Revetment Damage Progression Analysis Considering Reduction in Sea Ice Cover due to Climate Change, Kivalina, Alaska

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INTRODUCTION

Kivalina is a small city located in northwestern Alaska on a barrier island that separates the Kivalina Lagoon from the Chukchi Sea. The coastline and infrastructure on the barrier island have suffered damage by surge and waves associated with storms in the Chukchi Sea. These storms primarily occur in the beginning of the fall season prior to the formation of a consolidated sea ice cover which protects the Kivalina coastline from storms from approximately November through May.

Figure 1 – Location of Kivalina

Flooding and damage from storms, combined with the observed and foreseen impacts of global warming on the spatial and temporal coverage of sea ice in the Chukchi Sea, have led the city to consider relocation from the barrier island to the mainland since 1994. In the interim, erosion control and shoreline protection works have been completed to protect the infrastructure.

Among the key infrastructure assets is Kivalina's single airstrip that provides a vital emergency evacuation route. An armor stone revetment was constructed on the seaward side of the airstrip in 2019 to protect it from storms. On behalf of the Alaska Department of Transportation and Public Facilities, a cumulative damage progression analysis of the airstrip revetment is conducted to 1) estimate its remaining useful life considering the extended exposure to storms in the fall/winter expected to occur due to global warming along with sea level rise, and 2) identify improvements to the existing revetment and airstrip to extend their useful life in their current location before resorting to relocation.

METOCEAN DATA ANALYSIS

Water levels measured south of Kivalina at Red Dog Dock, offshore waves/winds from the Wave Information Studies (WIS) hindcast, and winds measured at the Kivalina Airport are analyzed, with a focus on the fall and winter seasons where storms are more frequent.

The WIS includes sea ice effects, turning water grid cells to land when the ice concentration threshold is exceeded. To fill in the gaps in the WIS record of significant wave height and peak wave period, attempting to capture future conditions when the sea ice cover ceases to exist, a Random Forest Regression machine learning technique is employed. The choice of the Random Forest Regression algorithm is driven by the strong correlation between winds from the WIS data point closest to Kivalina (ST82059) and winds measured at the Kivalina Airport. The mean square error is 0.01 m and 0.2 sec for significant wave height and peak wave period, respectively.

NUMERICAL MODELING

A coupled MIKE 21 hydrodynamic and wave model is used to transform offshore waves to the nearshore. Two sets of simulations are conducted:

1) Simulation of extreme events (10-, 25-, 50-, and 100-year return period). The events are defined by scaling the top WIS offshore wave event, using the extreme wave height log-linear formulation provided by WIS and extreme water levels for Kivalina from USACE (2016). The predicted nearshore wave parameters are used to determine the hypothetical armor stone size of the airstrip revetment for comparison against the existing airstrip revetment.

2) Simulation of "generalized" storm conditions defined by a matrix of water levels, offshore waves and winds covering a range of conditions characteristic of fall and winter storms, based on analysis of the peak events in the WIS record. The predicted nearshore wave parameters are used in the cumulative damage progression analysis.

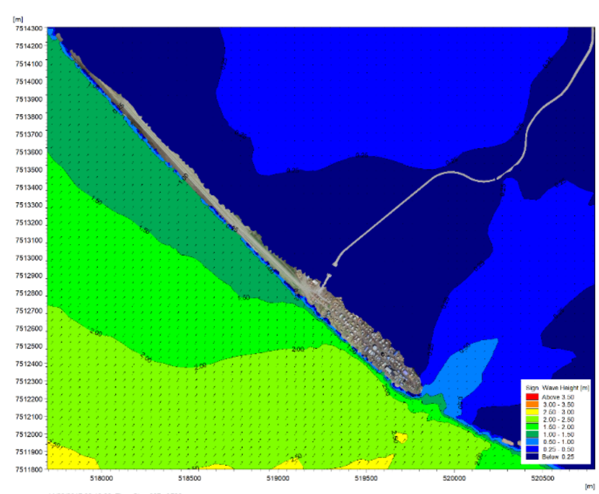

Figure 2 – Model-predicted nearshore wave heights (100-year event)

CUMULATIVE DAMAGE PROGRESSION ANALYSIS

A coastal revetment will experience a variety of events during its life, resulting in progressive damage. This damage is analyzed for the Kivalina airstrip using the method described in Melby (2005) which defines damage in terms of the average normalized cross-sectional eroded area of armor on the slope. A design life of 20 years is assumed for the analysis.

