8.9	28	89	280	890	2.8 10 <sup>3</sup>	8.9 10 <sup>3</sup>

Table 3.3 Return periods of surge duration above level zero used in the sensitivity analysis.

Based on these figures, contour plots of dune regression could be drawn as a function of the return periods of exceedance of surge height and duration, with doubly logarithmic axes. These contour plots are shown in the figures 3.18-3.20 below for surge maxima coinciding with high tide, zero tide and low tide.

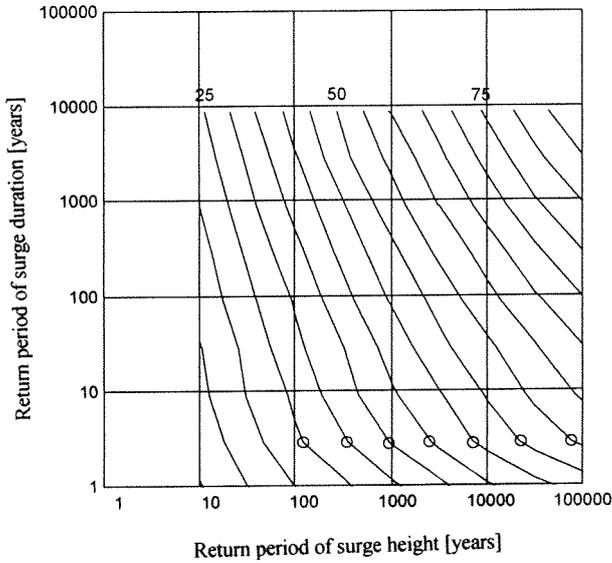


Figure 3.18 Lines of constant dune regression and "design points" (o) for surge maximum occurring at high tide ( $\beta = 0$ ); numbers 25, 50, 75 in plot indicate dune regression in metres.

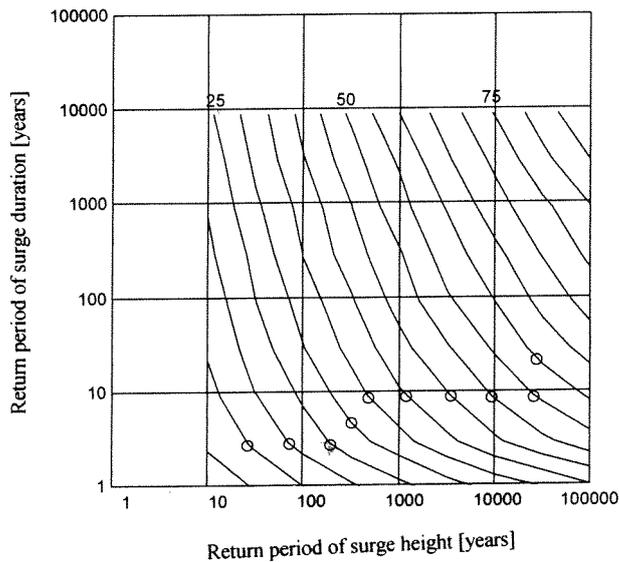


Figure 3.19 Lines of constant dune regression and "design points" (o) for surge maximum occurring at zero tide ( $\beta = \frac{1}{2}$ ); numbers 25, 50, 75 in plot indicate dune regression in metres.

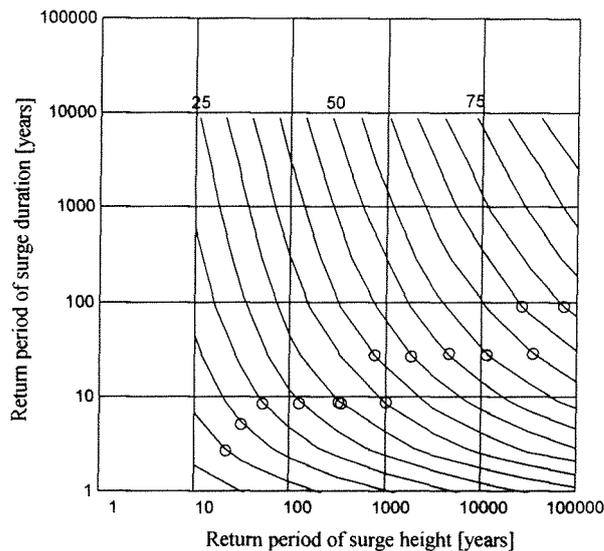


Figure 3.20 Lines of constant dune regression and "design points" (o) for surge maximum occurring at low tide ( $\beta = 1$ ); numbers 25, 50, 75 in plot indicate dune regression in metres.

Plotting these contours with marginal return periods on logarithmic axes is equivalent to converting surge height and duration to variables having an exponential distribution.

In methods for approximating frequencies of failure of structures such as FORM [Ditlevsen and Madson, 1996], the most relevant part of each contour of constant regression is the *design point*, which is the point with the highest probability density along the contour. If the design point is near the axis of one of the variables, the *tail* of the distribution function of this variable largely determines the frequencies of failure.

*Zwaan: tail?*

If we assume, following [Van Weerden et al, 1987] that height and duration of surges above the level zero are mutually independent, then the joint probability density is constant along a curve if the product of the return periods of surge height and duration is constant. In figures 3.18-3.20, these curves are straight lines with a slope of -1.

The design points on the contours of constant dune regression in these figures are therefore the points indicated with (o). These are generally seen to lie almost parallel to the surge height axis, indicating that the extreme heights are more important than the extreme durations. Only for surge maxima occurring at low tide, the tail of surge duration becomes important.

It must be stressed that these conclusions are only indicative, because they depend on so many assumptions. The marginal statistics used in our exercise are not very accurate. Moreover, the dependence of surge height and duration above the level zero will be addressed in Chapter 4, where it is shown that the assumptions of [Van Weerden et al., 1987] used in this section need to be improved.

## 4 Load modelling based on data-analysis

### 4.1 Objectives and approach

The ultimate goal is a statistical model of the behaviour of several offshore load variables (sea level, significant wave height, period, direction, wind speed) during storms which

- includes duration and temporal variability to a degree which is sufficient for dune erosion;
- is “attached” to the joint distribution of storm maxima of sea level, significant wave height etc.;
- can conveniently be linked to DUROSTA dynamic model simulations of dune regression to compute frequencies of occurrence of critical dune regression;
- requires as few assumptions as possible.

In this chapter, a data-analysis is reported to determine what type of models is suitable. A framework for such a model is presented which can be worked out in more detail in a follow-up study.

The main questions to be answered were:

- Do more severe storms last longer or shorter than less severe storms, or are the surge height and the duration of a surge above a fixed level independent as was concluded by [Van Weerden et al, 1987]?
- Duration cannot be unambiguously defined if the load is determined by several variables such as surge, tide, significant wave height, wave period and direction. There may also be time-shifts between the peaks of these variables during a storm. Data need to be analysed in order to find out which simplifications are justified to describe a storm history in a compact manner. In particular, if the instantaneous values of the different variables are already strongly dependent, we might be able to separate the description of the dependence among different variables from the description of time-dependence and duration.
- Which methods as sketched in Chapter 2 are likely to work well.

### 4.2 Data

Two data-sets were analysed in this study:

- A 3-hourly record of sea level (still water level) and astronomical tide data from Vlissingen covering the period 1911-1997. Three-hourly values of the surge were determined as observed sea level minus astronomical tide.
- A 3-hourly data-set of wave parameters at the offshore location ELD and of sea level, astronomical tide and wind data of Den Helder/De Kooi. This data-set covered the period from September of 1979 until December of 1991.

### 4.3 Analysis of surges at Vlissingen

#### Data processing

To analyse surges at Vlissingen, first a selection of distinct surge events was carried out. An event was simply defined as an excursion of the surge above 0.5 m, so it begins and ends when the surge crosses the 0.5 level. In principle, two surge events can be separated by only one 3-hour interval. This method of selection of events was validated by checking for clustering of events with surge maxima above 1 m. The results were satisfactory.

#### Duration above fixed thresholds

Following an earlier study of surge durations reported in [Van Weerden et al., 1987], we began with an analysis of surge maxima and surge durations above a *fixed* threshold. The marginal sample distributions of surge maximum and duration of the surge above the 0.5 m level are plotted below.

