Extreme Weather Events and Transportation Infrastructure: A Framework for Benefit-Cost Analysis

Samuel B. Merrill, Ph.D.
Climate Prediction Applications Science Workshop, Burlington, VT
March 24 2016
GEI Basics

- Founded in 1970
- 750+ Employees
- 37 Offices
- 35,000+ Projects in all 50 states and 25 countries
### Technical Practice Areas

#### Environmental
- Compliance
- Permitting
- Due Diligence
- Characterization
- Remediation
- Risk Assessment
- Restoration
- Asbestos
- Demolition
- Brownfields
- In-Water & Uplands

#### Geotechnical
- Coastal Engineering & Planning
- Foundations
- Excavation Support
- Construction
- Tunneling
- Dams
- Embankments
- Levees
- Failure Analysis
- Geotechnical Testing

#### Water Resources
- Conveyance
- Flood Control
- Water Management
- Water Supply and Storage
- Water Resources Support
- Hydropower

#### Ecological
- Ecotoxicology
- Monitoring
- Water Quality
- Aquatic Ecosystems
- Environmental Impact
- Laboratory Services
- Sensory Services
- Air Quality
US Capitol Visitor Center, Washington DC
Goldman Sachs Building, NY
Brickell City Centre, Miami
What storm do we currently consider in our design standards?

http://www.ncdc.noaa.gov/extremes/cei/graph/ne/4/01-12
A key measure of the value of any adaptation design investment is **cumulative avoided damage**

$$$$ Avoided  

$$ Avoided

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So what do we design for?
Engineering Project Timeline

- Planning
- Design
- Build

Cumulative Benefit-Cost Analysis

Start of Preliminary Design Phase

GEI Consultants
Cumulative BCA Summary

Cumulative BCA Start

Design 1

Design 2

Design 3

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, frequencies, and rates of change.
  - 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)

\[ y = 1.8841x - 3738.3 \]

\[ R^2 = 0.7593 \]

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

Sea Level, Portland, Maine
1993-2013 (through December 2013)

$y = 4.3739x - 8731.4$
$R^2 = 0.4044$

4.38 ± 1.21 mm per yr or 1.43 ft (17.2") per century

Data courtesy of NOAA CO-OPS. www.tidesandcurrents.noaa.gov
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*
Oil Refineries Will Face Increasing Vulnerability from Sea Level Rise and Storm Surge
COAST Software (Initially US EPA)
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
• Evaluating *cumulative* vulnerability to storm surge and/or sea level rise.
  – Tailored to specific engineered structures.
• Comparing costs and benefits of candidate adaptation actions or alternative designs.
<table>
<thead>
<tr>
<th>Some Project Sites Completed or Underway</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selsey, United Kingdom</td>
</tr>
<tr>
<td>Santos, Brazil</td>
</tr>
<tr>
<td>Fort Lauderdale, Florida</td>
</tr>
<tr>
<td>Key Largo, Florida</td>
</tr>
<tr>
<td>Islamorada, Florida</td>
</tr>
<tr>
<td>Kingston, New York</td>
</tr>
<tr>
<td>Piermont, New York</td>
</tr>
<tr>
<td>Catskill, New York</td>
</tr>
<tr>
<td>Groton/Mystic, Connecticut</td>
</tr>
<tr>
<td>Hampton, New Hampshire</td>
</tr>
<tr>
<td>Seabrook, New Hampshire</td>
</tr>
<tr>
<td>Hampton Falls, New Hampshire</td>
</tr>
<tr>
<td>East Machias, Maine</td>
</tr>
<tr>
<td>Falmouth, Maine</td>
</tr>
<tr>
<td>Portland, Maine</td>
</tr>
<tr>
<td>Bowdoinham, Maine</td>
</tr>
<tr>
<td>Old Orchard Beach, Maine</td>
</tr>
<tr>
<td>Scarborough, Maine</td>
</tr>
<tr>
<td>Bath, Maine</td>
</tr>
<tr>
<td>Farmington, Maine</td>
</tr>
<tr>
<td>New Sharon, Maine</td>
</tr>
<tr>
<td>Marshfield, Massachusetts</td>
</tr>
<tr>
<td>Duluth, Minnesota</td>
</tr>
<tr>
<td>Rochester, Minnesota</td>
</tr>
</tbody>
</table>
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.</th>
<th>Damage</th>
<th>Cost</th>
</tr>
</thead>
<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>
Depth Damage Functions
Designed for Each Candidate Action/Structure

- 0-7’ Negligible = $
- 7-8’ Slight = $$
- 8-11’ Moderate = $$$
- 11-12’ Serious = $$$$
- 14-16’ Extreme = $$$$$$

Waterway
Base Elevation

<table>
<thead>
<tr>
<th>Elev.</th>
<th>Damage</th>
<th>Cost</th>
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<tr>
<td>14-16’</td>
<td>Extreme</td>
<td>$$$$$$</td>
</tr>
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Burden with other costs

GEI Consultants
Exceedance Curves

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

Additional Risk from Sea Level Rise
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 56-foot steel 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.
### Bath

#### Low Sea Level Rise (3.3')

<table>
<thead>
<tr>
<th></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>$400,000</td>
<td>$697,476</td>
<td>$1,097,476</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$594,000</td>
<td>$697,476</td>
<td>$1,291,476</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$1,000,000</td>
<td>$281,242</td>
<td>$1,281,242</td>
</tr>
</tbody>
</table>

#### High Sea Level Rise (6')

<table>
<thead>
<tr>
<th></th>
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<th>TOTAL LIFE CYCLE COST BY 2100</th>
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<tbody>
<tr>
<td>Replace in Kind</td>
<td>$400,000</td>
<td>$1,867,580</td>
<td>$2,267,580</td>
</tr>
<tr>
<td>Replace with 3.3' SLR design</td>
<td>$594,000</td>
<td>$1,867,580</td>
<td>$2,461,580</td>
</tr>
<tr>
<td>Replace with 6' SLR design</td>
<td>$1,000,000</td>
<td>$916,598</td>
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**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.
Figure 4: Bowdoinham

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

#### Low Sea Level Rise (3.3')

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<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>
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<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>
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<tr>
<td>Replace with 6' SLR design</td>
<td>$491,000</td>
<td>$908,565</td>
<td>$1,399,565</td>
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**Replace with 6’ SLR design** was the most cost effective choice for both Low and High sea level rise scenarios.
Summary

- 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.

“...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??

### Bath

#### Low Sea Level Rise (3.3')

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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
Transferable Example – Going Inland

Farmington_2311

New Sharon_989720
No-regrets Design Across Futures

Cumulative Burdened Life-cycle Costs

Structure Designed For:
- Q25
- Q100

Farmington_2311
- Low Runoff
- Medium Runoff
- High Runoff

New Sharon_898720
- Low Runoff
- Medium Runoff
- High Runoff

More Expensive
Less Expensive
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!