consulting engineers and scientists

Extreme Weather Events and Transportation Infrastructure:

A Framework for Benefit-Cost Analysis

Samuel B. Merrill, Ph.D.
Society for American Military Engineers
Charleston, SC, April 5 2016
GEI Basics

- Founded in 1970
- 700+ Employees
- 37 Offices
- 35,000+ Projects in all 50 states and 25 countries
US Capitol Visitor Center, Washington DC
Goldman Sachs Building, NY, NY
What storm do we currently consider in our design standards?

http://www.ncdc.noaa.gov/extremes/cei/graph/ne/4/01-12
So what do we design for?

A key measure of the value of any adaptation design investment is **cumulative avoided damage**
Engineering Project Timeline

- **Planning**
  - Opportunity for Conceptual Design BCA

- **Design**
  - Start of Preliminary Design

- **Build**
Cumulative BCA Summary

Cumulative BCA Start

- Design 1
- Design 2
- Design 3

Cumulative Avoided Damages

- Construction and Cumulative Repair Costs

BCRs

- 5:1
- 1:1
- 0.2:1

25x savings
Methods to calculate cumulative avoided damages should:

- Track impact of events over an entire time period, not just as snapshots.
Methods to calculate cumulative avoided damages should:

• Track impact of events over an entire time period, not just as snapshots.
• Account for impacts of events with different intensities and frequencies
  – and their interactions.
Rates of Sea Level Rise are Increasing
Over the past 100 years, sea level rise in Portland has generally followed globally averaged long-term trends.

Sea Level, Portland, Maine
1912-2013 (through December 31, 2013)

- 1.88 ± 0.11 mm per yr or 0.63 ft (7.5") per century

y = 1.8841x - 3738.3
R² = 0.7593
Over the past 20 years, sea levels in Portland have risen far faster than the long-term trend. This change in rate is also being seen in global measurements.
Surge Events are Increasing

The Old Port, 3/10 at high tide (D. Yakovleff)
Surge Events are Increasing

The Old Port, 10/11 at high tide (M. Craig)
Surge Events are Increasing

East Bayside at High Tide 9/15 (Portland Press Herald 10/2/15)
Flood Frequency is Influenced by Sea Level

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Flood Stage (ft, MLLW)</th>
<th># times inundated</th>
<th>% of high tides</th>
<th>Duration, hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Flood</td>
<td>12.0</td>
<td>8</td>
<td>1.1%</td>
<td>8.6</td>
</tr>
<tr>
<td>+1 ft SLR</td>
<td>11.0</td>
<td>87</td>
<td>12.4%</td>
<td>121.8</td>
</tr>
<tr>
<td>+2 ft SLR</td>
<td>10.0</td>
<td>312</td>
<td>44.4%</td>
<td>575.3</td>
</tr>
<tr>
<td>+3.3 ft SLR</td>
<td>8.7</td>
<td>616</td>
<td>87.6%</td>
<td>1748.5</td>
</tr>
<tr>
<td>+6 ft SLR</td>
<td>6.0</td>
<td>702</td>
<td>99.9%</td>
<td>3816.3</td>
</tr>
</tbody>
</table>

*based on 2013 Portland tidal station data from the NOAA Inundation Analysis Tool*
Flood Frequency is Influenced by Sea Level

NOAA Technical Report NOS CO-OPS 073

Sea Level Rise and Nuisance Flood Frequency Changes around the United States

City Dock in Annapolis, Maryland. Photo Credit: Amy McGovern.

