21st Annual NJDOT Research Showcase

New Jersey DOT
Bureau of Research

RUTGERS
Center for Advanced Infrastructure and Transportation

The City College of New York

Risk-based Decision-making Model in Highway Bridge Foundation/Substructure Reuse

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Outline

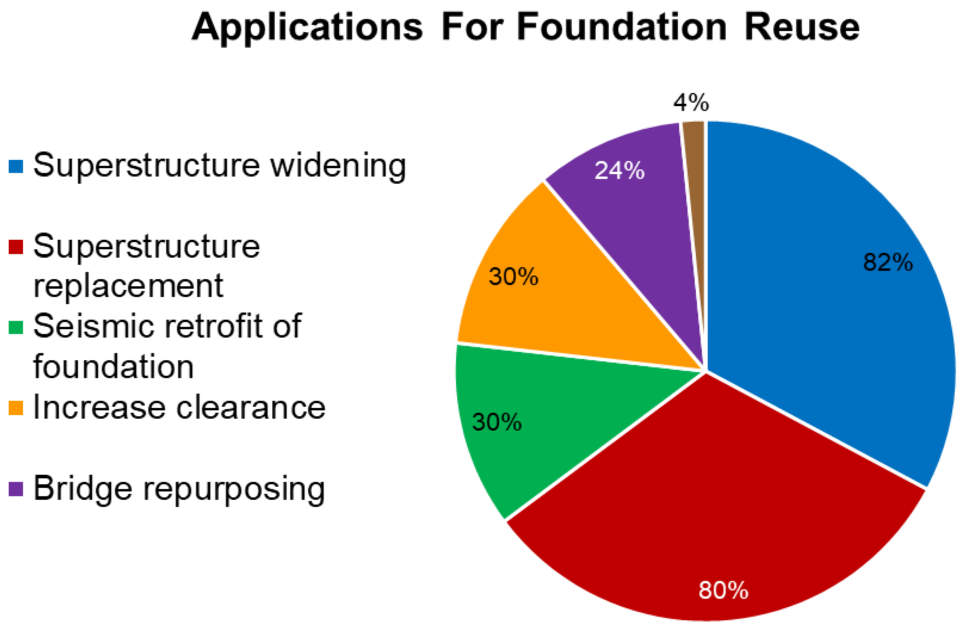
1. *Introduction*
2. *Analytical Hierarchy Process*
3. *Time-dependent Risk Estimation*
4. *Bridge Life-Cycle Cost Analysis (BLCCA)*
5. *Environmental Impact Assessment*

What is Foundation Reuse?

Definition: Use of an existing foundation or substructure of a bridge, in whole or in part, when the existing foundation has been evaluated for new loads.

Situations when foundation reuse may be considered:

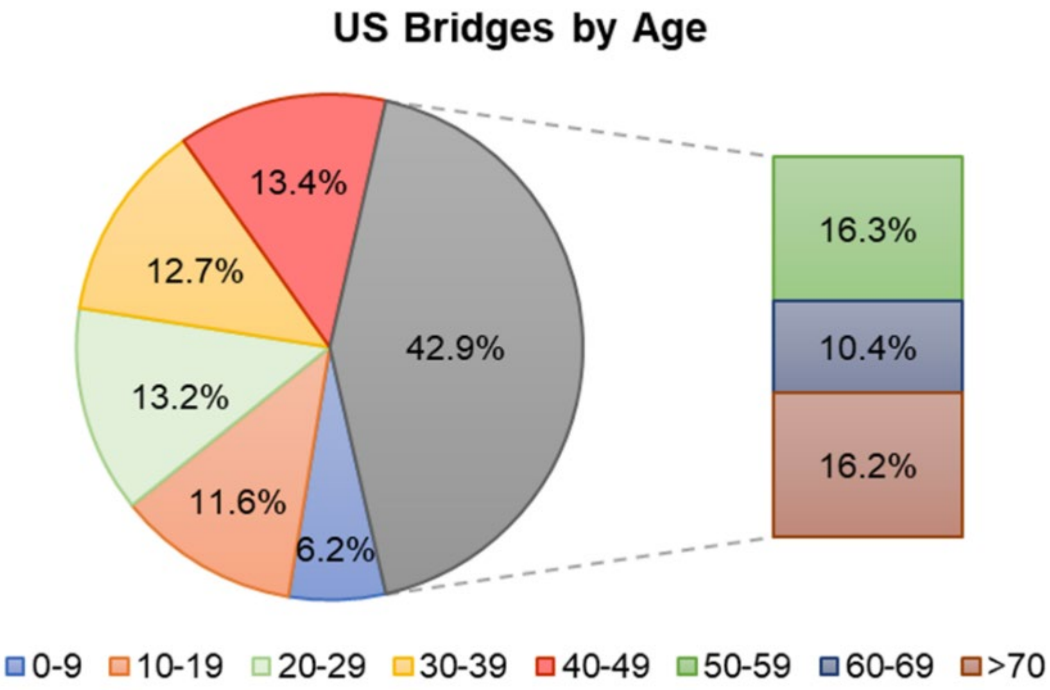
- Bridge superstructure replacement
- Bridge widening
- Bridge repurposing (local to state highway)
- Major retrofitting for seismic, scour, or other purposes.



NCHRP Synthesis 505 (Boeckmann and Loehr 2017)

Why Reuse?

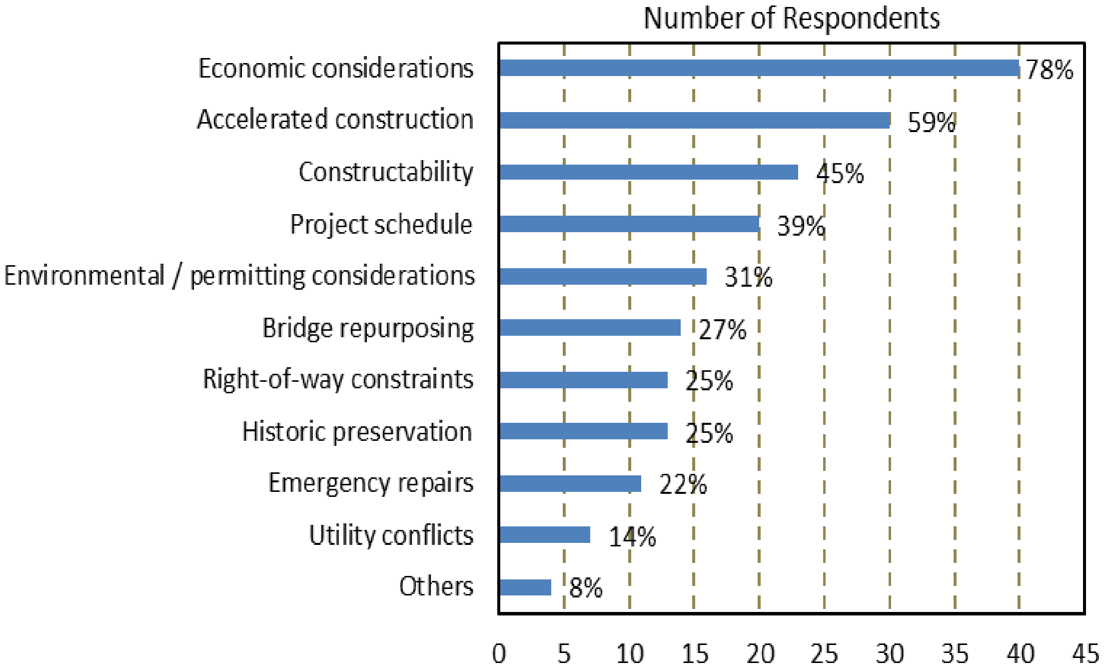
- The average age of US Bridges in 2019 is 45 years old.
- 8% bridges (47,619 out of 615,002) are in poor condition.
- 15% bridges are older than the average design life of 75 years for bridges.
- In 2012, $17.5 billion was spent on bridge construction.
- 94% of 17.5 BD ($16.4 billion) was spent to rehabilitate or replace existing bridges.
- Rehabilitation cost of a bridge is almost 68% of its replacement cost.



Data from NBI (FHWA 2018)

Reuse Motivations

- **Economical**
    - Reconstruction / Demolition Cost Savings
    - Right of way (ROW)
    - Utility coordination
    - User cost
- **Environmental**
    - Environmental permitting /NEPA
    - Waste disposals
    - Air quality emission
- **Social**
    - Impacts on mobility
    - Traffic management and traffic noise
    - Community impact
    - Work zone safety
    - Cultural preservation and archeology



Adapted from Boeckmann and Loehr (2017) NCHRP Synthesis

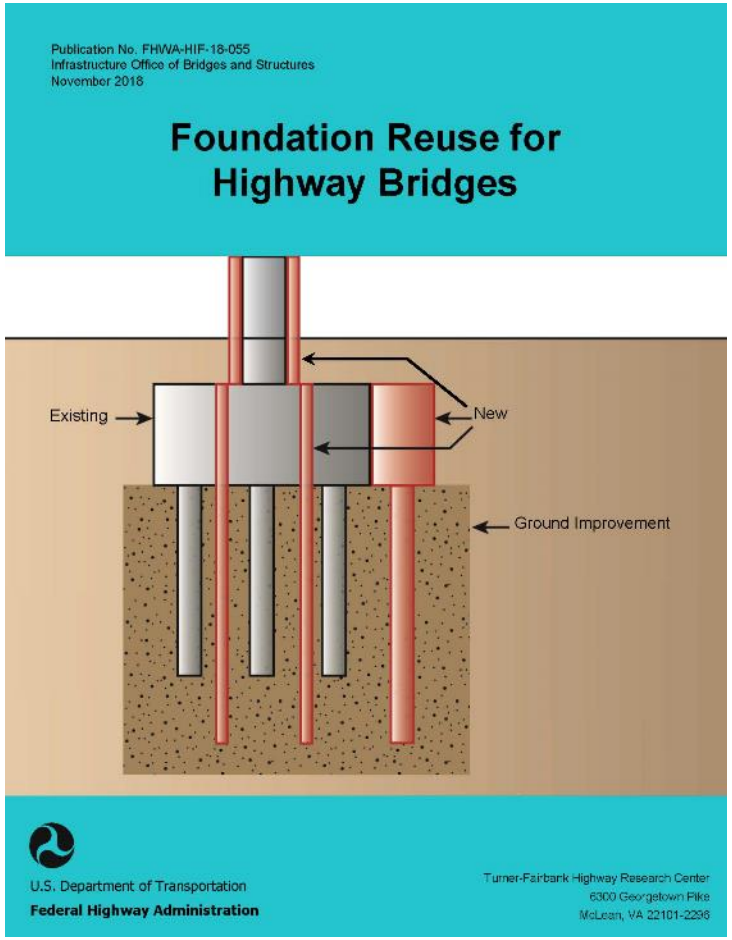
History of Foundation Reuse

- Foundation reuse in not a new idea
- Foundations reused regularly for buildings
  - Reuse of Foundations for Urban Sites(RUFUS): A Best Practice Handbook
- Foundations of bridges have been reused in U.S.
  - Illinois DOT: Bridge Condition Report Procedures and Practices
  - Maine DOT: Bridge Design Guide - Chapter 10
  - Massachusetts DOT: LRFD Bridge Manual
  - North Carolina DOT
  - FHWA workshop (2013) under the Foundation Characterization Program
  - NCHRP Synthesis 505:Current Practices and Guidelines for the Reuse of Bridge Foundations
  - FWHA Report: Foundation Reuse for Highway Bridges (2018)

Two Main Questions in Foundation Reuse

Is reuse feasible in comparison with the other options ? (Y/N)

- A decision-making process
- How to reuse? (As-is or enhanced?)



Publication No. FHWA-HIF-18-055
Infrastructure Office of Bridges and Structures
November 2018

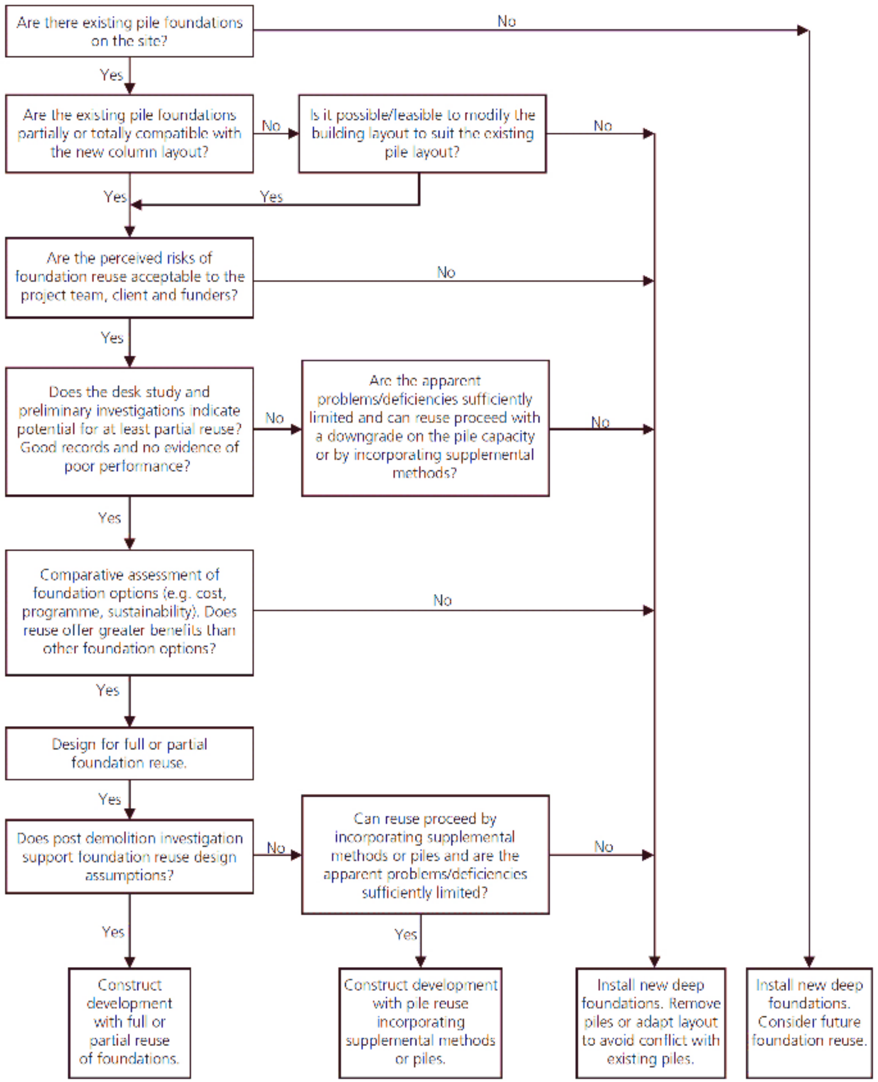
Foundation Reuse for Highway Bridges

U.S. Department of Transportation
Federal Highway Administration

Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

Agrawal et al. (2018)

Reuse Decision-making in Buildings



Are there existing pile foundations on the site?

Yes

No

Are the existing pile foundations partially or totally compatible with the new column layout?

No

Is it possible/feasible to modify the building layout to suit the existing pile layout?

No

Yes

Yes

Are the perceived risks of foundation reuse acceptable to the project team, client and funders?

No

Yes

Does the desk study and preliminary investigations indicate potential for at least partial reuse? Good records and no evidence of poor performance?

No

Are the apparent problems/deficiencies sufficiently limited and can reuse proceed with a downgrade on the pile capacity or by incorporating supplemental methods?

No

Yes

Comparative assessment of foundation options (e.g. cost, programme, sustainability). Does reuse offer greater benefits than other foundation options?

No

Yes

Design for full or partial foundation reuse.

Yes

Does post demolition investigation support foundation reuse design assumptions?

No

Can reuse proceed by incorporating supplemental methods or piles and are the apparent problems/deficiencies sufficiently limited?

No

Yes

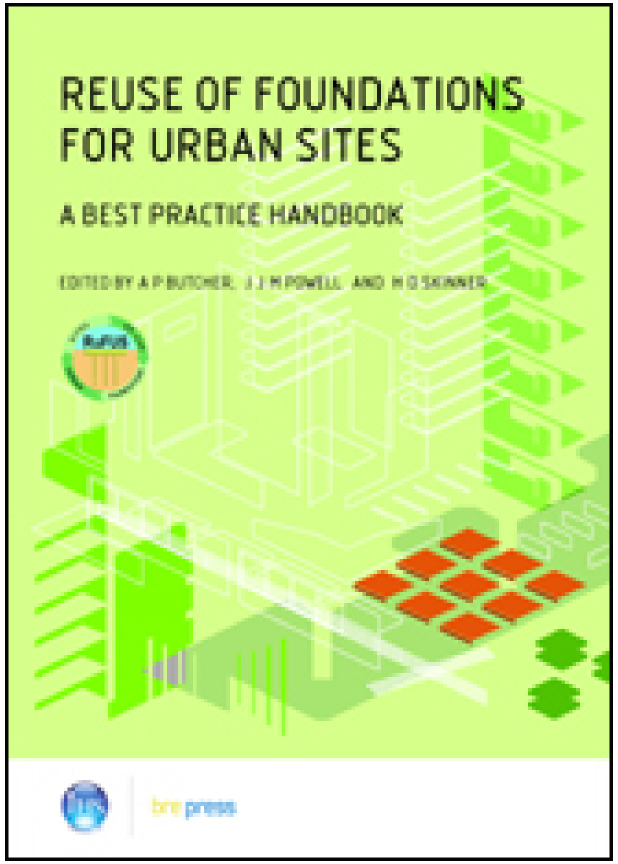
Yes

Construct development with full or partial reuse of foundations.