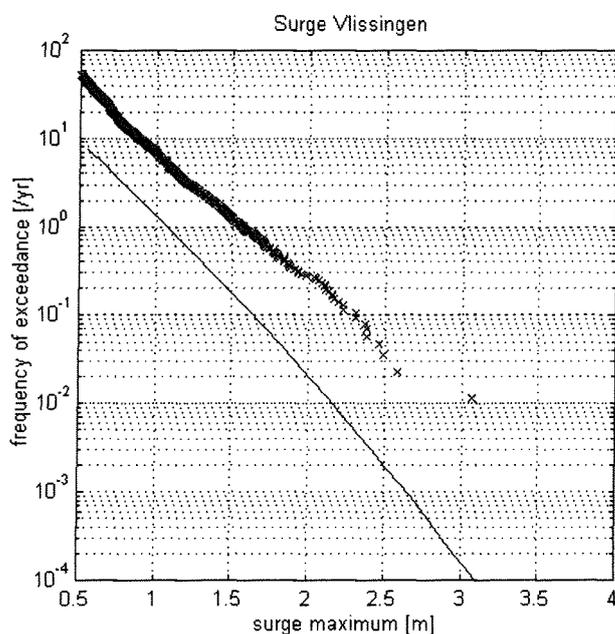


Figure 4.1 Exceedance frequencies of surge maximum at Vlissingen driven from 3-hourly differences of sea level and tide data (x) and curve of high-tide surge level from [Dillingh et al., 1993].

The sample distribution of surge maxima (crosses) from three-hourly data is plotted in figure 4.1 together with the distribution function of surge maxima estimated from the difference between sea level maxima and corresponding astronomical maxima [Dillingh et al., 1993]. A shift of about 0.5 m is present, which must be related to the fact that maxima are sampled only about every 12 hours so the probability of missing the true maximum is high. In addition, the three-hourly data overestimate the surge due to the effect of tide-surge interaction. It is recommended that this difference is investigated

in some more detail to find how much of it can be attributed to each cause, and to derive surge and tide statistics which are consistent with the statistics of sea level maxima in [Phillippart et al., 1995].

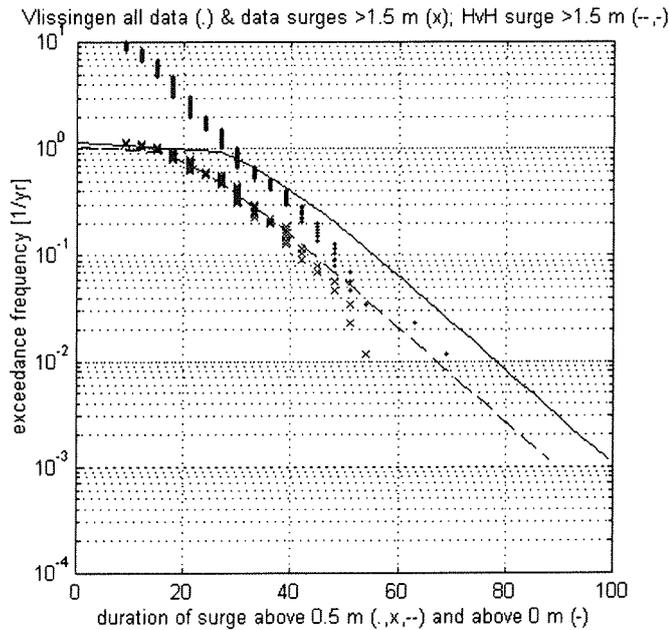


Figure 4.2 Exceedance frequencies of duration of surge above 0.5 m at Vlissingen from all surges (.) and only surges with maxima above 1.5 m (x). In addition, an exceedance frequency curve (-) has been drawn for surges above 1.5 m based on the distribution of surge duration above 0 m at Hoek van Holland from [Van Weerden et al., 1987], as well as the same curve shifted back over 11 hours to approximate the curve for surge duration above 0.5 m (--).

Figure 4.2 shows exceedance frequencies of duration above 0.5 m derived from the data of Vlissingen based on all data (.) and on only surges above 1.5 m. The latter is plotted because the distribution functions of surge duration at Hoek van Holland in [Van Weerden et al., 1987] were also derived from surges above 1.5 m. For comparison, an exceedance frequency curve of duration above 0 m derived from the lognormal distribution for triangular surges given by [Van Weerden et al., 1987, p. 26] is shown (-). It is higher than the samples curve from the data of Vlissingen (x). However, if we add 11 hours to correct for the difference between durations of surges above 0 and 0.5 m based on [Van Weerden et al., 1987, bijlage 5], then the agreement with the data of Vlissingen is close (compare (-) and (x)). We may conclude that the choice of a lognormal distribution by [Van Weerden et al., 1987] serves mainly to match the curvature which results from excluding surges with maxima below 1.5 m. If these are not excluded, the exceedance frequency curve of duration above 0.5 m resembles an exponential distribution.

The figure below shows a scatter plot of surge maximum and its duration above the 0.5 m threshold.

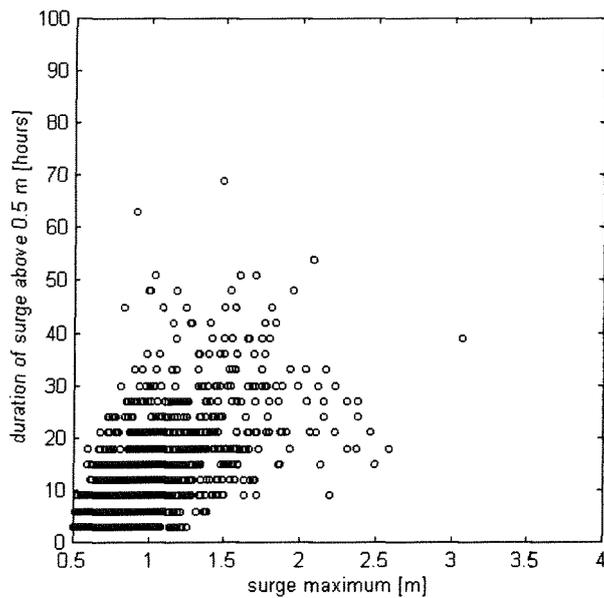


Figure 4.3 Scatter plot of surge maximum and duration above the 0.5 m level at Vlissingen.

In the range of low values, the dependence seems strong, but the cloud of samples widens with increasing height and duration. In fact, if only the points in figure 4.3 corresponding to surges above 1.5 m are considered, then the degree of scatter is similar to that in figure 2 of Chapter 2 taken from [Van Weerden et al., 1987, bijlage 11] of heights and durations of surges above 1.5 m at Hoek van Holland. [Van Weerden et al., 1987] concluded from their figure that surge height and duration above 0.5 m are independent. However, our comparison indicates that dependence is only revealed when lower surges are included as well, which makes it worthwhile do investigate this issue somewhat further using the data-set of Vlissingen.

For some events of long and relatively low surges at Vlissingen, the histories are plotted below.

