STORMSIM: A MODULAR APPROACH TO PROBABILISTIC COASTAL HAZARDS ANALYSIS

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INTRODUCTION

This research presents StormSim, which is a coastal engineering software toolkit tailored to probabilistically assess coastal hazards and evaluate coastal system design. It was developed in response to the increasing efforts to better incorporate uncertainties and reduce the complexity associated with Probabilistic Coastal Hazard Analysis (PCHA; Nadal-Caraballo, 2020). StormSim is used for probabilistic coastal analyses including, coastal structure responses, coastal storm risk management (CSRM) feasibility, coastal structure engineering, and flood risk management.

StormSim is a collection of MATLAB modules developed to simplify and automate PCHA. Two response-based computational frameworks are embedded in StormSim: 1) Probabilistic Response of Structures (StormSim-PROS) and 2) Life Cycle Simulation (StormSim-LCS). StormSim workflows maintain high-fidelity physics and statistics and incorporate associated aleatory and epistemic uncertainties. StormSim software has a centralized architecture for efficient and seamless communication between modules and computational frameworks.

StormSim is integrated with the Coastal Hazard System (CHS; https://chs.erdc.dren.mil). CHS contains high-fidelity hydrodynamic modeling of coastal storms that span the probability space and maintain spatial uniformity and density in the U.S. Associated aleatory and epistemic uncertainties are also available in CHS. StormSim's seamless integration with CHS allows fully automated computation of accurate coastal structure hazard responses for design and performance.

SOFTWARE ORCHESTRATION

StormSim's effectiveness is rooted in its modular design. This approach guarantees computational efficiency and expedites assessment of entire CSRM systems. StormSim requires four key project-specific components: 1) configuration file, 2) Protective System Elements (PSEs), 3) wave and water level storm forcing events, and 4) associated parameter aleatory and epistemic uncertainty. The configuration file holds project details, identifies directory paths to the other three components, and governs toolkit behavior. PSEs represent 1-D coastal structure transects. Storm forcing and associated uncertainties are downloaded from CHS as spatially distributed data containing peak and time series files.

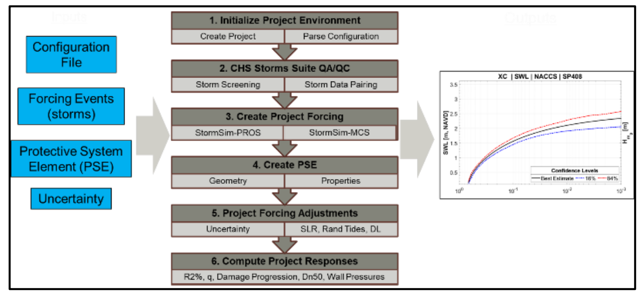

Figure 1: StormSim centralized execution, showing project components (left), StormSim modules (middle), and coastal structure hazard results (right).

Figure 1 illustrates StormSim's centralized architecture, showing the flow of key project components through modules to derive project responses. Project components are on the left and are loaded into the StormSim modules. Six steps are completed:

1. Initializing the project environment includes creating the project folder hierarchy, loading associated project dependencies, and parsing the configuration file. The configuration file contains necessary information to ensure consistency when calling the three other components and information for automated quality assurance and quality control (QA/QC) throughout the workflows.

2. CHS storm suite QA/QC involves importing and processing CHS forcing data. CHS consists of ADCIRC and STWAVE data in HDF5 (.h5) format. Non-CHS datasets are also compatible if formatted correctly. Data processing includes: 1) coupling surge and wave data, 2) QA/QC on CHS data, 3) generating alternate datasets for Wave Height Priority (WHP) and Water Level Priority (WLP). These priority datasets are created by linking either the peak wave or peak water level response to the priority variable peak in the timeseries datasets.

3. Create project forcing based on computational framework specified in configuration file. according to the computational framework.

4. Create PSE based on structure geometry and properties defined in the configuration file.

5. Project forcing adjustments are completed, including applying uncertainties to wave and water level storm forcings. Adjustments to water levels account for sea level rise (SLR) and tides and adjustments for wave parameters account for depth limitation (DL) at the structure toe.

6. Compute project responses using empirical or physics-based equations. Coastal structure responses include levee and rubble mound runup (R2%); levee, rubble mound, and floodwall overflow+overtopping rate (q) and overflow+overtopping discharge (Q); rubble mound stone sizing (Dn50); and floodwall Goda hydrodynamic and hydrostatic pressures. Results are stored in the project directory.

