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RESEARCH ARTICLE

Monte Carlo simulation model for economic evaluation of rubble mound breakwater protection in Harbors

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Abstract The US Army Corps of Engineers has a mission to conduct a wide array of programs in the arenas of water resources, including coastal protection. Coastal projects must be evaluated according to sound economic principles, and considerations of risk assessment and sea level change must be included in the analysis. Breakwaters are typically nearshore structures designed to reduce wave action in the lee of the structure, resulting in calmer waters within the protected area, with attendant benefits in terms of usability by navigation interests, shoreline protection, reduction of wave runup and onshore flooding, and protection of navigation channels from sedimentation and wave action. A common method of breakwater construction is the rubble mound breakwater, constructed in a trapezoidal cross section with gradually increasing stone sizes from the core out. Rubble mound breakwaters are subject to degradation from storms, particularly for antiquated designs with under-sized stones insufficient to protect against intense wave energy. Storm waves dislodge the stones, resulting in lowering of crest height and associated protective capability for wave reduction. This behavior happens over a long period of time, so a lifecycle model (that can analyze the damage progression over a period of years) is appropriate. Because storms are highly variable, a model that can support risk analysis is also needed. Economic impacts are determined by the nature of the wave climate in the protected area, and by the nature of the protected assets. Monte Carlo simulation (MCS) modeling that incorporates engineering and economic impacts is a worthwhile method for handling the many complexities involved in real world problems. The Corps has developed and utilized a number of MCS models to compare project alternatives in terms of their costs and benefits. This paper describes one such model, Coastal Structure simulation (CSsim) that has been developed specifically for planning level analysis of breakwaters.

Keywords coastal protection, Monte Carlo simulation (MCS), life-cycle modeling, risk analysis, rubble mound breakwaters, planning

1 Introduction

Risk-based life-cycle analysis of breakwater projects for purposes of choosing among different alternatives requires examination of the complex system that comprises the breakwater and protected area. This system includes the driving forces that create damages (the storms), the protective structure (the breakwater), the harbor, and the activities and assets that are protected. These protected assets and activities may include other coastal structures, harbor and transit operations, moored vessels, shoreline structures and businesses, recreational activities, sustenance and search and rescue activities, national security operations and many other things. Historically, risk assessments have evaluated these systems in a very simplified manner, typically modeling processes deterministically using return period storm events or using highly simplified reliability-based methods. This methodology provides useful information but may not consider the complex system behavior as the protective structure deteriorates or the built environment changes or the maintenance programs/priorities change during the life-cycle. In addition, storm events with widely varying wave and water level permutations can produce widely varying impacts to the protected environment. For example, a hurricane with high surge arriving on high tide with moderate waves may produce extensive flooding but relatively less structural damage while an extra-tropical storm with very large and long waves may produce extensive structural damage but little flooding. There is

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considerable uncertainty with both the future climate and with infrastructure management and growth that must be accounted for. Other issues not addressed using a single return period event or traditional reliability-based techniques are sequences of events causing accumulated damage, marginal risk from extreme storms occurring in succession, and added risk from a damaged structure.

Improvements in computational capabilities and advances in coastal process modeling have opened the door to time-dependent life-cycle modeling of these systems. Further, measurements and reasonably accurate hindcasts of wind, wave and water level dating back to 1970 or earlier are often available, allowing for improving extremal probabilistic modeling of wave and water level climates and the associated simulation of future climates. This has led to the development of computer modeling approaches that incorporate more of the inter-relationships and long-term behaviors that are seen in real world situations. The Coastal Structure simulation (CSsim) model is an example of such a model, designed to support the particular planning analysis methodology and philosophy utilized by the Corps for evaluation of coastal structure projects. The design of the model is general, but currently the model supports only rubble mound breakwaters as protective structures. This paper is oriented toward use of CSsim for economic evaluation within the Corps analysis framework. A detailed description of the model that is oriented toward the methodologies used for wave and water level simulation and damage progression of the breakwater is provided in Melby et al. (2011).

2 Planning methodology

The Corps goes through a formal planning process in order to determine if particular projects should be carried out, including new construction and rehabilitation and repair of existing construction (USACE, 2000). The process requires that proposed project alternatives be compared with the "without project" alternative, i.e., no new Federal actions, and determination of the costs and benefits for all situations be evaluated. Benefits are evaluated based on the increase in the net value of the national output of goods and services, expressed in monetary units. These are referred to as national economic development (NED) benefits. Benefits can include damages averted by virtue of implementation of the project. The planning methodology makes use of a discount rate to bring all future costs and benefits to a present value, important in the case of life-cycle analysis. In general, the preferred plan alternative, the so-called NED plan, is the one that provides the greatest net economic benefit (benefit–cost), consistent with protecting the environment.

