THE OHIO STATE UNIVERSITY

OPTIMAL RETROFIT DECISION-MAKING FOR BRIDGE SYSTEMS BASED ON MULTI-HAZARD LIFECYCLE COST ANALYSIS

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Introduction

- In the lifetime of an infrastructure, the system may experience multiple types of hazards.
- As an example, state of New York has identified the following hazards to be significant for their bridges:
  - Earthquakes
  - Hydraulic hazards
  - Collisions
  - Failure in details of steel structures
  - Failure in details of concrete structures
  - Overload

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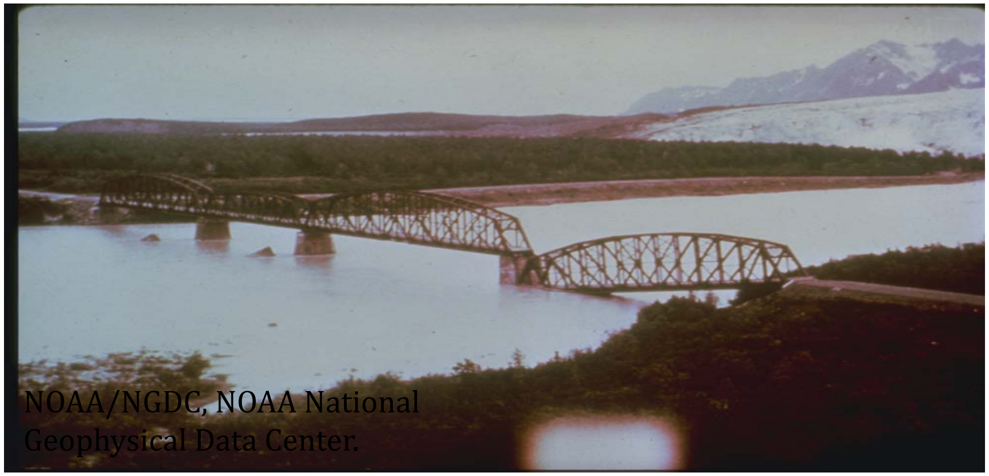
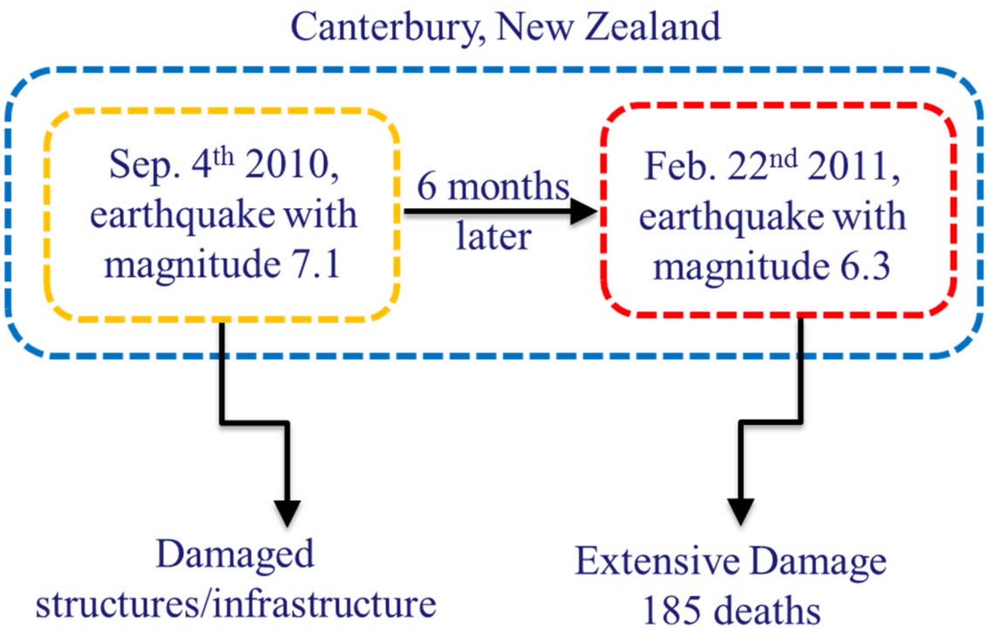


NOAA/NGDC, NOAA National Geophysical Data Center.

By H.G. Wilshire, U.S. Geological Survey - USGS page - Oakland, Public Domain

Introduction

- Structural integrity and functionality of bridges can be significantly affected by these hazard types.
- Each of these hazard types may occur several times in the lifetime of the system, which may:
  - Happen in a short period of time.
  - Aggravate the damage resulting from previous hazard types.