Silver Spring, Maryland
June 2014
Oil Refineries Will Face Increasing Vulnerability from Sea Level Rise and Storm Surge
COAST Software (Initially US EPA)
BCA for Infrastructure Upgrades

Muskie School of Public Service
University of Southern Maine
Based on numerous peer-reviewed method papers

Climatic Change
DOI 10.1007/s10584-011-0379-z

Simplified method for scenario-based risk assessment adaptation planning in the coastal zone

Paul Kirshen · Samuel Merrill · Peter Slovinsky · Norman Richardson

Received: 16 November 2009 / Accepted: 14 November 2011
© Springer Science+Business Media B.V. 2011
COAST is a means of:

- Evaluating *cumulative* vulnerability to storm surge and/or sea level rise, and their interaction.
  - Tailored to specific engineered structures.
- Comparing costs and benefits of candidate adaptation actions or alternative designs.
Methods Apply to Many Vulnerable Assets

- Bridges, roads, culverts, multimodal facilities
- Buildings and building contents
- Piers and other waterfront structures
- Wastewater treatment plants
- Oil refineries
- Dams and levees
Some Project Sites Completed or Underway

Selsey, United Kingdom
Santos, Brazil
Fort Lauderdale, Florida
Key Largo, Florida
Islamorada, Florida
Kingston, New York
Piermont, New York
Catskill, New York
Groton/Mystic, Connecticut
Hampton, New Hampshire
Seabrook, New Hampshire
Hampton Falls, New Hampshire

East Machias, Maine
Falmouth, Maine
Portland, Maine
Bowdoinham, Maine
Old Orchard Beach, Maine
Scarborough, Maine
Bath, Maine
Farmington, Maine
New Sharon, Maine
Marshfield, Massachusetts
Duluth, Minnesota
Rochester, Minnesota
Input Sea Level Rise Curves

- **Annual Sea Level at Key West**
- **Projected Sea Level Rise Range based on USACE Guidance**
- **Historic Key West Sea Level Rise Rate for Comparison**

- **2010** Sea level = 0
- **2030** 3-7 inches
- **2060** 9-24 inches
Input Flood Elevations and Recurrence Intervals

Can also use finer resolution data from ADCIRC and other models.
### Depth Damage Functions

*Designed for Each Candidate Action/Structure*

<table>
<thead>
<tr>
<th>Elev. (Ft)</th>
<th>Damage</th>
<th>Cost</th>
</tr>
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<tbody>
<tr>
<td>0-7</td>
<td>Negligible</td>
<td>$</td>
</tr>
<tr>
<td>7-8</td>
<td>Slight</td>
<td>$$</td>
</tr>
<tr>
<td>8-11</td>
<td>Moderate</td>
<td>$$</td>
</tr>
<tr>
<td>11-12</td>
<td>Serious</td>
<td>$$</td>
</tr>
<tr>
<td>12-14</td>
<td>Severe</td>
<td>$$</td>
</tr>
<tr>
<td>14-16</td>
<td>Extreme</td>
<td>$$$$</td>
</tr>
</tbody>
</table>

*Waterway Base Elevation*

0-7' Negligible = $
7-8' Slight = $$
8-11' Moderate = $$$
11-12' Serious = $$
12-14' Severe = $$$
14-16' Extreme = $$$$$
### Depth Damage Functions
Designed for Each Candidate Action/Structure

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<td>Extreme</td>
<td>$$$$</td>
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Waterway Base Elevation

Burden with other costs

GEI Consultants
Exceedance Curves

Probability

Elevation

100-yr Flood

50-yr Flood

25-yr Flood

10-yr Flood
How Vulnerable Are We If We Do Nothing?

![Graph showing the risk of different flood events](image)

- 100-yr Flood
- 50-yr Flood
- 25-yr Flood
- 10-yr Flood

RISK
How Vulnerable Are We If We Do Nothing?