It is not always simple to determine the nature of the "without project" alternative, particularly in the case of long-term lifecycle analysis. For example, for a project involving rehabilitation of an existing degraded breakwater through rebuilding the structure to a greater crest elevation than the original design, the without project condition might include routine ongoing repair, as needed, of the structure to the original design crest elevation. This can be distinguished from a "do nothing" approach in which the structure is simply allowed to degrade over time, with no repairs. Thus, the model must be able to incorporate a wide range of time-based interventions that modify the breakwater, either on a scheduled basis (a rehabilitation) or in response to degradation (repair).

3 Monte Carlo simulation (MCS) models for use in planning

The Corps planning guidance (USACE, 2000) clearly states that "Planners shall identify areas of risk and uncertainty in their analysis and describe them clearly, so that decisions can be made with knowledge of the degree of reliability of the estimated benefits and costs and of the effectiveness of alternative plans." MCS is a methodology for analyzing problems where there are uncertainties. It is particularly useful in representing real-world situations with many uncertain variables, but with defined interactions and behavior when values are known. Rather than solving the problem analytically, which can be difficult or impossible, a deterministic simulation of the problem, generally in the form of a computer program, is run many times, with inputs varying based on assumed probability distributions. The complete set of results is analyzed statistically, such that the inherent output of a MCS is a distribution of results, rather than a single number. MCS is thus intimately tied to the concept of risk and uncertainty. A number of MCS models are routinely used by the Corps of Engineers in studies of shore protection (Gravens et al., 2007) and harbor planning (Moser et al. 2004) to support the goals of being able to analytically describe risk and uncertainty.

Each individual simulation within a model run is referred to as an iteration or realization, indicating that it represents one possible set of results (given the specific inputs) out of a population of many such results. When sufficient iterations are run, and the problem is appropriately formed, the statistical measures associated with the solution converge.

Planning applications within the Corps generally require that performance be evaluated over the project lifetime. A "life-cycle" model thus attempts to represent, for each iteration, the behavior over a period of time, typically 50 or more years or project life. This means that driving forces or responses that change over that time frame must be represented in the model. Climate change (sea level rise) is a good example of such a longer-term process. Repair of damaged structures is not an instantaneous process, but takes place over weeks, months or years. The protected

asset inventory changes with time, and protective structures degrade, both due to individual storms and non-storm normal wave climate. Storms are a typical forcing function for coastal protection models. They occur with seasonal patterns, which should be represented in the model. Representation of these and other time-associated phenomena is thus important in development of planning models.

The Corps of Engineers is organized geographically into Divisions, which are in turn sub-divided into Districts. Basic planning work is accomplished at the District level, such that many Districts share the need for similar analysis tools. Thus, in developing models, it is important to produce models that are not tied to a particular location or situation, but rather are general in character, with the ability to represent individual projects and locations by changing data. Such models are referred to as "data-driven" models. CSsim is designed as a data-driven model.

4 Overall model structure

The Corps of Engineers is currently in the process of developing an overall framework for use by risk-based models in the coastal environment. The general schematic approach is as shown in Fig. 1. Driving forces, typically storms, have an impact on protective systems, in this case the breakwater. The protective systems attenuate the driving forces, which then act on protected assets (harbor wave climate and structures), resulting in damages. Improvement of the protective systems through management measures (rehabilitation and repair) increases the protective capability, and reduces the damages to protected assets.

This diagram is made more specific for the case of a breakwater in a harbor as shown in Fig. 2. The modeled environment consists of a set of storms, drawn from a repository of storm sequences, either historic or synthetic. These storm hydrographs are known at an offshore point, and are translated to nearshore points (near the structure and harbor entrances) using standard wave transformation methodologies (USACE, 2002). The breakwater attenuates waves on the lee side of the breakwater (Melby et al., 2011) of the structure, which are then transmitted to interior points of the harbor, where they manifest at "consequence areas" within the harbor where protected assets exist and economic evaluation is required.

A specific situation (Neah Bay, Washington State, US), used as test data during model development, is shown in Fig. 3. A breakwater extends from the shoreline to an island, and is divided, for analysis purposes, into reaches. An inlet to the harbor exists, allowing free passage of waves and vessels. This is referred to as an "open pass." Historic and synthetic wave information is available at the offshore location, and is transformed to nearshore locations at the open pass and each breakwater reach. Interior to the harbor, consequence areas are located where assets exist that can be affected by wave climate. The wave climate at the consequence area location is determined as the combined impact from waves at the lee of each reach, and the waves coming through the open pass area.

