MULTI-VARIATE STATISTICS OF HYDRAULIC BOUNDARY CONDITIONS FOR THE ROTTERDAM HARBOUR EXTENSION

P.B. Webbers[1], H.G. Voortman[2], P.H.A.J.M. van Gelder[3] and J.K. Vrijling[4]

Abstract:

The objective of this paper is to describe the hydraulic climate of the Southern North-Sea by statistical models and physical laws for wave heights, wind setup, wave periods and wind speed. The focus is on the selection and calibration of parametric physical models for the use in the description of the joint probability distribution of hydraulic loads. For the validation and calibration of these models, observations have been used. An application is presented about the Rotterdam harbour extension.

INTRODUCTION

In order to face future needs of space in the Rotterdam harbour, a land reclamation is under study. The project area of the planned harbour extension, called "Maasvlakte 2", is located along the southern North Sea coast (figure 1).

Sufficient protection of the area against flooding is created by a number of structures, like breakwaters, dikes, dams and dunes. It is important for design to determine the hydraulic loads on these structures. The origin of these loads are the different states of the hydraulic climate. To make probabilistic design and risk-based optimisation possible, the loads need to be described by a joint probability density function (JPDF). The hydraulic boundary conditions that are relevant for design are the water level (h) and the following long-term wave characteristics: significant wave height (H_s), peak period (T_p) and main wave direction (T_{h0}).

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The objective of the research in this paper is to describe the hydraulic climate at Maasvlakte 2 by statistical models and physical laws. The focus on this paper is on the selection and calibration of parametric physical models for the use in the description of the joint probability distribution of hydraulic loads. For the validation and calibration of these models, observations will be used. Similar research on modelling of the hydraulic climate has been done by Vrijling en Bruinsma (1980), Battjes (1984), De Valk (1996), Repko et al (2001), van Marle (1999) based on a method proposed by De Haan and Resnick (1977), Voortman (2002) and Hawkes et al (2002).

Suitability for the design process is an important requirement for the overall model. Designers generally require models that can give them quick but reliable insight in the sensitivity of a design to different variables. Comparing different design alternatives in an early stage of projects has to be possible. Consequently the models need to be as simple as possible, but in correspondence with reality.

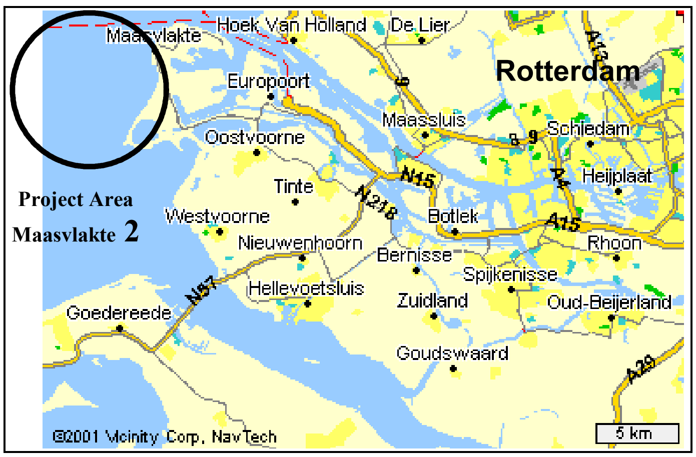

Figure 1: Location of project area Maasvlakte 2

The research in this paper is limited to the so-called Ultimate Limit State (ULS), which describes the states in which a structure collapses. For ULS the extreme events (like storms) need to be described. In case of Maasvlakte 2 only the combination of extremely high waves and extremely high water levels are studied. A similar approach as presented in this paper can be used for the hydraulic climate during daily situations, the Serviceable Limit State (SLS).