Construct development with pile reuse incorporating supplemental methods or piles.

Install new deep foundations. Remove piles or adapt layout to avoid conflict with existing piles.

Install new deep foundations. Consider future foundation reuse.

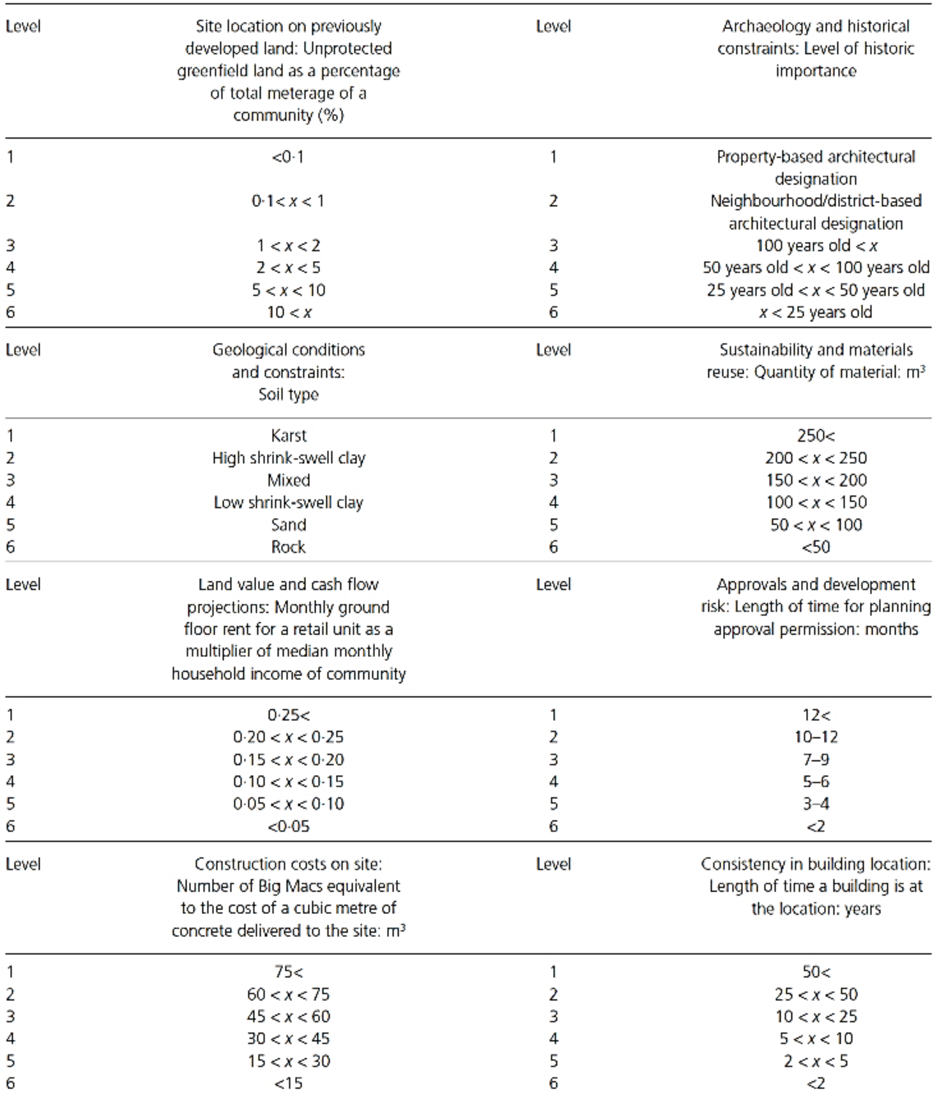


REUSE OF FOUNDATIONS FOR URBAN SITES

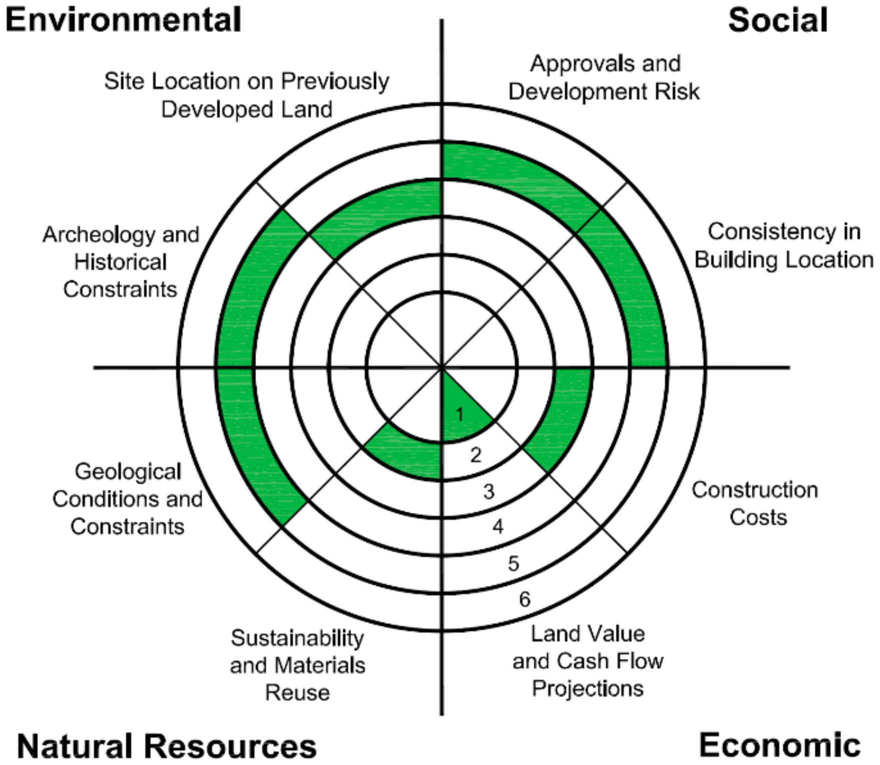
A BEST PRACTICE HANDBOOK

RuFUS Manual (Butcher et al. 2006)

Reuse Decision-making in Buildings



Level	Site location on previously developed land: Unprotected greenfield land as a percentage of total meterage of a community (%)	Level	Archaeology and historical constraints: Level of historic importance
1	<0·1	1	Property-based architectural designation
2	0·1 < x < 1	2	Neighbourhood/district-based architectural designation
3	1 < x < 2	3	100 years old < x
4	2 < x < 5	4	50 years old < x < 100 years old
5	5 < x < 10	5	25 years old < x < 50 years old
6	10 < x	6	x < 25 years old
Level	Geological conditions and constraints: Soil type	Level	Sustainability and materials reuse: Quantity of material: m^3
1	Karst	1	250<
2	High shrink-swell clay	2	200 < x < 250
3	Mixed	3	150 < x < 200
4	Low shrink-swell clay	4	100 < x < 150
5	Sand	5	50 < x < 100
6	Rock	6	<50
Level	Land value and cash flow projections: Monthly ground floor rent for a retail unit as a multiplier of median monthly household income of community	Level	Approvals and development risk: Length of time for planning approval permission: months
1	0·25<	1	12<
2	0·20 < x < 0·25	2	10–12
3	0·15 < x < 0·20	3	7–9
4	0·10 < x < 0·15	4	5–6
5	0·05 < x < 0·10	5	3–4
6	<0·05	6	<2
Level	Construction costs on site: Number of Big Macs equivalent to the cost of a cubic metre of concrete delivered to the site: m^3	Level	Consistency in building location: Length of time a building is at the location: years
1	75<	1	50<
2	60 < x < 75	2	25 < x < 50
3	45 < x < 60	3	10 < x < 25
4	30 < x < 45	4	5 < x < 10
5	15 < x < 30	5	2 < x < 5
6	<15	6	<2



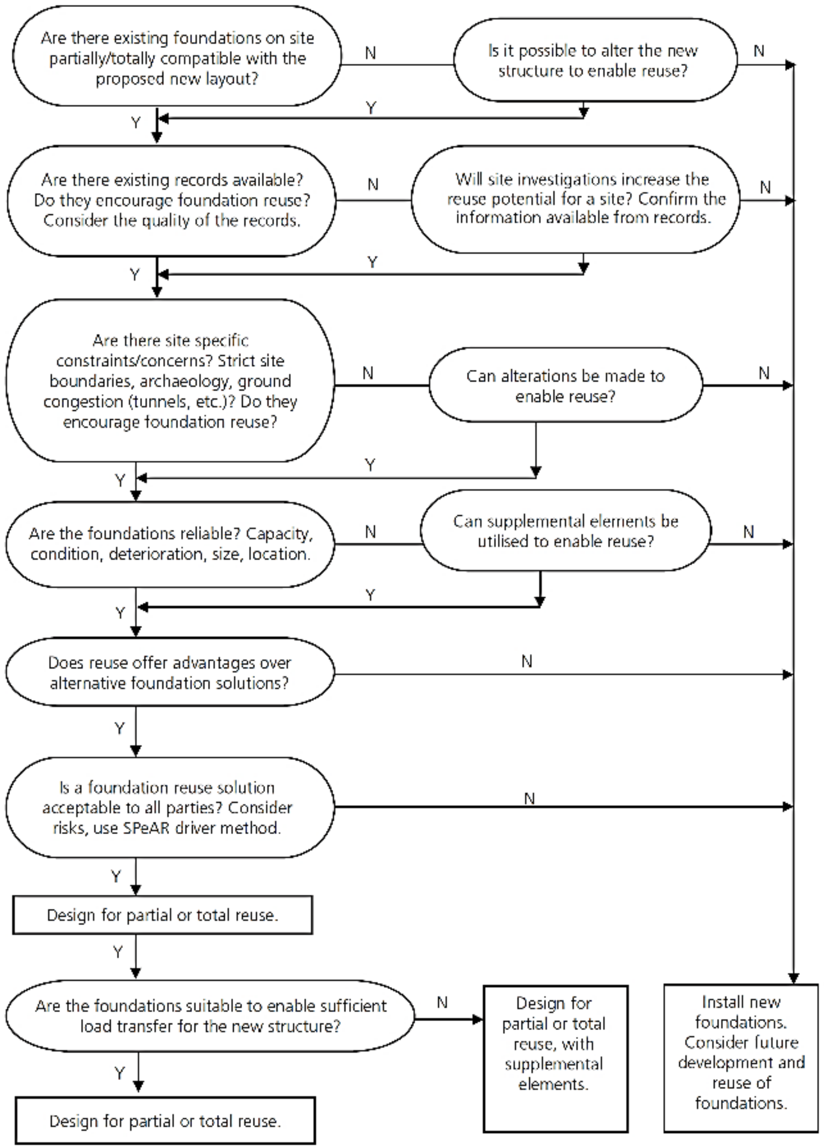
Modified SPeAR Diagram for a building site in NYC (Laefer 2011)

Reuse Decision-making in Buildings

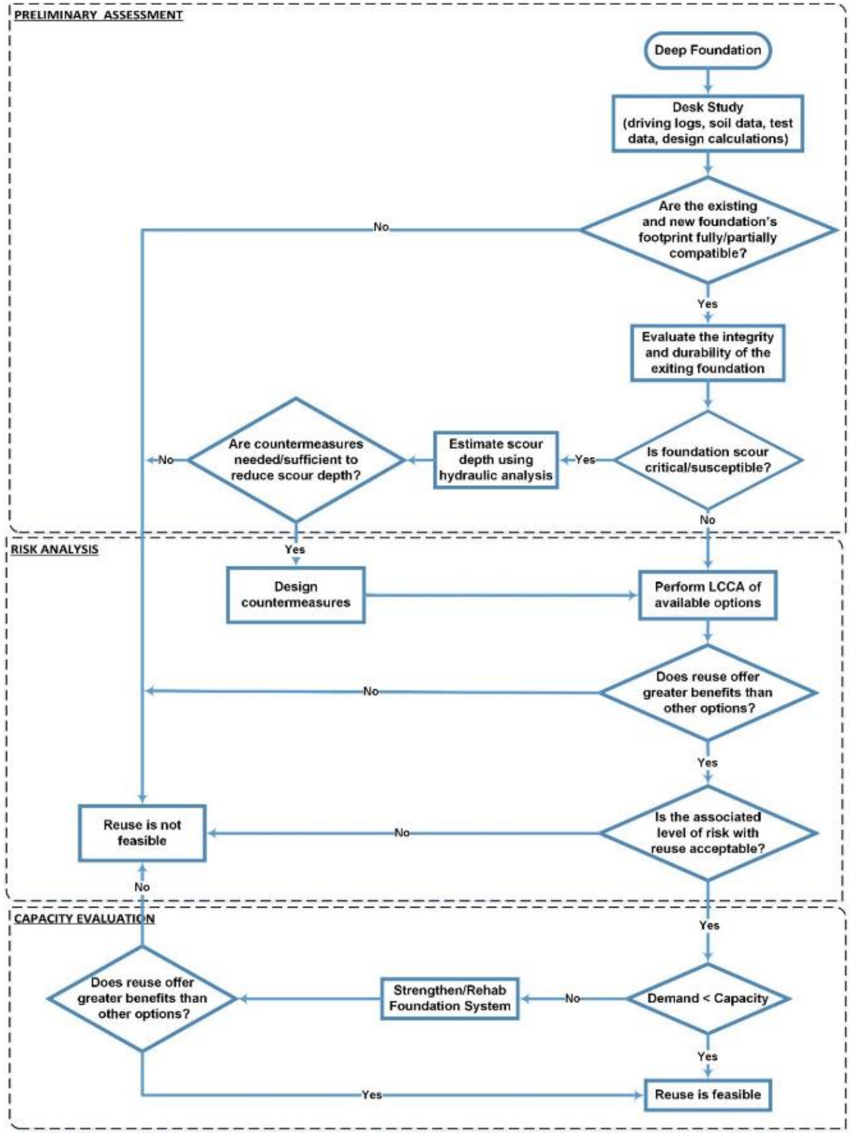
Hybrid Method (Laefer and Farrell 2015)

- A hybrid of three methods (RuFUS, SPeAR and Modifed SPeAR)
- Socio-economic evaluation

Considerations	Yes	No
Are there existing foundations on site partially/totally compatible with proposed new layout?		
Are there existing records available? Do they support foundation reuse? Consider the quality of the records.		
Are there site-specific constraints/concerns? Strict site boundaries, archaeology, ground congestion (tunnels etc.). Do they encourage foundation reuse?		
Are the foundations reliable? Capacity, condition, deterioration, size, location.		
Does reuse offer advantages over alternative foundation solutions?		
Is a foundation reuse solution acceptable to all parties? Fully explain risks. Utilise SPeAR method in explaining drivers and illustrating reuse potential.		
Are the foundations capable of ensuring sufficient load transfer for the new structure?		



Reuse Decision-making in Bridges



PRELIMINARY ASSESSMENT

Deep Foundation

Desk Study (driving logs, soil data, test data, design calculations)

Are the existing and new foundation's footprint fully/partially compatible?

No

Yes

Evaluate the integrity and durability of the exiting foundation

Is foundation scour critical/susceptible?

Yes

Estimate scour depth using hydraulic analysis

Are countermeasures needed/sufficient to reduce scour depth?

No

Yes

No

RISK ANALYSIS

Design countermeasures

Perform LCCA of available options

Does reuse offer greater benefits than other options?

No

Yes

Is the associated level of risk with reuse acceptable?

