MULTIVARIATE COASTAL HAZARD RESPONSE STOCHASTIC SIMULATION

Abigail L. Stehno, U.S. Army Corps of Engineers R&D Center, Abigail.L.Stehno@usace.army.mil
Jeffrey A. Melby, U.S. Army Corps of Engineers R&D Center, Jeffrey.A.Melby@usace.army.mil
Victor M. Gonzalez, U.S. Army Corps of Engineers R&D Center, Victor.M.GonzalezNieves@usace.army.mil
Norberto C. Nadal-Caraballo, U.S. Army Corps of Engineers R&D Center, Norberto.C.Nadal-Caraballo@usace.army.mil
Fabian A. Garcia-Moreno, U.S. Army Corps of Engineers R&D Center, Fabian.A.Garcia-Moreno@usace.army.mil
Kevin C. Hodgens, U.S. Army Corps of Engineers R&D Center, Kevin.C.Hodgens@usace.army.mil
Madison C. Yawn, U.S. Army Corps of Engineers R&D Center, Madison.C.Yawn@usace.army.mil

INTRODUCTION

Coastal structure risk analysis is sensitive to underlying physics and statistics. In post-Katrina U.S. studies, it has become increasingly apparent that statistical fidelity can be as important as physical fidelity to evaluate coastal structure responses to storm hazards as part of risk assessments. Fully probabilistic level III reliability techniques yield highly accurate results while also incorporating both aleatory and epistemic uncertainties. Novice application of these methods may seem intimidating; however, the StormSim tool suite eases the use of stochastic simulation for evaluation of coastal hazards and design of coastal structures. StormSim methods maintain multivariate statistical and physical interdependencies between coastal storm responses within a user-friendly, computationally efficient framework.

StormSim is a modular suite of software tools for stochastic analysis of coastal forcing hazards and assessment of coastal system responses. The StormSim modules described herein include 1) Joint Probability Method with Optimal Sampling (JPM-OS), 2) Stochastic Simulation Technique (SST), 3) optimal storm sampling 4) Probabilistic Response of Structures (PROS), and 5) Life-Cycle Simulation (LCS). Additional modules include multi-variate optimal storm sampling, wind-wave generation, economic LCS, and natural and nature-based feature responses. The StormSim tool suite computes a large variety of coastal hazard responses with high physical and statistical fidelities while optimizing computational efficiency and reducing user data acquisition and preparation efforts.

METHODOLOGY

StormSim is a component of the Coastal Hazards System (CHS, Nadal-Caraballo et al. 2020). CHS is a national-scale initiative for the quantification of coastal storm hazards and contains an online database (CHS-DB) of results from high-fidelity, physics-informed numerical modeling of coastal storm events spanning the practical probability space for the U.S. coastline. Synthetic tropical cyclones (TCs) and historical extra-tropical cyclones (XCs) were modeled in a high-fidelity coupled hydrodynamic framework (Massey et al. 2012) to produce coastal wave and water level responses as part of multiple regional studies. The modeling and statistics data from these studies were evaluated for multiple sea level rise conditions (SLRC), which are made readily available on CHS. Discrete storm weights (DSW) define the probability of each TC and are used to estimate hazards. Epistemic uncertainties are embedded in the CHS results.

Both peak and timeseries values of storm parameters are available in CHS, and StormSim directly ingests these results to estimate structure response hazards. StormSim can efficiently evaluate responses over entire timeseries within a probabilistic framework without large computational costs. User adjustments, such as applying tides and sea level rise and prioritizing peak wave height or peak water level are internally completed within StormSim. Tides can be either randomly sampled, applied as an uncertainty, or applied as a skew tide to better account for nonlinearities. Sea level rise adjustments may be applied to water levels linearly; however, nonlinear residuals are complex and influential in the nearshore, requiring multiple SLRC results in CHS. Within a timeseries, peak water level (WLP) or peak wave height (WHP) can be prioritized to supersede the peak value in the timeseries to ensure the greatest storm forcing parameter is evaluated.

Storm response hazards, such as waves and water levels, are estimated using StormSim-JPM for TCs (Nadal-Caraballo and Melby 2014) and StormSim-SST for XCs. The StormSim-JPM module estimates coastal responses from TCs. TC wave and water level responses are ingested into StormSim, aleatory uncertainty is applied using hundreds of thousands of storm realizations, and best-estimate (BE) exceedance probabilities are estimated using associated DSWs. Epistemic uncertainties are applied to the BE hazard curve to compute confidence limits. Details about coastal storm uncertainties are in Gonzalez et al. (2019). Storm response hazards for XCs are estimated using StormSim-SST. Modeled historical storms are ingested into the StormSim-SST framework and are bootstrapped sampled, including aleatory uncertainty to characterize multiple sequences or life cycles of storm responses. Extreme events from the sampling are identified using peaks-over-threshold and are fit to a generalized Pareto distribution (GPD) to capture the low-frequency tail of the storm response hazard. Storm response hazards from the individual TC and XC analysis are combined to estimate the full storm response hazard.

