Case Study of Bridge Hurricane Vulnerability and Resilience Retrofit Planning Considering Varying Sea Level Rise Predictions

First International Conference on Surface Transportation System Resilience to Climate Change and Extreme Weather Events

September 16, 2015

Brian Joyner, PE
Walter Kemmsies, PhD
Eric Vugteveen, PE
Introduction

• SLR effects on infrastructure are varied and locally specific
  – We’ll focus on sample effects for bridges in coastal VA

• It is important to include SLR estimates in the life cycle asset management choice space
  – Given the magnitude of investments needed to adapt
  – Proper Cost-Benefit models help define the choice space
  – Some things trump C-B, i.e. potential for loss of life

• Future research is needed to avoid over and under investment as well as identify the full range of options and consequences
(Relative) Sea Level Rise

- Simply, increase in mean sea level elevation, along with other tidal datums and storm tide levels
  - MLLW, MHHW
  - HAT, LAT
  - Total storm tide

- **Relative Sea Level Rise**
  - Combination of large-scale sea level rise with local oceanographic and geological effects
Historical SLR Ranges Along Mid-Atlantic Coast

- NOAA tide gauges, SLR in feet per 100 years
  - The Battery, NY = 0.93
  - Sandy Hook, NY, = 1.33
  - Atlantic City, NJ = 1.34
  - Baltimore, MD = 1.03
  - Norfolk, VA = 1.50
  - Beaufort, NC = 0.89
  - Charleston, SC = 1.02

http://tidesandcurrents.noaa.gov/sltrends/sltrends.html
How Does Sea Level Rise Play Into All This?

- Raises storm tide for same return period
- Lowers return period, increases annual chance of a given storm tide

(Fugro and M&N, 2010)
Storm Surge Study of Hampton Roads Bridges
Storm Surge and Wave Impacts on Bridges

- Capacity of existing bridge to handle wave loads on superstructure
Storm Surge and Wave Impacts on Bridges
Storm Surge and Wave Impacts on Bridges
Storm Surge Study: Level 1 Analysis

• Methods
  – Storm surge water levels from SLOSH and Flood Insurance Studies
  – Fetch-limited wind-wave hindcast (ACES)
Storm Surge Study: Level 2 Analysis

• Methods
  – Storm surge water levels from SLOSH and Flood Insurance Studies
  – Large-area 2-D spectral wave model
  – Wave pressures on bridge superstructure, based on Stream Function Theory
Storm Surge Study: Level 2 Analysis 2-D Waves

\[ E = \frac{1}{8} \rho g H_{m0}^2 \]

Sign. Wave Height [m]
- Above 3.5
- 3.0 - 3.5
- 2.5 - 3.0
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- 0.5 - 1.0
- Below 0.5
Level 2 Study: Storm Tide Freeboard and Vertical Wave Pressures (Uplift) on Superstructure

- Vertical loads per linear foot vs. surge freeboard
Level 2 Study: Storm Tide Freeboard and Horizontal Wave Pressures on Superstructure

- Lateral loads per linear foot vs. surge freeboard

![Graph showing relationship between relative freeboard and wave pressure]
SLR Projections for Hampton Roads, Virginia

Relative Sea Level Rise Values from USACE Calculator-Sewells Point (July 2015) and from VIMS Tidewater Recurrent Flooding Report (2012)

- USACE Low/NOAA Low
- NOAA Int High
- NOAA High
- VIMS High
- Monthly Mean - NOAA MSL Datum
- Trend: 1.74 ft / 100 years

USACE calculator – http://www.corpsclimate.us/ccaceslcurves.cfm
(Virginia Institute of Marine Science)
Level 2 Study: SLR Effects on Vertical Wave Pressures (Uplift) on Superstructure

- Raise storm tide by 1.5 feet ...load goes from 2 to ~4 kips/lf
- Raise by 3 feet, load goes from 2 to >7 kips/lf
Level 2 Study: SLR Effects on Horizontal Wave Pressures on Superstructure

- Raise storm tide by 1.5 feet ...load goes from 1.5 to ~3 kips/lf
- Raise by 3 feet, load goes from 1.5 to 4 kips/lf
Storm Surge Study: Level 2 Analysis 2-D Waves

Sign. Wave Height [m]
- Above 3.5
- 3.0 - 3.5
- 2.5 - 3.0
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- 0.5 - 1.0
- Below 0.5
Adaptation Decisions (Retrofit, Replace, etc.)

