Adaptation under extreme events. Predictive maintenance for risk reduction

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Introduction

Increasing human and climatic pressures on coastal systems and their infrastructure has resulted in cumulative loses for ecosystem services (e.g. Sanchez-Arcilla et al, 2022) and increasing degradation of coastal and harbour structures (e.g. Kong and Frangopol, 2004; Speijker et al 2000). The result has been a steady increase in risk levels, both for infrastructures (Al-Najjar, 2007) and coastal habitats (Coanda et al., 2020), compounded by a lack of bespoke predictive maintenance (Hermans et al., 2013). A predictive maintenance programme, linking observations and inspections with numerical and/or experimental analyses of water-sediment-structure-ecosystem interactions, specially under extreme conditions, would reduce coastal risks during the life cycle of coastal structures or habitats (Yang et al 2004; Yang et al 2006; Okasha and Frangopol, 2009).

By combining in-situ measurements with coupled modelling it should be feasible to assess structural and ecosystem performance before reaching tipping points or ultimate limit states (Sakib and Wuest, 2018). Locally tailored predictive maintenance programs result in monitoring/inspection plans (Orcesi et al, 210) that support a development of adaptation pathways based on objective data and the best level of available knowledge, aggregating past experiences, metocean forecasts (Sanchez-Arcilla et al, 2021) and climatic projections. The added value of these combined approaches should increase under future climate scenarios and extreme conditions (Strauss et al, 2008; Yuan et al., 2013). Moreover, predictive maintenance in other fields has increased socio-economic and natural system productivity, reducing breakdown times and in our case is expected to enhance coastal structural performance and ecosystem status. Predictive maintenance programmes should explicitely address the efect of extremes, both for drivers such as wave heights or storm surges or for responses, such as structural damages or peaks in the morphodynamic response. This is the approach followed in this work, based on extreme analyses for key drivers and responses in the coastal zone, such as incoming wind-waves or functional/resistant failures. From a comparative analysis of wave extremes along Cantabrian and Mediterranean coasts, we shall assess the sensitivity of extreme distributions to available data, invoked hypotheses and applied statistical techniques. The paper will next discuss how this uncertainty affects coastal risk levels and will conclude with some remarks to bound uncertaninty for improving coastal sustainability and the required proactive maintenance.

Materials and methods

Predictive maintenance, already a common approach in mechanical, electrical and some branches of civil engineering, is based on monetary costs formulated as a function of pre-defined levels of functionality or safety losses (e.g. Chen and Toyoda, 1990; Dey, 2001; de Pater and Mitici, 2021). Depending on structural or ecosystem type and the dominant maritime climate, risk assessment will require different combinations of driving factors (e.g. incident significant wave height, meteorological or astronomic tides) and different limit states, either functional or resistant (e.g. erosion or overtopping). The same applies to ecosystem service delivery, depending on functionality and structure for each coastal habitat. Predictive maintenance is known to reduce costs and impacts under current and particularly future scenarios and where extreme events play a key role due to the non linear formulations that reproduce ecosystem or structural responses (Ran et al, 2019). Non-linearities and uncertainties require monitoring risk levels by a smart combination of observations, inspections and simulations, from which it should be possible to establish an optimal maintenance to mimimize risks and costs, while increasing the life time of the considered structure or habitat.

Recent advances in modelling and observations (e.g. Sánchez-Arcilla et al., 2019) have paved the way to increase structural and ecosystem sustainability by means of proactive decisions, particularly urgent under extreme events or the expected acceleration in climate change. This approach is illustrated in the paper by combining a data-driven characterization of wave extremes with some non-linear formulations for the considered structural or ecosystem responses. The data analysed correspond to more than 30 years of wave series from buoys deployed at the Basque, Cantabrian and Catalan coasts. Extremes have been characterized with a number of statistical techniques that present increasing error intervals with return period, showing how the more energetic events, represented by a smaller sample, feature a higher uncertainty level. The error also varies with storm threshold

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and prevailing climates, with marked variations between Cantabrian and Mediterranean conditions

Coastal responses, such as structural damages, can be linked to operational or survival conditions, representing functional or resistant failure modes and their corresponding tipping points. Ecosystem responses can be linked to erosion, flooding or water quality degradation, associated to both operational (e.g. background erosion) and survival (e.g. impulsive beach breaching) conditions.

Results and discussion

The analysis of wave time series shows how uncertainty increases with storm energy level and depends on the selected variable. Nevertheless, this uncertainty can be decreased by propagation effects (Figure 1), raising the threshold to define wave storms or by applying conditional statistics, where Bayesian extreme wave height distributions present lower error bars for the upper distribution tail (Figure 2). These uncertainties also depend on the selected variable, illustrated in the figures by significant wave height and mean wave period (Figure 1), where the latter variable features a higher dispersion (Figure 2).

