Probabilistic modelling of the armor damage evolution of rock-armored groynes under ship-wave attack based on field data

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INTRODUCTION

Groynes and revetments have suffered an increase in the severity of their damage in the German estuaries during the past years due to the increase in the ship-induced loads. Consequently, there is a pressing demand for further tools to model the structure deterioration over time with the aim to facilitate the planning of maintenance and repair measures. This damage evolution is directly caused by the ship-induced waves and comes with a high level of uncertainty due to the complexity of the involved phenomena (e.g.: ship-wave generation or wave-structure interaction). Therefore, a probability-based estimate of that damage evolution over time is essential for the optimization of the maintenance/repair decisions of these structures.

The goal of this research is to quantify the survivability of a rock-armored groyne at Juelssand in the Lower Elbe Estuary based on field measurements. First, an algorithm to generate random damage curves (based on the field measurements) is developed to overcome the data scarcity from the field and improve the subsequent phases of the analysis. After that, a Gamma process is applied to model the structure survivability; it is fitted using the generated random damage curves and the survivability of the groyne is studied for different tolerable damage levels.

FIELD DATA

Melling et al. (2020) rebuilt two previously damaged rock-armored groynes in the tidal Lower Elbe using two innovative designs (one with a recessed root, G1, and one with a large-radius root, G2) with a view to increase the structure resistance. Here, groyne G1 is further investigated; G1 was covered with a rock grading CP90/250 (rock size D_{n50}=12.6cm) with iron-silicate rocks of high density (ρ_s=3.7t/m^3) and had a gentle lateral slope (1/4). G1 was tracked for a year; the armor layer deformation was recorded using a terrestrial, pile mounted laser. Note that during that year the structure went from just built to destruction (elements from the underlying layers were visible), so the whole damage evolution could be observed. Also, the incident ship-induced waves and water levels were measured using pressure sensor gauges.

DATA ANALYSIS

The laser scans were processed to derive damage curves along the life of the structure. The dimensionless armor damage parameter (S_e=A_e/D_{50}, where A_e is the eroded area) defined in Broderick (1983) is used to quantify armor damage in three cross-sections (see Figure 1).

Each increase in the obtained damage curves was attributed to one single ship-wave event as the largest event between that scan and the previous one. That way, the wave characteristics were related to the damage events. Also, the "memory" of the process was tested. The correlation between the pre-existing damage ($S_{e,i}$) and the increment of damage in the subsequent event ($\Delta S_{e,i+1}$) was measured using the Spearman's rank correlation coefficient. No significant correlation was obtained and, thus, damage events were assumed to be independent for further analysis.

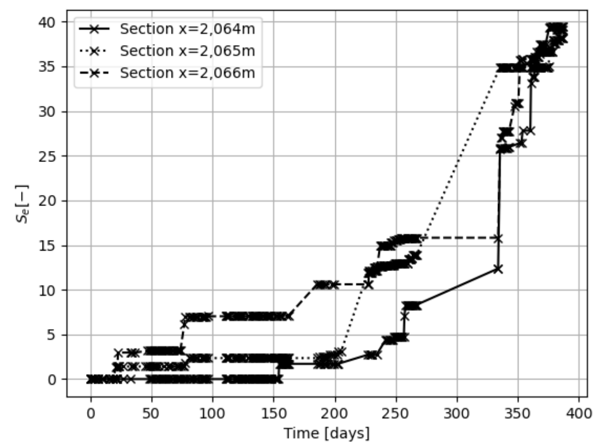

Figure 1 - Damage curves over time obtained from the laser scans.

RANDOM DAMAGE CURVES

As previously mentioned, an algorithm to generate random damage curves is proposed here. The outline is as follows:

(1) A Poisson distribution is used to model the number of ship-waves per day (N_w).

(2) A Bernoulli distribution was used to determine whether the N_w waves create damage or not. If no damage was produced by the wave ΔS_e=0. If damage was produced then we observe N_d the number of damaging waves and the following steps were performed.

(3) N_d random samples are taken from the Generalized Pareto distribution to model the primary wave height of the ship wave (H_p).

(4) Conditionalized samples of ΔS_e are drawn from the bivariate rotated (180º) Clayton copula which are used to model the dependence between H_p and ΔS_e.

(5) ΔS_e in is obtained by applying the inverse of the Exponential distribution used to model ΔS_e.

(6) ΔS_e is accumulated over time for simulations of one year in length.

Following the described procedure, 500 curves with a length of 365 days were computed. A comparison between the empirical damage curves and the generated ones is shown in Figure 2. The generated damage curves resemble the behavior of the empirical ones. Also, the final S_e in the empirical curves is around the mean final S_e

in the generated ones.