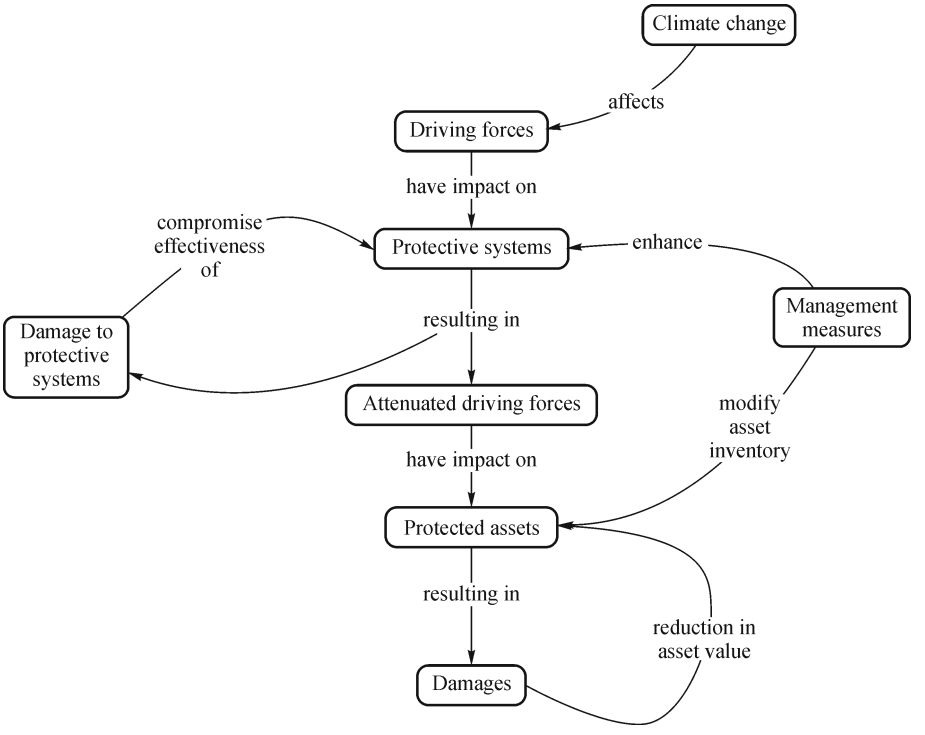

Fig. 1 General framework for coastal hazard modeling

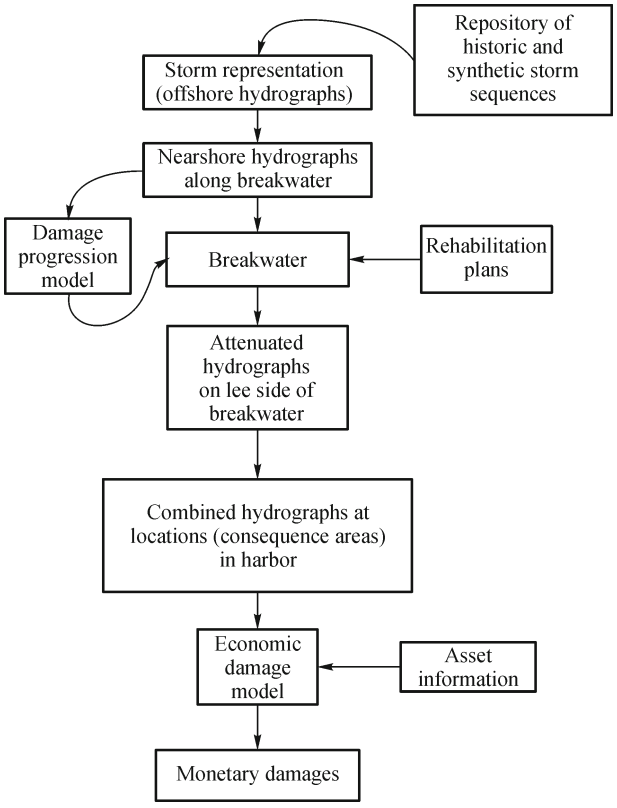

Fig. 2 Framework for breakwaters

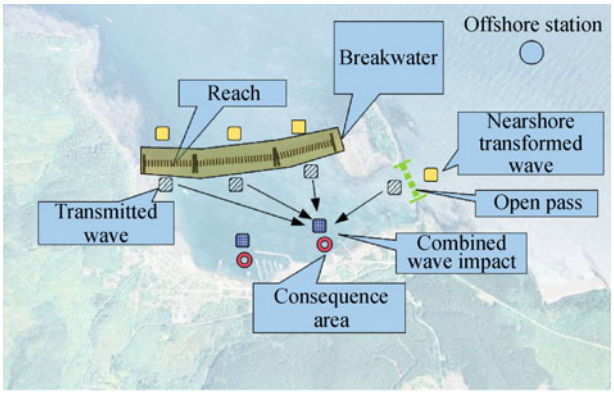

Fig. 3 Diagram of CSsim model elements

5 Storm characterization

Storms are described as individual events that occur at a specific time, e.g. a storm that started on December 14th, 1970 at 9:00 pm. For a given storm, internal storm detail is provided at fixed 3 h intervals, including information on wave height, water level, wave period, and wave direction, as shown in Fig. 4. CSsim provides capability to import storm information stored in spreadsheet format. The identification of storms from a continuous historical record, and the creation of synthetic storms, is a significant technical analysis issue, and is expected to be handled externally, through tools such as StormSim, a suite of Matlab® routines developed by the US Army Engineer R&D Laboratory for extremal analysis of storm data and simulation of future storm life cycles (Melby et al., 2011).