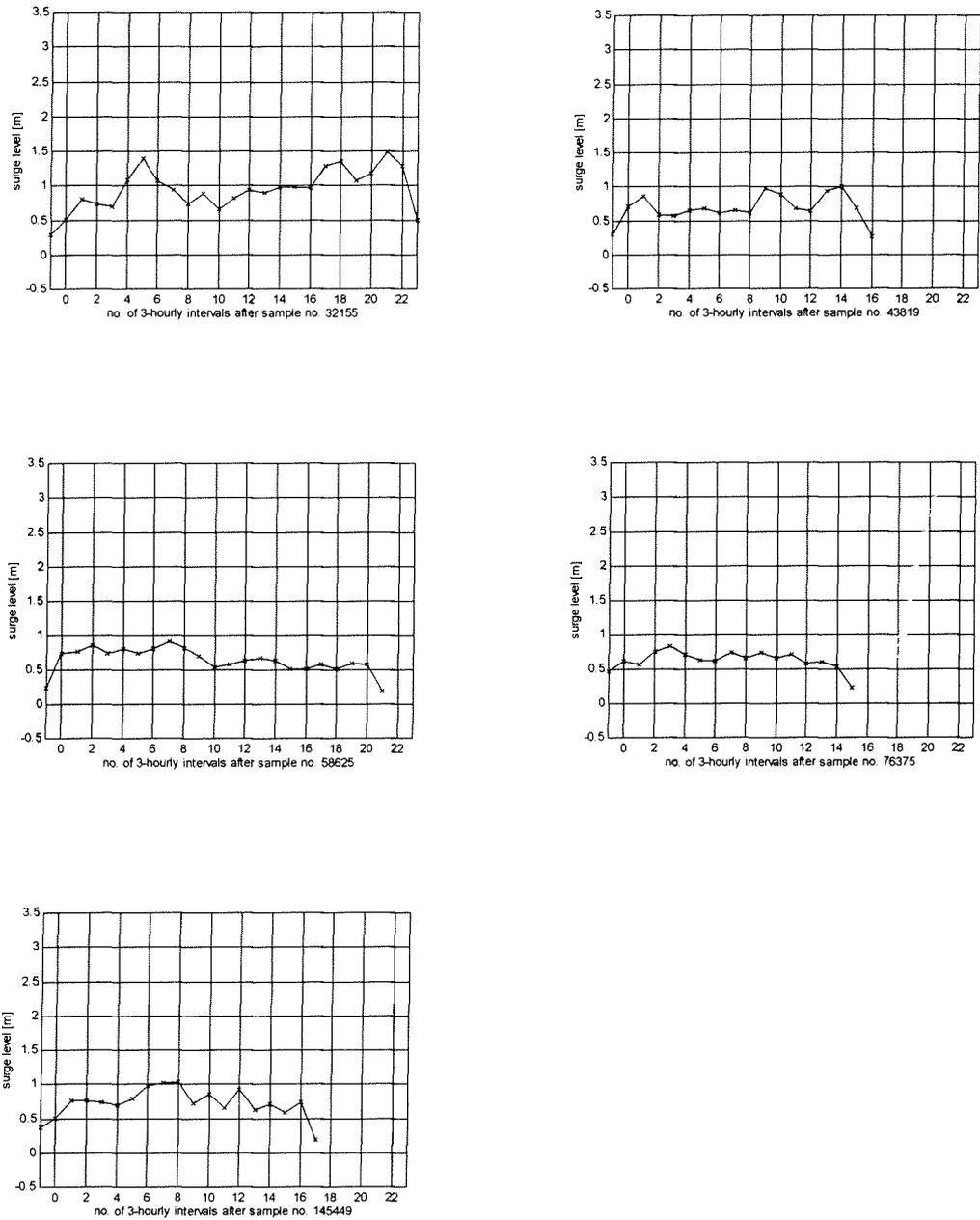


Figure 4.4 Examples of long and relatively low surges at Vlissingen

These surges differ markedly from the short and high surges. An arbitrary selection from that category is plotted in figure 4.5.

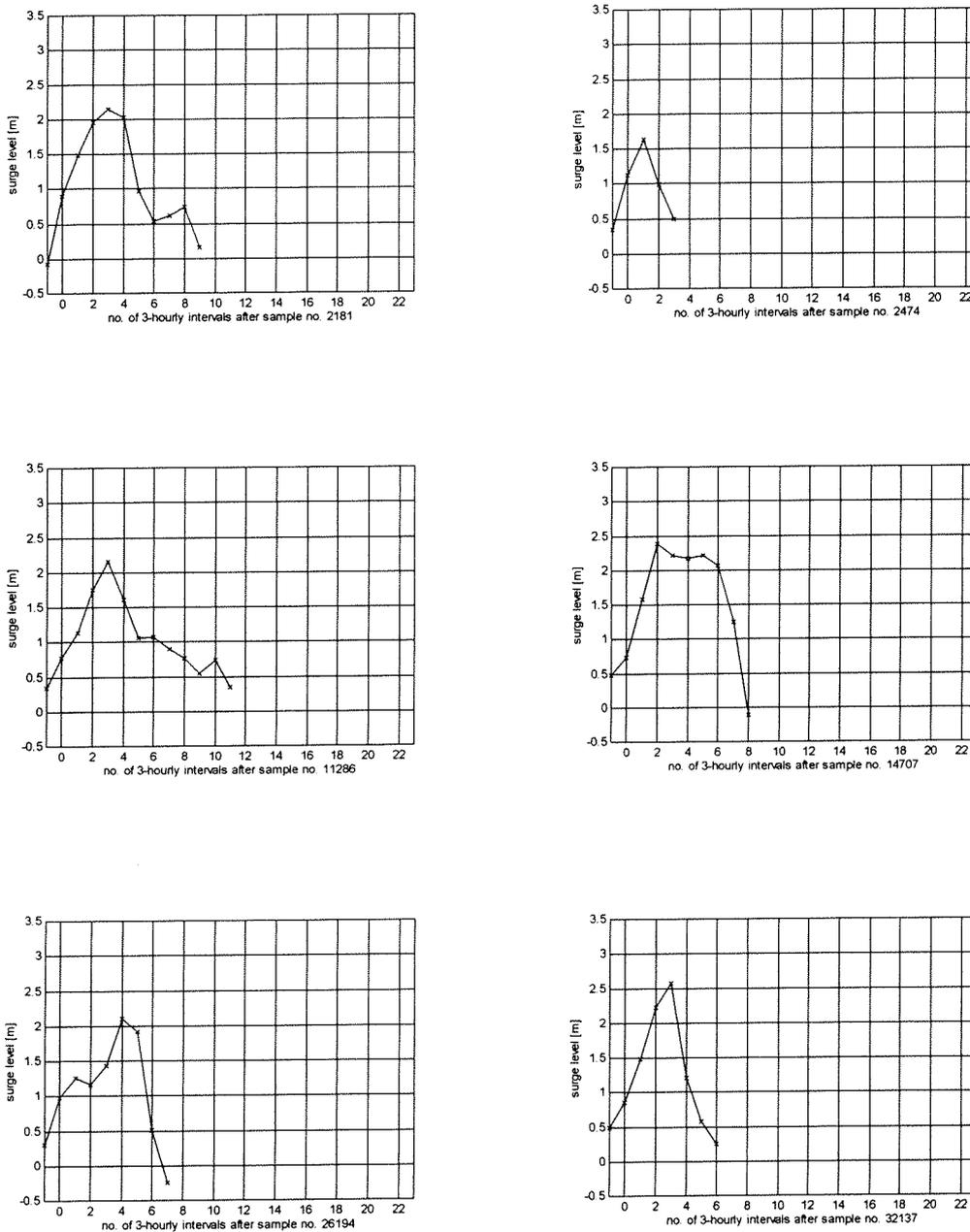


Figure 4.5 Examples of short and relatively high surges at Vlissingen

Comparison of long and short lasting surges shows that the shapes of both categories are markedly different. It may be worthwhile to compare surges of these extreme categories with the wind histories in order to find an explanation of the observed differences.

Figure 4.6(a) below shows also a scatter plot of surge maximum and duration above the 0.5 m threshold as in figure 4.3, but the values of both variables have been scaled in such a manner that the marginal distributions are both exponential. This is to be able to examine the dependence without being distracted by effects of the marginal distributions. The other subplots (b)-(e) shows the same type of scatter plot, but now for the duration of the surge above thresholds of 1.0 m, ..., 2.5 m.