Canterbury, New Zealand

Sep. 4th 2010, earthquake with magnitude 7.1

6 months later

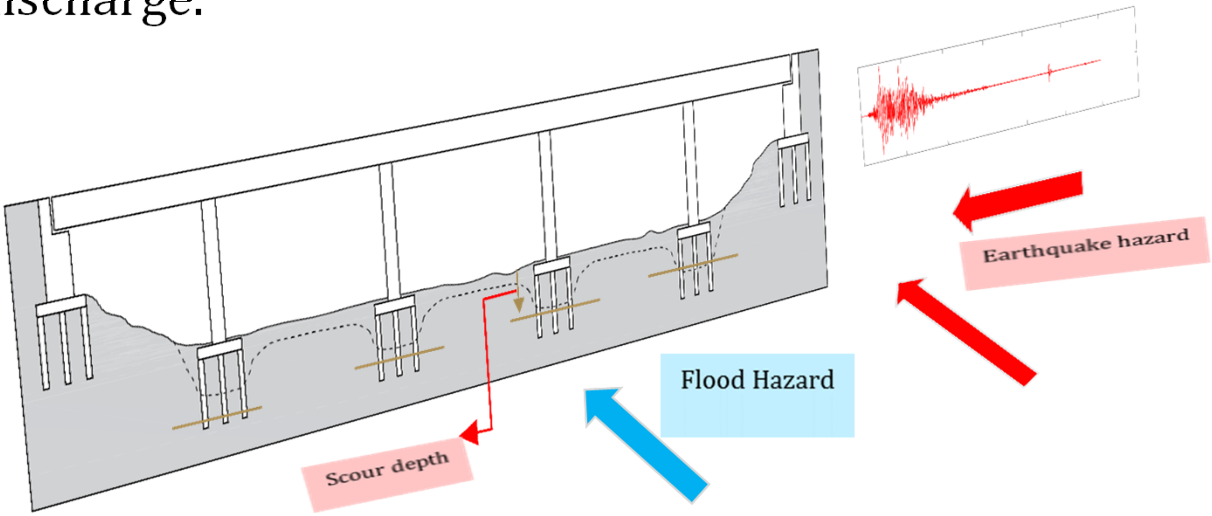
Feb. 22nd 2011, earthquake with magnitude 6.3

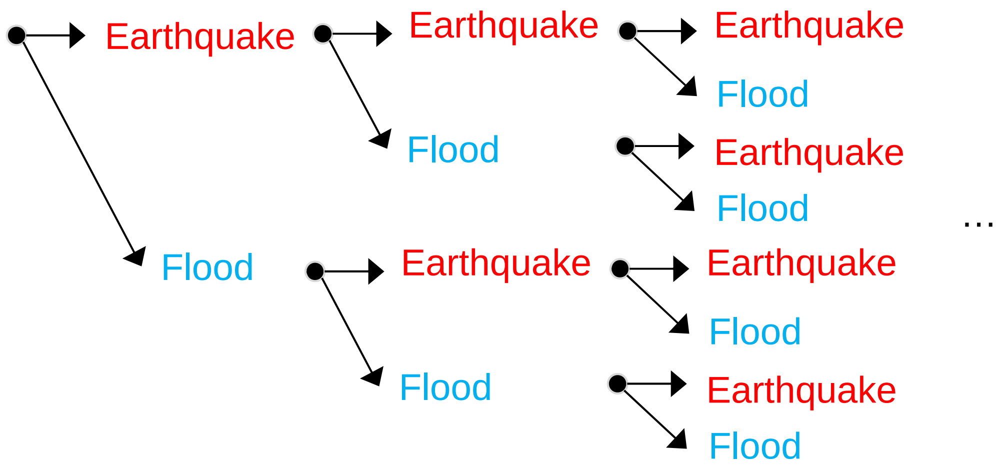
Damaged structures/infrastructure

Extensive Damage
185 deaths

Introduction

- Another example: an arterial bridge in a seismic zone, built upon a river with high discharge.





- Earthquake
  - Earthquake
    - Earthquake
    - Flood
  - Flood
    - Earthquake
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- Flood
  - Earthquake
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  - Flood
    - Earthquake
    - Flood

…

Introduction

- Each of these hazards is stochastic in:
  - Time of occurrence
  - Intensity
  - Extent of incurred damage

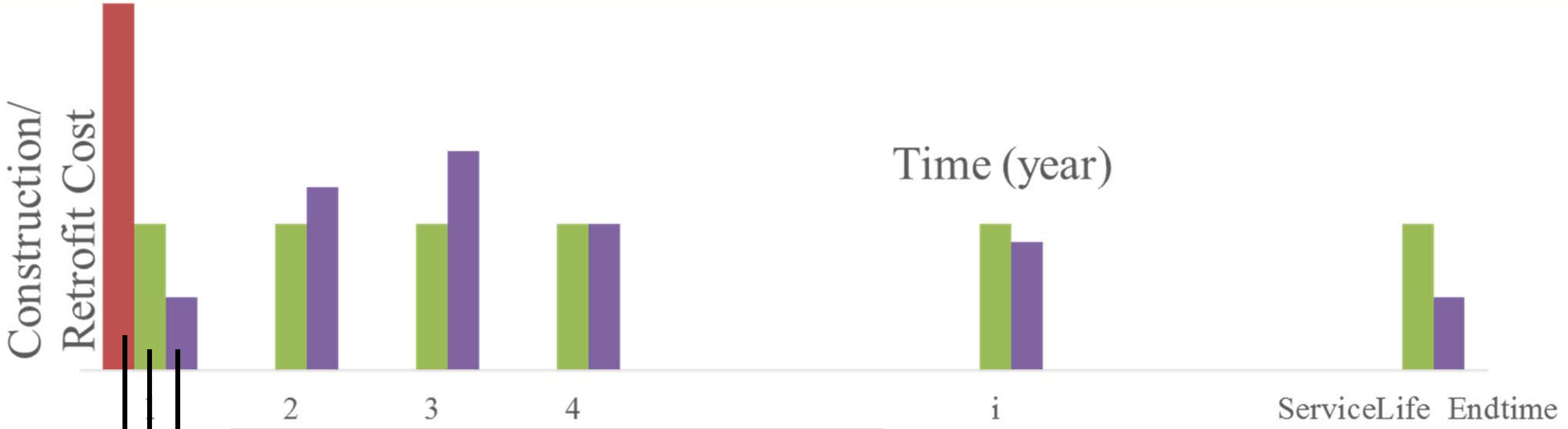
- Depending on the extent of damage, various levels of the following consequences may happen:
  - Bridge physical damage
  - Human casualties, and environmental damage
  - User delay from repair traffic disruptions
  - Economic consequences

- Followed by a damage, corrective repair actions are performed, which are costly and time-consuming, depending on the level of induced damage and the type of actions.
  - The implementation of actions may not finish before next hazards occur.