6 Damage progression on the breakwater

Seaside armor stability and profile evolution are computed based on Melby (2010) and Melby and Kobayashi (2011). Leeside armor stability and profile evolution and crest evolution are computed according to Melby (2010) for cases where wave runup exceeds the crest height. The CSsim life-cycle approach computes the time-dependent profile evolution at each time step within each life cycle. Wave runup on the structure and on any protected asset is computed using van Gent relations (van Gent, 2001) or using a lookup table generated using a nearshore wave transformation model that includes wetting and drying, runup and overtopping (e.g. CSHORE software (Kobayashi et al. 2008)).

At each time period for each storm, the effect of the wave on each breakwater reach is calculated. The crest elevation reduction is first determined to see if crest elevation needs to be lowered based upon cumulative damage to the reach. The critical armor stone size that will be damaged by the present wave is then determined. With this information, the incremental damages to the seaward and leeward sides of the breakwater are calculated, followed by a determination of the wave overtopping from the seaward side to the leeward side of the breakwater.

7 Wave transmission to consequence locations

The wave energy that passes over and through the reaches and through the inlet(s) will propagate to the consequence area locations. The wave transmission for a wide variety of cases is pre-computed and stored in a lookup table, which is then used to simulate the transformation of the wave energy. A wave model based on the Boussinesq equations (Nwogu and Demirbilek, 2001) was used to pre-compute the diffracted wave transmission for a wide variety of conditions. These data were used to develop a generalized tool based on a dimensionless lookup table with gap width, wavelength ratio, location behind structure, and wave direction as the input parameters.

Within the simplified approach in CSsim, the transmitted wave height for each structure reach and the incident wave at the inlet are assumed to all be independent. Each transmitted wave is diffracted to each consequence location independently using the diffraction lookup table and then the wave energies summed. This method provides

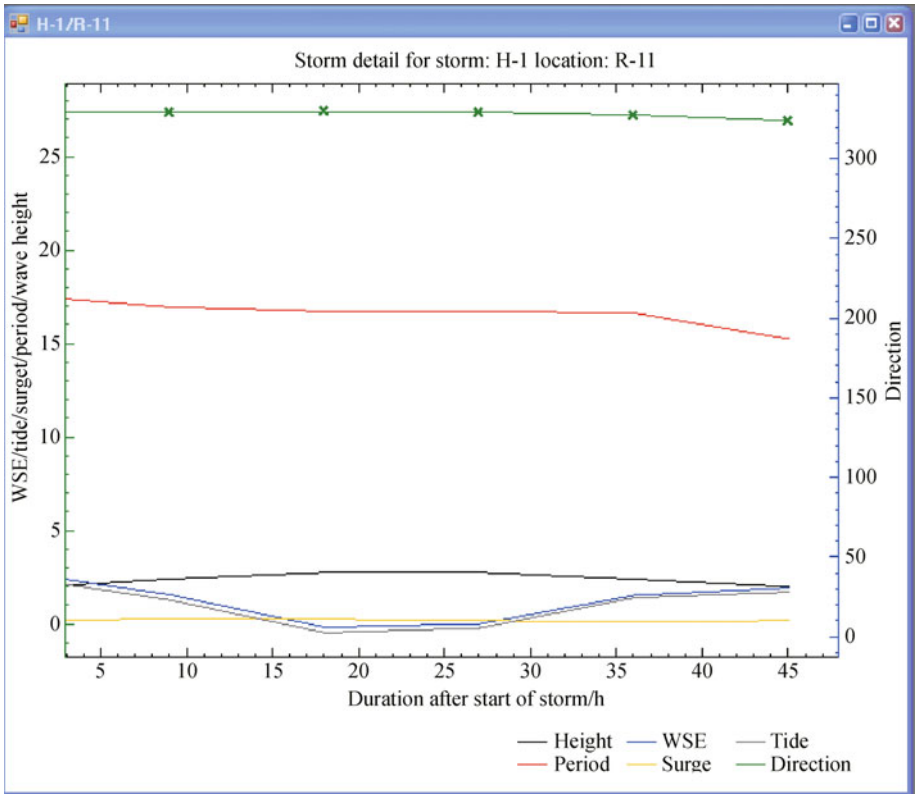

Fig. 4 Graph of internal storm detail from CSsim

a reasonable estimate of the total wave energy reaching consequence locations as a function of structure condition for life-cycle investigations. The method was checked for several severe historical storms for a site-specific project. The energy summation method produced an average error in transmitted significant wave height of roughly 4% for all consequence locations. However, there are likely to be cases where a site-specific analysis of wave transformation in the lee of the structure is required as opposed to the generalized diffraction lookup table. In those cases, a site-specific lookup table should be constructed or the generalized table enhanced.