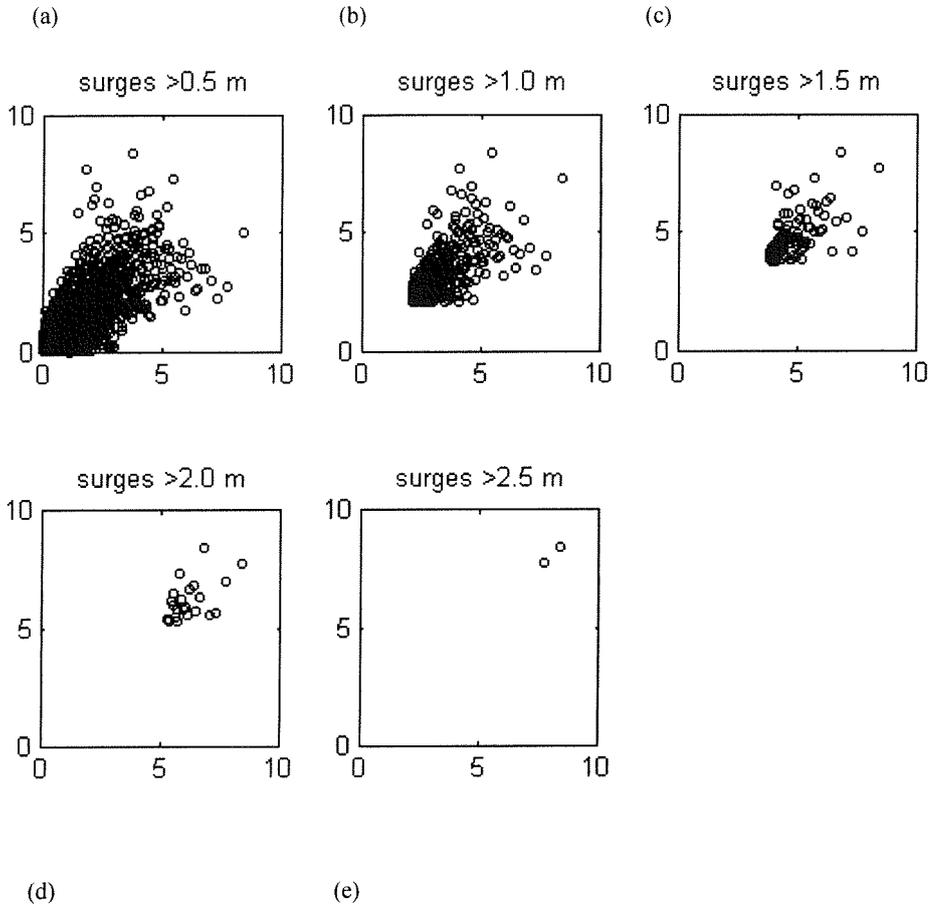


Figure 4.6 Transformed surge maximum (horizontal) versus transformed duration of surge excursion (vertical) above 0.5 m (a), 1.0 m (b), 1.5 m (c), 2.0 m (d) and 2.5 m (e)

When looking at duration above higher levels, the dependence between surge maximum and duration seems to strengthen. This picture is confirmed by the following analysis of the limiting dependence structure between surge maximum and duration above different levels.

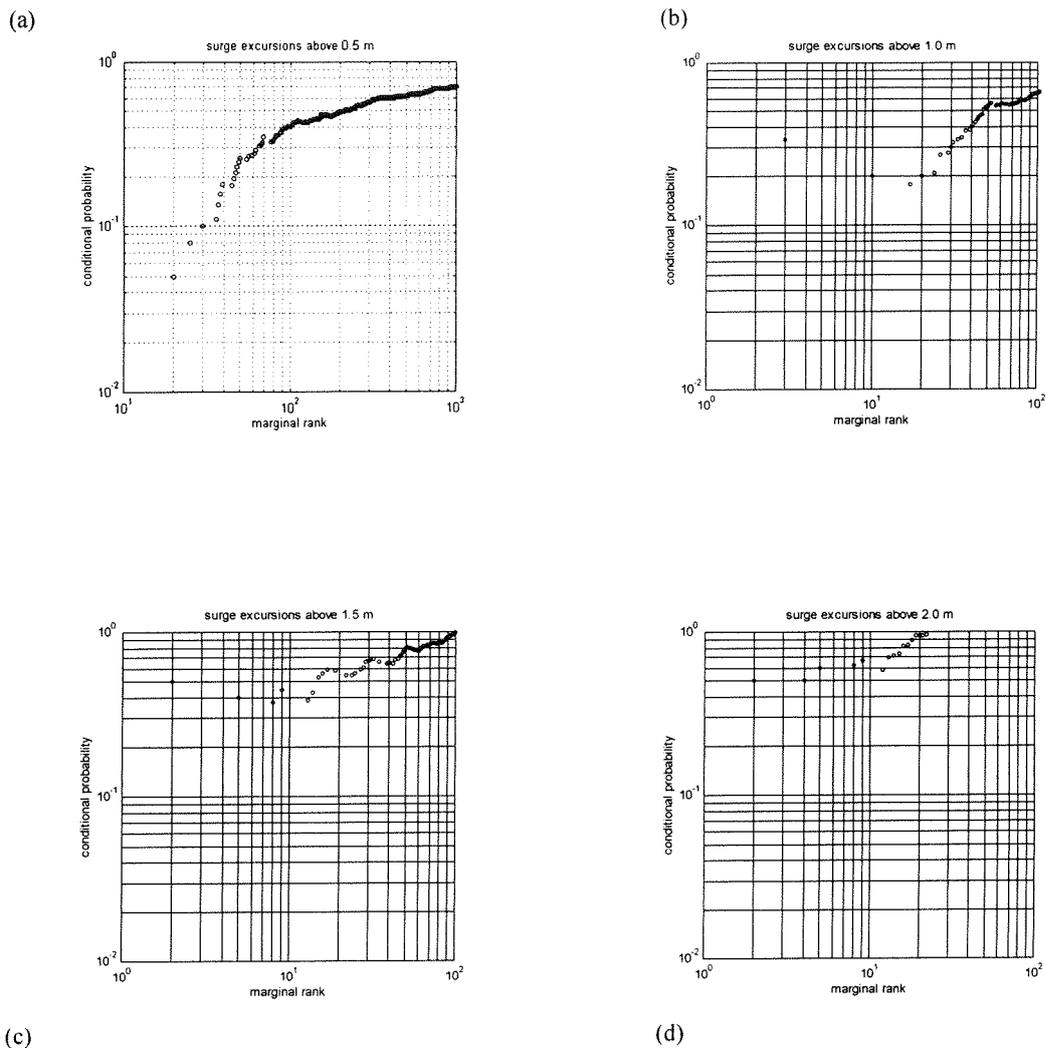


Figure 4.7 Results of a check of the strength of dependence between surge height and duration above 0.5 m (a), 1.0 m (b), 1.5 m (c), and 2.0 m (d). For an explanation, see the text below.

An  $f$ -quantile is the value of a variable exceeded with the frequency  $f$ . Figure 4.7 shows estimates the conditional probability  $p_f$  that the duration of surge above some level exceeds its  $f$ -quantile given that the surge maximum exceeds its  $f$ -quantile. In other words, if the values both variables are expressed in terms of the return periods of exceedance of these values (which is equal to  $1/f$ ) as in figure 4.8 below, then  $p_f$  is the conditional probability of a value in the doubly striped quadrant given that the surge maximum has return period in the vertically striped half-plane. Note that  $p_f$  does not alter when the variables are switched, so it really expresses only dependence.

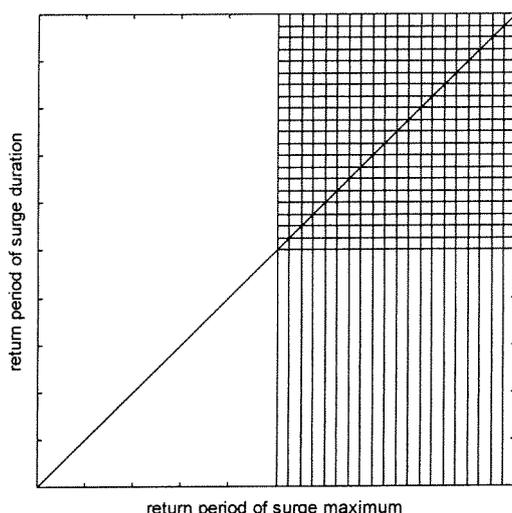


Figure 4.8 Illustration of the concept of asymptotic dependence

In figure 4.7, the frequency  $f$  of a level is expressed in terms of the number of storms in which the level has been exceeded (marginal rank); it is shown on the horizontal axis. If the conditional probability  $p_f$  tends to fluctuate around a fixed level with decreasing  $f$ , then surge height and duration are strongly dependent in the sense that sample points tend to be concentrated around the diagonal drawn in figure 4.8. They are then said to be *asymptotically dependent*. This is clearly not the case in figure 4.7. We see that the slope of a line through the points is less steep for the higher thresholds than for the lower thresholds, which indicates stronger dependence. In fact, the slopes in (c) and (d) are about 1:2, which means that surge heights and durations above levels of 1.5 m and 2.0 m are certainly *not independent* (otherwise the slope would be about 1:1).