Introduction

- To ensure safety and manage bridges in a cost-efficient manner, such risk costs should be considered.
- There are two more cost terms in the lifetime of bridges:
  - Initial retrofit/construction cost
  - Maintenance cost
- To account for these three costs, as an efficient tool, lifecycle cost (LCC) has been utilized for decision-making purposes.
- Many of former studies assessed systems under one type of hazard, and assumed repair actions to be instantaneous.
- In some others, effects of multi-hazards are accounted for independently.
- Other techniques require numerous scenario-based simulations; and therefore may not be practical.

Introduction



C_0 = Initial construction/retrofit cost

C_m = Annual maintenance cost

C_r = Expected cost of hazard risks at year i

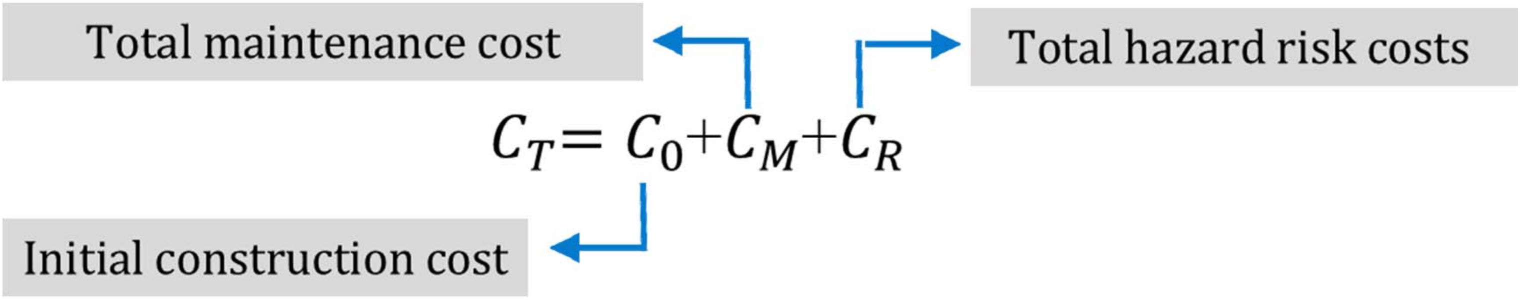
C_r is calculated considering the possibility of:

- Multiple types of hazards,
- Any number of hazards,
- Various intensities for each hazard
- Various structural damage levels
- And various repair times following damages

A fast recursive function

Analytical Framework

The total incurred cost in the service lifetime of a structure is:



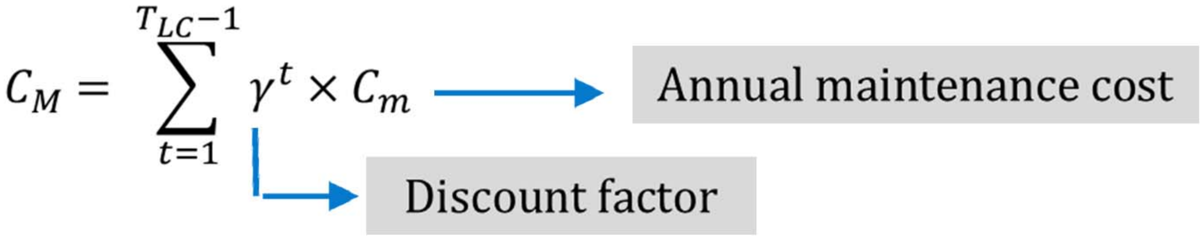
Total maintenance cost

Total hazard risk costs

$$C_T = C_0 + C_M + C_R$$

Initial construction cost

- Total maintenance cost:

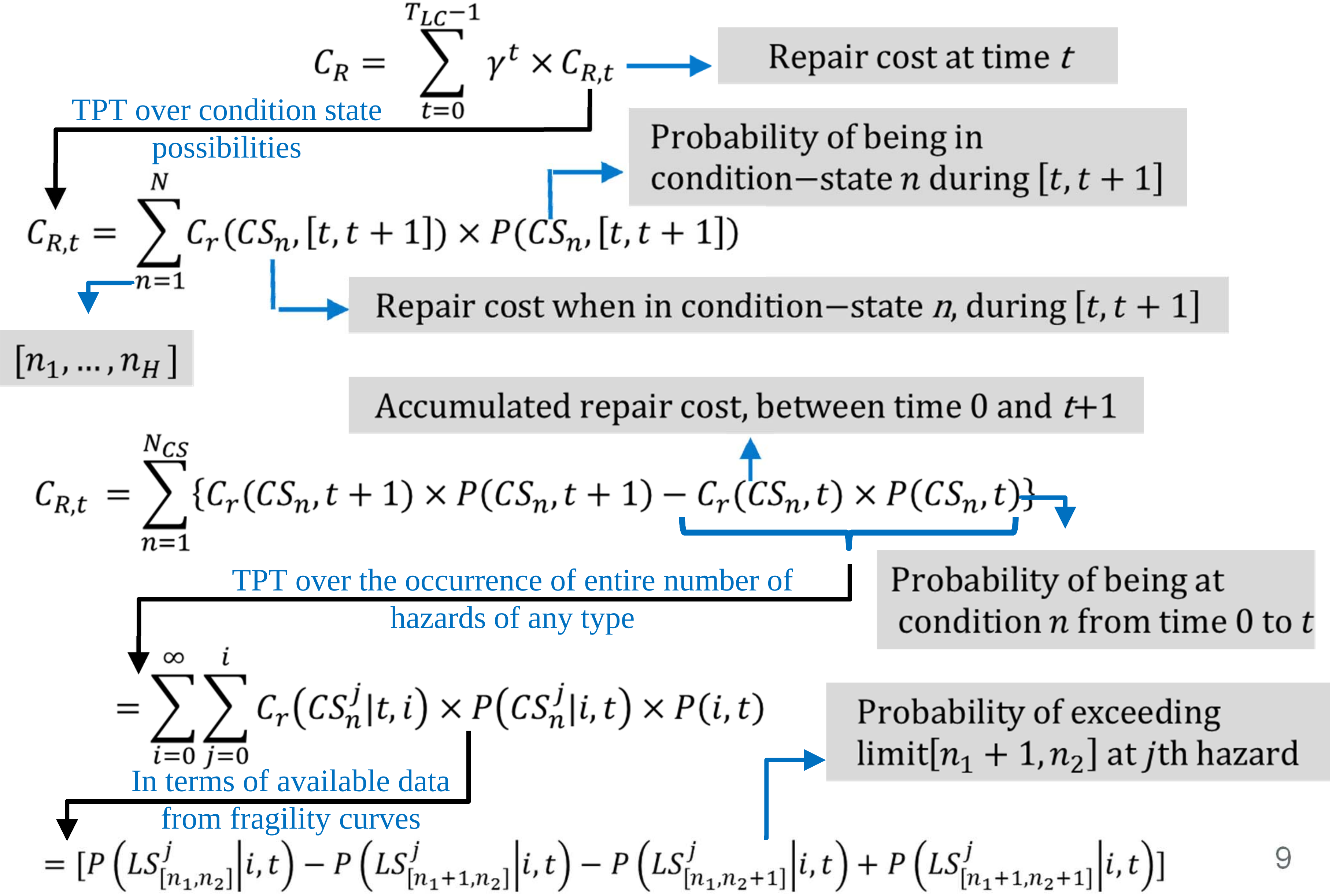


$$C_M = \sum_{t=1}^{T_{LC}-1} \gamma^t \times C_m$$

Annual maintenance cost

Discount factor

Analytical Framework
Total Repair Cost



$$C_R = \sum_{t=0}^{T_{LC}-1} \gamma^t \times C_{R,t}$$

Repair cost at time t

TPT over condition state possibilities

$$C_{R,t} = \sum_{n=1}^{N} C_r(CS_n,[t,t+1]) \times P(CS_n,[t,t+1])$$

Probability of being in condition−state n during $[t, t+1]$

Repair cost when in condition−state n, during $[t, t+1]$

$[n_1, \dots, n_H]$

Accumulated repair cost, between time 0 and t+1

$$C_{R,t} = \sum_{n=1}^{N_{CS}} \{C_r(CS_n,t+1) \times P(CS_n,t+1) - \underbrace{C_r(CS_n,t) \times P(CS_n,t)}\}$$