No

Reuse is not feasible

No

Yes

CAPACITY EVALUATION

Demand < Capacity

No

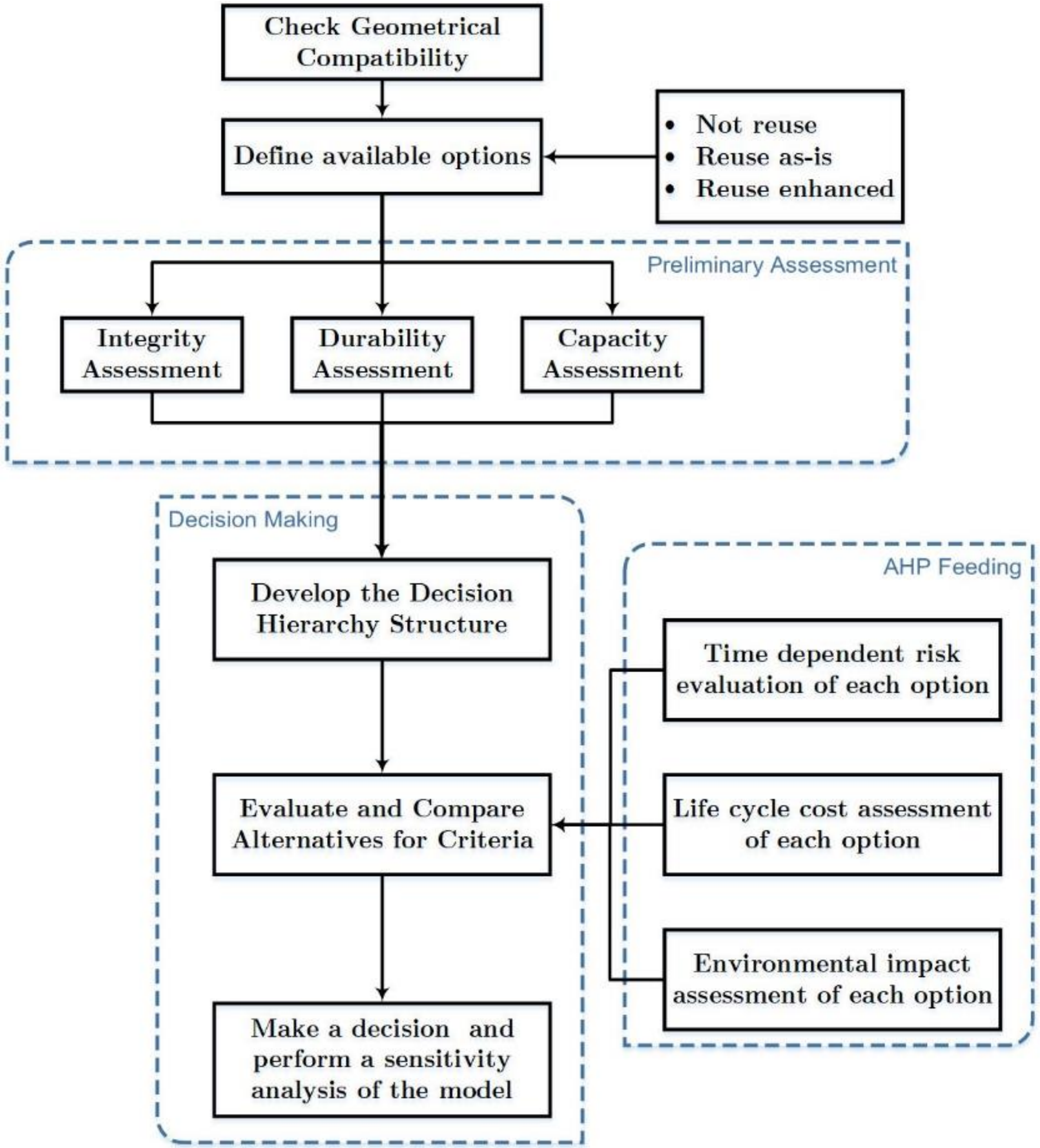
Strengthen/Rehab Foundation System

Does reuse offer greater benefits than other options?

Yes

Yes

Reuse is feasible



Check Geometrical Compatibility

Define available options

- Not reuse
- Reuse as-is
- Reuse enhanced

Preliminary Assessment

Integrity Assessment

Durability Assessment

Capacity Assessment

Decision Making

Develop the Decision Hierarchy Structure

Evaluate and Compare Alternatives for Criteria

Make a decision and perform a sensitivity analysis of the model

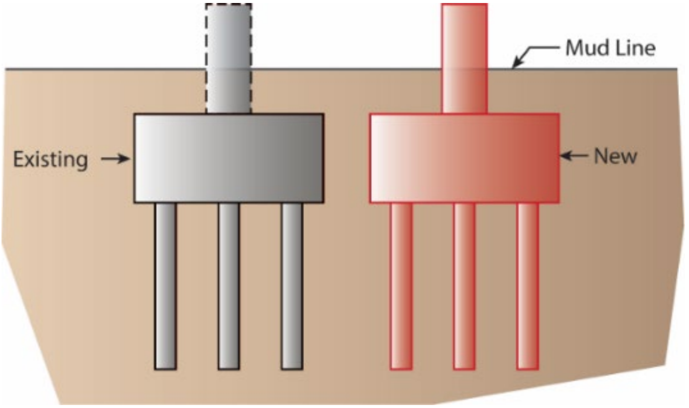
AHP Feeding

Time dependent risk evaluation of each option

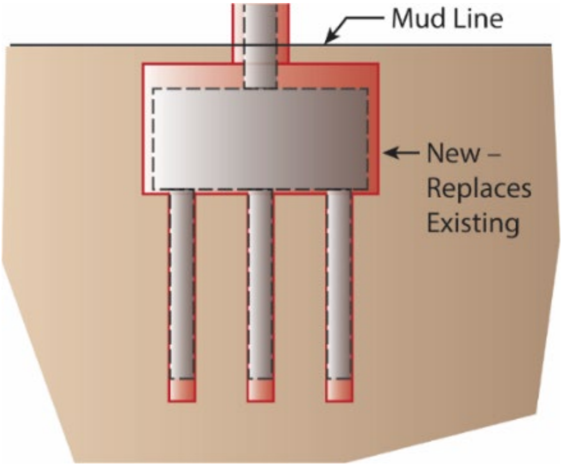
Life cycle cost assessment of each option

Environmental impact assessment of each option

Foundation Reconstruction Options



Option 1: Install new foundation on new alignment

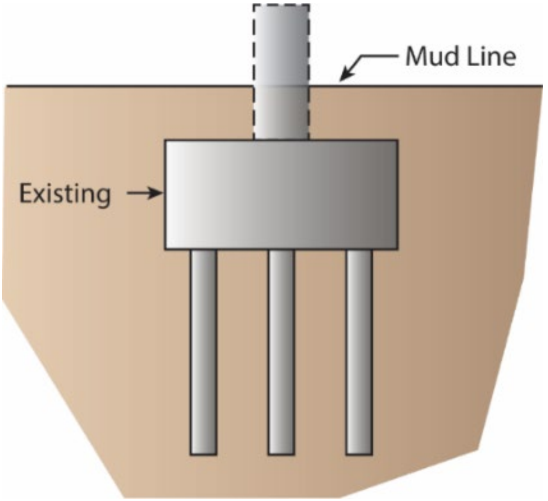


Option 2: Install new foundation on the existing alignment

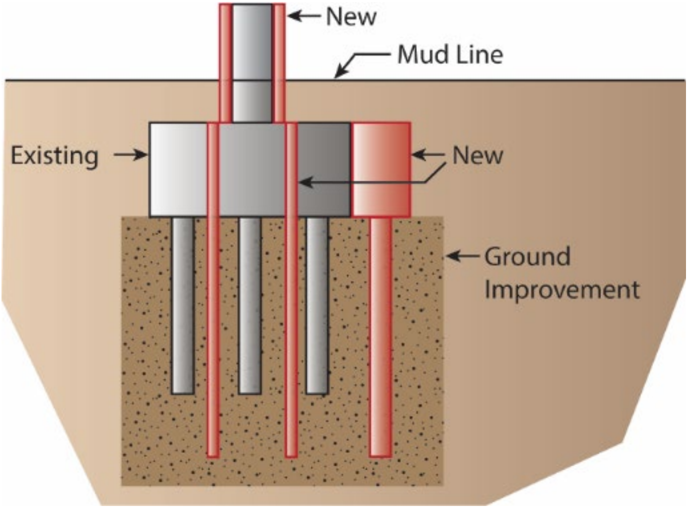
Hurricane Deck Bridge, Lake of the Ozarks, MO

Bridge B-23-005-M-18-002, Bridgewater, MA

Foundation Reconstruction Options



Option 3: Reevaluation and reuse existing foundation



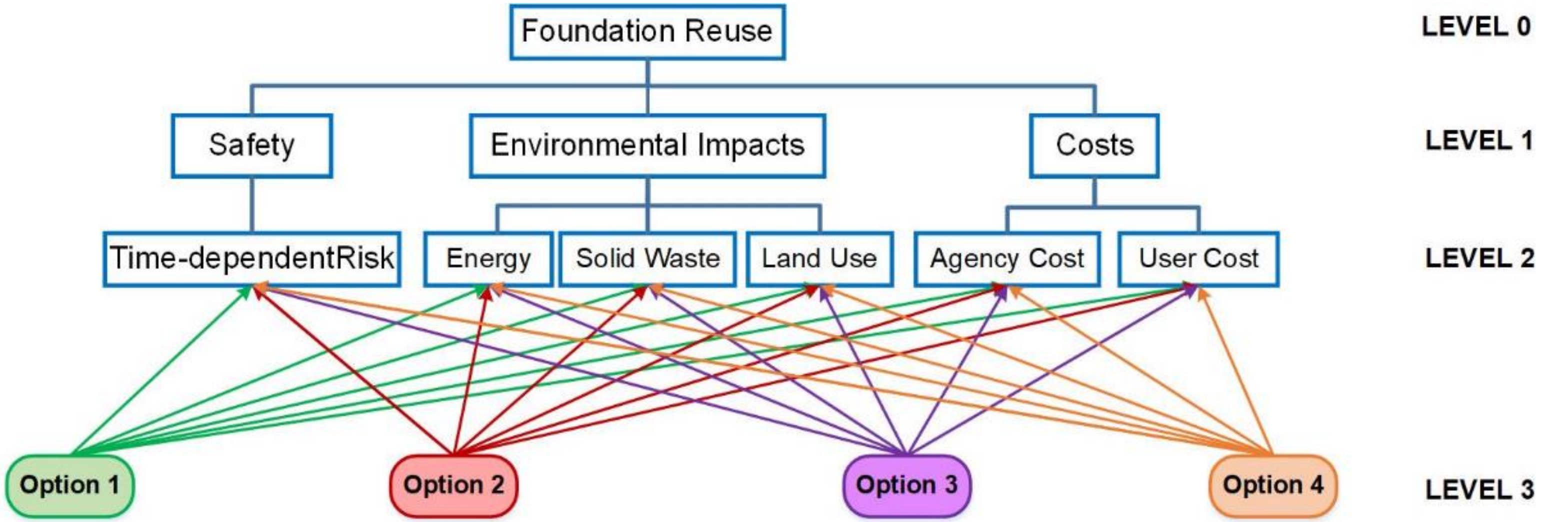
Option 4: Reuse existing foundation by strengthening it

ABC/PBES on I95 in Virginia

Huey P. Long Bridge in Jefferson Parish, Louisiana

Analytical Hierarchy Process (AHP) in Reuse

- The overall objective: To reuse the existing foundation in the most cost effective and safe manner with the least environmental impact.
- The ability of each construction alternative selected from one of the 4 options to achieve this objective can be evaluated with respect to the following criteria:
  - Safety of the bridge (S)
  - Cost effectiveness of the option (C)
  - Minimum impact on the environment and ecosystems (E)



Analytical Hierarchy Process (AHP) in Reuse

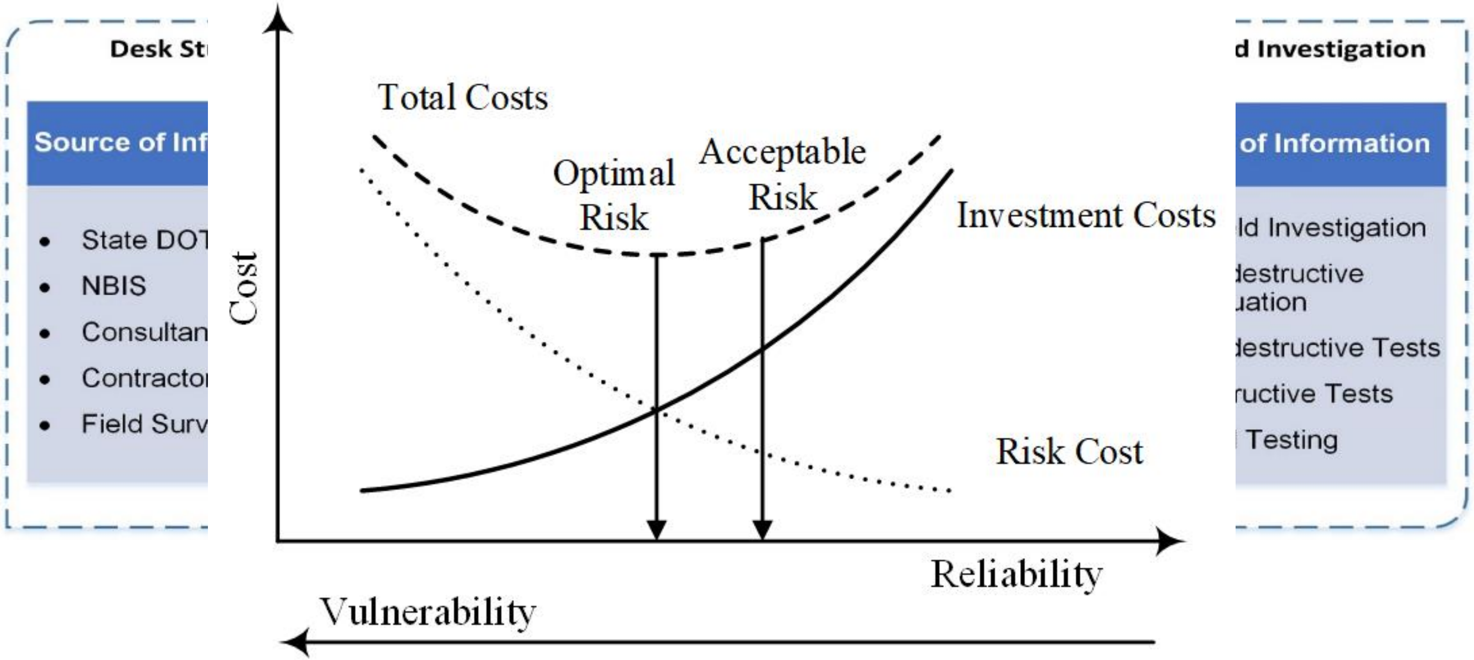
$$\begin{bmatrix} w_S / w_S & w_S / w_C & w_S / w_E \\ w_C / w_S & w_C / w_C & w_C / w_E \\ w_E / w_S & w_E / w_C & w_E / w_E \end{bmatrix}$$

Importance	Definition	Explanation
1	Equal Importance	Two Activities Contribute equally to the Objective
3	Weak Importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or Strong Importance	Experience and judgment strongly favor one activity over another
7	Demonstrated Importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Absolute Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate Values between two Judgments	Used to facilitate compromise between slightly differing judgments

$$\begin{array}{cc} & \begin{array}{cccc} \mathit{Opt}\ 1 & \mathit{Opt}\ 2 & \mathit{Opt}\ 3 & \mathit{Opt}\ 4 \end{array} \\ \begin{array}{c} \mathit{Opt}\ 1 \\ \mathit{Opt}\ 2 \\ \mathit{Opt}\ 3 \\ \mathit{Opt}\ 4 \end{array} & \begin{bmatrix} S_1 / S_1 & S_2 / S_1 & S_3 / S_1 & S_4 / S_1 \\ S_1 / S_2 & S_2 / S_2 & S_3 / S_2 & S_4 / S_2 \\ S_1 / S_3 & S_2 / S_3 & S_3 / S_3 & S_4 / S_3 \\ S_1 / S_4 & S_2 / S_4 & S_3 / S_4 & S_4 / S_4 \end{bmatrix} \end{array}$$

Why Foundation Reuse is Risky?

- Option 1: Few risks associated with the condition of the existing bridge.
- Option 2: Similar to option 1
- Option 3: Risks due to the use of existing components that may be of uncertain initial quality, condition, or design
- Option 4: The use of strengthening can also mitigate some of the risks associated with reusing an existing design.



Main sources of risk

Estimation of Risk

Safety Risk=Probability of Failure × Consequences Costs

$$R = \iint \dots \int C\left(x_1, x_2, \dots, x_n\right) f_X\left(x_1, x_2, \dots, x_n\right) dx_1 dx_2 \dots dx_n$$

$C(X)$ is the consequences associated with the hazard, $f_X(X)$ is the joint PDF of the random variables.