The focus in the paper is on a description of the hydraulic climate in the form of a JPDF at a relatively deep water location. In most cases only relatively deep water observations are available. The reason for performing measurements offshore is that nearshore data are generally not homogeneous, which makes statistical calculations useless. In a future stage of research a translation step has to be carried out to the shore (Maasvlakte 2) to obtain the description of the JPDF at this location. A possible alternative for the translation step could be for example to use the JPDF at relatively deep water as input for a physical-numerical model like SWAN (*Simulation of Waves Nearshore,* Booij et al. (1999)). This translation step is left out of consideration in this research but still has to be accomplished in further research (see figure 2).

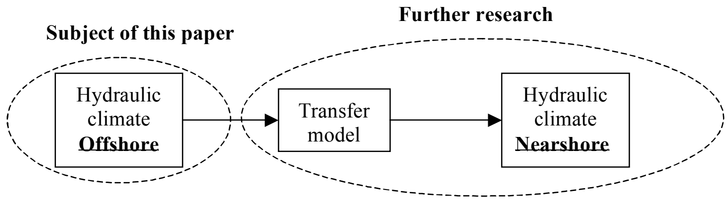

Figure 2: Subject of the paper

In many cases designers have to deal with a prescribed small probability of failure for the design, which leads to the need of extrapolation of extreme event data. The lack of extreme event data makes it difficult to decide which probability distribution is suitable and will describe the processes in a proper way.

In this paper extrapolation guided by mathematical models based on physical laws is used to solve this problem. In this way implementation of physical knowledge in statistical extrapolation methods is achieved.

APPROACH TO THE PROBLEM

To obtain a transparent approach to the problem the following steps are taken. Firstly a proper description of all relevant physical processes is developed, which forms the theoretical framework for describing the hydraulic climate.

Secondly, physical models are identified that describe the hydraulic conditions as a function of a input variable. In general these models describe the dependence between pairs of variables, like water level and wave height or wave height and wave period. A selection of models needs to be made such that all relevant variables are described.

Thirdly, the models are implemented, also consisting the calibration and validation based on field data.

Fourthly, the different models are linked together to find the description of the overall model.

FRAMEWORK PHYSICAL RELATIONS HYDRAULIC CLIMATE

In figure 3 the processes are given which determine the hydraulic climate. The hydraulic boundary conditions are formed by on the one hand the water level and on the other hand the long-term wave characteristics (H_s, T_p, T_{h0}). The water level can be seen as built up from two stochastically independent variables, the wind set-up and the astronomical tide. The wind-set up and the wave characteristics are caused by the wind field. Another influence on the wave characteristics and the wind set-up is the water depth. This water depth can be seen as built up of the bathymetry and the water level.

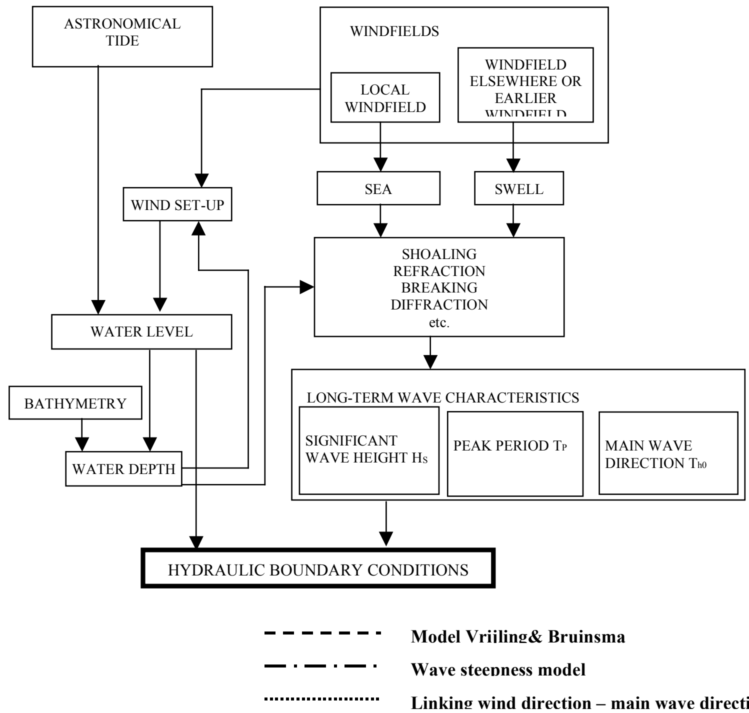

Figure 3: Diagram of the theoretical framework of physical relations (processes) used for the derivation of the description of the hydraulic climate (after Vrijling and Bruinsma (1980))

CHOICE OF PARAMETRIC PHYSICAL MODELS

The dependence models chosen to describe parts of the hydraulic climate, are listed below.