The earlier study by [Van Weerden et al., 1987] concluded that surge maxima above 1.5 m and durations of the same surges at low levels are independent. We found that this does not hold for durations above higher thresholds. These conclusions do not need to be inconsistent. We nevertheless tried to verify the claim of [Van Weerden et al., 1987] by plotting the mean duration above a threshold as a function of threshold for different classes of surge height in figure 4.9. Independence of surge height and duration above the level zero would imply that these curves intersect at the level zero. What we find, however, is that the curves are more or less parallel, so surge height and duration above zero cannot be independent.

Surge Vlissingen: lines correspond to surge maximum classes (each class: 20 storms)

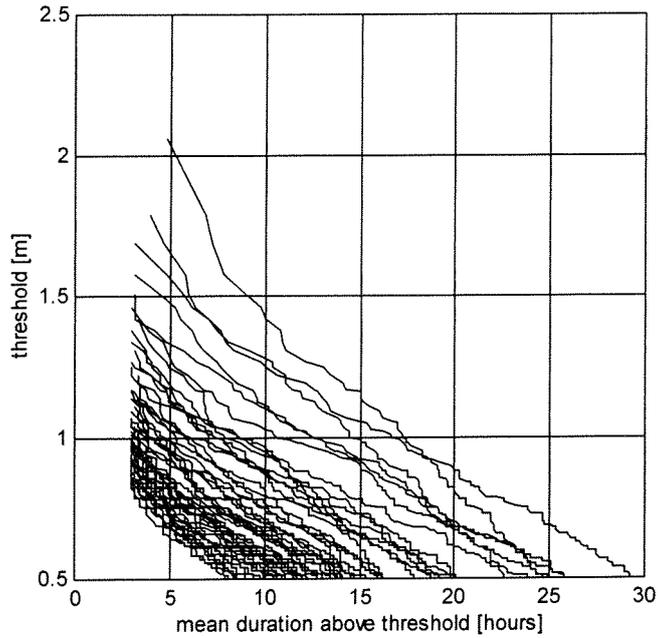
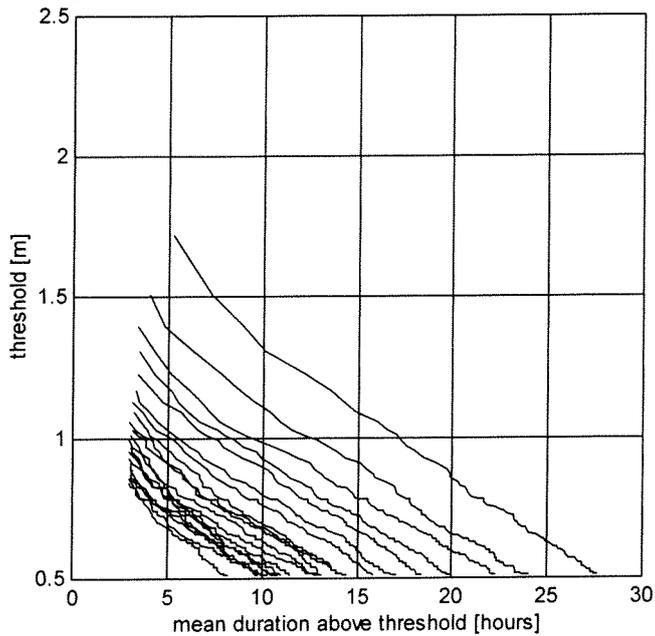


Figure 4.9 (a) Mean duration above a threshold versus threshold for different classes of surge height (each line stands for a class containing 20 surges). The curves to the right correspond with the highest surges.

Surge Vlissingen: lines correspond to surge maximum classes (each class: 50 storms)



*Onbegrijpelijk voor mij.*

Figure 4.9 (b) Mean duration above a threshold versus threshold for different classes of surge height (each line stands for a class containing 50 surges). The curves to the right correspond with the highest surges.

It must be noted that one should only adopt independence when strong evidence is present, because assuming independence will reduce the frequencies of occurrence of high loads. The present results do not support independence of surge heights and durations above a fixed threshold, even for low thresholds.

However, the dependence seems stronger for higher thresholds. This indicates that we may better look at durations above levels which are at some fixed distance below the surge maximum. An additional advantage is that this addresses specifically the surge profile near its peak and ignores the less relevant low values.

### **Duration above levels at a fixed distance below the peak**

The distance below the peak of a surge can be expressed in various ways, for example in metres. We have chosen instead to measure the distance of a level below the peak by the ratio of its exceedance frequency to the exceedance frequency of the peak. Advantage is that it will be easier to make comparisons between different locations. Figure 4.10 below shows plots of the strength of the dependence between surge height and duration at a fixed distance below the peak for different distances (ratio's of exceedance frequency). These plots have the same meaning as figure 4.7. For higher ratio's, there is a tendency to negative dependence (slopes steeper than 1:1); however, these results are not reliable because many data are missing for these high ratio's. However, for the smaller ratio's (considering durations at levels closer to the peak value), duration and height are independent (1:1 slopes).

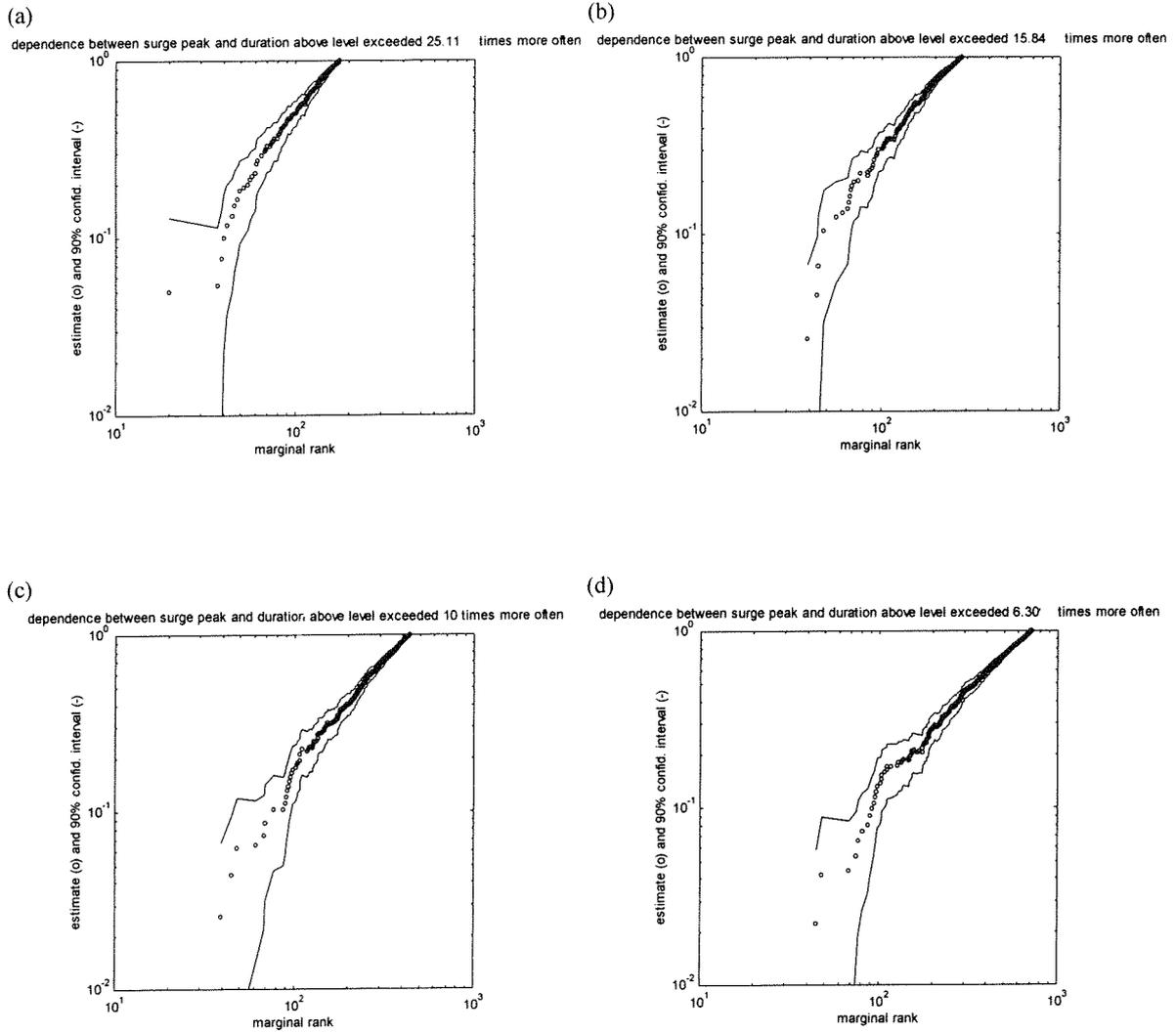


Figure 4.10 Results of a check of the strength of dependence between surge height and duration above a level exceeded  $q$  times more often than the peak, for  $q = 25, 16, 10, 6.3, 4.0, 2.5$  and  $1.6$ . For an explanation, see the text above and the text below figure 4.7.