Probability of being at condition n from time 0 to t

TPT over the occurrence of entire number of hazards of any type

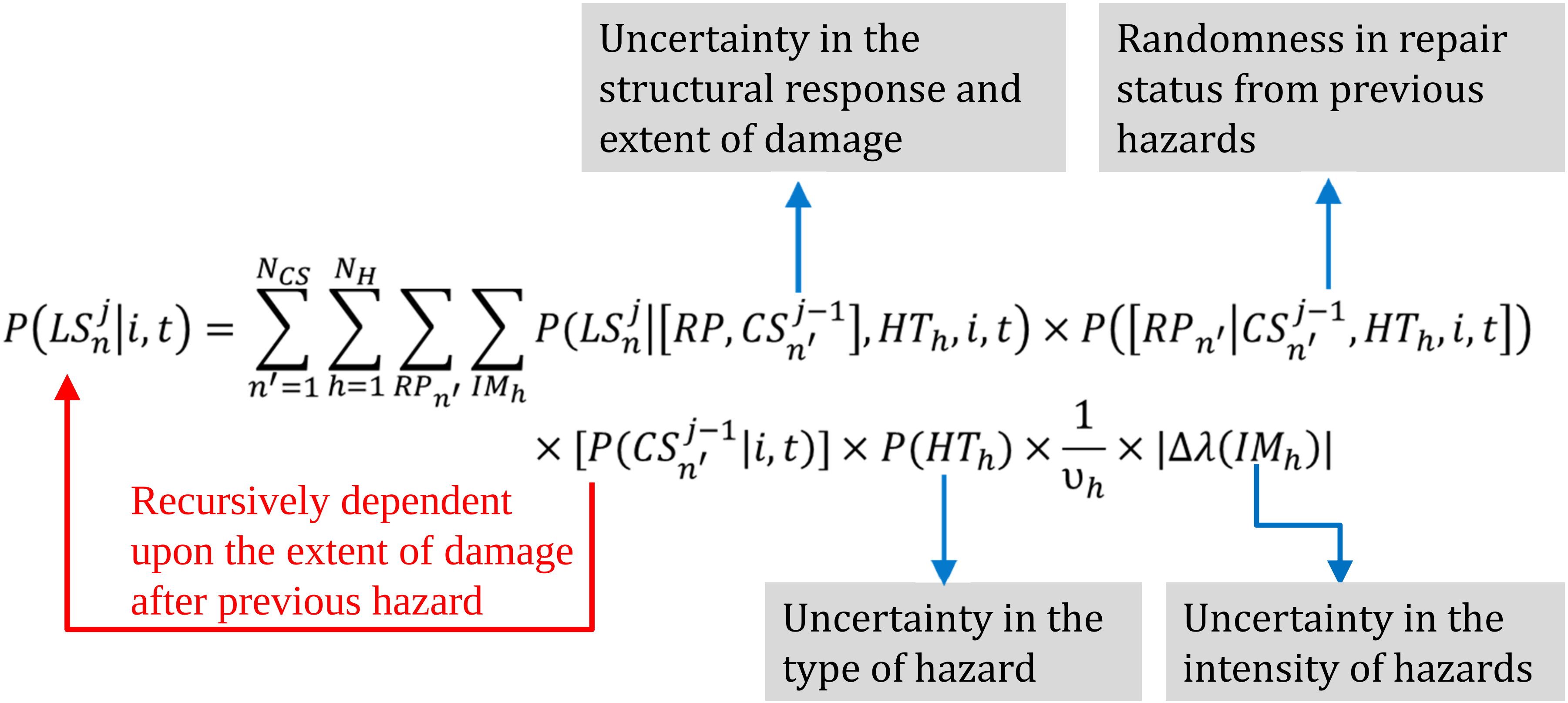
$$= \sum_{i=0}^{\infty}\sum_{j=0}^{i} C_r\left(CS_n^j|t,i\right) \times P\left(CS_n^j|i,t\right) \times P(i,t)$$

Probability of exceeding limit$[n_1 + 1, n_2]$ at jth hazard

In terms of available data from fragility curves

$$= \left[P\left(LS^j_{[n_1,n_2]}\middle|i,t\right) - P\left(LS^j_{[n_1+1,n_2]}\middle|i,t\right) - P\left(LS^j_{[n_1,n_2+1]}\middle|i,t\right) + P\left(LS^j_{[n_1+1,n_2+1]}\middle|i,t\right)\right]$$

Analytical Framework



Uncertainty in the structural response and extent of damage

Randomness in repair status from previous hazards

$$P(LS_n^j|i,t) = \sum_{n'=1}^{N_{CS}} \sum_{h=1}^{N_H} \sum_{RP_{n'}} \sum_{IM_h} P(LS_n^j|[RP, CS_{n'}^{j-1}], HT_h, i, t) \times P([RP_{n'}|CS_{n'}^{j-1}, HT_h, i, t]) \times [P(CS_{n'}^{j-1}|i, t)] \times P(HT_h) \times \frac{1}{\upsilon_h} \times |\Delta\lambda(IM_h)|$$

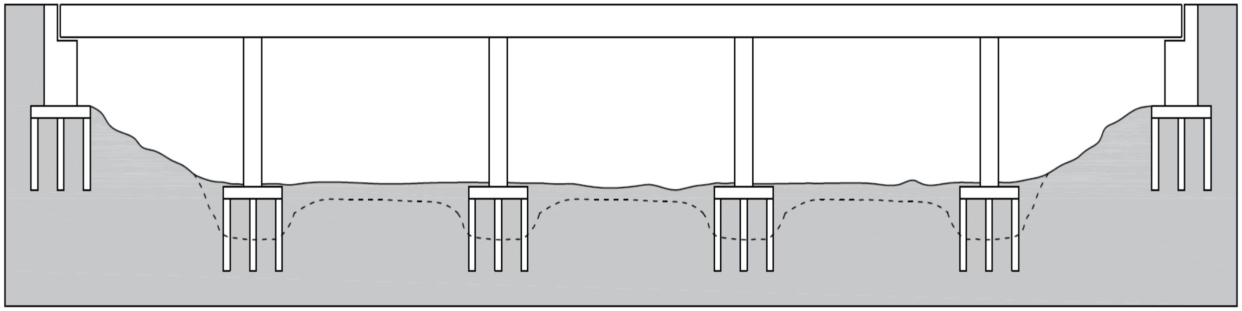
Recursively dependent upon the extent of damage after previous hazard

Uncertainty in the type of hazard

Uncertainty in the intensity of hazards

Case Study

- A realistic 5-span RC bridge model is used from literature.