The resultant combined wave climate at a particular consequence location for a storm (based on test data for Neah Bay, Washington) is shown in Fig. 5.

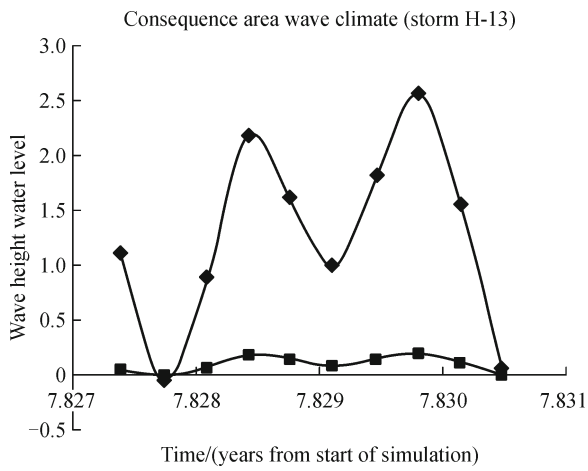

Fig. 5 Combined wave climate time series at one consequence area location for a single storm

8 Sea level change

For US Federal projects, sea level rise is computed according to EC 1165-2-211 (USACE, 2009), providing guidance for three different scenarios–low, intermediate, and high rates of sea level change. Expected sea level change is added to the simulated water level at each time step in the life-cycle simulation for each of the sea level change scenarios prior to computing wave transmission from offshore to nearshore. The transmitted waves are computed based on the revised water levels using the wave transformation lookup table.

9 Economic analysis

Economic analysis is carried out within CSsim by determining the life-cycle costs incurred for breakwater

repair and rehabilitation, and the damages that accrue to the individual assets. As noted previously, from the point of view of economic analysis, damages averted from construction of a project are considered to be benefits. Thus, the difference between damages in the without project condition and damages for a with-project alternative constitute benefits that are utilized in the calculation of net NED benefits used in project evaluation.

Repair costs are associated with each reach, and are specified as a repair plan, and a description of repair cost and time as triangular distributions. When the breaching criterion within CSsim is reached for a reach, the current repair plan for that reach is triggered, at the current repair cost and time. The repair plan specifies the post-repair physical conditions for the reach, such as crest height and stone size, essentially re-setting all of the initial conditions for that reach to the values specified in the repair plan after a user-specified waiting period that accounts for mobilization and repair time.

A rehabilitation plan is similar to a repair plan, in that it specifies all of the post-rehabilitation physical characteristics of the reach. However, rehabilitation of each reach is done at a scheduled time specified in the rehabilitation plan, and costs are defined separately in an associated cost schedule, because there are many joint costs (e.g. design, mobilization) that are shared across reaches, and not attributable to a specific reach. This is distinct from repairs, which are initiated based on damage progression, thus the time of the repair is determined internally within the model.

Damages are calculated separately for individual assets within a consequence area, based on wave height and water level information such as that shown in Fig. 5.

At present, CSsim has the capability to specify two types of assets: Physical assets that can be damaged by wave climate (e.g. vessels, docks); and usability affected by wave climate (availability of the harbor for use, for example as a harbor of refuge or for transit through a channel). CSsim does not currently provide capability for damage to land-based assets (structures, beaches), but does provide output of wave climate near shore that can be used to analyze those damages through other models. Assets are organized by user-defined class, for example recreational boats, fishing vessels, fixed docks, floating docks, and channel availability.

CSsim uses the concept of a "damage window" to describe the calendar time period during the year when damages can exist. For example, recreational boat harbors in colder climates are emptied during winter months, as boats are moved on shore, so a storm occurring during that time would not create damages. Similarly, fishing fleets may be out to sea on a seasonal basis, not moored in the harbor. The window during which the model estimates damages for an asset is described by a start month and day and an end month and day.

Certain types of assets, such as the number of boats in the harbor, can vary over time. CSsim provides for user input of a triangular distribution that will determine the number of units of the asset that are present. The user can also specify whether this number should be re-calculated at every storm, or once for each life cycle. Similarly, the value of each individual unit is described by a triangular distribution, and by a flag determining whether value is to be re-calculated once for the life cycle or at each storm event. Assets are also identified as rebuildable or not. If rebuildable, again a triangular distribution is used to determine how long the rebuilding takes before full value of the asset is restored.

CSsim uses the concept of damage functions to estimate actual damage. Based on guidance from Corps economists familiar with economic analysis of harbor protection projects, direct damage to and reduction of usability to assets is generally based on water level, wave height, and duration of exposure to higher water level and wave height. To capture this 3-dimensional variability in data, and also to allow for uncertainty in damage function estimates, a hierarchy involving damage functions, damage function families, and damage function sets is used. An individual damage function is defined for a particular duration of exposure as a percent of damage incurred for a range of wave heights. This results in a group of curves for a range of exposure durations, referred to as a damage function family, as shown in Fig. 6, showing individual damage functions for exposure durations of 0.1, 0.5, 1, and 2 h.