• There are many factors to consider when designing or retrofitting for SLR

• Besides environmental and design issues, there are timing and economic efficiency issues
  – again, human life preservation is imperative and may control some decisions

• Overall SLR design/retrofit is a life cycle asset management problem requiring various types of analytical tools to get the most for the least
Formulation of a Benefit Cost Model

Benefit Cost Ratio = Expected Present Value of Future Benefits/Upfront Costs

\[ \text{EPV(Benefits)} = \sum (\text{Probability of Event} \times \text{Cost of Event} \times \text{Time Discount Factor}) \]

- **Probability of event** = inverse of return period event frequency
- **Cost of event** = cost of superstructure repair + vehicle passenger time lost + freight time lost + cost of additional vehicle miles on roadway maintenance, accidents and the environment
- **Time Discount Factor** = time value of money and expected bridge deterioration

**Upfront Costs** = Unanticipated (at time of design) SLR Retrofitting Costs

*See Handbook of Retrofit Options for Bridges Vulnerable to Coastal Storms by Modjeski and Masters, Inc; Moffatt & Nichol, Ocean Engineering Associates, Inc; D’Appolonia and Dennis Mertz*
Real government long term average yield ~2.4%

Inflation-adjusted 10 Year Govt Bond Yield

Long Term Average = 2.4%
Cost Benefit Example

Assumptions:
- 15 year old bridge designed for 75 years, 4 lanes spanning 3,000 feet
- AADT of 40,000 vehicles of which 9% are trucks; passenger/freight time value assumptions based on VDOT data
- bridge replacement cost approx. $225/ft² and retrofit is 15% to 45% of replacement costs depending on design period and SLR assumptions
- SLR assumptions are USACE for Hampton Roads for intermediate and high scenarios over next 100 years
Considerations in Life Cycle Cost Decisions

- Two questions: Does the bridge need to be retrofitted? If so, when?
  - Factors impacting:
    - Condition of the bridge (c);
    - The sea-level rise (s);
- Thus the probability of serious damage / failure can be define as a function $f(c,s)$
  - Condition of the bridge is not constant, it changes according to a stochastic process
- Retrofit/maintenance improves the condition of the bridge and reduces the chance of failure over remaining design life
  - Bridge continues to deteriorate from its new or retrofitted condition
Considerations in Life Cycle Cost Decisions

- Objective is to minimize the remaining life cycle cost of the bridge. Calculation should consider:
  - Maintenance / retrofit cost (for a given service level)
  - Cost of service disruption due to bridge failure;

- Bridges should be replaced when the future minimum expected life cycle investment cost is higher than the replacement cost

- In the broader perspective this becomes a budget allocation problem: managing an inventory of bridges and aiming on minimizing the life cycle cost of the inventory within budget constraints
Summary: What does SLR mean for decision-making?

- SLR increases annual chance (and cumulative chance over design life) of any given storm tide water surface elevation
  - Non-linear impact of higher storm tide on wave pressures, structural calculations, change of damage

- Level 2 type numerical modeling studies (properly calibrated) provide more accurate wave pressures

- Multiple ways to include SLR in evaluations for new design or retrofits
  - assume a static value in setting design storm tide
  - SLR as a function in a stochastic Cost-Benefit analysis
Summary: What does SLR mean for decision-making?

• Every bridge has unique combination
  – storm surge
  – wave exposure
  – structure elevation profile
  – structure condition
  – structure criticality
  – remaining design life

• Unique cost difference between
  – retrofit and/or increased maintenance
  – replace early with design including projected SLR
Closing

• SLR effects on infrastructure are varied and locally specific
  – This was a sample analysis from existing data; could be replicated and improved for larger areas

• It is important to include SLR estimates in the life cycle asset management choice space
  – Given the magnitude of investments needed to adapt
  – Proper Cost-Benefit models help define the choice space
  – Some things trump C-B, i.e. potential for loss of life

• Future research is needed to avoid over and under investment as well as identify the full range of options and consequences
Thank you!

Brian Joyner, PE  
Norfolk, VA  
bjoyner@moffattnichol.com

Walter Kemmsies, PhD  
New York, NY  
WKemmsies@moffattnichol.com

Eric Vugteveen, PE  
Richmond, VA  
EVugteveen@moffattnichol.com