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Storm evolution characterization for analysing stone armour damage progression

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ABSTRACT

Storm evolution is fundamental for analysing the damage progression of the different failure modes and establishing suitable protocols for maintaining and optimally sizing structures. However, this aspect has hardly been studied and practically the whole of the studies dealing with the subject adopt the Equivalent triangle storm. As against this approach, two new ones are proposed. The first is the Equivalent Triangle Magnitude Storm model (ETMS), whose base, the triangular storm duration, D, is established such that its magnitude (area describing the storm history above the reference threshold level which sets the storm condition), H_T, equals the real storm magnitude. The other is the Equivalent Triangle Number of Waves Storm (ETNWS), where the base is referred in terms of the real storm's number of waves, N_z. Three approaches are used for estimating the mean period, T_m, associated to each of the sea states defining the storm evolution, which is necessary to determine the full energy flux withstood by the structure in the course of the extreme event. Two are based on the Jonswap spectrum representativity and the other uses the bivariate Gumbel copula (H_s, T_m), resulting from adjusting the storm peaks. The representativity of the approaches proposed and those defined in specialised literature are analysed by comparing the main armour layer's progressive loss of hydraulic stability caused by real storms and that relating to theoretical ones. An empirical maximum energy flux model is used for this purpose. The agreement between the empirical and theoretical results demonstrates that the representativity of the different approaches depends on the storm characteristics and point towards a need to investigate other geometrical shapes to characterise the storm evolution associated with sea states heavily influenced by swell wave components.

1. Introduction

Extreme actions in maritime engineering are determined by statistically processing climate variables which allow the design storm's return period for establishing the structure's lifetime to be defined. Statistical characterization of representative environmental variables was traditionally a marginal operation and the significant wave height, H_s, was considered to be a *main variable* whilst other variables such as the mean period, T_m, and the storm direction and duration, D, were also somewhat subjectively taken into consideration. Using this approach, the dependency between these variables was not taken into account and, consequently, the risk assumed in structure design remained unknown. An accurate statistical description would require the joint use of all marginal laws in order to obtain a representative multivariate distribution. Several works addressing classical design problems in coastal engineering demonstrate how useful copula functions are in coping with such a problem. The works of Coles and Tawn (1994); Coles et al. (1999); Guedes Soares and Scotto (2001) may be highlighted amongst the first maritime engineering works dealing with the joint behaviour of the representative variables $H_s - T_m$ by using copula functions. Other studies analyse the joint behaviour of the significant wave height, H_s, with other variables, such as the works of Morton and Bowers (1996); Nerzic and Prevosto (2000); Zachary et al. (1998) which assume the logistic dependency model for studying the joint behaviour of H_s and the wind speed, as well as the joint characterization of $H_s - D$ as analysed by Sobey and Orloff (1999). The correlation between storm surge and tides is studied by Tsimplis and Blackman (1997). Combined models of copula functions and functional relations between the variables H_s, T_m and sea level referring to the wave steepness are used by Hawkes et al. (2002); HR Wallingford and Lancaster University (2000) to establish the joint behaviour of successive storms. These works were hailed as a great advance in multivariate statistical characterisation. However, studies on the multivariate behaviour of the extreme event do not analyse a fundamental aspect, such as the

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characterization of the storm history enabling progressive failure modes to be studied. This research focuses on this aspect in proposing two new approaches and applying them to assess the damage progression on the breakwater armour layer.

There are a great number of multivariate flood storm models that analyse flood and drought evolution in terms of their duration, magnitude or peak value, e.g. (Biondi et al., 2002; De Michele and Salvadori, 2003; Goel et al., 1998; Shiau and Shen, 2001; Yue et al., 1999). Other important advance in hydrological field is the synthetic storm surge hydrograph equation proposed by Cialone et al. (1993), later modified by Zevenbergen et al. (2004) to better represent the falling limb. That equation is used by Melby et al. (2011) in order to model time series of wave and water level parameters.

Unfortunately, only a few approaches can be found in literature to cope with the storm history characterization, among them, the Equivalent Triangle Storm model (ETS), drawn up by Boccotti (2000) adopting a triangular shape, stands out amongst the early work analysing the storm evolution. In this model, the height of the triangle, "*a*", is assumed to be equal to the significant wave height at the storm peak. The base of the triangle, "*b*", (i.e., the duration of the equivalent triangle storm) is such that the maximum expected wave height of the triangle storm is equal to the maximum expected wave height of the real storm. Having defined the "*a*" and "*b*" parameters, the *equivalent sea* is defined as that part of the theoretical storm above the reference threshold, which sets the storm condition, H_T. Based on this model, De Michele et al. (2007) introduced the concept of storm magnitude inspired on the hydrological variable to define the flood volume (De Michele and Salvadori, 2003). An extension to the ETS model is that carried out by Arena and Fedele (2002), in order to take the seasonal nature and direction of the storm into account. This study compares the return periods resulting from using the triangle equivalent sea and the total sample methods. Later, Fedele and Arena (2009) presented a generalisation of the ETS model called Equivalent Power Storm (EPS), where a shape parameter, λ, was introduced, enabling the initial triangular model shape to be varied. Another approach is that of Corbella and Stretch (2012a) who also assumed a triangular shape, but the base is the real storm duration above the reference threshold, H_T. Most existing models address the evolution of the storm history with a triangular shape. However, this is not the most suitable for reproducing more developed waves (ROM 1.0-09 "Recommendations for the Project Design and Construction of Breakwaters", 2009).