The definition and selection of events is the basis of the damage progression analysis. An event is defined by constant wave conditions represented by a significant wave height, peak wave period, and duration. The selection of events in this study is based on the following process:

1) An event is defined by periods of offshore Hs ≥ 10 ft and a minimum duration of 12 hours. From this screening:
   a. The number of events in each year of the WIS record is calculated. From this vector, the mean (μ_{NE}) and standard deviation (σ_{NE}) of the number of events per year are calculated.
   b. The mean (μ_{PK}) and standard deviation (σ_{PK}) of the peak wave height in each event is calculated.

2) The number of events in each year (20 years total) is randomly drawn from the normal distribution specified by the corresponding mean and standard deviation (μ_{NE} and σ_{NE}, respectively).

3) The damage progression analysis then proceeds by individual years. Suppose that 4 events are assigned to year 1. The offshore wave conditions for each event of the 4 events are determined as follows, using event 1 as an example:

   a. The peak wave height for event 1 is randomly drawn from the normal distribution specified by the corresponding mean and standard deviation (μ_{PK} and σ_{PK}, respectively).
   b. Based on the randomly selected peak wave height, events in the WIS record identified in Step 1 with the closest peak wave height are gathered. A random number generator is then used to select a single event from the group. This is an event extracted from the WIS record (i.e., time series of offshore wave height and period with Hs ≥ 10 ft).
   c. The use of the Melby (2005) method requires the events to have constant wave conditions. This is accomplished by averaging the Hs and Tp of the event. An average storm surge of 2.5 ft is assumed.
   d. Event 1 is now defined in terms of an average offshore wave height and peak wave period. The results from the Generalized Storm Conditions are used to translate the offshore wave height to a nearshore wave height. The peak wave period is assumed to remain constant.
   e. Event 1, now defined by nearshore wave conditions, is used to calculate damage. The cumulative mean damage from event 1 becomes the initial damage for event 2.

4) Step 3 is applied to years 1 to 20.

5) The simulation of the 20 years is repeated 10,000 times (which is typically required in a Monte Carlo simulation) to generate consistent results given the various randomized selection processes.

6) Finally, exceedance curves are developed for mean damage at 5, 10, 15, and 20 years, using the results from the 10,000 simulations, for present and future sea ice conditions.

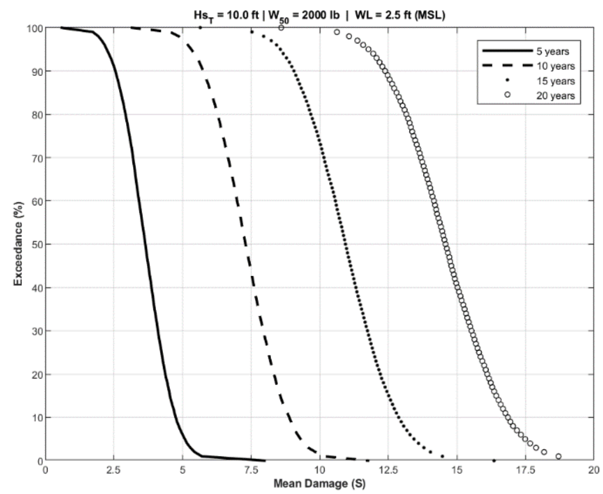

Figure 3 – Revetment damage progression exceedance curve, future sea ice conditions

ALTERNATIVES ANALYSIS

The results of the damage progression analysis suggest that the existing airstrip revetment will experience failure in the next 10 – 15 years, assuming damage is solely caused by waves and maintenance and repair works are not performed on the revetment.

Two alternatives are proposed to increase the resilience of the revetment: 1) Add another layer of armor stone and 2) raise the airstrip and revetment, adding a new layer of armor stone. Both alternatives are recommended in conjunction with performing maintenance and repair works in the summer months, paving the runway, and stabilizing the back slope on the lagoon side.

REFERENCES

Melby (2005): Damage Development on Stone-Armored Breakwaters and Revetments, ERDC/CHL CHETN-III-64.

USACE (2016): Causeway and Bridge Design Report, Kivalina Lagoon Crossing Planning Assistance to States.