Coastal Engineering 86 (2014) 1–13

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Probabilistic modelling of extreme storms along the Dutch coast

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ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form 12 December 2013
Accepted 17 December 2013
Available online xxxx

Keywords:
Multivariate analysis
Sea storm simulation
Copulas
Wave climate
Dependence

ABSTRACT

Due to the unprecedented growth in population and economic development along the coastal zone all over the world, knowledge about future extreme oceanographic events will assist in ensuring human and property safety. This will be a task with increasing significance in the light of projected climate change impacts. A joint estimation of extreme storm events' variates of deep water wave conditions was performed. It can be used for multivariate descriptions of wave climate variates, such as wave height, period, steepness, and storm duration. The storm sequences can be simulated and extrapolated from limited observational data for optimal structure protection strategies and various disaster risk analysis, like erosion or overtopping. The analysis not only shows the effectiveness of the proposed statistical approaches for improving multivariate modelling of the storm parameters but also highlights the most compatible approach for the Dutch wave climate data from 1979 to 2009. We used the Monte-Carlo method and four methods to construct the dependency structures, based on copula functions, physical relationship and extreme value theory. The marginal probabilistic distribution functions of wave climate variables and the joint probability were then obtained. The simulated data group performs a reasonable similarity to the field measurements according to the goodness-of-fit test, and the Gaussian copula model was found to be the best wave climate simulation method for the Dutch coast.

1. Introduction

In the context of coastal engineering, the probabilistic design of marine structures or sea defences is closely related to the statistical prediction of the ocean state, such as wave height, period, etc. These ocean wave climate elements are the data source for coastal hazard analysis and evaluation of the safety level of coastal structures in the so-called Source-Pathway-Receptor concept (Oumeraci, 2004). One of the challenges for scenario or event based coastal risk assessment is stochastically simulating and describing sea storms which may be customarily characterized in terms of maximum significant wave height ($H_{s,max}$), peak wave period (T_p), peak sea level (h), wave direction (θ_p) and storm duration (D). When dealing with the simulation of coastal erosion, inter-arrival time (I) or calm time between two independent successive storms is also a key variate among others. With the simulated events, the coastal erosion and flooding risk with various return periods will be quantified more accurately compared to the method based on a benchmark event (usually the largest measured historical event). That is because, for systems involving two or more random variables, the return period of outcomes is not equal to the forcing return period of a particular variate (Hawkes et al., 2002).

Due to the internal physical connections among these wave climate variates, generally there exists a mutual partial dependency between variates. Hence, an estimation of the joint probability distribution of wave climate variates is required, especially for the extreme storm events, which are of particular concern for coastal engineers. Univariate marginal distributions received considerable attention in the literature (Borgman, 1973; Ferreira and Guedes Soares, 2000; Forristall, 1978; Krogstad, 1985; Nerzic and Prevosto, 1998). Furthermore, research efforts in the past decades have led to various methods to study the bi-variate description of wave conditions; for instance, the joint probability of extreme significant wave heights and sea levels ($H_{s,max}$, h) (Hawkes et al., 2002; Li and Song, 2006), the joint distribution function of maximum significant wave height and wave period ($H_{s,max}$, T_p) (Myrhaug and Hansen, 1997; Repko et al., 2005), and the correlation between significant wave heights and associated durations (H_s, D) (Mathiesen, 1994; Soukissian and Theochari, 2001).

Recently, copula functions, first mentioned by Sklar (1959), have been increasingly popular in their application to various multivariate simulation studies in civil and offshore engineering. De Waal and van Gelder (2005) applied copulas to model extreme significant wave heights and wave periods ($H_{s,max}$, T_p); Wahl et al. (2012) applied copulas to statistically analyse peak sea levels and maximum significant waves ($H_{s,max}$, h); Corbella and Stretch (2012) used copulas to construct

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0378-3839/$ – see front matter
http://dx.doi.org/10.1016/j.coastaleng.2013.12.009

a trivariate model of significant wave height, storm duration and wave period ($H_{s,max}$, D, T_p); De Michele et al. (2007) used copulas to provide a four-dimensional, multivariate frequency analysis of ($H_{s,max}$, D, I, θ_p).

One of the advantages of copulas is that they are able to correlate two or more variables without changing their marginal distributions. In this paper, as it will be described later in more details, Archimedean and Gaussian copulas (also known as normal copula) were used to construct a multivariate dependency structure for the significant wave height, storm duration, surge level and peak wave period ($H_{s,max}$, D, h, T_p) for the purpose of wave climate simulations. The wave direction (θ_p) was treated individually by fitting to an empirical distribution. And based on the simulated wave climate, a large number of synthetic storm surge events can be obtained by the incorporation of the storm frequency (F_s), defined as the storm number per month, instead of the storm inter-arrival time (I). This model may be utilized for coastal risk assessment and integrated coastal management by using the Monte-Carlo technique to avoid the drawback of using a benchmark event.

The aim of this paper is to present an example of a full temporal simulation for storm events along the Dutch coast by means of a statistical mechanism. In Section 2 the study site and required variates are introduced. The marginal distribution functions of these variates, and the dependency structure for the dependent variates are studied in Section 3. Section 4 compares the simulated data and observed data. Sections 5 and 6 include the discussion and the conclusions of the work respectively.