Water level h – significant wave height H_s

To describe the strong dependence in the North Sea between the water level and the significant wave height a parametric model is applied, which is proposed by Vrijling and Bruinsma (1980) for the design of the Eastern Scheldt Storm Surge Barrier.

The main assumptions in this model are:

- The astronomical tide can be seen as stochastically independent of wind set-up (shown by Schalkwijk (1947) and Weenink (1958)), which leads to:

$$\underline{h} = \underline{a} + \underline{s} \quad (1)$$

  where a represents the astronomical tide during a maximum high water level in [m +NAP] and s represents the wind set-up in [m]. The underlining of a variable means that the variable is stochastic.
- The significant wave height and the wind set-up are caused by the same common cause, the windfields, so that the wind speed may be used to establish a relation between water levels and wave heights

The wind set-up model described by Weenink (1958) leads to the following expression for each wind direction:

$$u = \sqrt{\frac{s \cdot g}{\alpha}} \tag{2}$$

where u represents the wind speed, g represents the acceleration of gravity in [m/s^2] and α is a dimensionless constant depending on the wind direction.

By combining the wind set-up model described by Weenink and the astronomical tide, the water level as a function of wind speed can be derived for each wind direction.

By using a wave growth formula of Bretschneider (1952, 1958) for the wind driven part of the waves and using the wave height of swell for calibration, the following wave growth formula can be obtained for the overall wave height:

$$H_s = \sqrt{H_{s,swell}{}^2 + \left[0.283 \cdot \frac{u^2}{g} \cdot \tanh\left[0.53 \cdot \left(\frac{g \cdot d}{u^2}\right)^{0.75}\right] \cdot \tanh\left[\frac{0.0125 \cdot \left(\frac{g \cdot F}{u^2}\right)^{0.42}}{\tanh\left[0.53 \cdot \left(\frac{g \cdot d}{u^2}\right)^{0.75}\right]}\right]\right]^2} \tag{3}$$

where

F = fetch [m]

u = wind speed [m/s]

d = water depth [m]

$H_{s,swell}$ = significant wave height of swell

By applying characteristic wind speed as the combining variable, and for d the average water depth of the North Sea basin and for F the possible fetch in the main wind direction, the relation between the significant wave height and the water level is achieved. Still possible breaking of waves must be checked.

Significant wave height H_s -peak period T_p (wave steepness model)

To find the dependence between H_s en T_p the wave steepness model proposed by Vrijling (1996) and applied by Repko (2001) is implemented. The main assumptions in this model are:

- The deep water wave steepness s_{0p} is stochastically independent of the significant wave height H_s;
- The significant wave height of swell is negligible compared to the significant wave height of wind driven waves during extreme storm events.

Repko uses the deep water wave steepness defined by:

$$s_{0p} = \frac{H_S}{\left(\frac{g \cdot T_p^2}{2 \cdot \pi}\right)} \tag{4}$$

Another more theoretical model based on a universal relation between total wave energy (actually the variance of the surface elevation), the peak frequency of the energy spectrum and the wind speed, for wind driven waves, is proposed by Mitsuyasu et al (1980). A comparison is made between this model and the first assumption of the wave steepness model mentioned above.

Based on Mitsuyasu et al, Battjes (1984) derived the following equation:

$$H_s^2 T_p^{-3} = c \cdot g \cdot u \tag{5}$$

where c equals $0.99 \cdot 10^{-4}$.