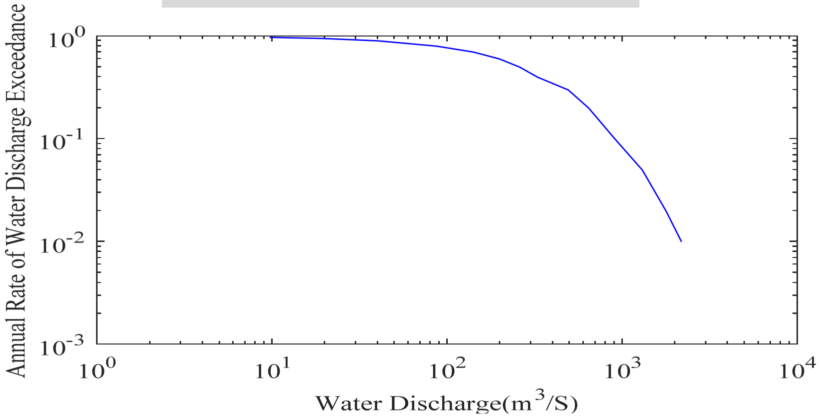


- The bridge is assumed to be located at the City of Sacramento on the American river; exposed to frequent:
  - flooding
  - earthquakes
- Four retrofit plans will be evaluated using the proposed LCC framework:
  - Status quo
  - Retrofitting piers with steel jacketing
  - Performing scour countermeasures
  - Performing both steel jacketing and scour countermeasures

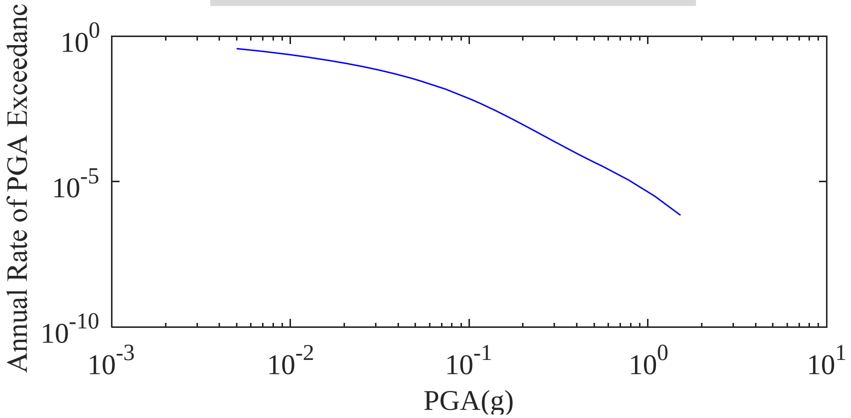
Input Variables for the Framework

- Input variables for the framework include:
  - Hazard curves: Flood and earthquake

