Risk - Based Inspection Frequencies

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April 23, 2013

Northwest Bridge Inspector’s Conference
This investigation was sponsored by TRB under the NCHRP Program. Data reported are work in progress. The contents of this presentation has not been reviewed by the project panel or NCHRP, nor do they constitute a standard, specification, or regulation.
NCHRP 12-82 Goals

• Goal: Improve the safety and reliability of bridges
  – focusing inspection efforts where most needed
• Optimize the use of resources
  – Better match inspection requirements to inspection needs
  – Develop a rational process for assessing inspection needs using reliability theories
Agenda

- Background
- Overview of the approach
- Example
- Future testing
Definitions

• **Reliability:** Ability of an item, component or system to operate safely under designated operating conditions for a designated period of time or number of cycles.
  – 1-likelihood

• **Risk:** Combination of the probability of an event and its consequence.
  – Likelihood x Consequence
Background

• NBIS Standards were originally implemented in 1971 in response to the collapse of the Silver Bridge on December 15, 1967.
  – Uniform guidelines and criteria
  – 2-year inspection cycle (first cycle by July ’73)
  – Detailed reporting format, appraisal ratings
  – Inspection types: inventory, routine, damage, in-depth, and interim
• Uniform inspection interval does not consider
  – New bridges with little existing damage
  – Environments or condition where deterioration is unlikely
  – Bridges with long histories of good performance
  – Damage that has little effect on safety or servicability
  – Etc.
Motivation

Typical lifetime performance

Time to corrosion initiation for RC
Motivation

• Pareto principle
  – Reliability-based maintenance
  – 20% of the machines caused 80% of the problems……
Reliability (sic. Risk)-Based Bridge Inspection

- Inspections that consider
  - The reliability of bridge elements
    - Likelihood of deterioration and damage
      - Condition, design, materials and loading
    - The consequences of that damage
      - Minor serviceability issues, safety issue?
- Inspection interval and scope
  - Match inspection requirements with inspection needs for a bridge
- Approach is modeled on approaches used in other heavy industries (API, ASME/Nuclear, ABS, etc.)
Reliability-Based Inspection (RBI)

• What can go wrong?
  – Identify damage modes for elements
  – Deterioration mechanisms

• How likely is it?
  – Categorization based on reliability characteristics of bridge elements
    • Based on expert judgment and expert elicitations
      • Past experience
      • Analysis of existing or potential damage modes
    – Deterioration data if available (and relevant)

• What are the consequences?
  – How important is it?
Risk Matrix

- Plot values of likelihood and consequence
- Components in the top right corner are “high risk”
- High likelihood may not mean high risk, if consequence is small
- High consequence may not be high risk, if the likelihood is low

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What can go wrong

• Credible damage modes that lead to poor condition ratings / condition states / maintenance and repair needs

• Identified through expert elicitation
  – Engineers working on subject inventory
## Example

<table>
<thead>
<tr>
<th>Cause of death</th>
<th>Likelihood (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart attack</td>
<td>●●●●●●○○○○○○</td>
</tr>
<tr>
<td>Hit by car</td>
<td>●●●○○○○○○○○ ○</td>
</tr>
<tr>
<td>Murdered</td>
<td>●●○○○○○○○○○○</td>
</tr>
<tr>
<td>Brain Aneurism</td>
<td>○○○○○○○○○○○○○</td>
</tr>
<tr>
<td>Lightning</td>
<td>○○○○○○○○○○○○○</td>
</tr>
</tbody>
</table>

http://thewritepractice.com/emergency-your-creativity-is-dying/
Damage Modes

![Bar chart showing Likelihood of Occurrence for Damage Modes]

- Corrosion
- Fatigue
- Overload
- Impact/fire

Participant 1
Participant 2
Participant 3
Participant 4
Participant 5
Participant 6
Participant 7
Participant 8

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How likely is it?