Substituting equation (4) in equation (5) the deep water wave steepness can be written as:

$$s_{0p} = \frac{2\pi \cdot c^{2/3}}{g^{1/3}} \cdot \frac{u^{2/3}}{H_s^{1/3}} \tag{6}$$

Equation (5) is used for the actual comparison.

Main wave direction T_{h0} - main wind direction

The combination of extreme water levels and extreme wave heights are assumed to be caused by wind fields with a similar characteristic wind direction as the wind field with the largest possible fetch. The main wave direction T_{h0} is assumed to equal this main wind direction.

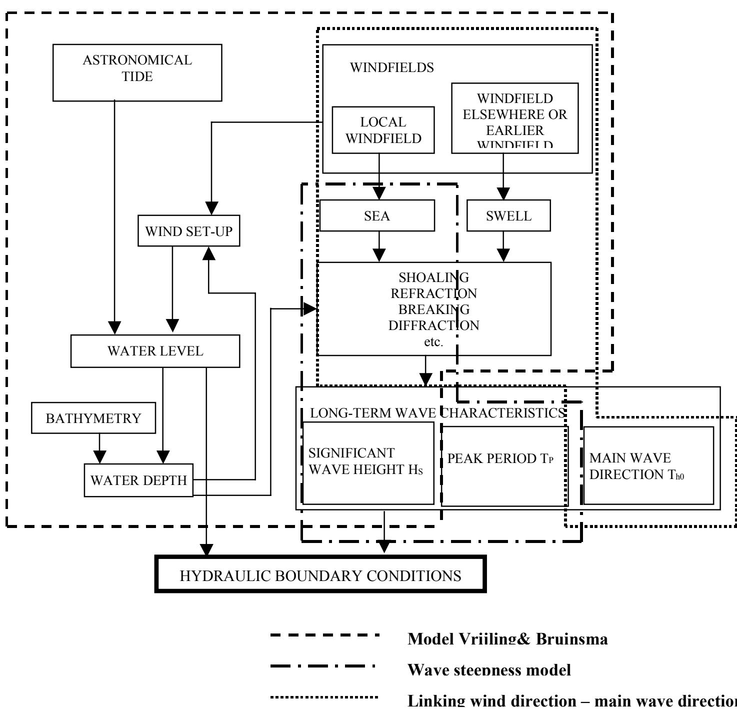

Figure 4: Diagram of the three integral models for description of the hydraulic climate

Figure 4 shows the chosen models covering different parts of the theoretical framework.

The JPDF of the hydraulic climate can be derived by combining the marginal distribution of a chosen input variable, the dependence models based on physical relations and model uncertainties.

In this case, the water level is used as the input variable (see also Vrijling and Bruinsma, 1980). The value of the input variables is not known with certainty. Therefore they need to be described by probability models. Long records of water level observations, also in extreme situations (for instance the extreme storm surge 1953) are available, has led to this choice.

Thus, the JPDF can be derived:

$$f_{\underline{h},\underline{H}_S,\underline{T}_p,\underline{\theta}_{h0}}\left(h,H_S,T_p,\theta_{h0}\right)=f_{\underline{T_p}|h,H_S,\theta_{h0}}\left(T_p|h,H_s,\theta_{h0}\right)\cdot f_{\underline{H_s}|h,\theta_{h0}}\left(H_s|h,\theta_{h0}\right)\cdot f_{\underline{\theta_{h0}}|h}\left(\theta_{h0}|h\right)\cdot f_{\underline{h}}\left(h\right) \tag{7}$$

IMPLEMENTATION AND VALIDATION OF MODELS

Case description

In the case of Maasvlakte 2 no hydraulic measurements are available at the location of the project area. Nineteen years of simultaneous observations of hydraulic conditions are available on relatively deep water, at the Euro-0 platform (see figure 5). Wind observations are available from the location of Hook of Holland.