Damage function families are organized into "damage function sets," collections of damage function families representing minimum, most likely, and maximum damage at a given water level. Each asset is associated with a

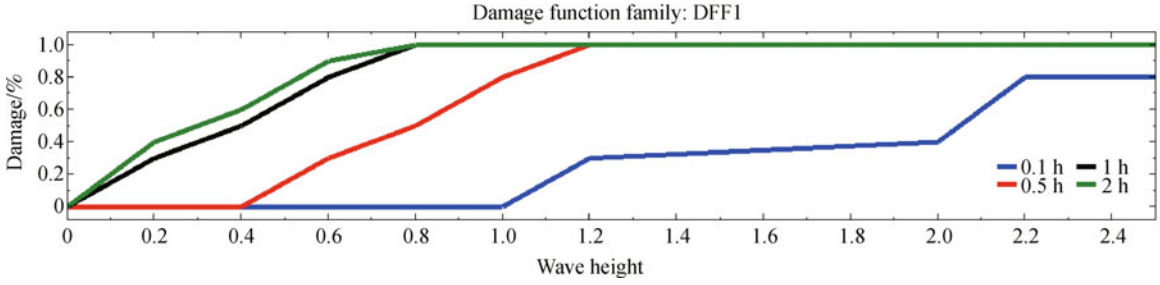

Fig. 6 Damage function family

particular damage function set. Then, when damage to that asset is to be calculated, the particular damage function set is known (from the data associated with the asset), as is the water level, from the calculated wave climate for the consequence area associated with the asset. The closest water level is determined, identifying the three associated damage function families for minimum, most likely, and maximum damage estimation. Wave height and duration of exposure are also known for the consequence area and thus the asset, so it is possible to interpolate in the damage function family (Fig. 6) to determine the appropriate percent damage. This is done three times, once for the minimum, once for the most likely, and once for the maximum, resulting in three values that are used to define a triangular distribution, from which a random variable expressing the percentage damage to be applied to the asset is drawn. For physical assets, the reduction in asset value is taken as the percentage damage multiplied by the current value of the asset. A time for rebuilding is also calculated. For usability assets, damage is determined by the fractional damage times the current value times the duration of unavailability, currently taken as the total storm duration.

While this process is somewhat complex, it does allow for a good deal of flexibility in describing the economic analysis, and is completely governed by user specification of data.

10 Model architecture, user interface and status

CSsim is written for the Microsoft Windows™ environment, in the c#.Net language. Data are stored in a Microsoft SQL Server Express database, a freely available database capable of storing large amounts of relational data. Development was done entirely with free or open-source tools, including Microsoft Visual Studio Express 2008. No proprietary software was utilized.

The initial startup screen for CSsim is shown in Fig. 7. Three panels are used–a tree format "Project Explorer," a map panel, and a data grid panel at the bottom. The Project Explorer Tree in the left-most panel presents project information in a hierarchical format, allowing users to access data and definitions for basic project setup, storm data, breakwater reach data and consequence data through a typical, mouse clickable, menu tree. The map view shows the geographic layout of the project. During the course of simulation, the color coded condition of the physical system by breakwater reach and consequence area is shown on the map panel. The project setup, storm, breakwater, and consequence data can be accessed through the "Project Explorer" tree and data grids. Import capability from the user interface is provided to allow project information to be created in spreadsheet format and