“Occurrence Factor”

• How likely is it that severe damage (i.e. failure) will occur in a bridge element over the next 72 months?
  – What is the current condition?
  – What are its durability/reliability attributes?
    • Design
      • Concrete cover, epoxy coated rebar, fatigue resistant details
    • Loading
      • Salt application, ADTT
    • Condition
      • Existing damage
        • Spalling, cracking, etc.
      • Precursors
        • Leaking joints

Experience, expert judgment, deterioration data

• **Prioritize** attributes in terms of their importance
  – Develop scoring scheme to estimate Occurrence Factor
  – Remote, low, moderate or highly likely?
Where does a bridge fall on the distribution?

Yr. in Condition Rating

Histogram of CR=4

Lognormal

Loc 1.544
Scale 0.7701
N 357

Frequency

Years

0.0 3.6 7.2 10.8 14.4 18.0 21.6 25.2

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Attributes

- **Attributes**: Characteristics that affect the reliability of a bridge or bridge element.
  - Ex. Corrosion resistance, current condition, precursors to damage, known problems
- Prioritize affect on likelihood of serious damage in the next 72 months
  - 4 categories from remote to high
Concept - Likelihood
Concept - Likelihood

Bad attributes

Unique

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Prioritize Attributes

- What characteristics / attributes contribute durability / reliability
- “How likely is it that this deck will deteriorate to a serious condition in the next 72 months”
- What do you need to know to make this prediction?
- Prioritize
Prioritization

Beaus birthday list

1. Striker's wing sets or halo
2. Mini Sport mix
3. Gamestop gift card
4. Regular money
5. Only I Pad tetch
6. Play station 3 (new used)

10 = Good
1 = Bad
Prioritization

Beaus birthday *list
10 = Good
1 = Bad

4. Star Wars lego sets or halo
5. Mario Sport mix
6. GameStop Gift Card
7. Regular Money
8. Only I Padotech
9. PlayStation 3 (Concealed)

10. Star Wars lego sets or halo
   Mario Sport mix
Prioritization

<table>
<thead>
<tr>
<th>Rank</th>
<th>Item Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Sticks legs sets or hole</td>
</tr>
<tr>
<td>9</td>
<td>Nano sport mix</td>
</tr>
<tr>
<td>8</td>
<td>Gamestop gift card</td>
</tr>
<tr>
<td>7</td>
<td>Regular money</td>
</tr>
<tr>
<td>6</td>
<td>Only I fed trash</td>
</tr>
<tr>
<td>5</td>
<td>Play Station 3 (con'v used)</td>
</tr>
</tbody>
</table>

4: Gamestop Gift Card
Prioritization

1. Beaus birthday list
   - 10 = Good
   - 1 = Bad
2. Strike's leg sets or hole
3. Mac's Sport mix
4. Gas Stop Gift Card
5. Regler Money
6. Only I pad touch
7. PlayStation 3 (re-used)
8. 7/7 Regler money
### Occurrence Factor

<table>
<thead>
<tr>
<th>Level</th>
<th>Qualitative Rating</th>
<th>Description</th>
<th>Likelihood (POF)</th>
<th>Expressed as a percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Remote</td>
<td>Remote probability of occurrence, unreasonable to expect failure to occur</td>
<td>≤1/10,000</td>
<td>0.01% or less</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Low likelihood of occurrence</td>
<td>1/1000-1/10,000</td>
<td>0.1% or less</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>Moderate likelihood of occurrence</td>
<td>1/100-1/1,000</td>
<td>1% or less</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>High likelihood of occurrence</td>
<td>&gt;1/100</td>
<td>&gt; 1%</td>
</tr>
</tbody>
</table>

Occurrence factor rating scale - 72 month time window

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Concept - Consequences

- Water = low consequence
- Nuclear waste = Severe
Consequences…

- Ex. Multi-girder 3 span PS vs. pin and hanger in two-girder (fracture critical) bridge
- Low, moderate, high and severe
- Design characteristics, scenario, documented experience, calculation
Consequences…

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Consequence Factors

• Presuming the damage occurs, what are the possible consequences?
  – Focuses attention on the damage that is most important
  – Could this damage result in collapse, is it a local failure, or is it benign?