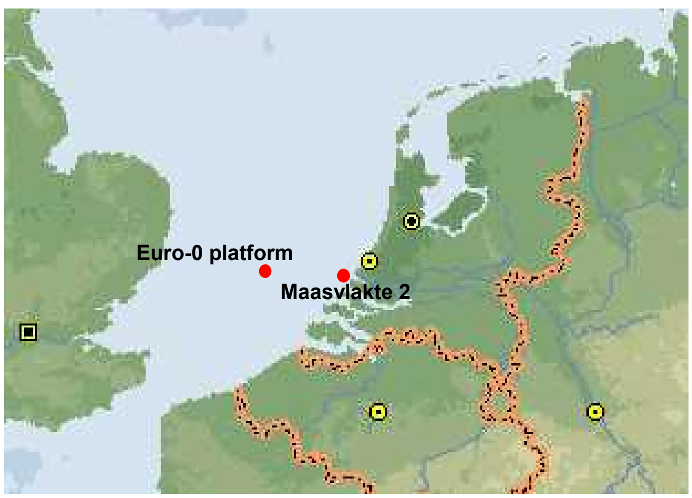

Figure 5: Location of project area and observation station (Euro-0 platform)

Data selection

From the available data 10 independent storms are extracted, which can be characterized by extremely high waves and extremely high water levels. The selection takes place by using the widely used Peak-Over-Threshold (POT) method and comparing the results with the method of depression route selection as proposed in the Report of the Delta Committee (1960). The POT method is used for starting variable *h*. For every independent observation of *h*, simultaneously measured values are selected of the following variables:

- Significant wave height H_s ;
- Peak period T_p ;
- Main wave direction T_{h0} ;
- Wind speed u ;
- Wind direction.

After analysing the selected storms it appeared that those storms were all from the same North Westerly direction. It also appeared that those North westerly storms all were caused by fixed routes of the depression cores. The cores of the depression, causing the 10 North Westerly storms, all follow a very similar route from the region somewhere between Iceland and Scotland towards the area Denmark and North Germany. This is in harmony with the route Bouws (1978) described as characteristic for the extreme wave climate.

The route of one of the selected storms is shown in figure 6 and the development of the wind and wave direction is shown in figure 7. In the Netherlands, extreme storm events are reported by RIKZ (see RIKZ, various years).

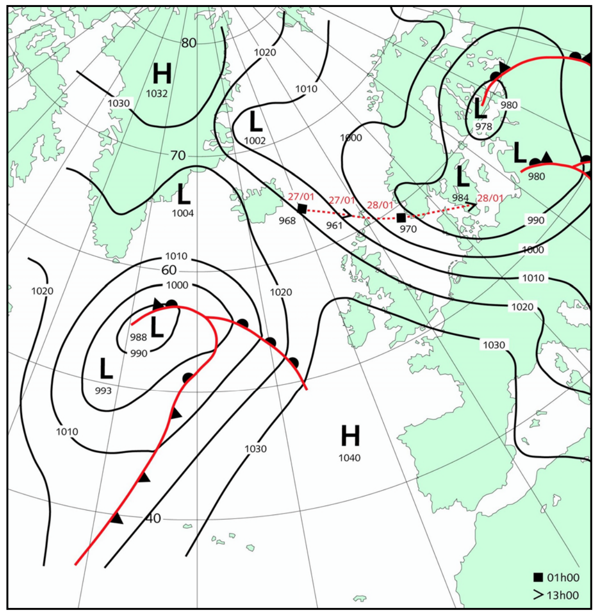

Figure 6: Map with the route depressions and the air pressure distribution above the North Sea (RIKZ, 1994))