Furthermore, all these approaches concentrate on estimating the design storm's return period but do not explicitly address the estimation of the mean period of each sea state that makes up the storm and this is decisive for determining the structure's vulnerability. Three approaches have been adopted to define the mean period, T_m.

The study carried out by Thompson and Shuttler (1975) may be highlighted amongst the first dealing with the rubble mound breakwater damage progression, they concluded that the erosion rate is strongly dependent upon the significant wave height, H_s, decreasing the damage rate with time. They performed a series of trials which Van der Meer (1988); Van der Meer and Pilarczyk (1984) would later analyse, and obtained the ratio between the damage and the number of waves, appropriate for irregular waves. The new wave height parameter, H_n, proposed by Vidal et al. (1995) for intermediate or shallow water breakwaters design, was the average of the "n = 100" highest waves that reach the breakwater during its lifetime, $H_n = H_{100}$. This suggestion is based on the fact that at a given time, the damage will be related to the largest waves supported by the breakwater. Later Vidal et al. (2006), using Thompson and Shuttler's (1975) laboratory data, concluded that H_{50} was the most representative parameter to damage prediction and is independent of the wave height distribution. Using the Vidal et al. 2006 wave height parameter, H_{50}, instead of the significant wave height, H_s, in the recent stability formulae, Etemad-Shahidi and Bali (2012) founded that this modification yields more accurate results. Then, two new design formulae were proposed. Another approach is the Medina (1996, 1997) exponential equation, attempting to reproduce the number of waves associated to each of the sea states defining the storm history.

Although all this approaches represent a great advance in the final damage knowledge, the damage progression is not considered being an important aspect in order to establish the appropriate maintenance and reparation structure periods. This aspect is considered in Lepetit and Feuillet's (1979) equation which was subsequently amended by

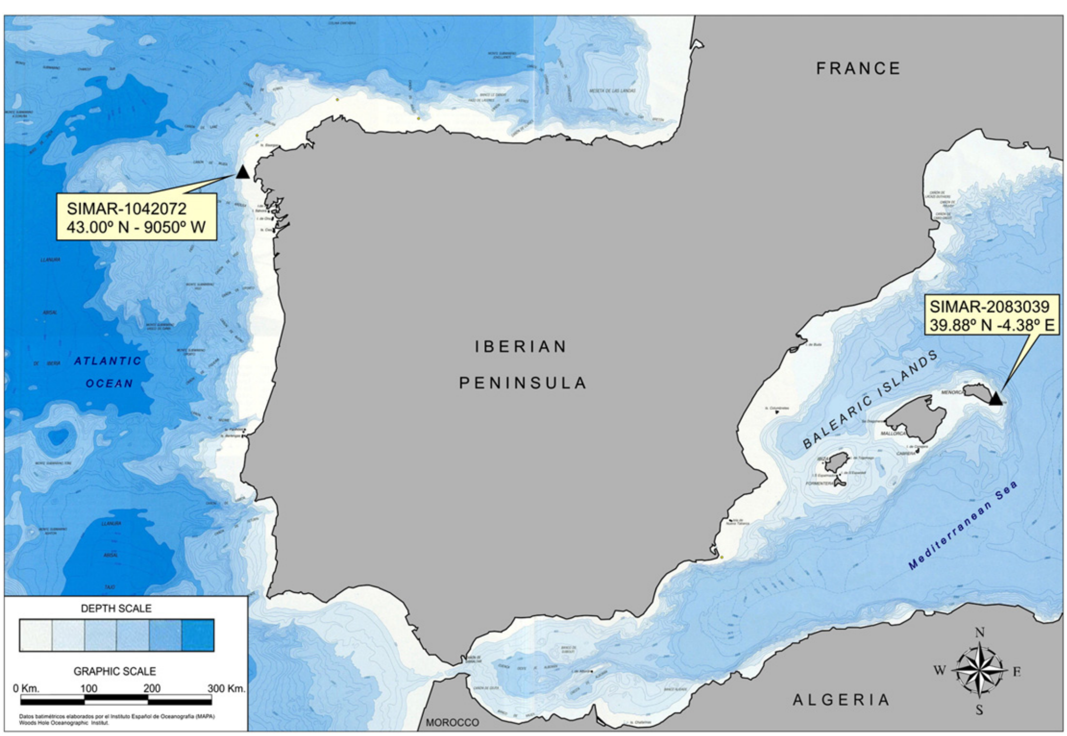

Fig. 1. Location of the SIMAR-44 points studied.