By assuming the hazards are mutually exclusive and collectively exhaustive:

$$R = \sum_{i=1}^{n} C \times P\left(F \mid H_i\right) P\left(H_i\right)$$

Hazards: Members deterioration, increase in live load, and extreme events (i.e. earthquake, scour, and extreme wind)

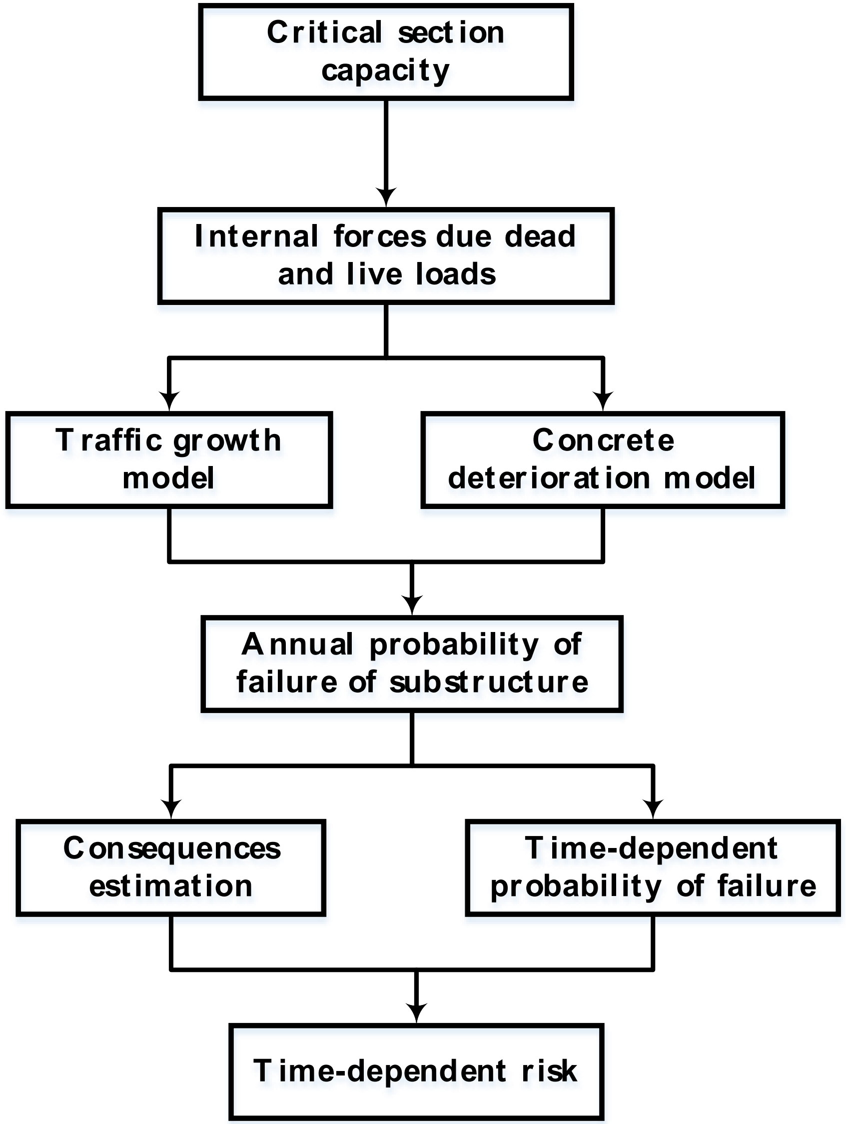
$$R = C \times P\left(F \mid H\right) P\left(H\right)$$

Estimation of Time-dependent Risk

Since demand and capacity are functions of time, safety risk also becomes a function time:

$$R(T) = \sum_{t=1}^{T} N_c C_{tot} f_{f,t}$$

where N_C is the epistemic uncertainty coefficient referring to the consequences, C_{tot} is total failure cost, $f_{f,t}$ is the PDF of the time-dependent failure, t is the time (in year).



Critical section capacity

Internal forces due dead and live loads

Traffic growth model

Concrete deterioration model

Annual probability of failure of substructure

Consequences estimation

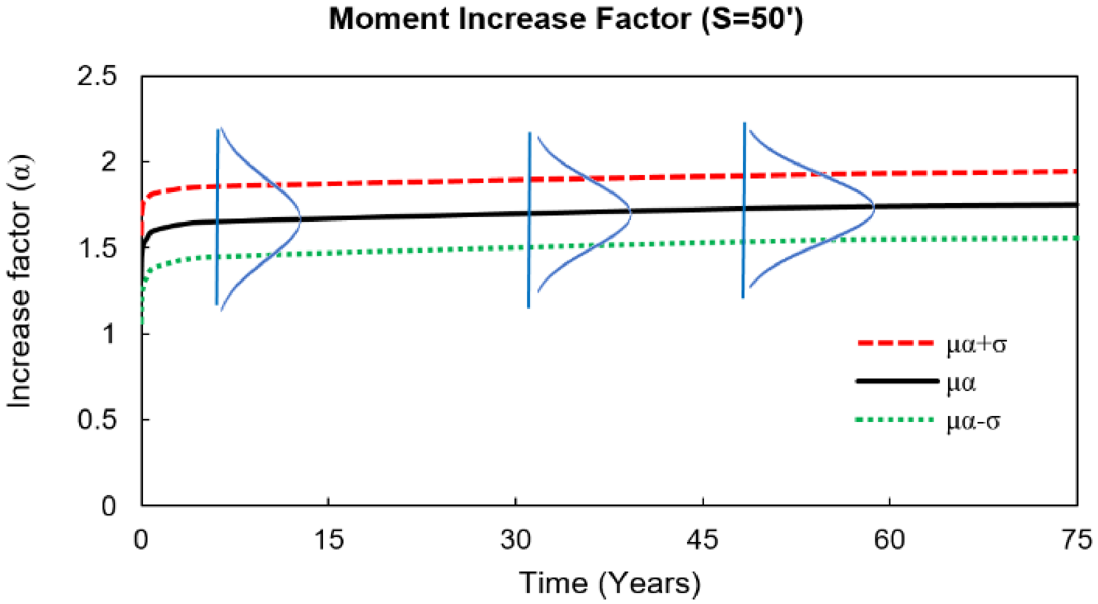
Time-dependent probability of failure

Time-dependent risk

Time-Depend Demand

Loads in Reuse:

- Dead Load
- Live Load
  - span length, truck weight, axle loads, axel configuration, position of the vehicle on the bridge (transverse and longitudinal), truck traffic volume (*ADTT*), number of vehicles on the bridge (multiple presence), girder spacing, and stiffness of structural members (Nowak and Hong 1991).



Data extracted from Nowak (1999)

- By increasing the average daily truck traffic, the probability of extreme-weight vehicles occurring increases.
- Extreme value distribution type I (Gumbel distribution)

$$\mu_{F_n} = \mu + \sigma\left(u_n + \frac{\gamma}{\alpha_n}\right)$$

$$\sigma_{F_n} = \frac{\pi}{\sqrt{6}}\frac{\sigma}{\alpha_n}$$

Time-Dependent Capacity

- Corrosion in steel rebars

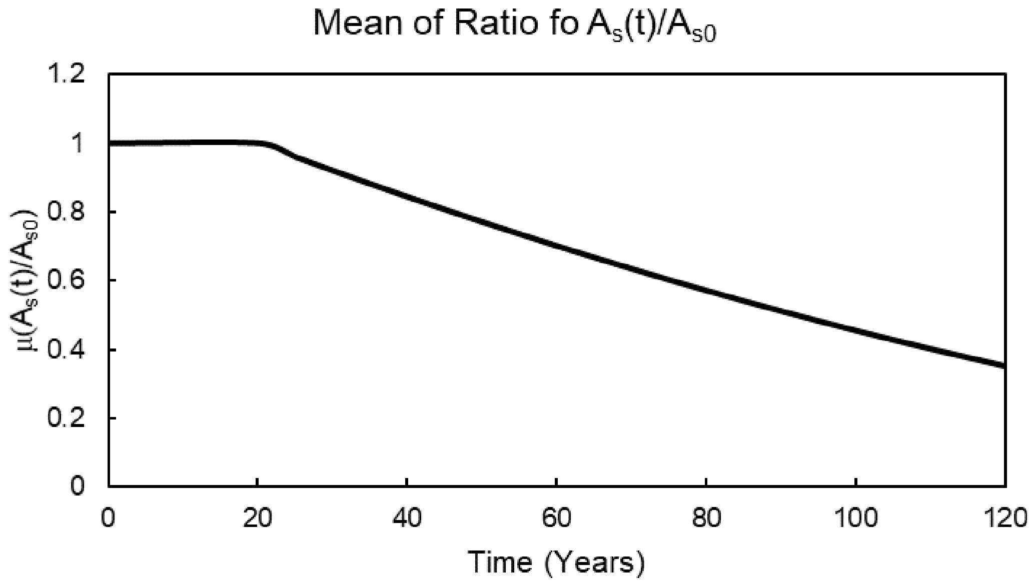
$$A_s(t) = \begin{cases} \frac{1}{4} n\pi D_i^2 & t \le T_i \\ \frac{1}{4} n\pi \left[D_i - 2\lambda(t - T_i)\right]^2 & T_i < t \le T_i + D_i / 2\lambda \\ 0 & t > T_i + D_i / 2\lambda \end{cases}$$

$C_r = \lambda = 0.0203 i_{corr}$: rate of corrosion

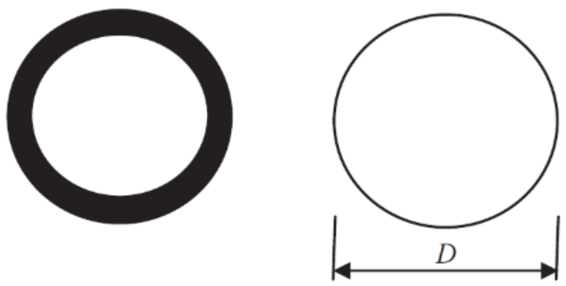
Corrosion Rates Measured

	Corrosion Rate mm/year	
Condition	**Tape water**	**1% NaCl+0.5% Na_2So_4**
Noncoated	0.0678	0.0980
Coated	0.0073	0.0130

Source: Adapted from El-Sayed et al., *Corrosion Prevention and Control*, February 1987.



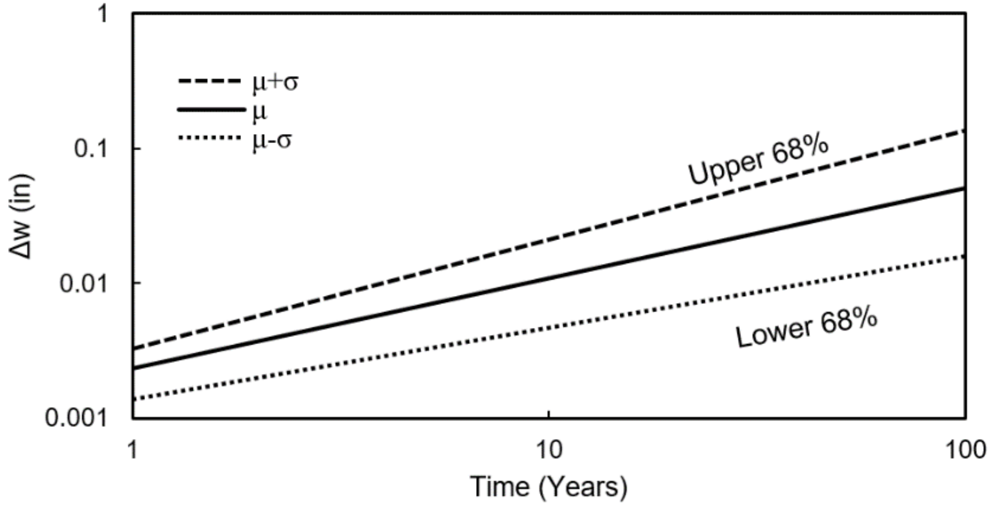
$\mu_{icorr} = 2.5$ mA/cm^2



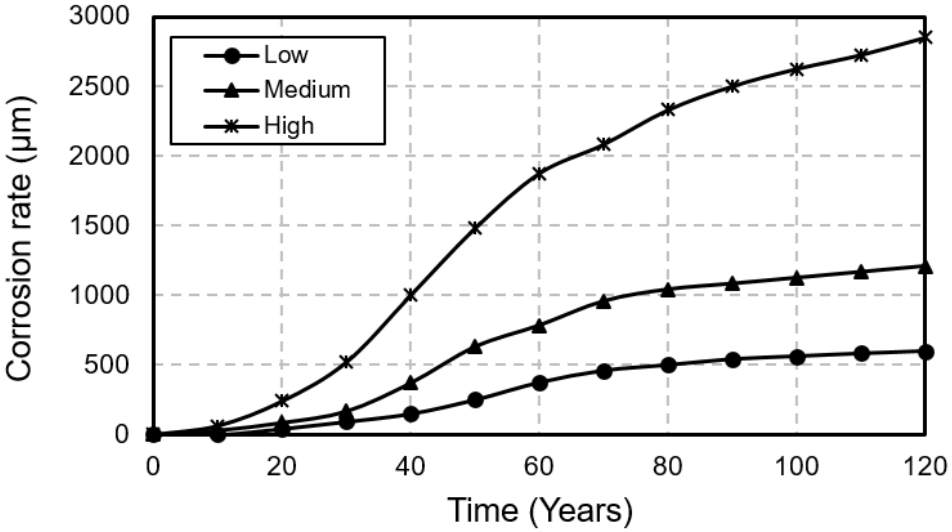
Time-Dependent Capacity

- Corrosion in steel piles (Albrecht and Naeemi 1984):

$$\Delta w = \rho t^{b}$$



Total thickness loss of pile section from corrosion (Decker et al. 2008)



Corrosion rate of steel girder bridges, data from Park and Nowak (1997)

Reliability Analysis

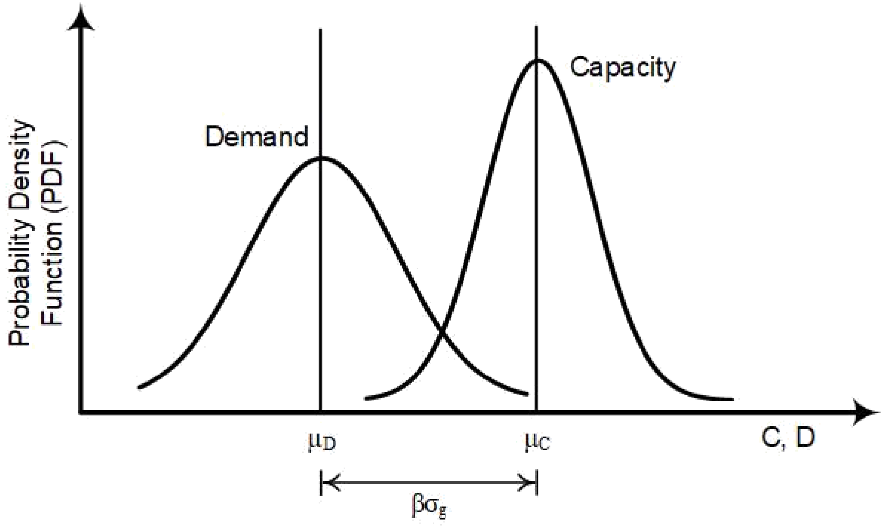
Time-dependent probability of failure

$$P_f^{(i)}(t) = P\left[g_i(t) \le 0\right] = P\left[C_i(t) - D_i(t) \le 0\right] \qquad i = 1, 2, \ldots, k$$

$P_f^{(i)}(t)$ is the time-dependent probability of failure for the failure mode *i*,

$g_i(t)$ is the time-dependent performance function,

$C_i\,(t)$ and $D_i\,(t)$ are time-dependent capacity and demand function associated with failure mode *i*, respectively.

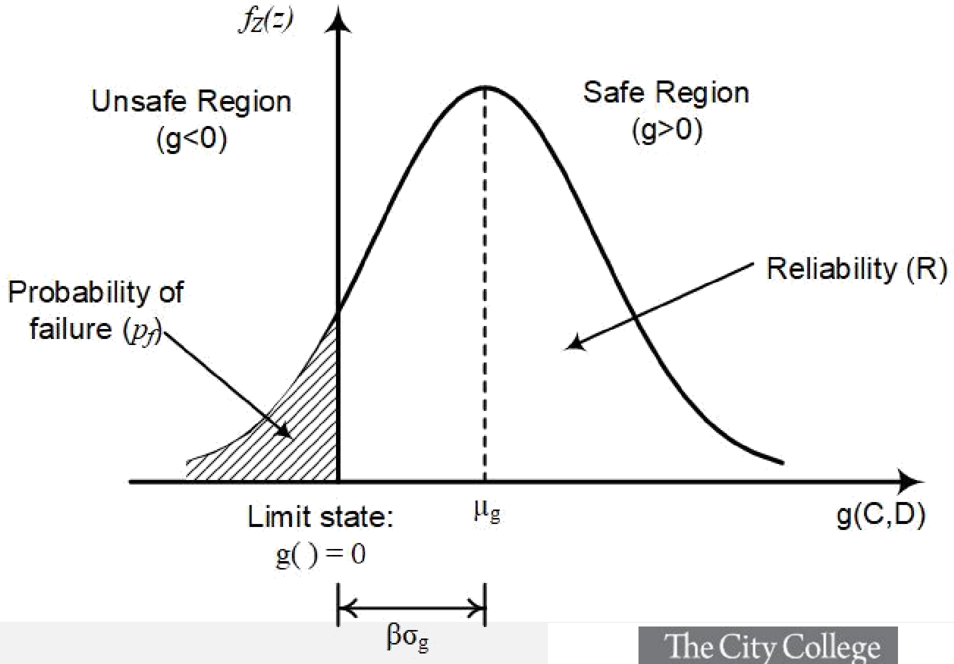


$$p_{f,loc} = \sum_{i=1}^{n} p_{f,loc}^{(i)}$$

$$P_{f,loc} = \max\left[p_{f,loc}^{(i)}\right]$$

$$P_{f,sys} = \int \ldots \int f_X(x_1, x_2, \ldots, x_n)\,dx_1 \ldots dx_n \qquad \beta_{sys} = \Phi^{-1}\left(1 - P_{f,sys}\right)$$

Approximate methods (e.g., FOSM, SORM, AFOSM)



Consequences Evaluation

- Loss of life
- Bridge replacement costs,
- Loss of equipment
- Cost of temporary measures
- Road user costs (delayed traffic costs due to slowing down of traffic, costs due to detours of traffic) composed of additional costs for vehicle operating, travel time and accidents, costs of non-travelling—no detours possible—and social impact costs.