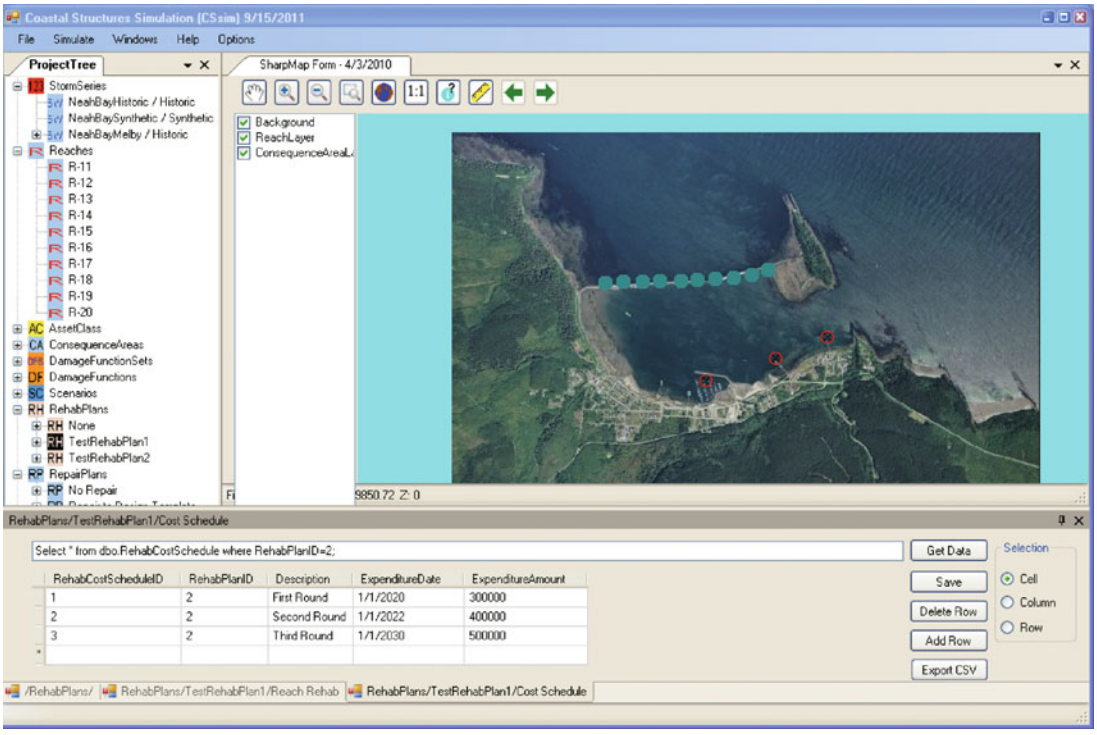

Fig. 7 CSsim initial screen

converted to the CSsim database structure.

During the course of the simulation, optional graphical display at each time step shows the behavior of the system (Fig. 8). This display contains a number of informational panels recording the sequence of events and the status of reaches and consequence areas. This display can be turned off to increase the speed of computation.

The breakwater reach panel shows the initial crest height, damaged crest height, leeside wave height, storm water level, and storm water level plus runup (Fig. 9).

Reach condition is illustrated as stoplight colors on the map panel (Fig. 10). Consequence area condition is illustrated with a bar graph of the wave height at each location (Fig. 11) as well as stoplight color coding on the map when wave height exceeds a user-set threshold (Fig. 12). The simulation display can be paused at any time to allow data to be interrogated, explored, and copy/pasted. This allows the user to understand the physical processes and their impacts on project performance, particularly for the historical life cycle.

During the course of simulation, outputs are written to data files in spreadsheet-compatible format as comma separated value (CSV) files. These files allow for detailed examination of the internal behavior of the model as well as post-processing for additional analysis beyond that provided in the model, e.g. for more complex economic consequence evaluation. Outputs include information on each reach for each storm, resulting consequence area wave climate over time, asset damage, and asset value over time. Additional outputs can easily be added to the model as study needs dictate.

Analysis of alternative projects is readily accomplished through the use of the model, for example examining ranges of armor stone size, structure geometry, an indestructible structure (no damage), infinitely tall structure (no overtopping), and varied repair philosophies in order to determine the most significant economic influences. Typically, separate alternatives are evaluated for different repair strategies. For the *do-nothing* alternative, no repair is allowed. Other repair alternatives might include no minor maintenance (fix-as-fails), maintenance as required, and repair at fixed times in the life cycle. Information is presented as statistical distributions of outcomes, together with standard statistics (maximum, minimum, mean, standard deviation), in order to allow choices based on risk-informed decision-making.

At present (October 2011), the model is being utilized in conjunction with a study of rehabilitation of breakwaters at Point Judith, Rhode Island, USA, and is being revised to suit the needs of this study, in particular the economic analysis. The Point Judith breakwaters were originally built between 1891 and 1914, with the latest construction in 1984. The main breakwater is currently in a severely damaged state. The primary assets that are protected by the breakwater are: A harbor of refuge; a channel through which an important commercial fishing fleet, charter boats, ferries (both passenger and supply), and recreational boat traffic transits; sandy beaches, wetlands, and shorefront development, including houses; docks; and groins. Interviews will be conducted with representatives of the fishing industry in particular to determine under what wave climate conditions they reduce activities, in order to