Flood hazard curve

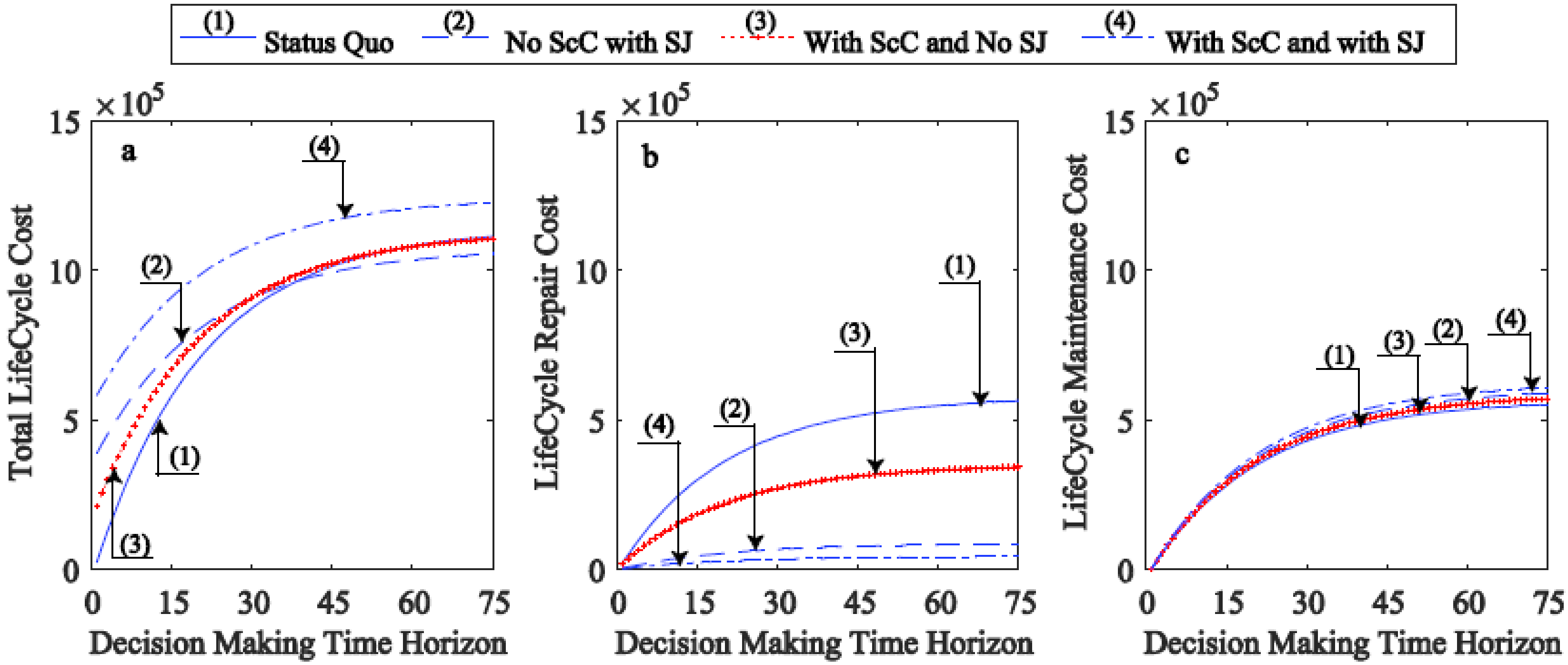


Seismic hazard curve



  - Damage-state dependent fragility curves
  - Repair times for each type of damage-state
  - Agency and user costs at each combination of damage-state:
    - Physical cost of repair, cost of delay time on users, extra vehicle operations, excess gas emissions, economic loss, and human casualties

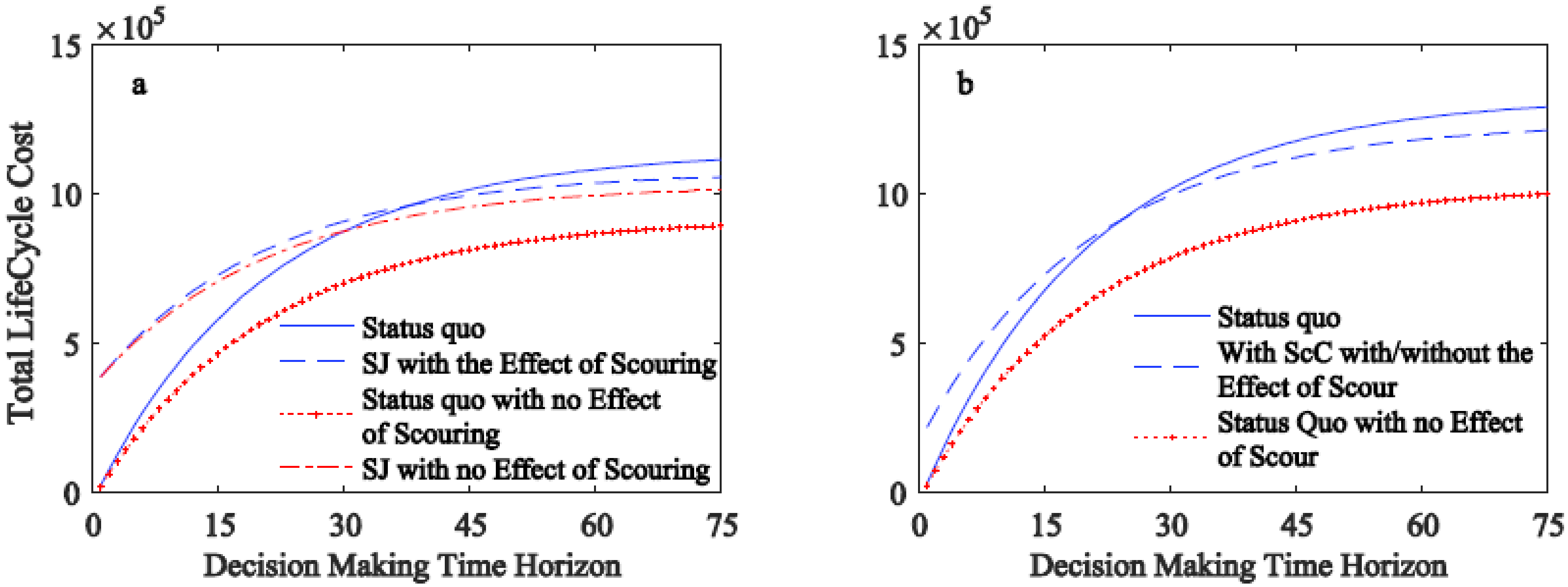
Numerical Results



SJ=Steel Jacketing, ScC=Scour Countermeasures

- Both steel jacketing and scour countermeasures reduce the risk of hazards, while the former reduces the risk the most.
- Since applying steel jacketing is costly, it will be the optimal decision for lifespans longer than 35 years.

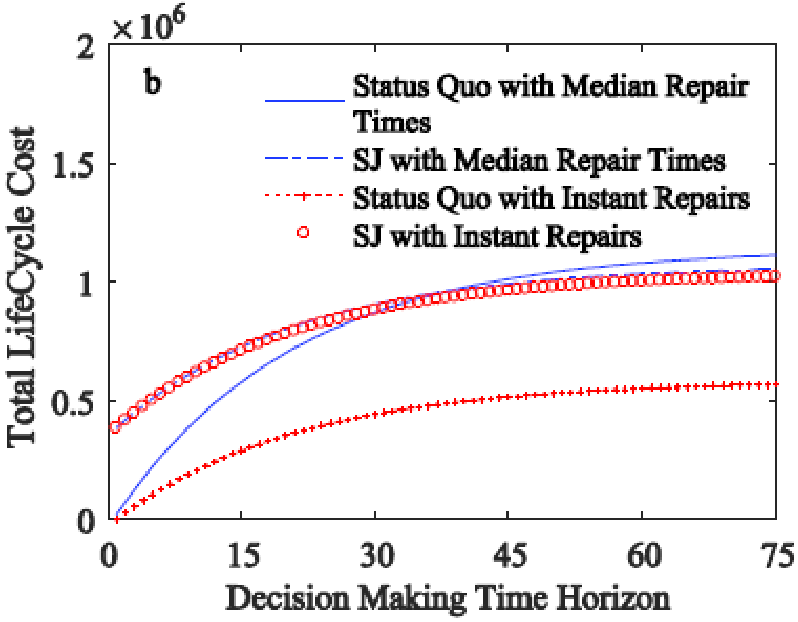
Importance of Incorporation of Multi-Hazard