Additional Risk from Sea Level Rise

Damage

Probability

$-$

$50,000,000$

$100,000,000$

$150,000,000$

$200,000,000$

$250,000,000$

$300,000,000$

$350,000,000$

$400,000,000$
Bridge Sensitivity to Elevated Water Levels

View of a bridge over the Sandy River on ME-41 in Farmington, an example of the types of structures that have been evaluated with the COAST software.
Transferable Examples

Figure 3: Bath

Bridge #2604 is a 50-foot single span over the New Meadows River. This girder-floorbeam structure on Old Bath Road was reconstructed in 1974; the original bridge was constructed in 1918. Condition of this bridge ranges from poor (substructure) to satisfactory (deck). Preliminary engineering for replacement is scheduled for 2015.
Transferable Examples

<table>
<thead>
<tr>
<th></th>
<th>Low Sea Level Rise (3.3')</th>
<th>High Sea Level Rise (6')</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Construction Costs</td>
<td>Total Damage/Repair Costs by 2100</td>
</tr>
<tr>
<td>Replace in Kind</td>
<td>$400,000</td>
<td>$697,476</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$594,000</td>
<td>$697,476</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$1,000,000</td>
<td>$281,242</td>
</tr>
<tr>
<td>Replace in Kind</td>
<td>$400,000</td>
<td>$1,867,580</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$594,000</td>
<td>$1,867,580</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$1,000,000</td>
<td>$916,598</td>
</tr>
</tbody>
</table>

**Replace in Kind** was the most cost effective choice for a Low sea level rise scenario, but **Replace with 6’ SLR design** was the most cost effective choice for a High sea level rise scenario.
Transferable Examples

Figure 4: Bowdoinham

Bridge #5190 is a 156-foot span, steel truss-thru design constructed in 1953. Route 24 passes over the Castine River on this structure, which has fair (substructure) to good (deck) condition ratings.
## Bowdoinham

### Low Sea Level Rise (3.3')

<table>
<thead>
<tr>
<th>Replacement Type</th>
<th>Initial Construction Costs</th>
<th>Total Damage/Repair Costs by 2100</th>
<th>TOTAL LIFE CYCLE COST BY 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace in Kind</td>
<td>$250,000</td>
<td>$1,656,830</td>
<td>$1,906,830</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$394,000</td>
<td>$1,162,080</td>
<td>$1,556,080</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$491,000</td>
<td>$205,159</td>
<td>$696,159</td>
</tr>
</tbody>
</table>

### High Sea Level Rise (6')

<table>
<thead>
<tr>
<th>Replacement Type</th>
<th>Initial Construction Costs</th>
<th>Total Damage/Repair Costs by 2100</th>
<th>TOTAL LIFE CYCLE COST BY 2100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace in Kind</td>
<td>$250,000</td>
<td>$2,163,283</td>
<td>$2,413,283</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$394,000</td>
<td>$1,900,813</td>
<td>$2,294,813</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$491,000</td>
<td>$908,565</td>
<td>$1,399,565</td>
</tr>
</tbody>
</table>

**Replace with 6’ SLR design** was the most cost effective choice for both Low and High sea level rise scenarios.
In terms of fiscal efficiency, there is no one right answer to the question “what design standard should we use?” Site-specific analysis is required.

Summary

“...The construction costs of seawall and road elevation are different for different states or situations, so the economic analysis should be conducted based on the actual construction plan in proposed locations.”
But many futures are possible!

- How do we pick whether to build for a low or a high sea level rise scenario?

<table>
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But many futures are possible!

- How do we pick whether to build for a low or a high sea level rise scenario??

- Still needed is a means of selecting from candidate designs in a way that minimizes risk across modeled future scenarios.
Transferable Example – Going Inland

Farmington_2311

New Sharon_989720
Cumulative Burdened Life-cycle Costs

Structure Designed For:
- Q100 +52%
- Q100 +24%
- Q100
- Q25

Low Runoff | Medium Runoff | High Runoff

Farmington_2311

New Sharon_898720

More Expensive

Less Expensive

No-regrets Design Across Futures
How High Should Road or Other Elevations Be?

- When curves cross, appropriate height is at the curve intersection.
- When curves don’t cross, appropriate height is at the best ratio between them.

- If choosing to build to a standard other than ideal, you at least have an estimate of how efficient the investment will be.
Thank You!

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