

MULTIVARIATE COASTAL HAZARD RESPONSES WITH STOCHASTIC SIMULATION

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INTRODUCTION

Improvements to deterministic coastal structure design equations and evaluation methodologies are documented in several studies and incorporated into software that supports probabilistic coastal structure design and coastal hazard analysis. These improvements followed advancements in computational infrastructure, coastal structure research and development, and regional high-fidelity hazard datasets spanning the practical probability space for coastal storm events. With completion of the South Atlantic Coastal Study (SACS), high-fidelity numerical model results and associated statistics are now available to stakeholders performing probabilistic risk and risk-mitigating design analyses via the Coastal Hazards System (CHS; <https://chs.ercd.dren.mil>). This data is available for the entire Gulf of Mexico and Atlantic Ocean shorelines of the United States, including Puerto Rico and the U.S. Virgin Islands (Nadal-Caraballo et al., 2022). With the ability to easily acquire probabilistic coastal hazard datasets from the CHS, advancements to established deterministic approaches for coastal structure design are possible (Melby et al., 2005). Described herein are some of the feasibility and design studies of coastal risk mitigation alternatives that contributed to the creation of the Stochastic Storm Simulation (StormSim) tools.

StormSim was developed as a modular suite of software tools to perform high-fidelity probabilistic analyses of coastal structures, incorporating epistemic and aleatory uncertainty of hazards obtained from the CHS. Uncertainty is carried through the StormSim workflow through its inclusion in established deterministic empirical structure response, reliability, and consequence equations developed from laboratory studies (Melby et al. 2005). The StormSim tool suite allows users to optimize structure designs to maintain responses below established limit states (e.g., overtopping of earthen levee systems), provide given reliability levels across a (or many) project lifecycle(s) (i.e., rubble mound structure damage progression), or to balance armor stability with initial construction and repair costs.

METHODOLOGY

Probabilistic coastal structure response hazards can be computed within either a threshold or life cycle framework. StormSim tools have been developed for both frameworks to fully propagate complex, high-fidelity physics and statistics throughout the workflow while also incorporating aleatory and epistemic uncertainties. StormSim-PROS (Probabilistic Response of Structures)

is designed for threshold responses, including levee, floodwall, and rubble mound overtopping and volumetric discharge, levee and rubble mound runup, floodwall hydrodynamic and hydrostatic pressures, and rubble mound stone stability. StormSim-LCS (Life Cycle Simulation) is designed to evaluate coastal structure responses within a life cycle context, such as rubble mound armor damage and dune erosion. An extension of StormSim-LCS includes the economic evaluation of initial construction and repair costs associated with a given alternative. The methodologies and workflows included in StormSim were developed from planning and design analyses from many different projects within the continental United States. Several important studies are highlighted to showcase the development and example applications of StormSim.

APPLICATIONS - EXAMPLE STUDIES

The first implementation of the approach employed in StormSim was in support of the Mid Bay and Poplar Island ecosystem restoration Feasibility Study located in Chesapeake Bay, Maryland, U.S. (Melby et al. 2005). The analysis varied rubble mound structure crest heights to evaluate wave runup and overtopping responses and varied armor and toe stone sizes to evaluate predicted damage levels for proposed revetments and low-crested breakwaters. Partially empirical physics-based stone sizing design equations from Melby and Hughes (2004) were used within the stochastic analysis to relate stone stability to maximum wave momentum flux. A time dependent life-cycle generator was developed to represent future conditions statistically consistent with historical storm forcing and sequencing, identified as 52 tropical cyclones and 43 extratropical cyclones affecting the area between 1851-2003 and 1954-2003, respectively. The life cycles of hazards and subsequent structure responses were applied for economic optimization of structure configurations, balancing initial construction and maintenance costs. This project is presently in the Preconstruction Engineering Design (PED) phase and is addressing some of the shortcomings identified in Melby et al. (2005) for discontinuities in emergent/submerged breakwater and toe stability equations. These deficiencies have been addressed in the StormSim software.

In 2018, a design effort to inform repair decisions for the Coos Bay, Oregon, U.S. navigation jetties was driven by a performance requirement such that the head of the north jetty would maintain its functional performance over the 50-yr design life (i.e., avoid recession of the jetty head).

The effort first calculated an initial design stone size based on a 0.02 annual exceedance probability event and the wave momentum flux stability formula from Melby and Hughes (2004). This initial design stone size was evaluated with a physical model that informed calibration of the life-cycle damage progression model. The Coos Bay effort demonstrated response-based cumulative structure damage predictions over a 50-yr design life including uncertainty and sea level change. The response-based approach was found superior to simply applying armor stability equations for a single storm event (event-based), which proved to *not* be conservative (Gonzalez et al. *in press*).

The Alabama Barrier Island Restoration Project (Gonzalez et al. 2020) evaluated feasibility and cost associated with restoration actions of a rubble mound berm within a life cycle context using StormSim-LCS and considering three sea level rise scenarios. This included evaluating berm functionality through damage, wave transmission, and reliability, as well as evaluating the fronting beach morphologic effects on these parameters. One-thousand, twenty-year life cycles were generated based on the Poisson distribution and the individual storm recurrence rates of the 295 synthetic tropical cyclones modeled in the coupled ADCIRC-SWAN model. These storms were additionally sampled based on a storminess bin associated with island response to the storm frequency and intensity at the project location. The storms were also modeled in X-Beach and results from that modeling were used to bracket the berm toe elevations used as input in the structural response and reliability analyses. The study concluded that maintaining the beach in front of the structure improves reliability two-fold given the reduced exposure to damaging waves.

The Sabine-to-Galveston (S2G; Melby et al. 2021) study evaluated coastal levee and floodwall overtopping, floodwall hydrostatic and hydrodynamic pressures, and floodwall nappe geometries within the StormSim-PROS fully probabilistic framework for three coastal storm risk management systems. Large, regional high-fidelity coupled wave and circulation modeling was completed on three different sea level rise scenarios following the process described in Massey et al. (2012). Tides were included as a standard deviation and the peak values from each storm were used within the computation. Crest elevations were set for over a hundred reaches for each protection system by finding the crest elevation that satisfied the overtopping hazard found in StormSim-PROS to an overtopping threshold associated with damage. This project used a 189-storm sample, efficiently sampled from the CHS suite of 660 synthetic tropical cyclones developed for Coastal Texas. This study identified improvements to coastal structure threshold response analysis by demonstrating response-based methods are more accurate than frequency-based methods. Stehno and Melby (*in review*) concluded from this study that the probability of the structure response is not necessarily the same as the probability of the storm forcings.

LOOKING FORWARD

Investments in the StormSim tool suite is expected to continue with platform and accessibility expansion through cloud-based services as well as functionality additions including natural and nature-based feature responses, wave transmission, and additional design applications detailed in the Coastal Engineering Manual. Efforts are underway to improve response equations between submerged versus emergent breakwater conditions where Melby et al. (2005) noted they were not continuous. Further, StormSim will extensively support new tools for analyzing Coastal Storm Risk Management feasibility studies within a probabilistic life-cycle analysis approach that accounts for nonstationary hazards, protective measures, and damageable assets.

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