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Probabilistic estimation of coastal dune erosion and recession by statistical simulation of storm events

F. Li[a,b,*], P.H.A.J.M. van Gelder[a], J.K. Vrijling[a], D.P. Callaghan[c], R.B. Jongejan[d], R. Ranasinghe[a,e,f]

[a] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft CN 2628, The Netherlands
[b] School of Hydraulic, Energy and Power Engineering, Yangzhou University, Yangzhou, 225127, China
[c] Division of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia
[d] Jongejan Risk Management Consulting, Delft DX 2628, The Netherlands
[e] Deltares , Delft MH 2600, The Netherlands
[f] Department of Water Engineering, UNESCO-IHE, Delft AX 2611, The Netherlands

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ABSTRACT

Knowledge about future oceanographic events will assist governments to better manage risk in coastal zones, a crucial task in the light of projected sea level rise, population growth and economic development. In this study, a 31-year data set of deep water wave climate parameters and bathymetry measurements (yearly cross-shore transect surveys) at Noordwijk, the Netherlands, were analysed to jointly estimate storm events variates of deep water wave conditions, and to probabilistically compute dune erosion volume and the resulting dune retreat distance with the simulated wave climate and possible local sea level rise scenarios by 2100. The probabilistic dune retreat models were applied and adjusted to the study site. Based on the outcomes of this application, a modelling technique can be established to propose a framework for probabilistically describing the coastal erosion and recession along the coast protected by dunes.

1. Introduction

Dunes act as a defence against flooding and storm erosion in the Netherlands. About 255 km (70%) of the Dutch coast is protected against flooding and storm surges by dunes. Another 43 km is defended by dikes with a sandy nearshore [1]. This type of flexible and natural protection will erode in a short time during extreme storm events leading to socio-economic losses in the coastal zone (e.g. coastal towns such as Scheveningen and Zandvoort) and might breach flooding of the low-lying hinterland. Since 1990 a policy has been adopted that aims to control structural erosion mainly through sand nourishments. This policy has proven to be successful to date, keeping the coastline at its 1990 position. However, in view of sea level rise (SLR), the nourishment volume required to maintain the 1990 coastline position is expected to increase. It is therefore necessary to have a sound knowledge of possible future increases in dune erosion volumes in order to inform coastal management/planning strategies.

Statutory safety standards for the Dutch sea defences are expressed as exceedance probabilities of extreme loading conditions that should be safely withstood. For the dunes, these safety standards have been translated to maximum allowable failure probabilities that range from 1×10^{-4} to 5×10^{-4} per years [2]. The failure probability is the probability of failing to withstand extreme sea storms, while failure means overtopping and/or breaching during a storm. An acceptable probability of failure of 10^{-5} per year is dictated for the most valuable parts of The Netherlands, i.e. the Holland Coast. However, a fundamental issue when using the presently adopted benchmark event method is the underlying assumption that for example, a 1 in 100 year storm event will result in a 1 in 100 year dune erosion volume. More often than not this is not true due to the non-linear behaviour of the coastal response to environmental forcing. For a system involving more than one random variable, such as the coastal system, the return period of a certain response is not equal to the forcing return period of a particular variate [3].

This study attempts to quantify the potential probability of dune erosion volume (R) and retreat distance (RD) via a physics based statistical modelling method which goes beyond the benchmark event method.

In order to model and simulate the multivariate storm events, a conceptually and numerically simple and computationally efficient method is required. Scheffner and Borgman [4] developed a method for generation of a realistic wave sequence from a small number of stored parameters, including approximately correct distributions of wave height, wave period and wave direction, and dependence and sequencing between them. The method preserves the primary statistical properties of the observed data in the generated storms; however, this method is also known to provide not-so-accurate estimations of extreme events [3], which in fact is the focus of the present

* Corresponding author. Tel.: +31 0152785013.
E-mail address: fan.li@tudelft.nl (F. Li).

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study (dune erosion is driven largely by extreme storm events). Therefore, in this study the JPM (joint probability method) presented by Callaghan et al. [16] is used to generate future storm time series. The JPM is specifically designed to provide estimates of extreme storm events while ensuring that the individual properties of each storm (peak wave height, storm duration, wave period, direction, storm surge, etc.) will still not depart from their historical statistical distributions. For the purposes of this study, which is to simulate future dune erosion and retreat with an acceptable level of statistical accuracy, the level of physical reality associated with storm time series obtained via the JPM approach should be sufficient.

The copula approach is a fundamental tool to model the multivariate extreme values. Corbella and Stretch [5] used the Archimedean copulas, which is extended into three-dimension, to simulate the sea storm. Recently, the multi-parameter multivariate extreme value (MEV) copulas [6] and the vine copula [7] were proposed due to its more flexible property. But they are not as mathematically tractable as the Archimedean copulas [5]. Li et al. [8,9] studied Gaussian copula, Archimedean copulas and the Logistic model [10] for the study site and concluded that the Gaussian copula is the most appealing method according to the K-S and Chi-square test. Furthermore, the property of easily extending to higher dimensions also makes it as the best option among the others.