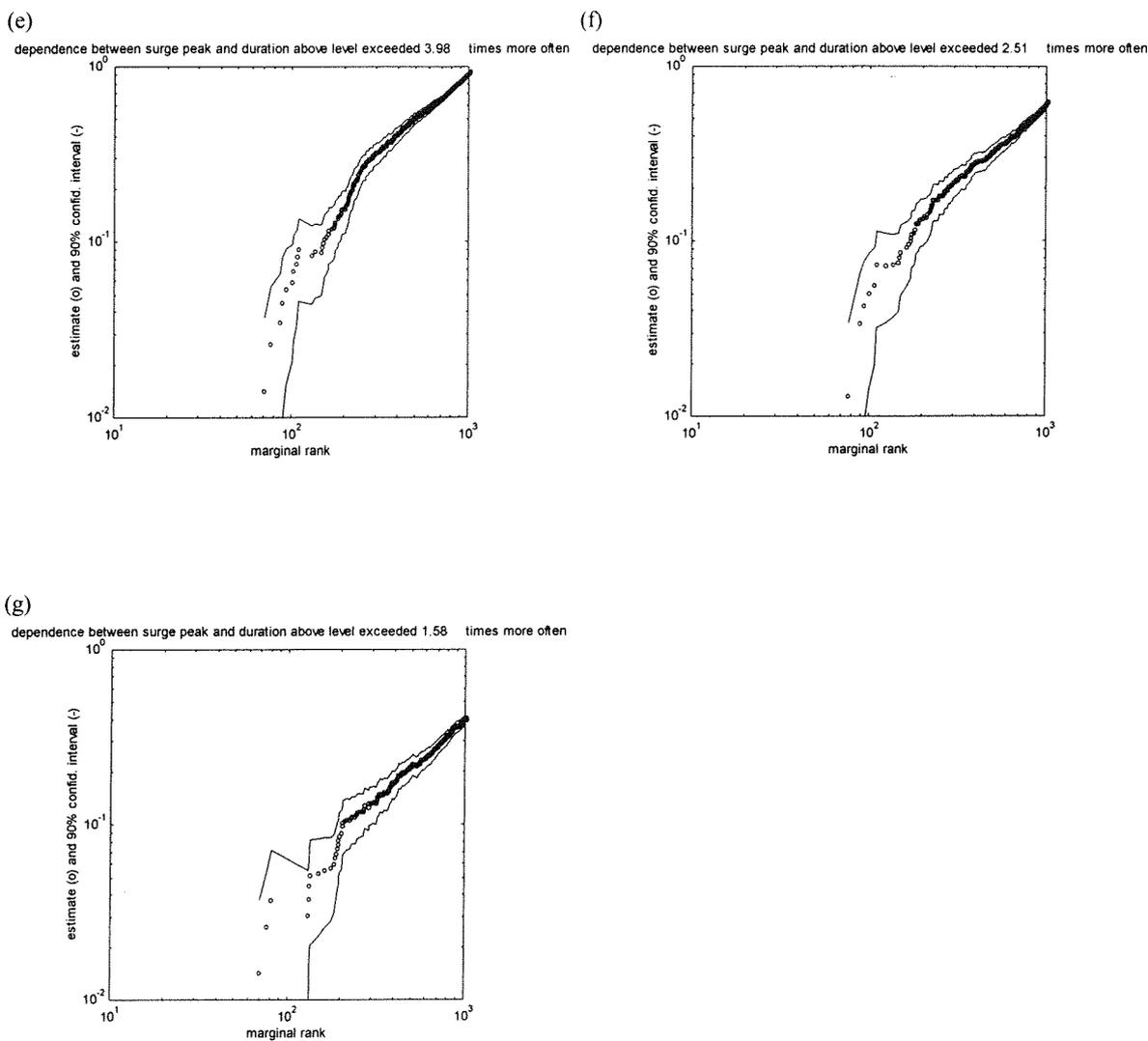


Figure 4.10 Results of a check of the strength of dependence between surge height and duration above a level exceeded  $q$  times more often than the peak, for  $q= 25, 16, 10, 6.3, 4.0, 2.5$  and  $1.6$ . For an explanation, see the text above and the text below figure 4.7.

Figure 4.11 shows the mean duration above a level as a function of the ratio of its exceedance frequency to that of the peak. According to figure 4.11, the mean duration for a fixed surge height is practically a linear function of the logarithm of exceedance frequency. So if the distribution function of the surge height exponential (which it nearly is), then the surge profile is on average triangular.

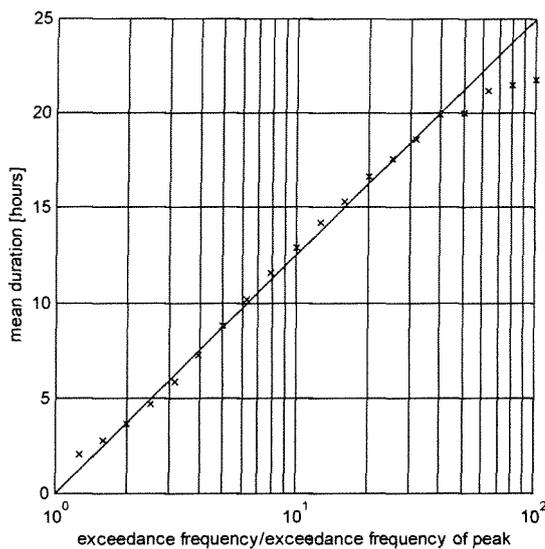


Figure 4.11 Mean duration above a level as a function of the ratio of its exceedance frequency to that of the peak.

The consequences for load modelling of the findings about surges in Vlissingen will be discussed in section 4.5.

#### 4.4 Analysis of wave and sea level data

So far, we have considered only one load variable, the sea level. However, dune regression is affected by wave parameters as well. Therefore, data of significant wave height, peak period, mean wave direction from the offshore location ELD and sea level, astronomical tide, wind speed and direction Den Helder were analyzed to define an approach for jointly modelling extremes and duration of extreme events of these variables. Wind and offshore wave parameters were both included because nearshore wave conditions may depend on either wind or offshore wave conditions, or on both.

The analysis was focused on the dependence of these variables. The dependence was analyzed in the same manner as done with surge height and duration in Section 4.3, but now also for combinations of more than two variables. Recapitulating, an  $f$ -quantile is the value of a variable exceeded with the frequency  $f$ . A key parameter of the dependence is the conditional probability  $p_f$  that all variables considered exceed their  $f$ -quantiles given that one of them has exceeded its  $f$ -quantile. The frequency  $f$  of a level is expressed in terms of the number of storms in which the level has been exceeded (marginal rank). If the conditional probability  $p_f$  tends to (fluctuate around) a fixed level with decreasing  $f$ , then heights and durations of surges are *asymptotically dependent*, which essentially means that all samples are concentrated along a single curve. Asymptotic dependence is particularly easy to model. Moreover, it is important to recognize asymptotic dependence, otherwise frequencies of failure of coastal structures may be underestimated.

When we restrict the analysis to the data which coincide with the surge maxima of all storms, all four variables significant wave height, peak period, surge and wind speed appear to be asymptotically dependent. This follows from figure 4.12 showing the conditional probability  $p_f$  remaining on the same level with decreasing  $f$ .