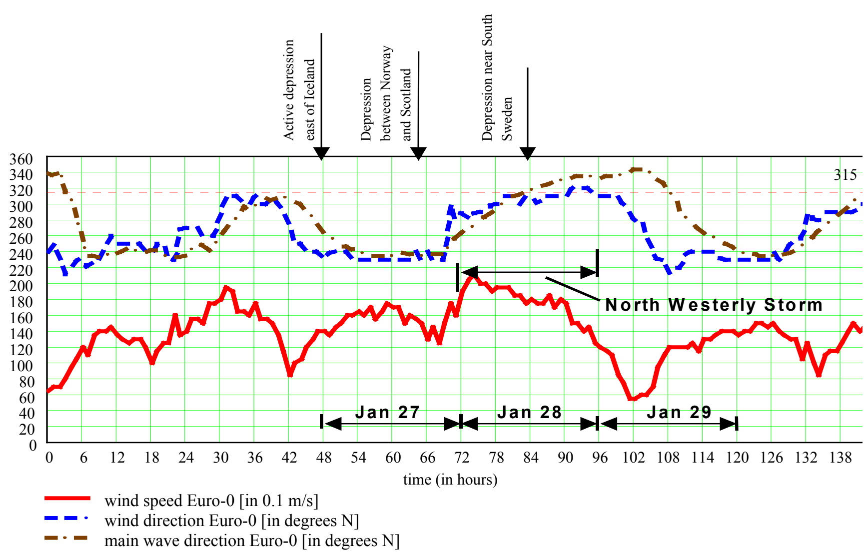

Figure 7: Development in time of the wind speed, wind direction and main wave direction during a storm at Euro-0 (28th January 1994), including comment from RIKZ (1994)

Figure 8 shows the result of using the wind set-up model described by Weenink (1958) combined with the average as proposed by Vrijling and Bruinsma (1980). Considerable uncertainty exists on the used wind set-up-wind speed relation, may be caused by using the wrong characteristic wind speed.

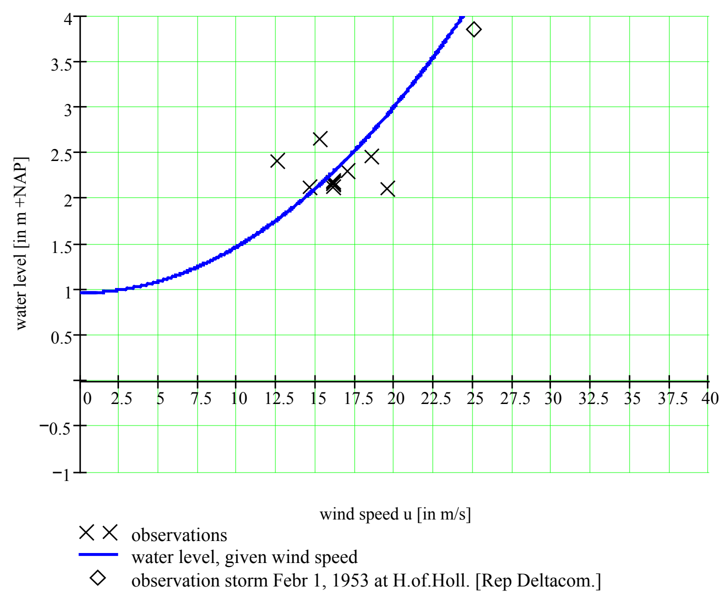

Figure 8: water level as a function of wind speed (platform Euro-0)

By using the same wind speed, the North Westerly wind direction in the wave growth formula of Bretschneider (eq. 3), figure 9 can be obtained, in which the amount of swell is varied. The fetch F is 800 km and the water depth d of the North Sea equals 35m. Apparently breaking of waves can be neglected at Euro-0 (Webbers 2000).

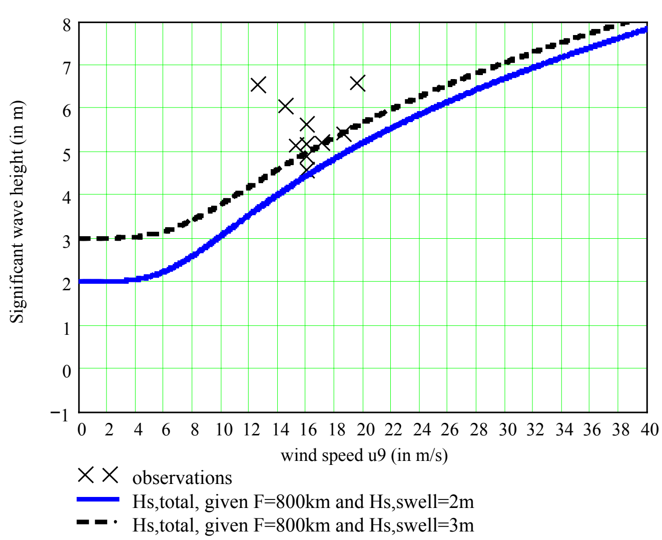

Figure 9: Significant wave height as a function of wind speed (platform Euro-0)

