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Effect of surge uncertainty on probabilistically computed dune erosion

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ABSTRACT

To assess the flood protection capacity of dunes in The Netherlands, a semi-probabilistic dune-erosion prediction method is currently in use in which uncertainties in input parameters of an empirical dune erosion model were taken into account, with the exception of the uncertainty in the extreme surge distribution. Previous research has shown that the surge is by far the most influential parameter affecting erosion in the currently used erosion model, which is due both to the influence of the surge level itself and to the conditional dependence of the wave height and period on the surge level in the probabilistic model used for the assessment. Furthermore, the distribution of extreme surge levels has been shown to contain large statistical uncertainty. The inclusion of uncertainty in input variables into probabilistic models results in more extreme events (in this case erosion) for the same exceedance probability, largely due to the incorporation of higher values of the input variables. The goal of the research described in this paper was to determine the impact of the inclusion of uncertainty in the extreme surge distribution on the estimate of critical erosion (erosion associated with an exceedance frequency of 10^{-5} per year). The uncertainty in the surge distributions was estimated and parameterized, and was incorporated into the probabilistic model. A reduction in uncertainty was subsequently imposed to estimate what value a reduction in uncertainty can offer, in terms of the impact on critical erosion. The probabilistic technique first-order reliability method (FORM) was applied to determine the relative contribution of the uncertainty in the surge distribution (as well as the remaining stochastic variables) to the critical erosion. The impact of the inclusion of uncertainty in the surge distribution on the critical retreat distance was found to be substantial with increases ranging from 34% to 93% of the original estimate at five locations along the Dutch coast. The reduced uncertainty showed a more subtle impact, with increases in critical retreat distance ranging from 10% to 26% of the original estimate. The relative importance analysis showed that the uncertainty in the surge distribution has a strong influence, with the relative importance ranging from 10% to 23% for an exceedance frequency of 10^{-5} per year.

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1. Introduction

For the purpose of flood protection, a semi-probabilistic dune-erosion prediction method was previously developed (Delft Hydraulics, 2007) for the assessment of dunes in The Netherlands. The method is referred to as 'semi-probabilistic' because the assessment is based on a deterministic computation, in which the input variables were determined through probabilistic computations. Specifically, representative hydraulic conditions, sediment diameter and correction factors (for prediction errors) are determined based on probabilistic computations, in which a dune erosion model is run for numerous sets of input values. The representative values are defined as a probable set of conditions that lead to dune erosion with a specified exceedance frequency, known as a safety standard (e.g. 10^{-5} per year for large parts of the Dutch coast). These representative values are then used in combination with information about the dune profile to deterministically compute the critical dune erosion. The critical dune erosion is defined as the amount of erosion a dune must be able to withstand to maintain its functionality as a flood defense. If a dune is unable to withstand the critical erosion, it is said to not meet its safety standard. The applied erosion model is based on an empirical deterministic dune erosion model (van de Graaff, 1986; Vellinga, 1983), in which input values were 1) initial dune profile, 2) storm surge levels, 3) wave height, and 4) sediment diameter. The model used in this study was slightly modified to include the peak wave period (Delft Hydraulics, 2007). Storm surge refers to the total water level, including wind set-up and tidal effects. Dune erosion is quantified as a retreat distance (Fig. 1), which represents the horizontal distance between the reference point, which is the point where the original dike profile exceeded a specified reference line and the retreat point, which is the point at the top of the eroded front. Recent developments in dune erosion modeling in The Netherlands are described in van Gent et al. (2008) and van Thiel de Vries et al. (2008).

In the probabilistic dune erosion prediction method described in (Delft Hydraulics, 2007) the input values, with the exception of the surge, consist of a best estimate (central value), around which an uncertainty is defined in the form of a distribution, e.g. a normal

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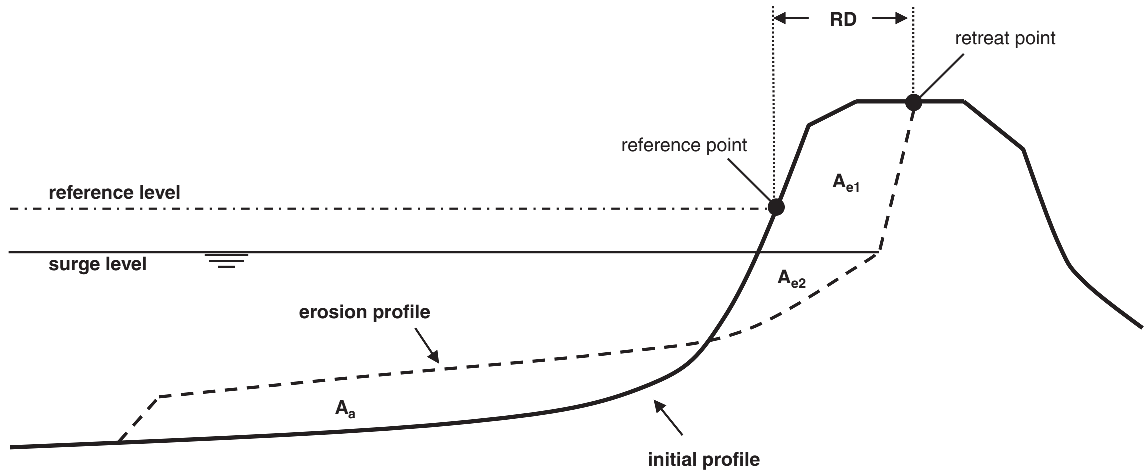