• Four general consequence scenarios proposed
  – Low, Medium, High, Severe
  – Credible consequence scenarios
  – Rule-based to identify analysis needs
    • Documented past experience
    • Analysis or modeling
    • Other rationale

• NOTE: This is not the condition nor the predicted condition of the element, it’s the condition assumed to be the failed state (poor to severe condition)
  – “Hypothetical” condition
  – Used to rank the most important damage modes, i.e., those likely to have the greatest consequence if they were to occur
Reliability Matrix

- Set inspection interval based on this assessment
  - Selected to ensure low likelihood of severe damage between inspections
  - 12-96 months
  - Maintenance inspections
Inspection Procedures

• Scope of inspection to detect/assess damage modes identified
  • Focused on need
  • Emphasis
  • More intense than min. routine
    • Prioritize damage modes through engineering analysis
    • Inspection priority number
      • O × C

– Quantifies damage modes that are most important for a given bridge

– Example
  • O = 3, C = 4, IPN = 12
  • O = 3, C = 2, IPN = 6
### Example

#### Strand Fracture Likelihood

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.1  Current Condition Rating</td>
<td></td>
</tr>
<tr>
<td>•Superstructure condition rating is greater than four</td>
<td>Pass</td>
</tr>
<tr>
<td>S.6  Longitudinal Cracking in Prestressed Elements</td>
<td></td>
</tr>
<tr>
<td>•Significant cracking is not present</td>
<td>Pass</td>
</tr>
<tr>
<td>Corrosion Profile score</td>
<td>60</td>
</tr>
<tr>
<td>L.6  Subjected to Overspray</td>
<td></td>
</tr>
<tr>
<td>•Bridge not over a roadway, not exposed to overspray</td>
<td>0</td>
</tr>
<tr>
<td>C.1  Current Condition Rating</td>
<td></td>
</tr>
<tr>
<td>•Superstructure condition rating is eight</td>
<td>0</td>
</tr>
<tr>
<td>C.4  Joint Condition</td>
<td></td>
</tr>
<tr>
<td>•Joints are present but not leaking</td>
<td>5</td>
</tr>
<tr>
<td>C.8  Corrosion-Induced Cracking</td>
<td></td>
</tr>
<tr>
<td>•No corrosion-induced cracking noted</td>
<td>0</td>
</tr>
<tr>
<td>C.10 Delaminations</td>
<td></td>
</tr>
<tr>
<td>•No delaminations found</td>
<td>0</td>
</tr>
<tr>
<td>C.11 Presence of Repaired Areas</td>
<td></td>
</tr>
<tr>
<td>•No repaired areas</td>
<td>0</td>
</tr>
<tr>
<td>C.12 Presence of Spalling</td>
<td></td>
</tr>
<tr>
<td>•No spalling present</td>
<td>0</td>
</tr>
<tr>
<td>C.16 Longitudinal Cracking in Prestressed Elements</td>
<td></td>
</tr>
<tr>
<td>•No longitudinal cracking in the girders</td>
<td>0</td>
</tr>
<tr>
<td>Strand Fracture point total</td>
<td>65 out of 285</td>
</tr>
<tr>
<td>Strand Fracture ranking</td>
<td>0.91 Remote</td>
</tr>
</tbody>
</table>
Consequence Analysis

• RAP considers the scenario of a member losing 100% of its load carrying capacity
• Follow guidelines for consequence assessment

Rationale

• The bridge is redundant, based on AASHTO definitions
• The bridge is very similar to other bridges where a member failure has occurred, but did not result in collapse of the bridge or excessive deflection
• The bridge capacity far exceeds required Inventory and Operating ratings
• The bridge has low ADT, such that there will not be a major impact on traffic
• The bridge is located over a non-navigable stream. Thus, the risks to people or property under the bridge are minimal