The resulting risks for coastal systems will increase due to the expected structural and ecosystem degradation, until a threshold is reached. This increase of risk levels can be bounded by a bespoke predictive maintenance (Figure 3) programme, where proactive action is taken whenever risk levels approach some co-designed threshold. Such a predictive maintenance will therefore result in shared benefits for coastal environments and the socio-economic activities they support. Predictive maintenance programmes should also address the interaction between coastal dynamics and infrastructures, with important savings in costs such as, for instance, when siltation closes harbour mouths during energetic storms. These events could be easily prevented by a validated early warning system (Lorente et al, 2021) accompanied by a monitoring and predictive maintenance programme.

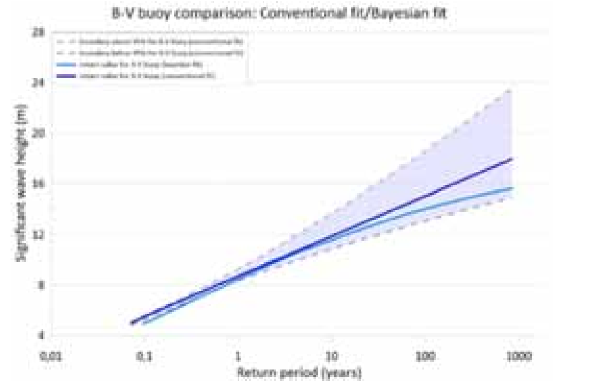

Figure 2. Comparison of conventional and Bayesian extreme distributions showing the reduction of wave heights and uncertainty intervals.

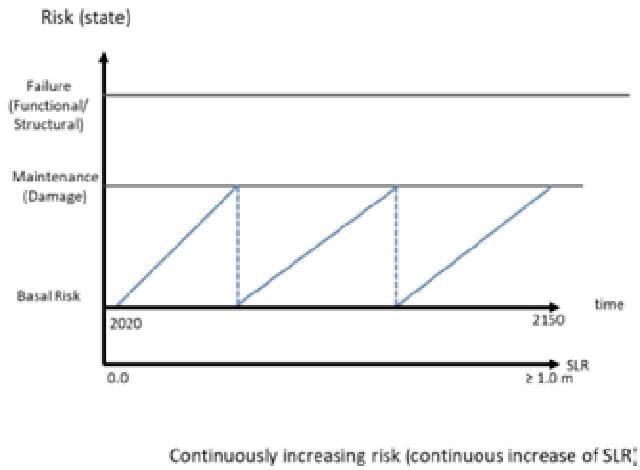

Figure 3. Schematic representation of how a predictive maintenance program can bound time-evolving risk levels.

Conclusions

A smart combination of observations, modelling and maintenance can result in a significant reduction of coastal risks, both for infrastructures and natural habitats. Predictive maintenance, anticipating the expected degradation of

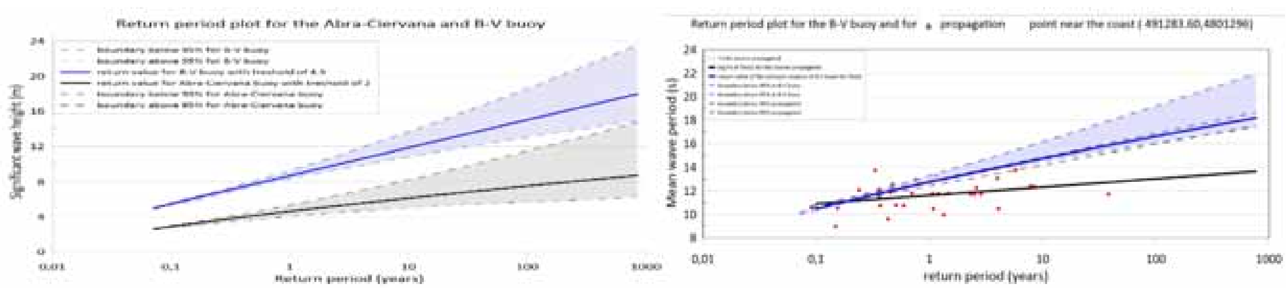

Figure 1. Comparison of 95% confidence intervals for extreme significant wave heights at two depths (left) and for mean wave period (right).

structures and habitats, should lead to a significant reduction of risks and undesired impacts, enhancing ecosystem service delivery, saving costs and reducing the carbon footprint to maintain assets and risk levels under increasing human and climatic pressures. This would, in turn, increase the funding and commitment to maintain these coastal structures and ecosystems in a good status.

The combination of a multi-disciplinary monitoring programme with a continuously validated early warning system that incorporates structural and ecosystem services, could efficiently support proactive decisions to reduce coastal hazards and vulnerabilities, while increasing coastal health. Such an approach, structured along time to tackle climatic variability and socioeconomic changes (e.g. new infrastructure, degradation of existing works or habitat losses), could produce a set of adaptation pathways with tipping points to maintain coastal ecosystems and infrastructures. The support of observations, together with harmonised metrics, to assess the performance of coastal systems, should increase the added value of monitoring and maintenance programmes, particularly urgent under present extremes (e.g. energetic storms) or the expected acceleration of climate change (e.g. for sea level rise).

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