SJ=Steel Jacketing, ScC=Scour Countermeasures

- In case flood hazard is not considered in LCC analysis, impacts of scouring on seismic vulnerabilities will not be accounted for:
  - For 75 years of lifetime, an extra of $60,000 would have been incurred.
- Deciding whether or not to just perform ScC, if the region is considered to have more business around (with twice as the current economic consequences), false identification of optimal action:
  - For 75 years results in $80,000 loss.

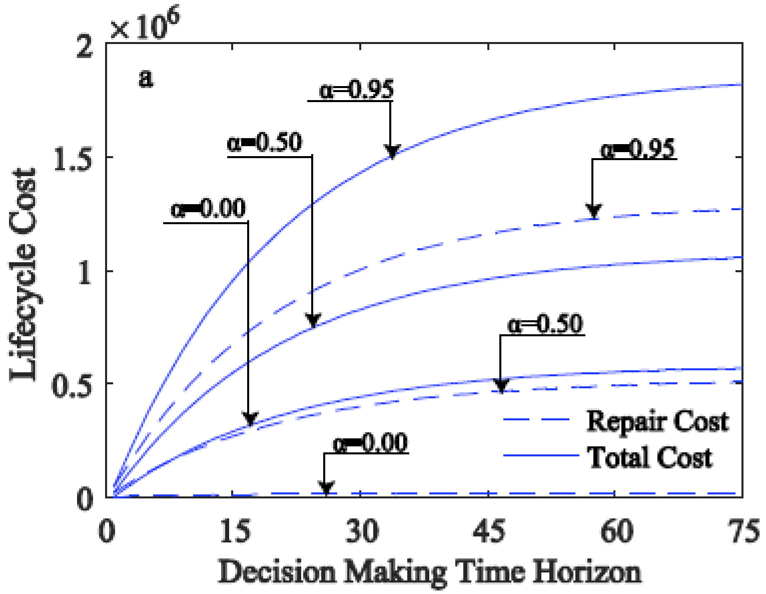
Importance of Incorporation of Repair Times



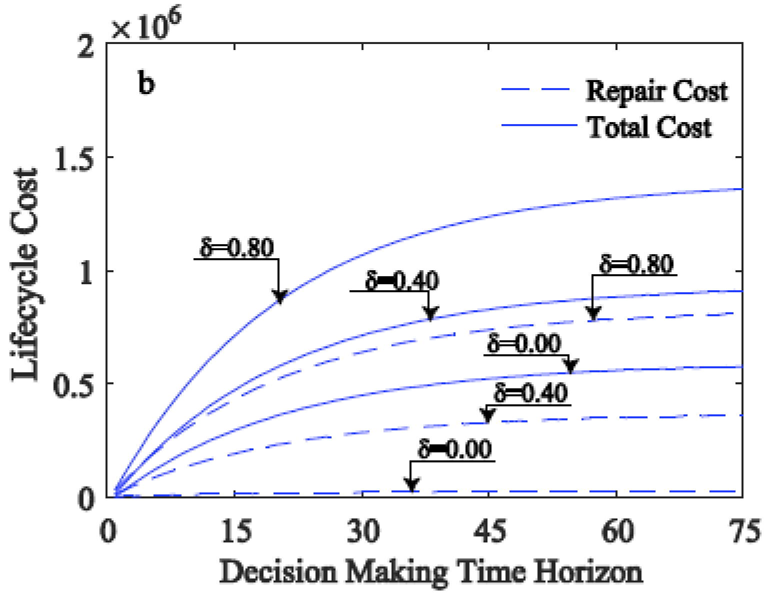
SJ=Steel Jacketing

- Not considering repair time durations will result in:
    - False identification of the optimal retrofit plan as status quo,
    - An extra incurred cost of $60,000, for 75 years of lifetime.
    - Underestimation of the total LCC of the system by almost 50% ($5e-5), which can be problematic for management purposes.

Variation of LCC to repair times and ADT



Sensitivity to repair time durations



Sensitivity to average Daily Traffic

- As the required repair times increase, the incurred LCCs grow significantly;
- As expected, the more traffic on the bridge, the more the incurred cost due to potential hazards and therefore the higher the total lifecycle costs;

Conclusion

- This study proposes a new framework for LCC of infrastructures that:

Is comprehensive in hazard modeling	Multiple types, Multiple occurrences of each type, all the scenarios for the order of events.
Incorporates dependencies	Between incurred damages of various types and the capacity of the structure for future hazards, if repair is incomplete.
Is computationally efficient	Such damage-state probabilities after each hazard occurrence is computed through a **dynamic programming procedure.**
Requires limited input	Only requires **hazard curves**, **cost values**, **damage-state dependent fragility curves** and **repair times**.
Helps decision-makers to reliably	**Select retrofit strategies that considerably reduce expected LCC of infrastructures.**
	Invest on factors that reduce the lifecycle costs the most.

Conclusion