Result: Moderate, C=2
## Summary

<table>
<thead>
<tr>
<th>Element</th>
<th>Damage</th>
<th>Occurrence Factor (O)</th>
<th>Consequence Factor (C)</th>
<th>Maximum Interval</th>
<th>O x C (IPN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deck</td>
<td>Corrosion Damage</td>
<td>Low (2)</td>
<td>Moderate (2)</td>
<td>72 months</td>
<td>4</td>
</tr>
<tr>
<td>Prestressed Girders</td>
<td>Bearing Area Damage</td>
<td>Low (2)</td>
<td>Moderate (2)</td>
<td>72 months</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Corrosion Between Beam Ends</td>
<td>Low (2)</td>
<td>Moderate (2)</td>
<td>72 months</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Flexural/Shear Cracking</td>
<td>Remote (1)</td>
<td>Moderate (2)</td>
<td>72 months</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Strand Fracture</td>
<td>Remote (1)</td>
<td>Moderate (2)</td>
<td>72 months</td>
<td>2</td>
</tr>
<tr>
<td>Substructure</td>
<td>Corrosion Damage</td>
<td>Low (2)</td>
<td>Low (1)</td>
<td>72 months</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maximum Inspection Interval: 72 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Emphasis Items</td>
</tr>
<tr>
<td>S.6 Longitudinal Cracking in Prestressed Elements</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RBI Damage Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Element</strong></td>
</tr>
<tr>
<td>Deck</td>
</tr>
<tr>
<td>Prestressed Girders</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Substructure</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Applications

• Can be applied to:
  – Identify bridges for extended intervals
  – Identify bridges for reduced intervals
  – Prioritize repair/maintenance
  – Identify special inspection needs
  – Provide documented rationale for decisions/ actions including maintenance, closures, load restrictions, etc.

• Not different from what engineers to every day
  – Documented and systematic

• Update bridge inspection to state-of-the-practice
48 Month Policy (T 5140.21)

- **Bridge cannot** be considered for an extended interval
  - (a) Bridges with any condition rating of 5 or less. (*Likelihood*)
  - (b) Bridges that have inventory ratings less than the State's legal load. (*Likelihood*)
  - (c) Structures with spans greater than 100' in length. (*Consequence*)
  - (d) Structures without load path redundancy. (*Consequence*)
  - (e) Structures that are very susceptible to vehicular damage, e.g., structures with vertical over or underclearances less than 14'-0", narrow thru or pony trusses. (*Likelihood*)
  - Uncommon or unusual designs or designs where there is little performance history, such as segmental, cable stayed, etc. (*Uncertainty*)
  - A new or newly rehabilitated bridge should not be considered for inspection intervals longer than 2 years until it has received an inventory inspection and an in-depth inspection 1 or 2 years later (*Infant mortality*)

  - **Risk-Based Inspection Frequency**
Future Work

• Verifying process through case studies
• Texas – Steel Beam
• Oregon – PS beam
• Back-casting using criteria developed
Back-Casting

- Example bridge component
  - Review of NBI / Element History
  - Maintenance and R & R activities
    - Incidence not reflected in inspection data
Bridge #356-72-06433

- Carries: SR356 over Waterway
- Date of Reconstruction: 1980
- Location: Scott County
- Deck Type: Concrete Cast-in-place
- Wearing Surface: Latex Concrete
- Superstructure Type: Prestressed Concrete Box Beam
- Substructure Type: Reinforced Concrete
- ADTT: <100
- Exposure Environment: Moderate
#356-72-06433

- 1986 – 48 months
- 1993 – 48 months
- 1998 – 48 months
- 2002 – 48 months
- 2006 – 24 months

**Legend**

- Bearing Area Damage
- Flexural Cracking
- Deck Corrosion
- Corrosion b/n Beam Ends
- Shear Cracking
- Substructure Corrosion
Potential Benefits of RBI

• Better, more effective and purposeful inspections
  – Inspection plan (scope and interval) supported by engineering assessment by RAP
    • Vs. Calendar-based inspection strategy
  – Rational inspection strategies
    • Flexible intervals based on need and engineering analysis

• Allocate resources more effectively
  – Focus inspections resources where most needed

• Improved bridge reliability and safety
• Questions?