COMPUTATIONAL FRAMEWORKS

StormSim has two main computational frameworks: StormSim-PROS and StormSim-LCS. These frameworks handle tasks such as receiving and organizing project input data, computing coastal structure responses, and presenting results as plots and data files. StormSim-PROS probabilistically estimates threshold project responses, while StormSim-LCS computes time-dependent stochastic analyses of project responses.

StormSim-PROS computes coastal structure responses, such as overtopping and stone stability, for structure design. The response-based methods do not assume structure response probabilities are equal to storm forcing probabilities. To do this, aleatory uncertainty is applied to storm forcing parameters through sampling and replicates, structure responses are computed for every storm, then the exceedance probabilities of the structure response itself is computed to produce the structure response hazard. Epistemic uncertainties associated with storm forcing and empirical structure response equations are applied as confidence limits.

StormSim-LCS computes time-dependent coastal structure responses to evaluate structure performance. StormSim-LCS uses a modified Monte Carlo sampling scheme to select storms with respect to both frequency and intensity. Storms are sampled using a Poisson distribution to construct a life cycle that accurately represents the broader population of storm intensities and associated probabilities at the study location. Extra-tropical events are sampled either historically or stochastically using Gaussian Copula, while Tropical Cyclones are sampled based on Distributed Storm Weights (DSW). Stochastic sets of life cycles are defined by the number of life cycles in the set and simulation length of the life cycles (years per cycle). StormSim provides flexibility for users to test statistical stability of the numbers of cycles to ensure convergence.

COMPUTATIONAL EFFICIENCY

Computational efficiency within StormSim is achieved through vectorization and isolation of core processes. Simple modules can be used across multiple computational frameworks. Additionally, the centralized architecture can reach across multiple project environments to leverage processes that have previously been completed. For example, StormSim will recognize if Steps 1 and 2 were completed within a separate computational framework then re-use those results. This is beneficial when multiple PSEs and alternatives with identical storm forcings are being evaluated. Automation reduces user interaction in data setup and formatting, narrowing focus to analysis results. This seamless integration of modularity, computational efficiency, and automation enhances StormSim's reliability in coastal hazard assessment.

Computational efficiency testing was conducted on a Windows desktop PC with an i7 - 13700KF @ 3.40 GHz processor, 32 GB of RAM @ 5600 MHz, using MATLAB R2022b. The testing for a rubble mound PSE involved 1) running both computational frameworks, 2) loading peaks and timeseries datasets from CHS involving 1050 tropical cyclones and 100 extra-tropical cyclones, 3) generating alternate WLP & WHP datasets, 4) Utilize a rubble mound PSE (which yields the most responses). The rubble mound PSE was tested because it yielded the most structure responses for StormSim's native coastal structures. These structure responses in StormSim-PROS include runup, overflow and overtopping rate and discharge, and stone sizing and in StormSim-LCS include armor damage progression. Table 1 has computational time results for StormSim-PROS, typically used for structure design, and Table 2 has computational time results for StormSim-LCS, typically used for structure performance evaluation. Steps 1 and 2 are not included in Table 2 because the software automatically detected and loaded processed storm data completed in Table 1.

Table 1. StormSim-PROS execution times. Steps correspond to central architecture in Figure 1.

Step #	Time [s]	Time [min]
1	128.019	2.134
2	1.811	0.030
3	0.565	0.009
4	0.7932	0.013
5	18.98	0.32
6	571.11	9.52
Total Time	721.27	12.02

Table 2: StormSim-LCS execution times for 1000 life cycles at 50 years duration.

Step #	Time [s]	Time [min]
3	217.2	3.62
4	0.7932	0.013
5	37.98	0.633
6	800.2	13.33
Total Time	1056.17	17.596

CONCLUSION

StormSim stands as a pivotal advancement in coastal engineering. This software offers a computationally efficient and adaptable tool for PCHA used in structure design and performance evaluation. Its modular framework is optimized for effectiveness and allows for ongoing development. StormSim's high-fidelity statistical capabilities, computational efficiency, and modularity makes the suite of tools increasingly beneficial for coastal engineering design and hazard analysis.

REFERENCES

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.