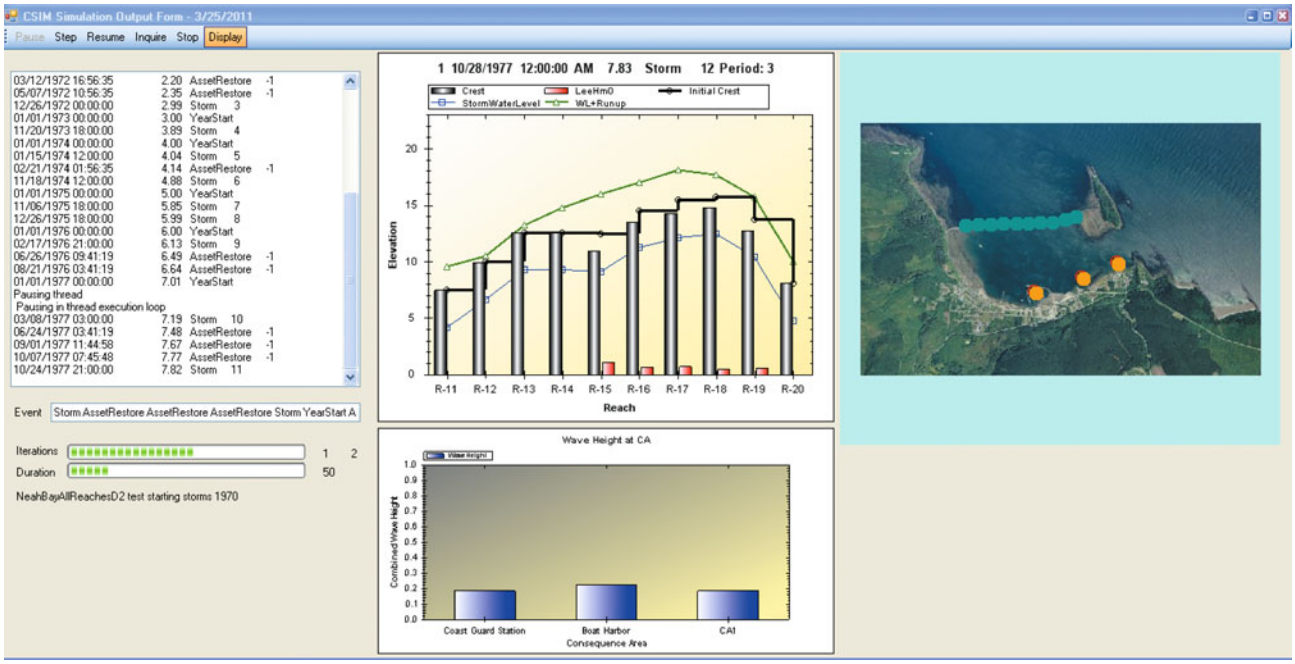

Fig. 8 Within simulation user interface display

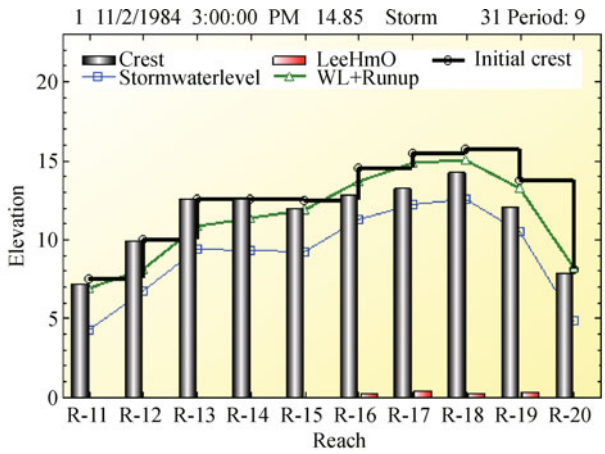

Fig. 9 Reach detail graph

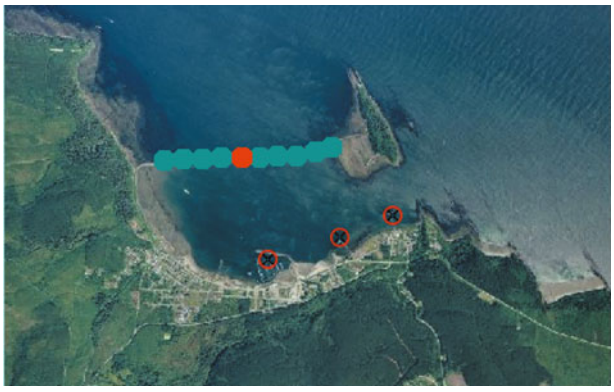

Fig. 10 Color-coded reach condition showing breached reach

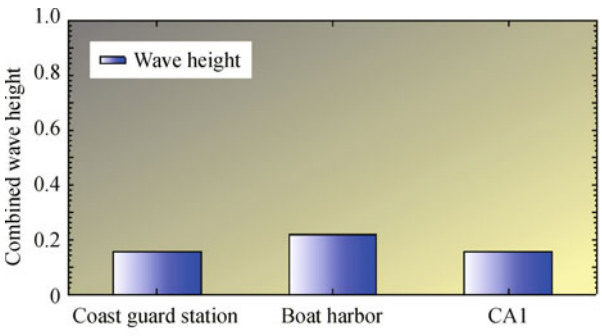

Fig. 11 Consequence area wave height

develop damage functions that can be used within CSsim.

Following modification and application for the Point Judith study, the CSsim model is expected to undergo review within an internal Corps model certification process, prior to being made available as a general purpose tool.

Fig. 12 Consequence areas with wave height above threshold

11 Conclusions

The CSsim model is an engineering-economic MCS model that can be used to evaluate alternative strategies for construction, rehabilitation, and repair of rubble mound breakwaters. It is designed to be consistent with US Army Corps of Engineers planning methodologies and best practice for planning-level analysis of storm and coastal processes. As a data-driven model, it is applicable to similar problems in different locations.

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