1. Commercial Loss
2. Safety Loss

$$C_{tot}(t) = C_{CL}(t) + C_{SL}(t)$$

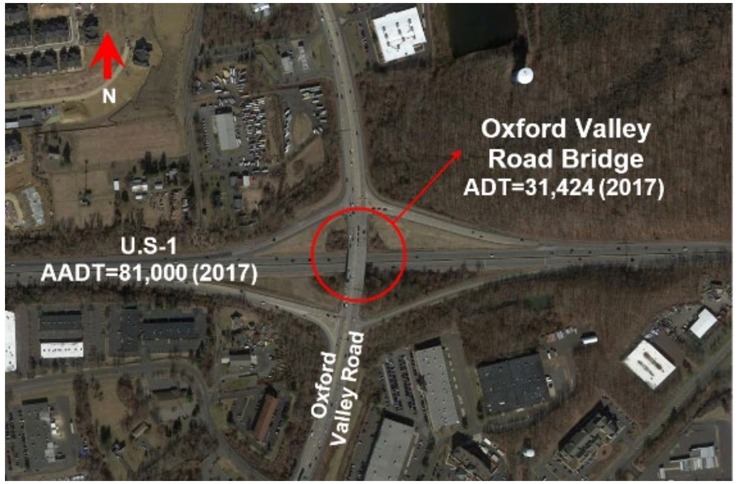
$$FV = PV(1+r)^t$$

$$C_{CL}(t) = C_{Rec}(t) + C_{opr}(t) + C_{TT}(t)$$

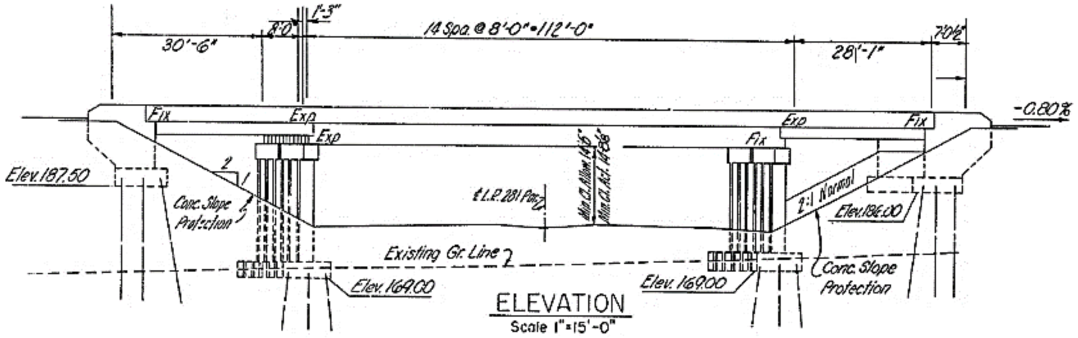
$$C_{SL} = \left(\frac{L}{D_s} + 1\right)\left[\left(1 - \frac{T}{100}\right)n_{car} + \frac{T}{100}n_{trk}\right].ICAF(1+r)^t$$

Case Example: Oxford Valley Road Bridge over U.S-1

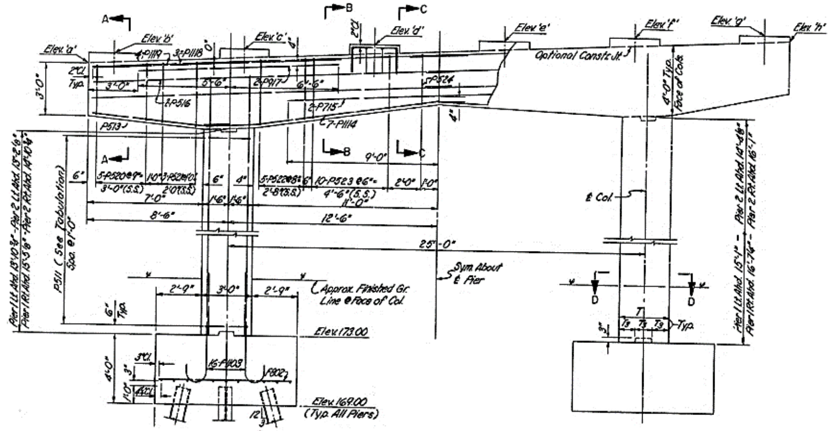
- Three-span steel girder cast-in-place concrete bridge
- Constructed in 1972 in Bucks County, Cochranville, PA.
- Bridge superstructure was evaluated structurally deficient and replaced in 2017.
- The existing bridge consisted of three spans of 34.5’-100’-32’ and skewed 6 degrees.
- The abutments are retaining walls with constant sections sitting on H-piles.

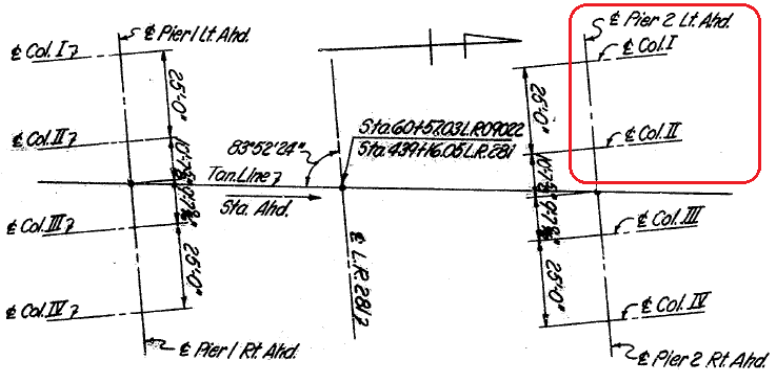


Case Example: Oxford Valley Road Bridge over U.S-1

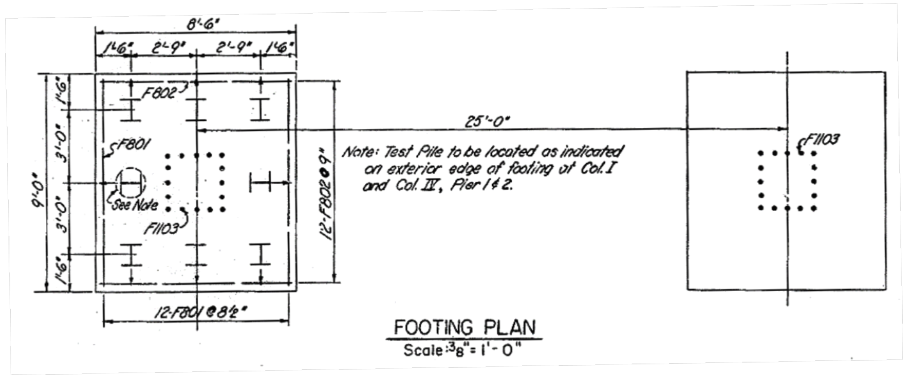


ELEVATION
Scale 1" = 15'-0"

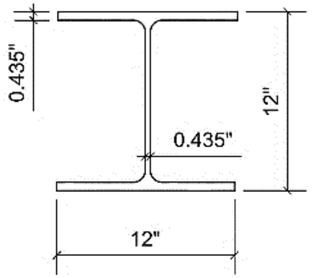




PIER SCHEMATIC
No Scale

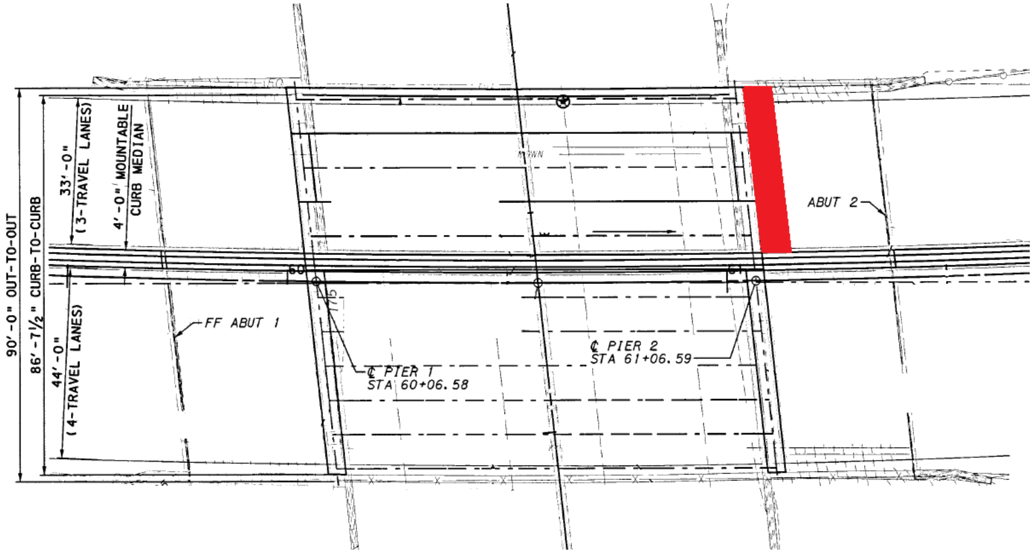


FOOTING PLAN
Scale: ⅜" = 1'-0"

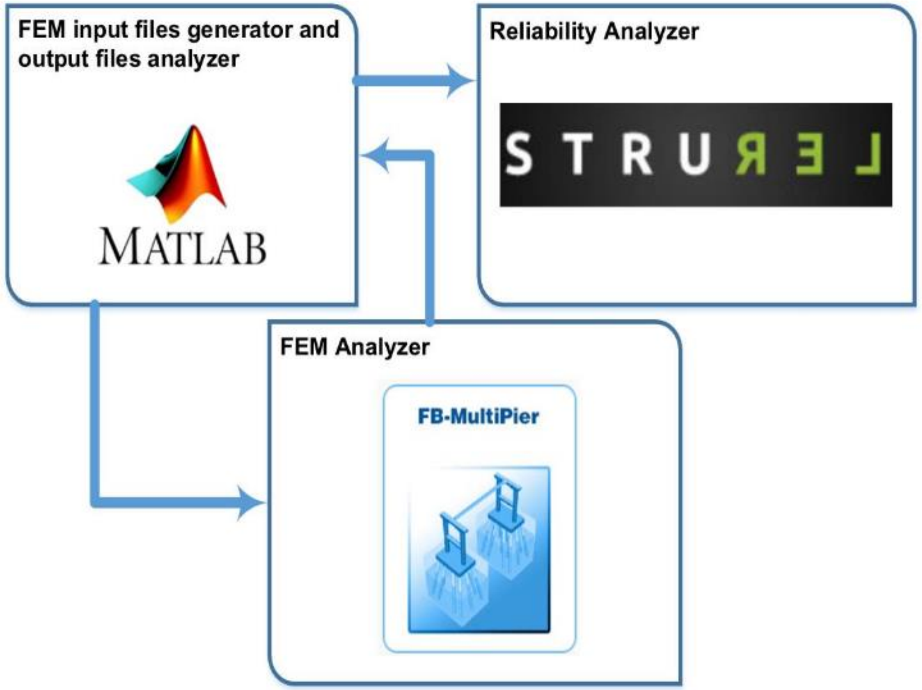


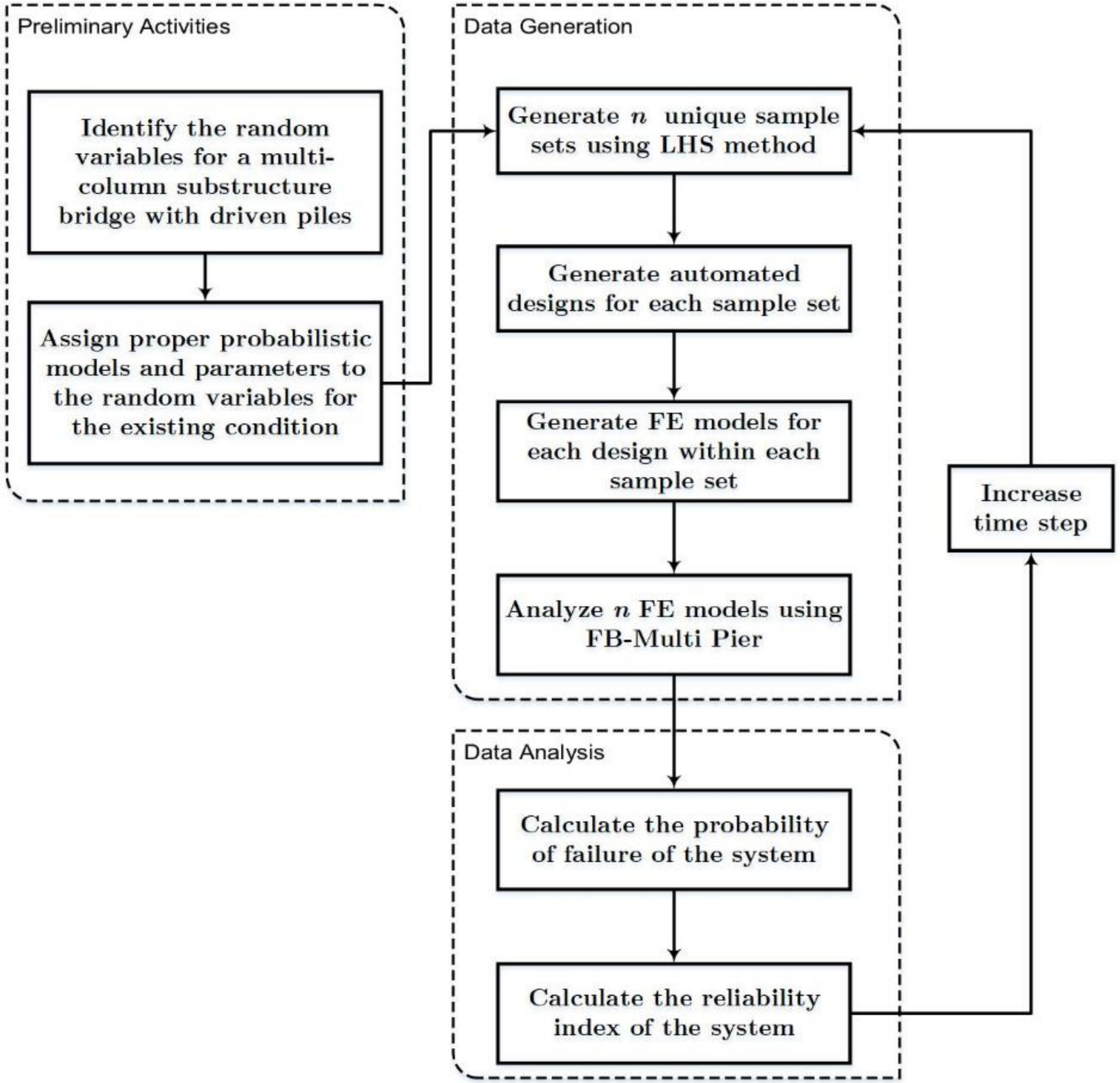
Defining the Options

- Option 2 is defined as construction of a new pier with the same geometrical and structural details at the north side of the existing pier (Pier 2 Lt. Ahd) and south of abutment 2.
- Option 3 can be defined as reusing the existing substructure and foundation with minor rehabilitations (patching spalled, deteriorated, and cracked parts of the pier cap without any corrosion mitigation).
- Option 4 can be defined as reusing the existing pier and steel piles with retrofitting the deteriorated parts of pier and corrosion mitigation.