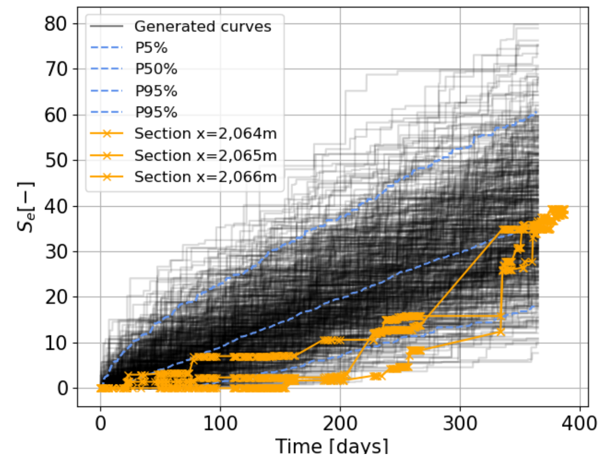

Figure 2 - Empirical and generated damage curves over time and percentiles of the generated curves.

GAMMA PROCESS: GROYNE SURVIVABILITY

Using the generated damage curves, a Gamma process is fitted. The Gamma process is a stochastic process over time with independent gamma-distributed increments (see more in Van Noortwijk, 2009). The Gamma process is applied here to model the armor damage and presents the following properties: (1) at time t=0, $S_e(0)$=0; (2) $S_e(t)$ has independent increments, and (3) the increments of the random variable $S_e(t)$-$S_e(r)$ follow a Gamma distribution with shape parameter $\alpha(t)$-$\alpha(r)$ and rate parameter β for any $t > r \geq 0$.This stochastic process allows to compute the probability of reaching a level of S_e ($S_{e,lim}$) at time t as

$$F(t) = P[S_e(t) \geq S_{e,lim}] = \frac{\Gamma(\alpha(t), S_{e,lim}\beta)}{\Gamma(\alpha(t))}$$

where α(t) is the shape parameter function of the time, and β is the rate parameter.

To select the expression to describe α(t), the percentiles 5%, 50% and 95% of S_e at each day is computed based on the generated random damage curves. As shown in Figure 2, the mean evolution over time is approximately linear. Thus, α(t)=ct, where c is a constant to be fitted and t is the time in days. The Gamma process was fitted by moments minimizing the mean squared error of

$$\mathbb{E}(S_e(\mathrm{t})) = \frac{ct}{\beta}$$

$$\mathbb{V}\mathrm{ar}(S_e(\mathrm{t})) = \frac{\mathrm{ct}}{\beta^2}$$

where $\mathbb{E}(S_e(\mathrm{t}))$ and $\mathbb{V}\mathrm{ar}(S_e(\mathrm{t}))$ are the mean and the variance of the observed S_e at time t. c=0.023 and β=0.22 are obtained.

Using the fitted Gamma process, the survivability of the rock-armored groyne is assessed for different $S_{e,lim}$. Based on the qualitative damage levels defined in Herrera et al. (2017) and Mares-Nasarre et al. (2021), three damage levels are defined: Initiation of Damage ($S_{e,lim}$(IDa)=0.5), Initiation of Iribarren's Damage ($S_{e,lim}$(IIDa)=2), and Initiation of Destruction ($S_{e,lim}$(IDe)=6). An additional level is defined at $S_{e,lim}$(IDe)=10 to study an extremer case. The survivability analysis for the four studied levels is shown in Figure 3.

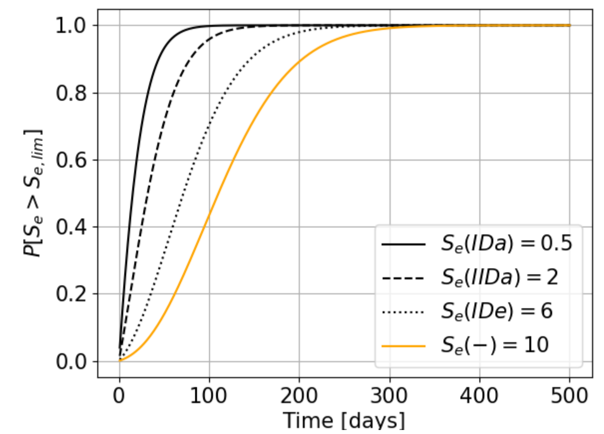

Figure 3 - Survivability of the groyne over time for the defined tolerable damage levels ($S_{e,lim}$).

According to Figure 3, after 150 days, the structure would have achieved almost surely (that is with probability 1) damage higher than $S_{e,lim}$(IIDa)=2 and there will be an exceedance probability P[S_e≥6]=0.91 and P[S_e≥10]=0.72. This tool can be used for maintenance scheduling defining a $S_{e,lim}$ based on the structure needs and usage.

ACKNOWLEDGEMENTS

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