Fig. 1. Schematic illustrating the initial and eroded dune profiles and the retreat distance (RD); A_{e1} and A_{e2} represent the eroded volume above and below the surge level; A_a represents the accretion volume.

distribution with a given mean and standard deviation. The surge best estimate is an extreme surge distribution, which is a distribution fitted to surge peaks over a threshold and extrapolated to very low exceedance probabilities (see Section 2). The statistical uncertainty in the distribution, which refers to the uncertainty in the distribution parameters caused by estimating them from a limited set of data, was not taken into account. Results show that surge is by far the most influential parameter affecting erosion (Den Heijer et al., 2008a, 2008b; van de Graaff, 1986). This has to do with the fact that both wave height and wave period are expressed in the probabilistic model as functions of the surge (see Section 4.2). Furthermore, the estimated distribution of extreme surge is known to contain large statistical uncertainty (Callaghan et al., 2008; Van den Brink et al., 2005a, 2005b). The inclusion of uncertainty in input variables into probabilistic models results in more extreme events (in this case erosion) for the same exceedance probability, largely due to the incorporation of higher values of the input variables. Therefore, the inclusion of the uncertainty in the extreme surge distribution in the probabilistic model is expected to increase the critical retreat distance.

The goal of the research described in this paper is to quantify the increase in the critical retreat distance that results from the incorporation of the uncertainty in the extreme surge distribution. The statistical uncertainty in the surge distribution was estimated using a bootstrap method, and subsequently parameterized as a function of the surge exceedance probability. The impact of the inclusion of the extreme surge distribution uncertainty was computed using Monte Carlo with importance sampling. To determine the relative contribution of each of the stochastic variables to the critical retreat distance, first-order reliability method (FORM) was used (see Section 4.2 for more details). As an additional investigation, the uncertainty in the surge distribution was reduced in order to estimate the impact of uncertainty reduction on the critical retreat distance.

2. Extreme surge distribution

The extreme surge distributions used in flood risk analysis in The Netherlands have an unusual history, that is useful to first briefly describe. The distributions are based on a comprehensive study carried out with data through 1985 (Dillingh et al., 1993). Extreme value theory was used to extrapolate observed surge peaks at five stations in the North Sea: Vlissingen, Hoek van Holland, Den Helder, Harlingen, and Delfzijl. Several statistical distributions, including the generalized Pareto distribution (GPD), as well as distribution-free methods were tested, and a distribution-free method referred to as the VVM-0 method based on de Haan (1990) and de Haan and Rootzén (1993) was selected to statistically estimate the 1/10,000-year surge at the five stations. Subsequently, physically-based numerical models were applied to estimate the 1/10,000-year surge level at the five stations. The final estimate for the 1/10,000-year surge was taken to be a weighted average of the statistical and physical estimates (Philippart et al., 1993). The estimates of the 1/10,000-year surge were then spatially interpolated so that extreme surge estimates would be available at other locations besides the five base stations (Philippart et al., 1995).

The 1/10,000-year surge levels, based on combined statistical and physically-based estimates at the base stations, and on spatial interpolation thereof at other locations, were no longer part of a statistical distribution. To address this, the generalized Pareto distribution (GPD) was fitted through three points: 1) the 5/10-year surge, 2) the 1/10-year surge, and 3) the 1/10,000-year surge estimate (Philippart et al., 1995). The first two points can be derived directly from the measurements, and the third point is the value that represents the weighted average of statistical and physical estimates (or the interpolation thereof for stations other than the five base stations).

The uncertainty was not estimated for the final 1/10,000-year surge estimates, and further no uncertainty was estimated on the final three-point GPD distribution (the GPD fitted through three points). Because the parameters of the three-point GPD are not estimated from a series of peaks over a threshold, traditional uncertainty estimation methods such as the delta method (Coles, 2001) or bootstrapping cannot be carried out. These distributions are currently used in the safety assessment of the dunes in The Netherlands, and serve as the central estimate of surge. To estimate the uncertainty around the central estimate, we made use of the original GPD, fitted to surge peaks above a threshold, prior to any manipulation for the incorporation of results of the physically-based numerical models. For the threshold, equivalent values to those used in Dillingh et al. (1993) were applied, corrected for sea level rise.

3. Dune erosion model

The applied erosion model is based on an empirical deterministic dune erosion model (van de Graaff, 1986; Vellinga, 1983), with modifications as described in Delft Hydraulics (2007). The input values to the model are 1) initial dune profile, 2) storm surge levels, 3) wave height at a depth of 20 m below Amsterdam Ordnance Datum (AOD), 4) peak wave period, and 5) sediment diameter. The model describes

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