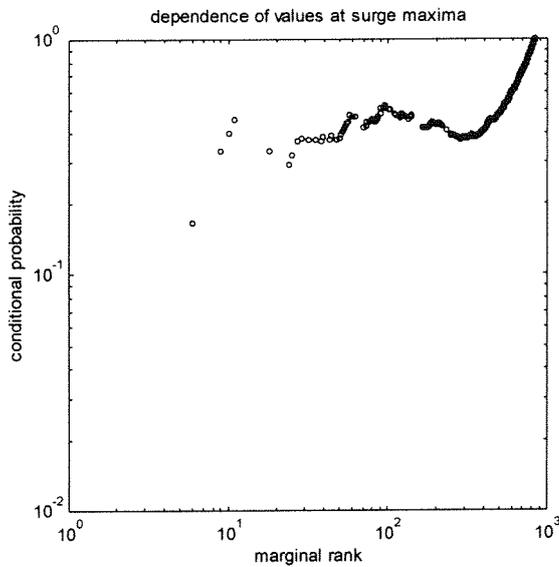


Figure 4.12 Results of a check of the dependence between values of significant wave height, peak period, surge and wind speed at the surge maximum (see text).

This result indicates some "minimal" form of dependence: at one particular moment during the storm, the variables are asymptotically dependent. Note that the maxima of variables other than surge do not need to coincide with the surge maximum. Therefore, this result is of limited use. However, any model proposed should at least include asymptotic dependence of values coinciding with the surge maxima. To check whether a wider form of asymptotic dependence holds, the same test was applied to storm maxima of the same four variables.

The result is plotted in figure 4.13 below.

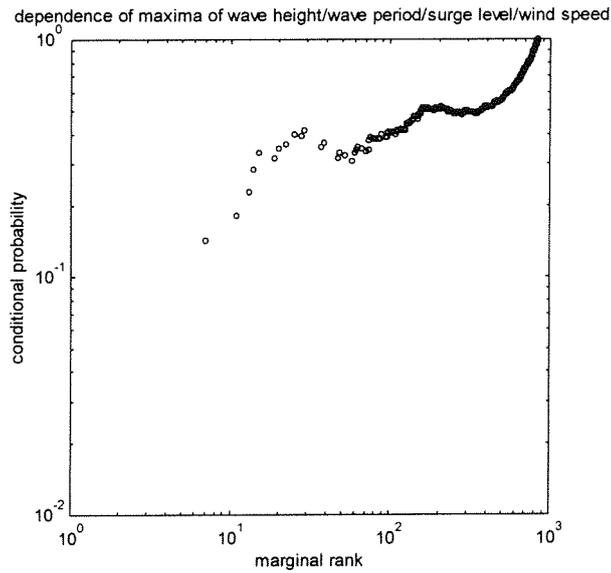


Figure 4.13 Results of a check of the dependence between maxima of significant wave height, peak period, surge and wind speed (see text).

The conditional probability  $p_f$  decreases steadily with decreasing  $f$ , so not all four maxima are asymptotically dependent. However, the following figure 4.14 shows that by leaving the peak period out, the maxima of the other three variables appear to be asymptotically dependent.

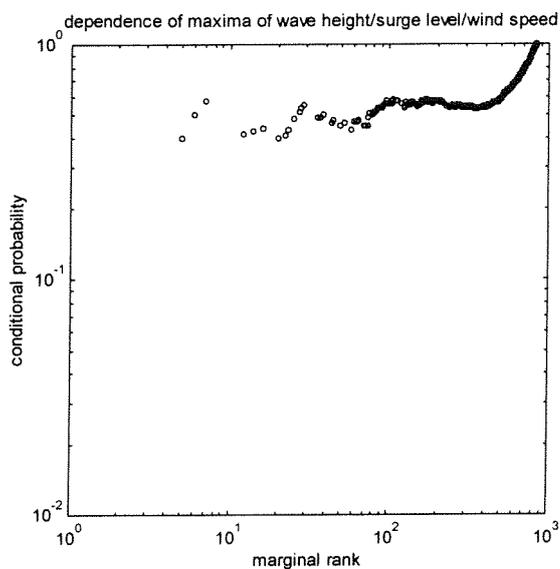


Figure 4.14 Results of a check of the dependence between maxima of significant wave height, surge and wind speed (see text).

This result is remarkable; significant wave height was even measured at another location than wind and surge. The figure below shows the same type of plot for only significant wave height and peak period. These are strongly associated as the conditional probabilities are overall high. However, a small but consistent decrease with decreasing  $f$  can be observed, which is clearly seen with an enlarged vertical scale. Such a trend is not found when enlarging the vertical scale of figure 4.14; see figure 4.16.

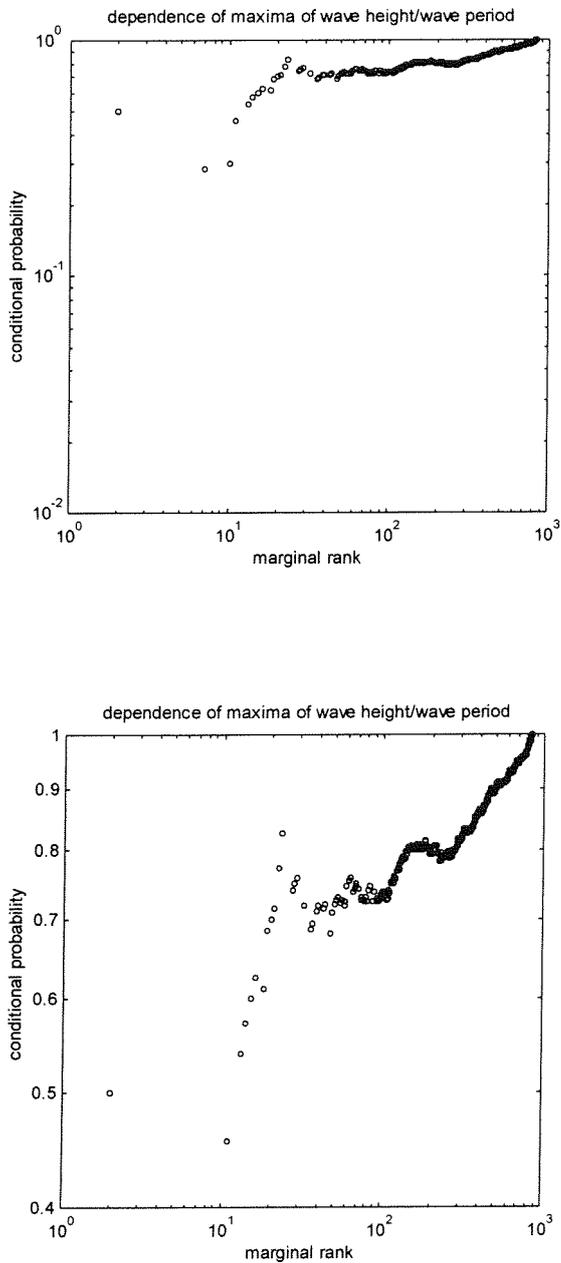


Figure 4.15 Results of a check of the dependence between maxima of significant wave height and peak period with the conditional probability plotted on two different scales (see text)

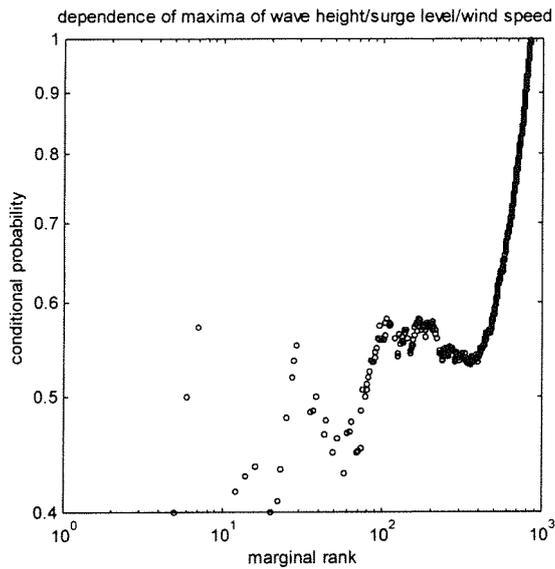


Figure 4.16 As figure 4.14 but with an enlarged vertical scale.

It is not clear why including peak period reduces the dependence between maxima so much. It has nothing to do with time-shifts between peaks of different variables because we consider the storm maxima. One possible reason is that long waves generated elsewhere have propagated toward the buoy at ELD (swell), and the peak of the spectrum contains a substantial amount of propagated energy. This hypothesis is supported by the finding that at the surge maximum, the peak period does seem to depend rather strongly on the other variables (figure 4.12).