Calculation Procedure



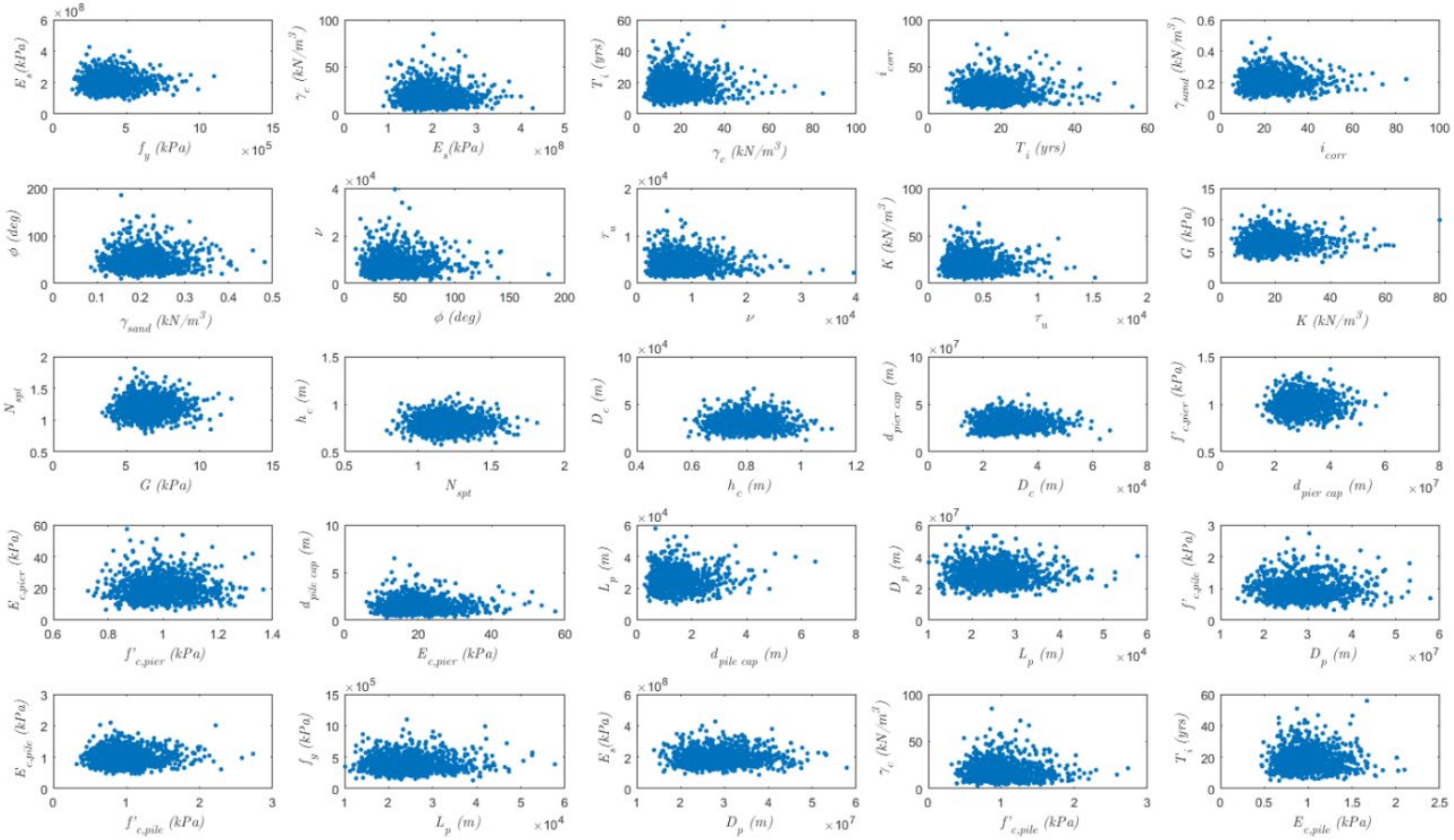


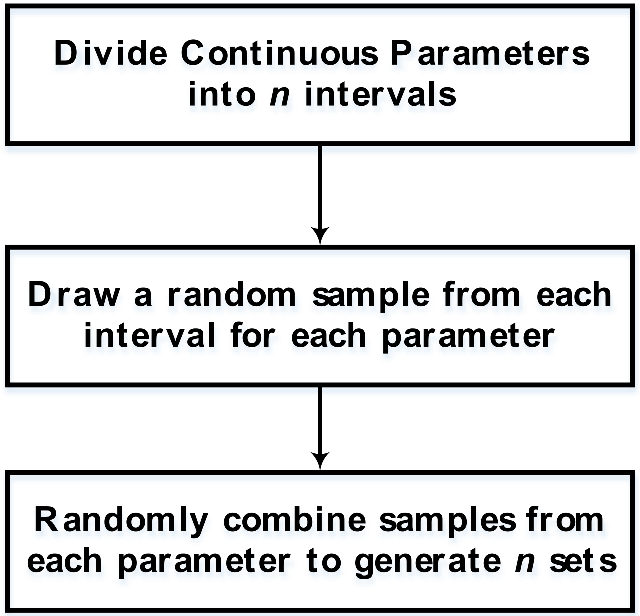
Random Variables and Associated Statistical Parameters

Random Variable	Mean	COV	Dist.	Reference
Steel rebar yielding stress (f_{yr})	60 ksi	0.11	LN	COV based on Estes (1997)
Steel pile yielding stress (f_{yp})	36 ksi	0.09	LN	
Steel modulus of elasticity (E_s)	29,000 ksi	0.06	LN	Nowak et al. (1994)
Steel unit weight (γ_s)	490 pcf	0.01	LN	
Concrete compressive strength (f'_c)	4 ksi	0.07	LN	COV based ACI (2002)
Concrete modulus of elasticity(E_c)	4000 ksi	0.05	LN	COV based on Estes (1997)
Concrete unit weight (γ_c)	150 pcf	0.03	Normal	Naaman and Siriaksorn (1982)
Column width (W_c)	3 ft.	0.016	LN	COV based on Mirza and MacGregor (1979)
Pile cap depth (d_{pc})	4 ft.	0.01	LN	COV based on Mirza and MacGregor (1979)
Driven pile length (L_p)	20 ft.	0.01	LN	COV assumed
H-Pile web thickness (t_w)	0.435 in.	0.015	LN	COV based on Decò and Frangopol (2011)
H-Pile depth (d_p)	11.8 in.	0.015	LN	COV based on Decò and Frangopol (2011)
Live load (LL)	Varies	Varies	Gumbel	Nowak and Hong (1991)
Epistemic uncertainty for demand	1	0.11	LN	Ang and Leon (2005)
Epistemic uncertainty for capacity	1	0.06	LN	Ang and Leon (2005)
Corrosion initiation time (T_i)	19 yrs	0.273	LN	Estes (1997)
Steel bar corrosion rate (λ)	3×10^{-4} in/yr	0.29	Uniform	Thoft-Christensen et al. (1996)
Steel pile corrosion parameter ρ	0.0002 in.	0.41	LN	Decker et al. (2008)
Steel pile corrosion parameter b	0.67	0.21	LN	Decker et al. (2008)

Layer No.	Description	Top (ft)	Bottom (ft)	N_{spt}	Lateral Resistance	Axial Resistance	Torsional Model
1	Sandy Clay	172.7	164.5	15	Clay (Stiff)	Driven Pile	Hyperbolic
2	Very Stiff Clay	164.5	160.5	20	Clay (Stiff)	Driven Pile	Hyperbolic
3	Schist Rock	160.5	154.6	31	Weak Rock	Driven Pile	Hyperbolic
4	Schist Rock	154.6	143.9	60	Weak Rock	Driven Pile	Hyperbolic
5	Schist Rock	143.9	138.5	N/A	Strong Rock	Driven Pile	Hyperbolic

Latin Hypercube Sampling (LHS)

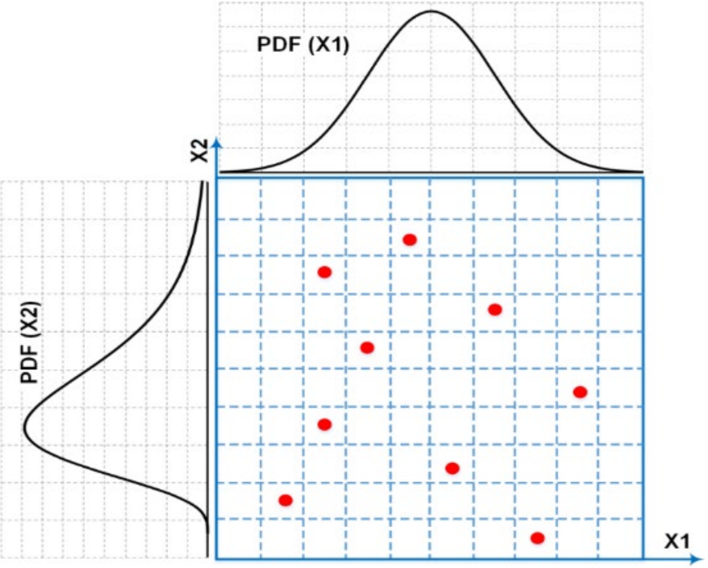




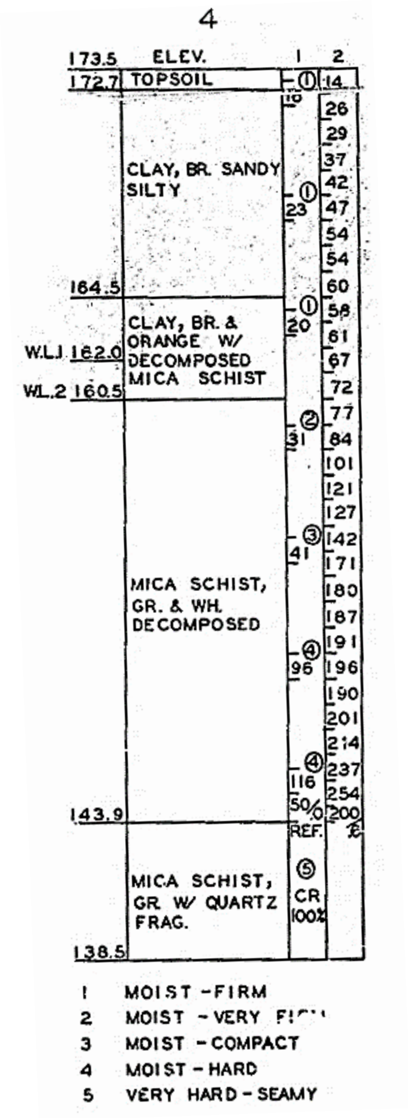
Divide Continuous Parameters into *n* intervals

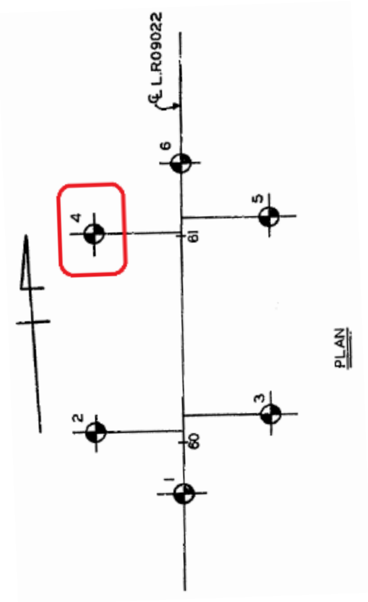
Draw a random sample from each interval for each parameter

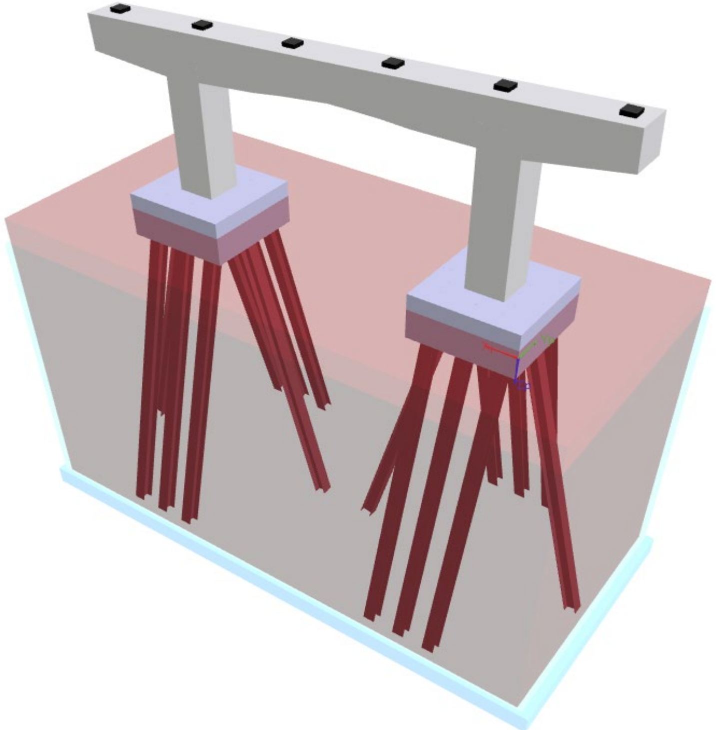
Randomly combine samples from each parameter to generate *n* sets