Dune erosion is a basic coastal engineering problem that has been studied for a long time [11–15]. Several researchers have proposed a probabilistic modelling approach combined with erosion models to estimate coastal erosion hazards. Callaghan et al. [16] used joint probability and a non-homogenous Poisson distribution in their JPM model to simulate storm events and estimate the coastal erosion probability, using a time convolution shoreline response model of Kriebel and Dean [12]. Callaghan et al. [17] later used the JPM model to compare the performance of three different structural functions of varying complexity (Kriebel and Dean [12], SBEACH [18], and XBeach [19]). Ranasinghe et al. [20] applied a physics based model which provides probabilistic estimates of SLR driven coastal recession in combination with an analytical dune erosion model [13]. Corbella and Stretch [21,22] used Archimedean copulas based on a non-stationary multivariate statistical model to derive the most-likely design events [23] and used them in SBEACH [18], XBeach [19] and Kriebel and Dean [12] models to predict potential future dune erosion. The most-likely design events method is an improvement of the traditional benchmark event method, but it is still insufficient to cover all the possibilities compared to the standard Monte Carlo method. Furthermore, the Gaussian copula method used in this study is much simpler than the Archimedean copulas and computationally faster when extending to four dimensions.

In this study, we use a Gaussian copula to fit and simulate the storm related parameters and a adjusted dune erosion rule (DUNERULE) model [15] on the basis of XBeach to estimate the probability of dune erosion and retreat distance by 2100 considering the possible SLR. This method was applied to Noordwijk coast, located along the Dutch coast, to illustrate its potential. The selected method has the capability to overcome the drawbacks of the benchmark event method and reduce the computation time and complexity for storm events and erosion hazards simulations. Hence, this method offers an acceptable balance between the model complexity and practicality.

2. Study site and data preparation

Noordwijk aan Zee, located on the central Dutch coast (Fig. 1), is a sandy, wave dominate coast of about 120 km long and about 100 m in width. The wave climate data for the study site (including maximum significant wave height, $H_{s,max}$; peak wave period, T_p; peak water level, h; wave direction, θ_p) were collected at IJmuiden Munitiestortplaats (YM6, period: 1979–1992, location: 52°33′00″ N, 4°03′30″ E) and Noordwijk Meetpost (MPN, period: 1993–2009, location: 52°16′26″ N, 4°17′46″ E) in the North Sea over a period of 31 years by the Rijkswaterstaat, the executive branch of the Dutch Ministry of Infrastructure and Environment. YM6 station is located 26 km from the coast, where the local water depth is 21 m. The MPN station is located 9.5 km offshore, where the depth is 18 m (Fig. 1). The analysis of the wave climate data in 1992 and 1993 of the two gauges indicates that they belong to a homogeneous region in terms of wave climate conditions. Therefore, the observations of the two gauges were merged into one single dataset without adjustment. The missing data were complemented and corrected by adjacent gauges, to avoid errors and ensure consistency. The transect profile of No. 8250, locates in the middle between 82 and 83 beach pole in Fig. 1, was selected to compute as the study profile from JARKUS dataset [24]. The JARKUS is an annually bathymetry measurement along the Dutch coast (acronym of JAaRlijkse KUSTmeting in Dutch).

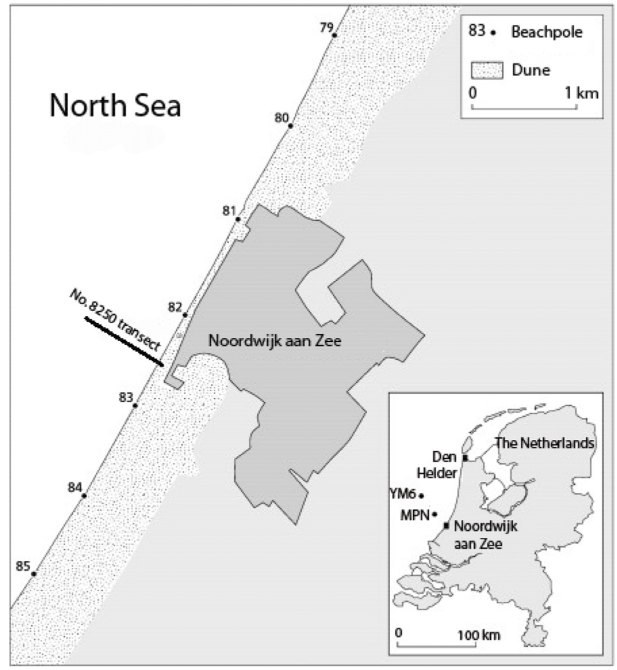

Fig. 1. Map of the Netherlands with the wave climate data collection point, the position of Noordwijk and the selected transect (modified after Quartel et al. [26]).

Following previous studies by Quartel et al. [25,26], the storm events which will cause a morphological change at Noordwijk were defined as periods where the significant offshore wave height exceeds 3 m and the tidal anomaly (*TA*, defined as actual water level minus the astronomical tide level) is simultaneously higher than 0.5 m. To guarantee the independence of selected storms, the minimum time interval between two storms was set as 24 h, any two storms with time interval less than 24 h were considered as one storm event (Fig. 2). The raw observations were selected and processed to obtain a time series of independent storm events, characterized by the maximum significant wave height ($H_{s,max}$), wave period (T_p), water level (h), wave direction (θ_p), and storm duration (D). In this study, the $H_{s,max}$ is defined as the maximum significant wave height during the defined storm duration, while the storm duration D was defined as the period when the $H_{s,max}$ and *TA* both satisfy the condition mentioned above. The peak wave period T_p is the concomitant wave period of $H_{s,max}$, and the peak sea level h is the highest total water level during a storm. And the wave direction θ_p is measured at the time when $H_{s,max}$ occurs. The storminess was characterized by the storm frequency (F_s), which is the number of storm event in a month. Fig. 2 shows the definition of a storm event and the related parameters.