In fact, the peak period is not a very robust parameter because it does not need to coincide with the periods in which the bulk of the surface variance is located. Therefore, it may be possible that the dependence increases if peak period is replaced by a period determined by spectral moments, such as the period derived from the magnitude of the average group velocity vector (which is flux of variance divided by the variance) through the dispersion relationship.

Overall, the degree of dependence found between the different variables is surprisingly high. A previous analysis [De Valk, 1996] did not reveal such a strong dependence but this study was using sea level data instead of surge data. Removing the tide apparently brings out the dependence more clearly. The consequences for formulating load models are discussed below.

## 4.5 Discussion

Two alternative approaches to model the maxima and durations of surges seem to emerge from the literature and from the analysis of the surge data of Vlissingen:

- 1 a model which describes durations of excursions above fixed thresholds. Both our analysis and [van Weerden et al., 1987] seem to indicate that the dependence between surge height and duration of the surge above a low threshold is weak.
- 2 a model which describes the length of time that the surge is above a level at a given distance below the peak.

The analysis in Section 4.3 shows that the second approach is the most promising. The length of time that the surge is above a level at a fixed distance below the peak can be modelled as independent of the height of the surge. This provides a good description of the surge profile in particular near the peak, which is the most important part anyway. The distance of a level below the peak has been measured by the ratio of its exceedance frequency to that of the peak. The mean duration above a level as a function of this ratio is approximately linear, which suggests that an average surge profile can be described by a triangle when the surge height has an exponential distribution. To estimate the frequency of failure of a structure depending on surge height and duration, a parametric model of storm surges could be employed. It prescribes the distribution functions of surge height and its duration over a variable threshold, assuming a triangular profile of the surge. Some correction of the statistics of the surge height for surge-tide interaction may be needed. This is then combined with a distribution function of tidal amplitude and phase.

The model then contains four mutually independent random variables:

- surge height,
- duration above a variable threshold at fixed distance from the peak,
- tidal amplitude,
- tidal phase

and may in addition take surge-tide interaction into account in transforming these variables to sea level. To estimate the probability of failure of a dune, the joint distribution function of these four parameters must be integrated over the failure region. This failure region is approximated by interpolation between runs of the dune erosion model driven by various combinations of values of the four variables. A method based on extreme value theory developed in the framework of the UBW project of Rijkswaterstaat [Vrouwenvelder et al, 1997; *Bijlage B.4.1*] might be used to integrate over the failure region. This method generates more extreme and rare values of the four variables in a particular manner and estimates the frequency of failure from these modified surges. It can be applied using either observations or Monte-Carlo simulations. When using observations, we might even replace parametric surge profiles by the original measured profiles, which are then scaled and dilated to generate more extreme events. A drawback of this approach is that it requires the construction and use of a fast *dynamic* approximation of the dune erosion model. It seems unlikely that using measured profiles would make a big difference, so it is recommended to start with computations based on

parametric surge profiles. This will be more acceptable as well because it is more compatible with current practice.

In determining marginals, a major concern is the large deviation observed between the sample distribution of surge maxima derived from the difference of 3-hourly sea level and tide and the distribution of surge maxima estimated from the difference of sea level and tide *maxima*. A difference can be expected because of the difference in sampling rate and surge-tide interaction, which needs to be clarified. It must be ensured that exceedance frequencies of sea level maxima reconstructed from those of surges and tides are consistent with the established values of [Phillippart et al., 1995]. The next step in the modelling of a storm profile is to include wave parameters and wind in the model. The analysis of section 4.4 has shown that this is feasible, because maxima of surge, wind speed and significant wave height during a storm are *asymptotically dependent*. This is a strong form of dependence which simplifies the model considerably. Peak period seems to be more weakly dependent on the other variables, which may be caused by advection of long waves from elsewhere. This may be ignored initially, which is somewhat conservative but will keep the model simple. Besides the dependence between peak values, average peak shapes and statistics of time-shifts between peaks should be estimated. The resulting model provides the joint distribution function of the values of all variables at the peak of the surge, which should match the observed dependence of these values.

## 5 Conclusions and recommendations

### 5.1 Conclusions

#### *Conclusions from the sensitivity analysis of the dune erosion model*

- 1 Preliminary results indicate that the frequency of failure of a dune profile is mainly determined by the frequency of occurrence of extreme surge height; the frequency of occurrence of extreme duration of the surge above the level zero is less important. The calculations leading to these results are based on the assumption of independence of surge heights and durations at a low level from [Van Weerden et al., 1987].
- 2 In computations of dune regression with the model DUROSTA, dune erosion appears to be sensitive to the tidal phase, at least for surges of relatively short duration; see figures 3.15-3.16. This indicates that an accurate representation of the profile of the surge around its peak is of some importance as well.

#### *Conclusions from the data-analysis*

- 3 In contrast with a conclusion of [Van Weerden et al., 1987], the analysis of surge data from Vlissingen shows that surge height and duration above a fixed low level are dependent, although the dependence is not very strong; see figures 4.3-4.9. On average, high surges last longer than low surges.
- 4 This implies that frequencies of occurrence of extremely long surges may be somewhat more important in determining the frequency of failure of a dune profile than suggested by the preliminary conclusion 1.
- 5 We found that the duration of a surge above a level at a fixed distance below its peak value is nearly independent of the height of the surge peak; see figure 4.10 and the preceding explanation.
- 6 This means that on average, the profile of a surge around its peak is the same irrespective of the height of the peak. The average profile is nearly triangular; see figure 4.11.
- 7 This makes it possible to represent the top of a surge in a rather simple manner by two mutually independent parameters: its peak height, and its duration above a level exceeded say five times more often than the level of the peak. This describes the part of a surge profile which is most critical for the reliability of dunes and other coastal structures (see 1 above).
- 8 Storm maxima of other relevant variables such as significant wave height, peak period and wind speed generally do not coincide with the surge maximum. However, we found that *asymptotic dependence*, a strong form of dependence, applies to
  - the values of all four variables at the maximum of the surge

- the values of the storm maxima of surge, wind speed and significant wave height. (see figures 4.12 en 4.14 and accompanying text).

Based on these clear results, it must be feasible to construct a parametric model of the peaks of all four variables which incorporates time-shifts between their peaks in such a way that the dependencies are consistent with the results of the data-analysis.

- 9 Construction of such a model will require more accurate statistics of surge peak heights than are available at present. Determining statistics of surges and tides which agree with the established exceedance frequencies of sea levels will be somewhat complicated by tide-surge interaction.
- 10 An alternative to the load model proposed under 8 is to estimate frequencies of failure of dune profiles by a method with scales measured profiles of different variables to simulate extreme storm events. Although such a technique may be simple from the statistical point of view, a parametric model as proposed under 8 will be easier combined with numerical simulation of dune regression.

## 5.2 Recommendations

- 1 To improve the analysis of surge data in this study, it is recommended that a similar analysis be carried out using hourly data instead of three-hourly data. In particular the surge profile near the peak may be determined more accurately from hourly data.
- 2 An analysis of surge data is needed to determine accurate statistics of peak heights , which is missing at present. The analysis should reconcile the apparent discrepancy between exceedance frequencies of surge maxima from 3-hourly tide residuals and frequencies from high-water surges (the differences between sea level maxima and astronomical maxima). Both surge-tide interaction and the effects of sampling frequency should be addressed.
- 3 If these analyses of surge data prove successful, they can be performed for a number of tide gauge stations along the Dutch coast where long data records are available.
- 4 Once improved statistics of surge heights and durations are available, it is recommended that a case study be carried out estimating the frequency of failure of a dune using the dune erosion model DUROSTA. In this study, wave parameters can still be related deterministically to the surge. This is a suitable approximation in view of the strong dependence between surge, significant wave height and wind speed found in the present study.
- 5 Next, the load model can be extended with wave parameters and wind along the lines indicated in section 4.5 of this report and evaluated in a second case study. Such a model could also involve time-varying wave and wind directions. A comparison can then be made with the simpler model which assumes deterministic relationships between surge, waves and wind in order to determine whether the added complexity of modeling different variables individually is worthwhile.

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