Storm hazard responses may be used as-is from the CHS and StormSim analysis; however, studies, such as coastal storm risk management feasibility and design, may require higher physics resolution around the system or with-project structure modifications in the hydrodynamic modeling grids. Additional high-fidelity coupled hydrodynamic modeling is completed with a focus on the project location itself. To reduce computational costs, optimal storm sampling in StormSim produces a reduced storm suite from the large regional CHS datasets. A genetic algorithm finds the optimal subsample of storms that most nearly match storm hazards at the study location and these storms are re-modeled in the hydrodynamic models with updated grid modifications.

Coastal structure response hazards, such as overtopping, stone stability, and beach morphology, are estimated in a response-based methodology to maintain the high fidelity multivariate statistical and physical interdependencies. Response-based methods maintain multivariate relationships between storm forcing parameters without assuming identical probabilities of forcing parameters and structure responses. Stehno and Melby (*in review*) found that the structure response probability is not equal to the storm forcing parameter probabilities; therefore, the response-based method is more accurate for estimating coastal structure response hazards than frequency-based methods. Although the response-based method is seemingly more complex than the frequency-based method, StormSim modules streamline the response-based workflow for the user. The influence of tides, SLRC, and WHP/WLP are carried through the entire StormSim workflow to eliminate severing complex nearshore physical processes. StormSim-PROS estimates threshold structure response hazards, while StormSim-LCS estimates time-dependent structure responses within a life cycle context.

StormSim-PROS uses response-based methods to probabilistically estimate threshold coastal structure response hazards. Coastal structure responses include floodwall, levee, and rubble mound overtopping and volume discharge, levee and rubble mound runup, floodwall hydrodynamic and hydrostatic pressures, and rubble mound stone stability. StormSim-PROS leverages StormSim-JPM and StormSim-SST workflows to compute structure response hazards. Structure responses are computed for hundreds of thousands of storm realizations after sampling and applying aleatory uncertainty. The exceedance probability of the structure response itself is then estimated using StormSim-JPM for TC structure responses and StormSim-SST for XC structure responses. Epistemic uncertainties associated with empirical equations are combined with storm forcing epistemic uncertainties into a singular uncertainty value and are applied as confidence limits to the BE response hazards. Results from StormSim-PROS are used for coastal structure design when designs require non-exceedance of a structure response hazard at a given probability.

Time-dependent stochastic analyses of coastal structure responses are computed using StormSim-LCS. Current coastal structure responses include dune and beach morphology and rubble mound armor damage progression. Within StormSim-LCS, life cycles are created from sampled storms. Storms are sampled using a Poisson distribution to create a life cycle reflective of the larger population of storm intensities and associated probabilities at the study location. XCs may be sampled either historically or from stochastic simulation using bivariate or multivariate Gaussian copulas, while TC storms are sampled using DSWs. Additional sampling techniques include binning storms by intensity prior to sampling, then sampling from the intensity bins to represent storm intensity probabilities more accurately throughout the entire life cycle. Hundreds of life cycles are created to stochastically account for aleatory uncertainties, and the use of a large amount of life cycles ensures statistical convergence.

Structure reliability can be estimated from the set of life cycles generated by StormSim-LCS. Structure responses are computed for the storms within each life cycle to evaluate time-dependent damage and morphology. The reliability and probability of failure is computed over each life cycle. Performance can be estimated using $G = R - F$, where G is performance, R is response, and F is forcing. Reliability is computed as 1 - sum($G<0$) over the life cycle, and probability of failure is 1 - Reliability. In StormSim-LCS, this is completed for hundreds of life cycles and statistics about structure performance can be computed. These statistics can be used in coastal structure design to estimate expected structure performance, number of repairs, and associated costs over the entire life cycle of the structure.

The StormSim suite of tools is a powerful coastal statistics and structure design-support software that propagates high fidelity statistics and physics throughout the entire coastal hazard analysis for storm and structure responses on a user-friendly platform. StormSim tools allow users to simulate coastal structure responses efficiently and accurately within a probabilistic framework without needing to reduce either the statistical or physical fidelity during coastal system feasibility and design studies.

REFERENCES

Gonzalez, Nadal-Caraballo, Melby, Cialone, (2019). Quantification of uncertainty in probabilistic storm surge models: Literature review. ERDC/CHL SR-19-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Massey, Wamsley, and Cialone (2012): Coastal Storm Modeling – System Integration. In Proceedings of Solutions to Coastal Disasters Conference 2011, pp. 99-108.

Nadal-Caraballo, Melby, (2014). North Atlantic Coast Comprehensive Study Phase 1: statistical analysis of historical extreme water levels with sea level change. Technical Report ERDC/CHL TR-14-7, US Army Engineer R&D Center, Vicksburg, MS.

Nadal-Caraballo, Campbell, Gonzalez, Torres, Melby, Taflanidis, (2020). Coastal Hazards System: A Probabilistic Coastal Hazard Analysis Framework. In: Malvárez, G. and Navas, F. eds., Global Coastal Issues of 2020. Journal of Coastal Research, Special Issue No. 95, pp. 1211-1216.

Stehno, Melby (*in review*). Practical coastal structure stochastic response simulation using multi-variate hazards. Coastal Engineering (In review).