2. Study site and data preparation

The probabilistic method was adopted to estimate storm events along the Holland coast (from the Hoek van Holland to Den Helder, Fig. 1), The Netherlands. The wave climate data was collected in the North Sea at IJmuiden Munitiestortplaats (YM6, period: 1979–1992, location: 52°33′00″N, 4°03′30″E) and at Noordwijk Meetpost (MPN, period: 1993–2009, location: 52°16′26″N, 4°17′46″E) by Rijkswaterstaat, the executive branch of the Dutch ministry of Infrastructure and Environment, over a period of 31 years. The analysis of the wave climate data in 1992 and 1993 of the two gauges indicates that they belong to a homogenous region in terms of wave climate conditions. Therefore, the observations of the two gauges were merged into one single dataset without adjustment. The YM6 station is located 26 km from the coast, where the local depth is 21 m. The MPN station is located 9.5 km from the coast, where the local depth is 18 m. The missing data is complemented and corrected by adjacent gauges, to avoid errors and to ensure consistency.

The storm events which will cause a morphological change were considered and defined as periods where significant offshore wave height exceeds 300 cm and where simultaneously the surge (*TA*, defined as actual water level minus the astronomical tide level) is higher than 50 cm (Quartel et al., 2007). To guarantee the independency of selected storms, the minimum time interval between two storms was set as 6 h, any two

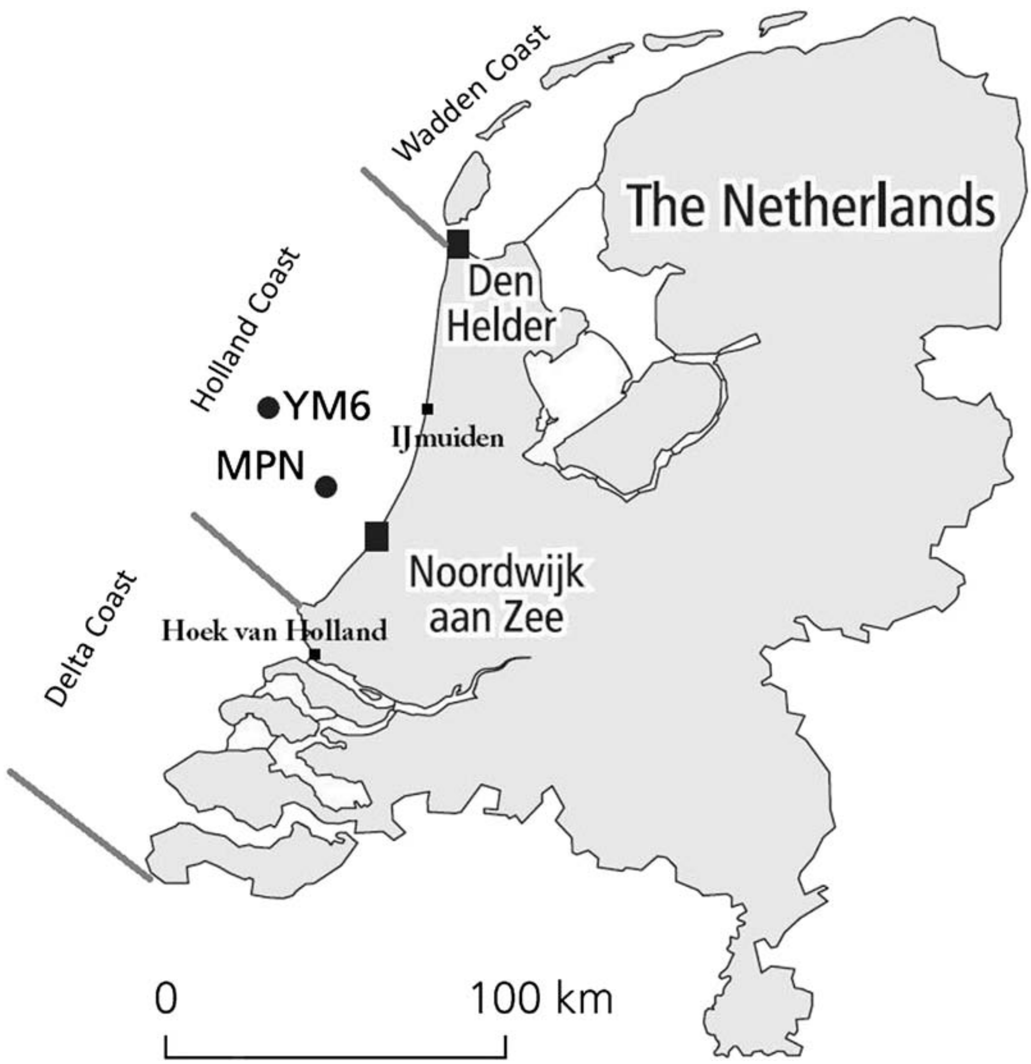

Fig. 1. Locality map for field measurements.