According to the model of Vrijling and Bruinsma (1980) the characteristic wind speed is applied as the common variable. Subsequently the relation between the significant wave height and the water level is achieved (figure 10).

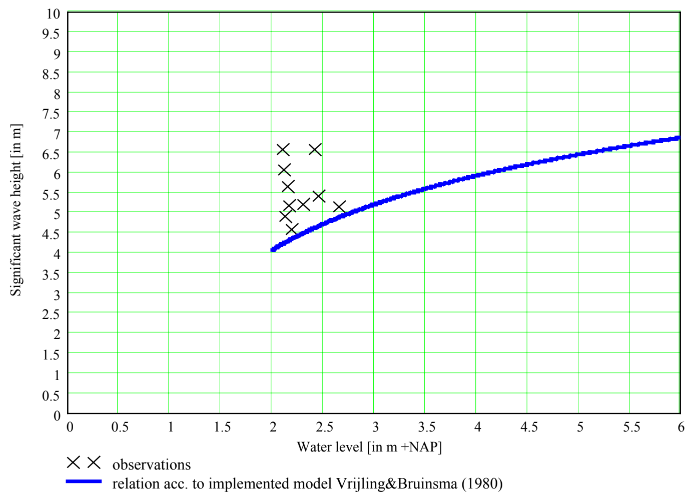

Figure 10: Significant wave height as a function of water level (platform Euro-0)

Comparing the observations to the parametric model, it appears that the model gives a underestimation of the wave heights. It is assumed that this underestimation is caused by neglecting the spatial variability of the wind speed. In fact a false wind speed is taken into account, namely the speed at the shore (as mentioned in *Case description*). It is very likely that the characteristic wind speed is higher, since the wind speed above the sea is actually causing the hydraulic climate and not at the boundary.

Before implementing the model of Repko et al (2001), the assumption of independence is verified (figure 11). The assumption is not falsified by the calibration data. The data is too limited to infer the shape of the distribution with certainty, but a normal distribution is not rejected.

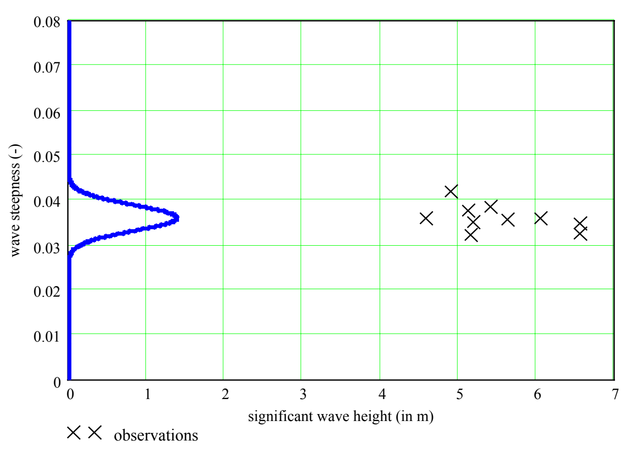

Figure 11: Deep water wave steepness as a function of significant wave height (platform Euro-0)

Also the model by Mitsuyasu et al (1980) as proposed by Battjes (1984), is considered for comparison. The results of using relation (5) are represented by the curves in figure 12. It appears that in the extreme area (high waves) the curves become more and more horizontal. It appears that the Mitsuyasu model supports the assumption of stochastically independent wave height and steepness during extreme storms. In this case a systematic underestimation of the wave steepness seems to appear, probably due to neglecting the spatial variability of the wind speed above the North Sea as mentioned before.
Using the model of Repko et al, the relation between the significant wave height and the peak period can be determined (figure 13).