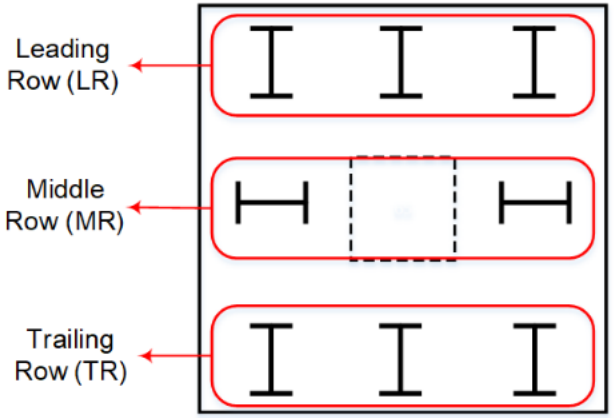


Finite Element Modeling

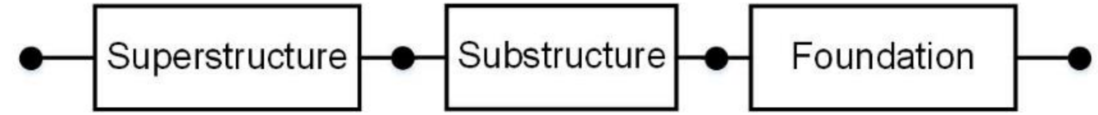


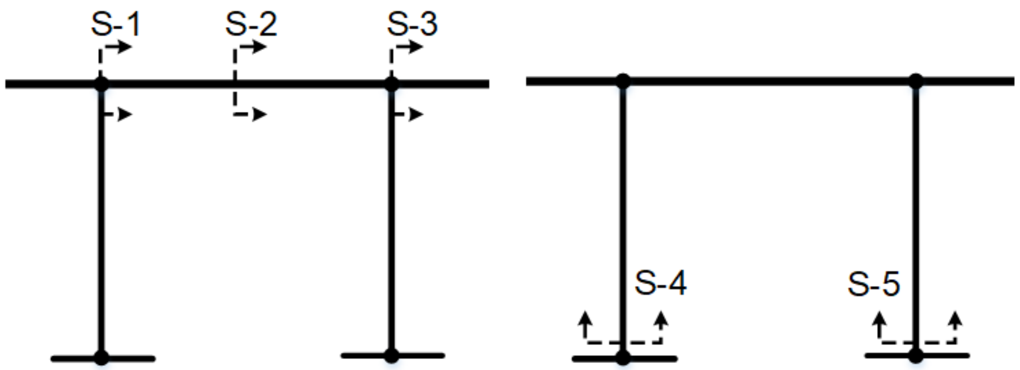


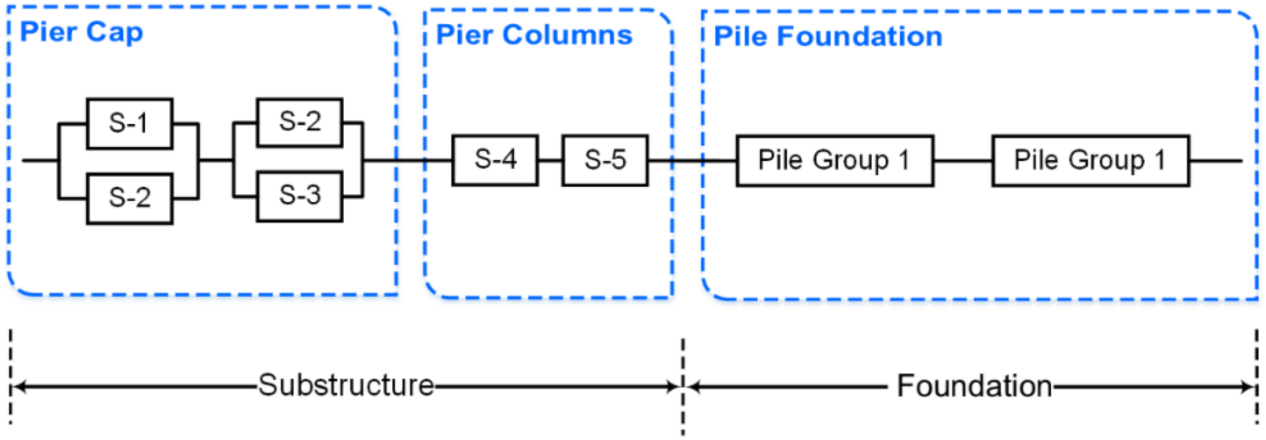


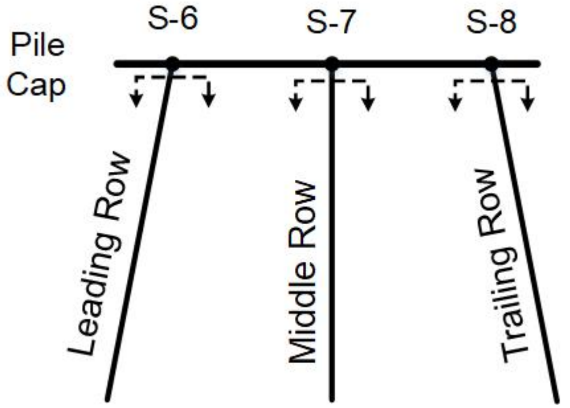


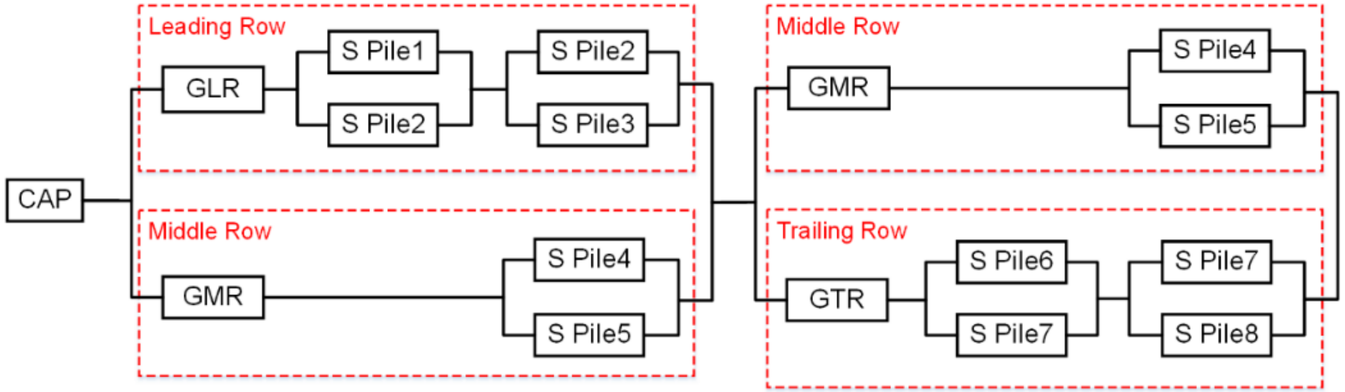
Series-parallel System Model











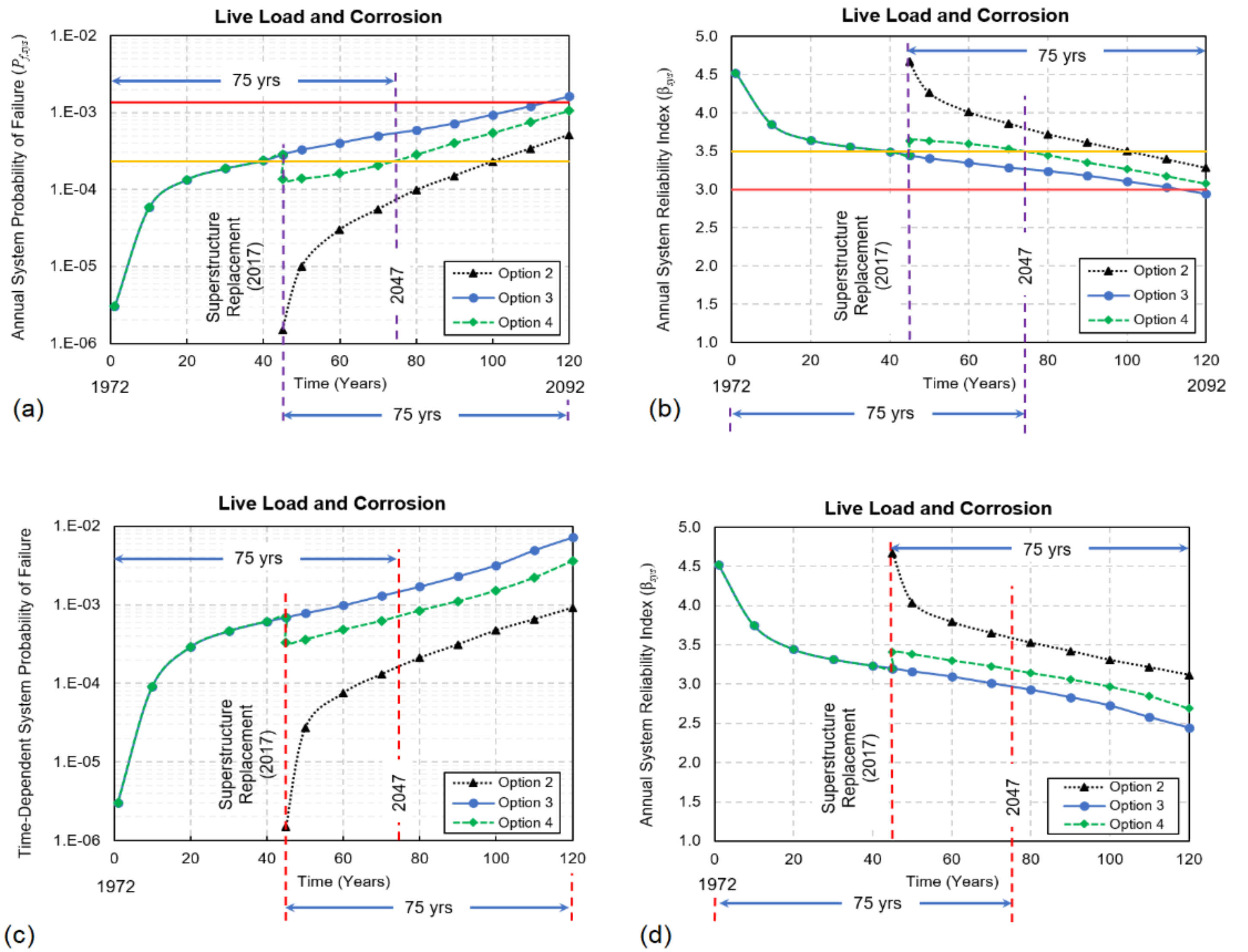
Probability of Failure

- Among all 4,000 FE models created to run in FB-MultiPier, it is probable that some cases do not converge because of the random variables have been sampled from extreme tails of probability distribution functions.

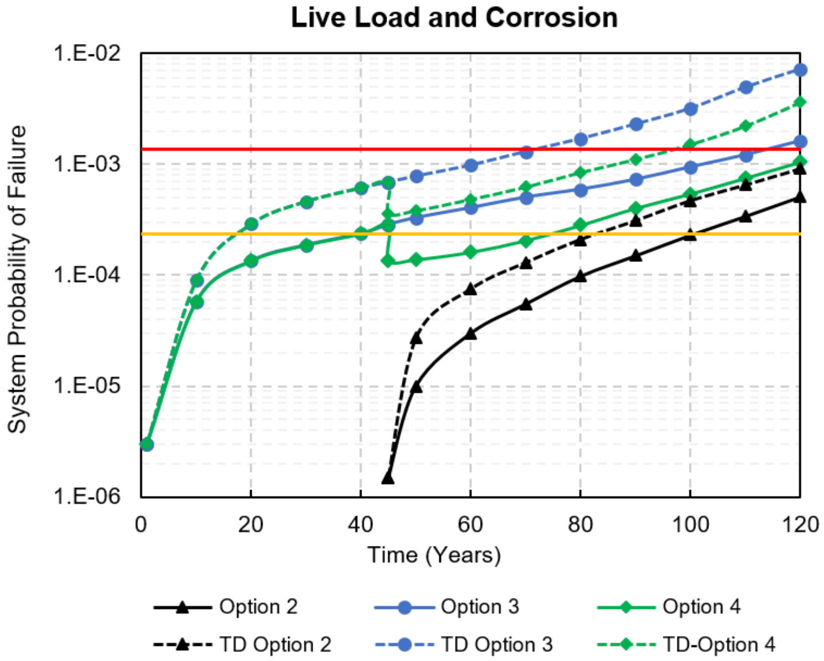
$$p_f = P_{f(cs)} P(CV) + P_{f(ncs)} P(NCV)$$

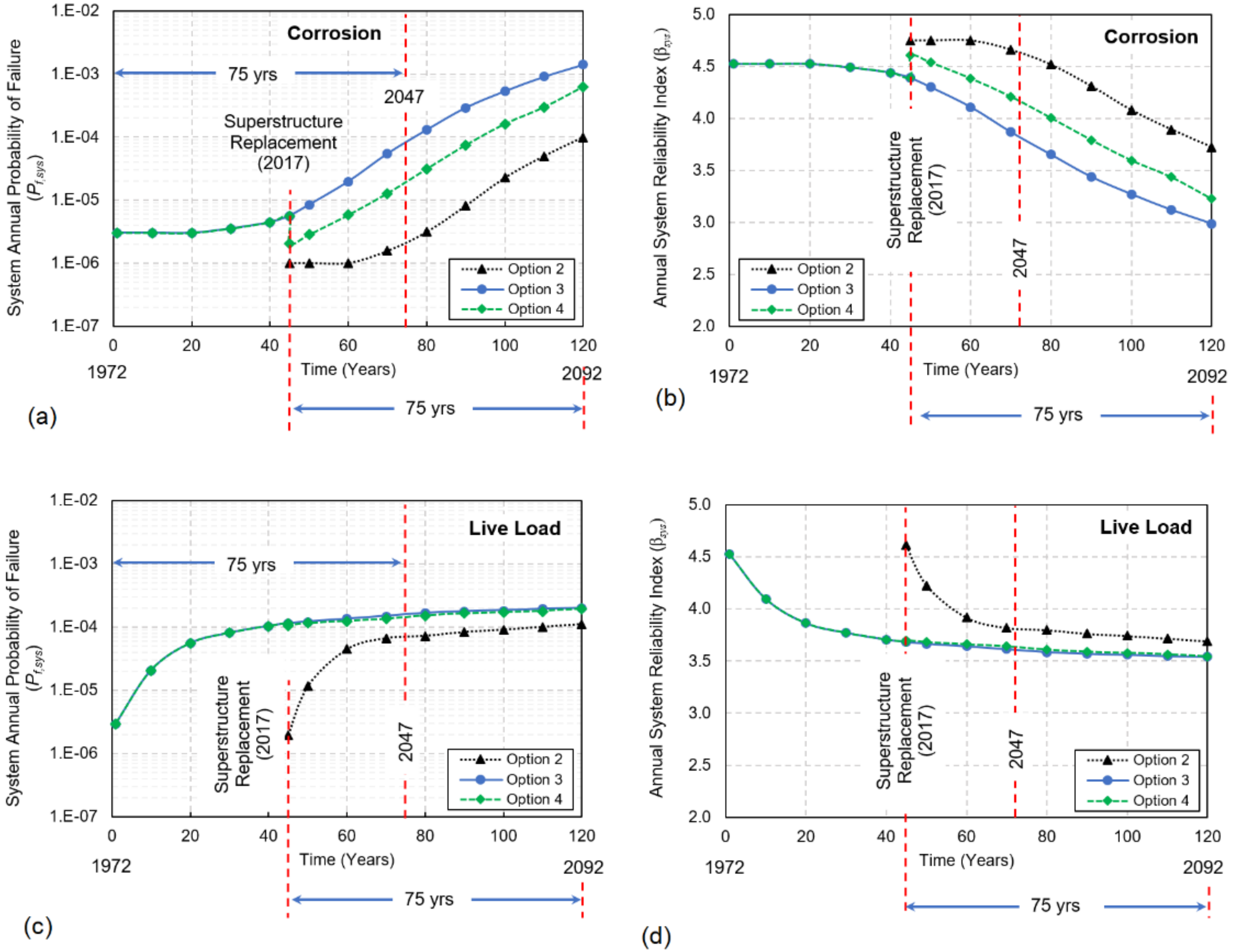
- p_f is the probability of failure of the substructure
- $P_{f(cs)}$ is the probability of failure on the given converged models
- $P(CV)$ is the probability of convergence in analysis
- $P_{f(ncs)}$ is the probability of failure on the given diverged models which is 1.0
- $P(NCV)$ is the probability of models not converging

Substructure System Reliability Analysis

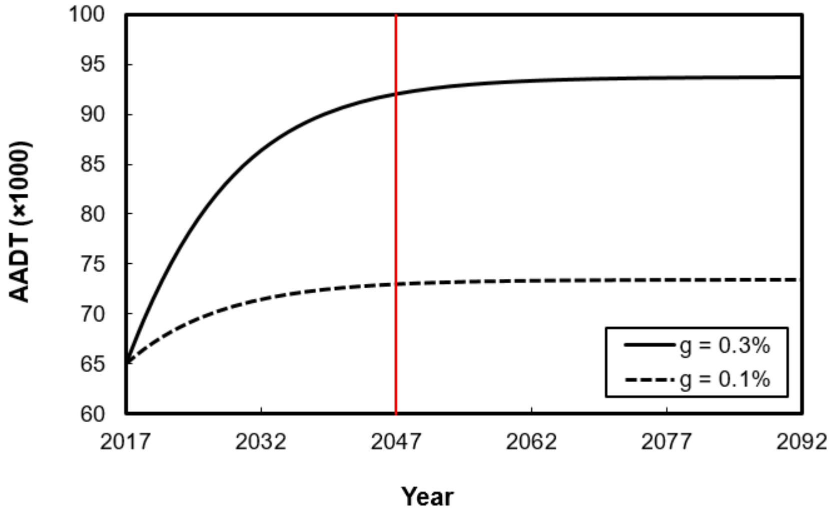


Substructure System Reliability Analysis





Evaluation of Consequences

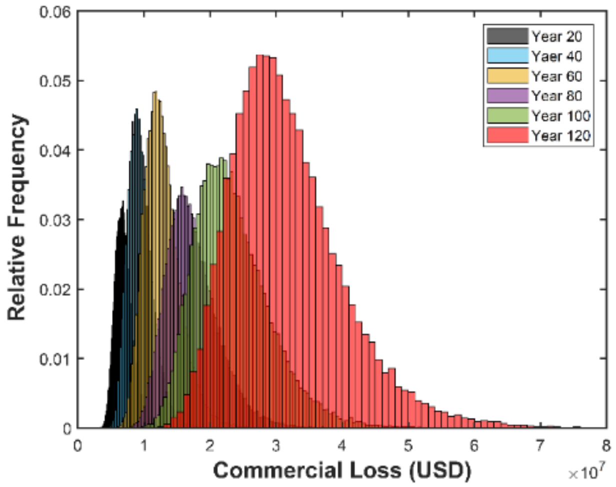


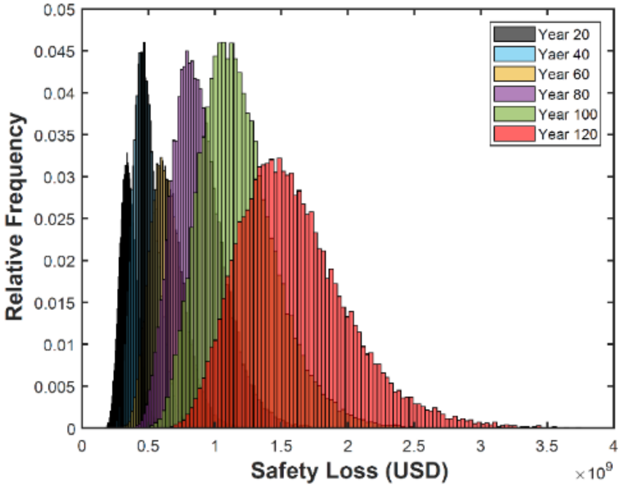
Random Variable	Mean	COV	Distribution	Reference
ADT	65,000	0.2	LN	Decò and Frangopol (2011)
VOC_u	0.74 \$/mile/veh	0.05	LN	Assumed
L_d	3.9 miles	N/A	N/A	-
d	6 month	0.1	LN	Assumed
V	15 mph	0.15	LN	Decò and Frangopol (2011)
C_{AT}	32.54 \$/adult/hour	0.15	LN	AASHTO (2010)
C_{TR}	35.47 \$/hour	0.15	LN	AASHTO (2010)
ICAF	2.5×10^6 \$	0.11	LN	Rackwitz (2002)
n_{car}	1.5	0.15	LN	Decò and Frangopol (2011)
n_{trk}	1	0.15	LN	Decò and Frangopol (2011)
T	2%	0.2	LN	Mahmoud et al. (2005)
L	150 ft	N/A	N/A	-
D_s	6 ft	N/A	N/A	-
r	3%	0.10	LN	Assumed
C_{Rec}	301 \$/ft²	0.2	LN	FHWA (2018b)