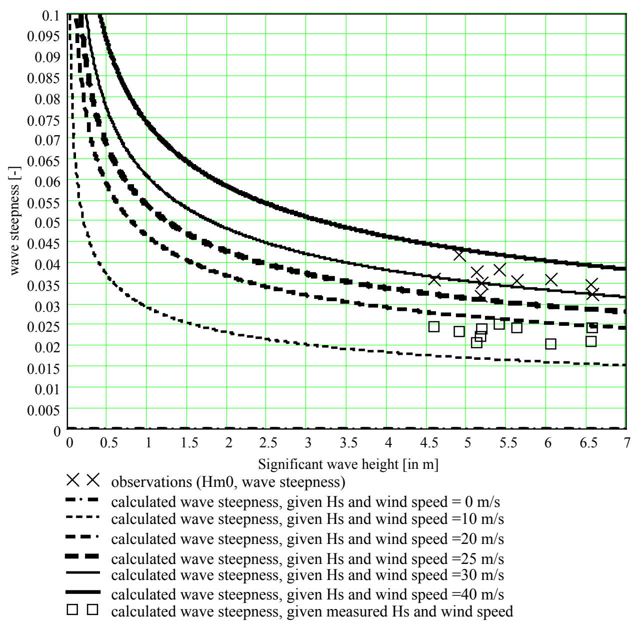

Figure 12: Deep water wave steepness as a function of significant wave height (Euro-0)

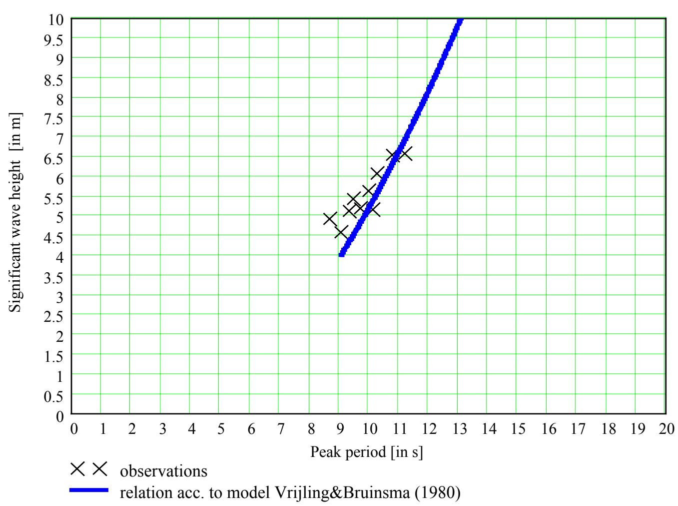

Figure 13: Peak period as a function of significant wave height (platform Euro-0)

CONCLUSIONS AND RECOMMENDATIONS

The description of the JPDF of the hydraulic boundary conditions by linking the proposed statistical models based on physics, seems to be promising after applying it to the case study of the Euro-0 platform. Also the different shortcomings in the overall model has been identified. Important conclusions:

- Apparently the extreme high waves in combination with the high water levels are caused by North Westerly storms (fixed routes depression cores).
- During the efforts to calibrate and validate the bivariate model of water level and significant wave height with field data, it turned out that there is a systematic underestimation of the wave height, probably caused by neglecting the spatial variability of the wind speed.
- Other models support the relatively simple model of wave steepness to describe the dependence between significant wave height and peak period.

Because of the fact that the spatial variability plays an important role in the problems during the (further) calibration and validation, the utilisation of wind data at the whole North Sea during the storms is a very strong recommendation. Of course the translation step to the shore (Maasvlakte 2) still has to be established. Furthermore, comparison with physical-numerical models like SWAN would be still interesting. Finally, when also more years with observations (also near the shore) are available, it is highly recommended to use them in further research.

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