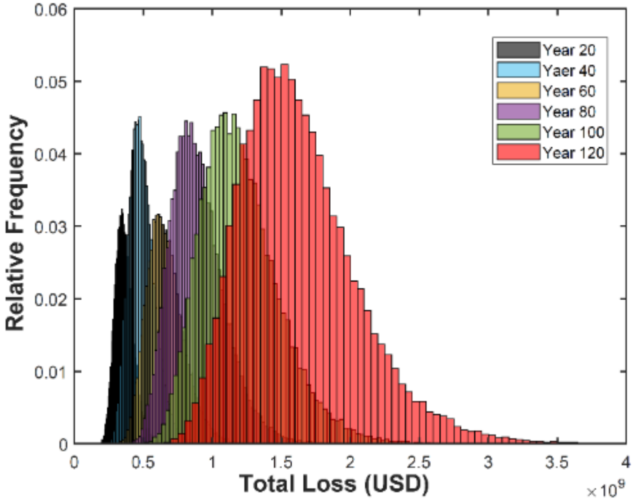
ADT is the average daily traffic (vehicle/day)
VOC_u is the average unit vehicle operating cost (USD/mile/vehicle)
L_d is the additional length of the detour route (mile)
d is the duration of a detour (month)
V is the average velocity of vehicles (mph)
C_{AT} is the value of time per adult (USD/adult/hour)
C_{TR} is the value of time for a truck (USD/hour)
ICAF is the implied cost of averting a fatality

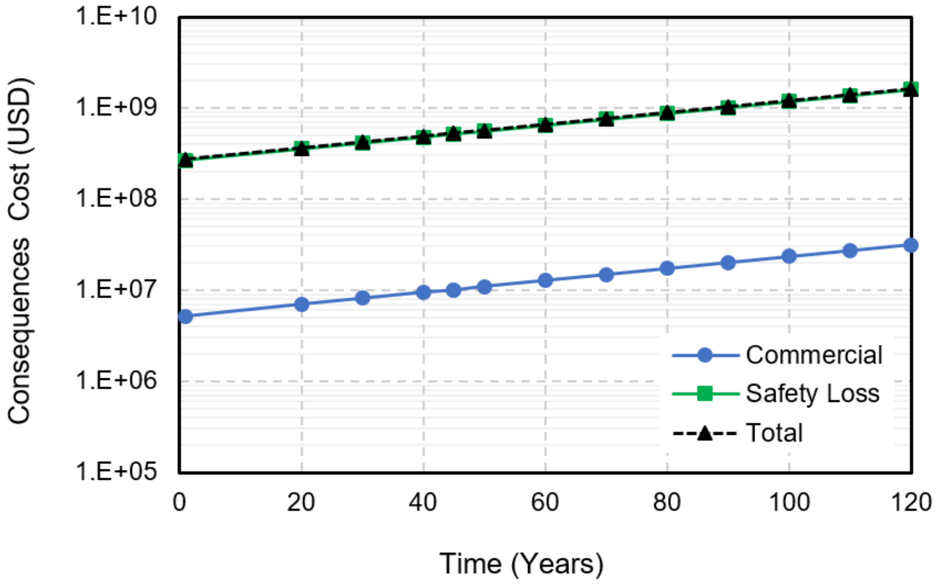
n_{car} is the average number of people per vehicle for cars(person/vehicle)
n_{trk} is the average vehicle occupancy for trucks
T the average truck daily traffic percentage (%)
L is the total bridge length (ft)
D_s is the safe following distance during driving (ft)
r is the annual discount rate
C_{Rec} is reconstruction cost

Evaluation of Consequences

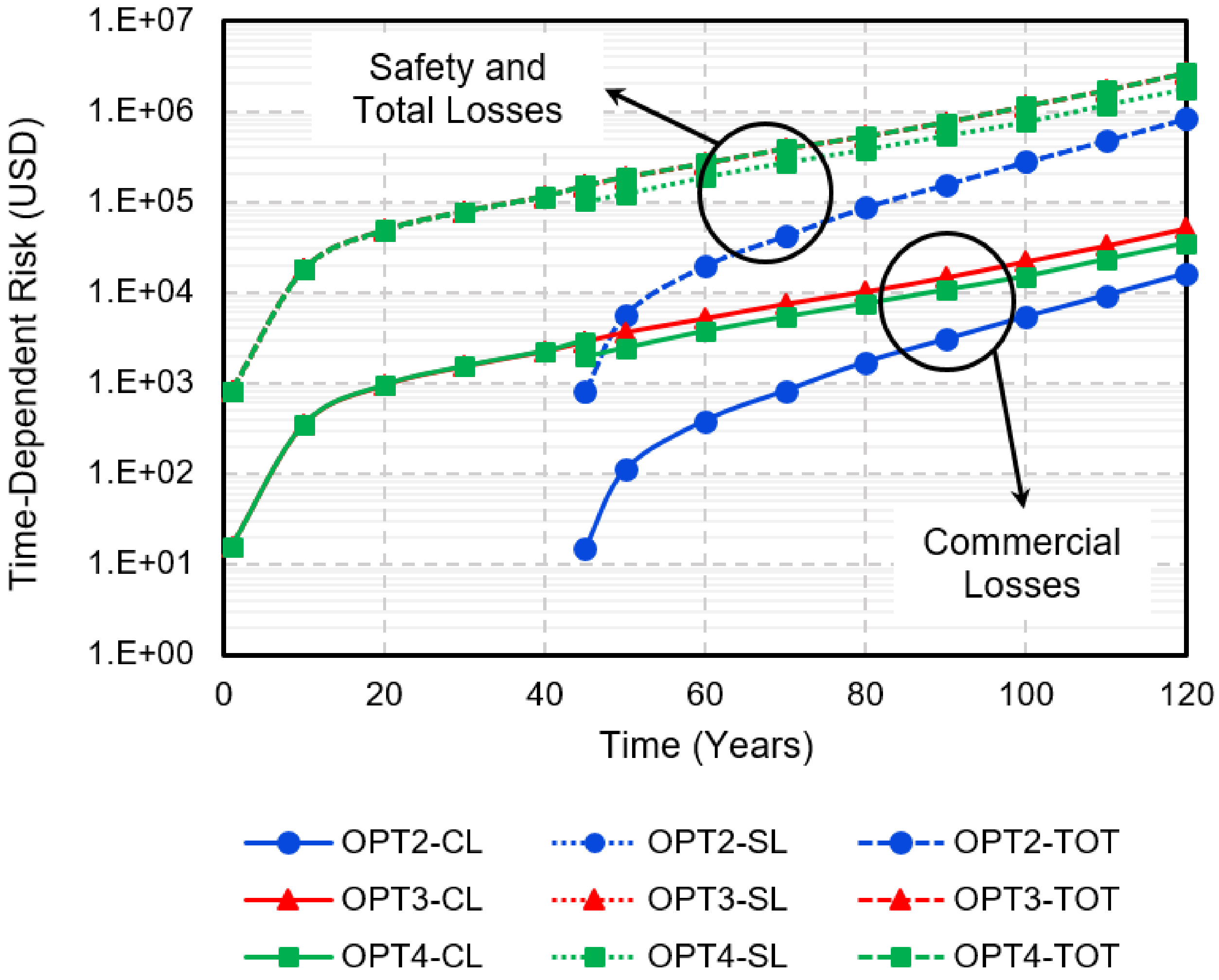








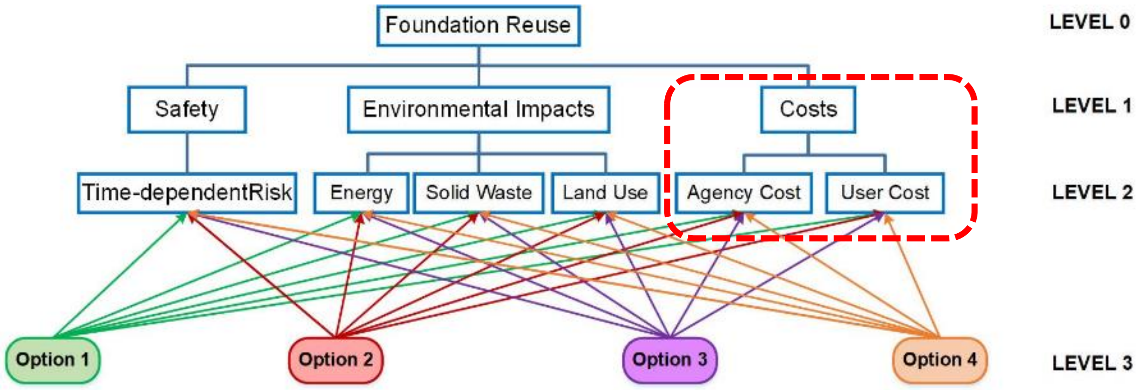
Time-dependent Risk



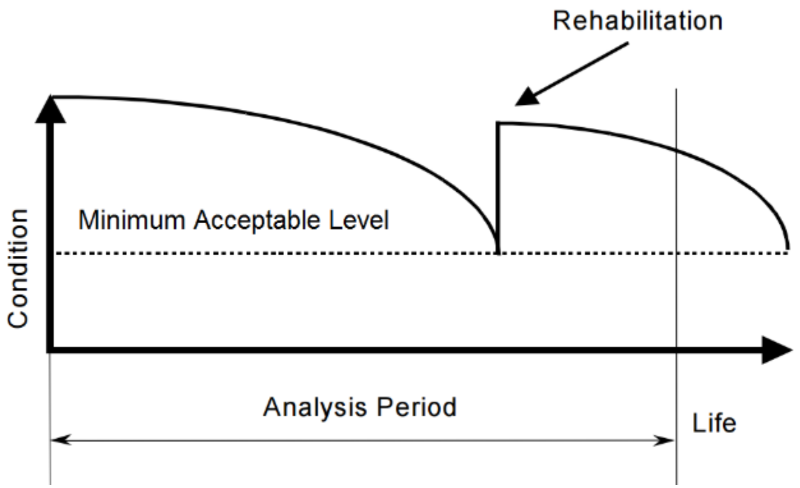
Bridge Life-Cycle Cost Analysis (BLCCA)

The costs of project alternatives should be Compared over the entirety of the project lifespan.

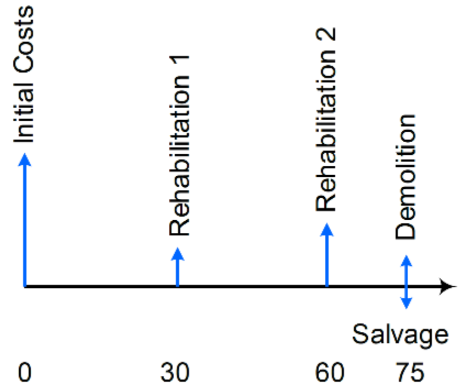
1) Determining analysis period
2) Cost estimation (agency and user)
3) Life-cycle costs computation



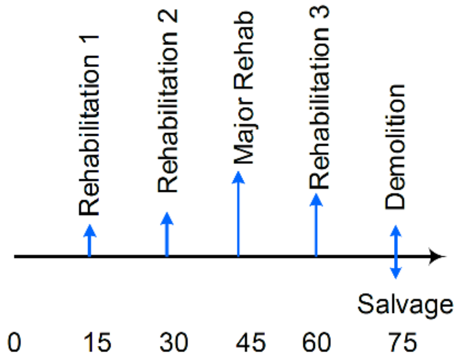
- Deterministic life-cycle cost analysis
- Probabilistic life-cycle cost analysis



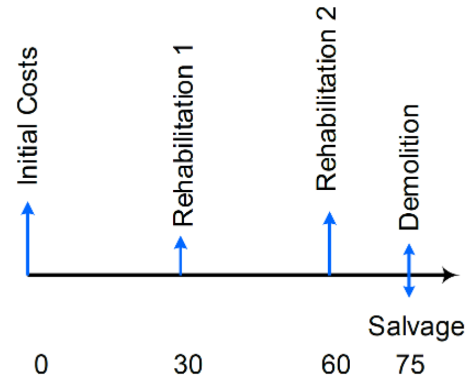
Bridge Life-Cycle Cost Analysis (BLCCA)



Option 2



Option 3

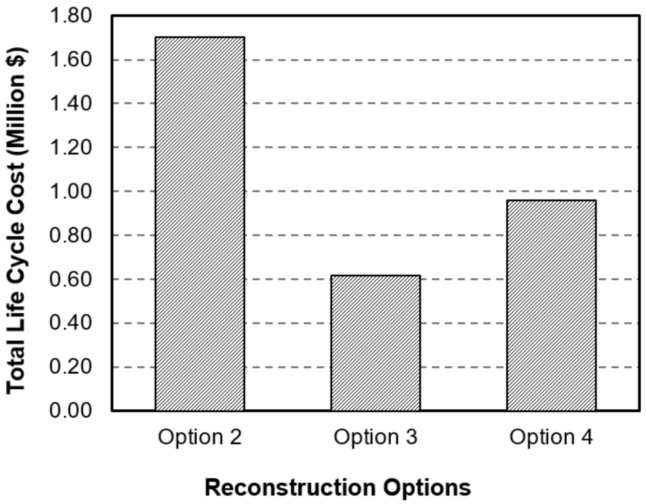


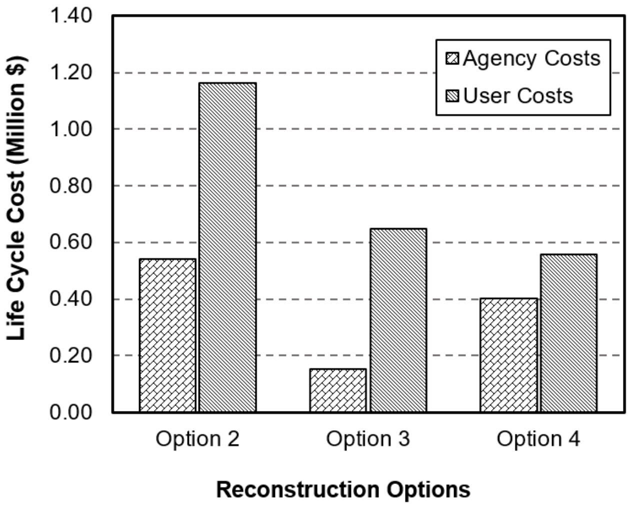
Option 4

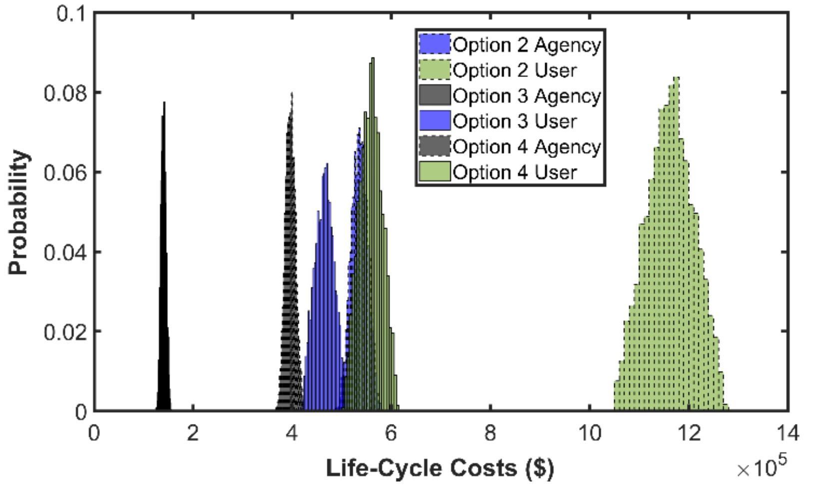
Cost item	Option 2	Option 3	Option 4
Design and Engineering	$18,993	$0	$14,730
Construction	$316,545.84	$54,340	$185,500
Corrosion Mitigation	$0	$0	$55,087
Traffic Control	$172,521	$10,514	$93,485
Construction Inspection	$15,827	$0	$9,275
Maintenance & Repair	$27,976	$57,652	$27,976
Demolishing	$31,655	$31,655	$31,655
Salvage	-$9,496	-$7,597	-$8,547

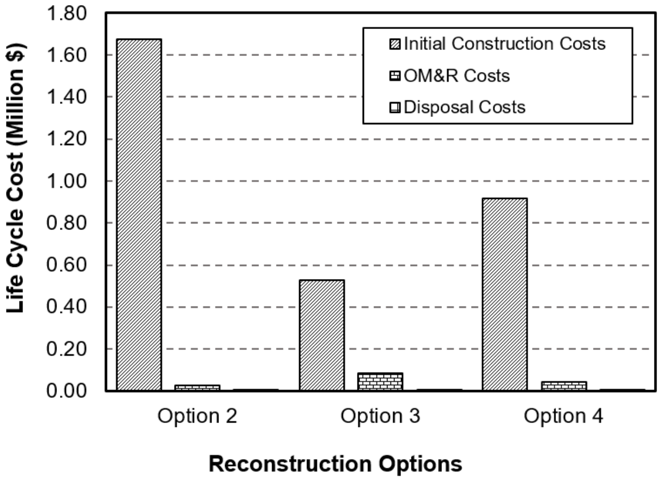
Type	Parameter	Value
Work zone dimension	Length of work zone (mile)	1.6
Normal driving condition	Driving speed (mph)	55
	Accident rate (MVMT*)	0.011
Work zone driving condition	Driving speed (mph)	25
	Accident rate (MVMT)	0.018
Costs	Drivers Delay (USD/hr)	30.12
	VOC (USD/hr)	10.64
	Accident (USD/accident)	99,558

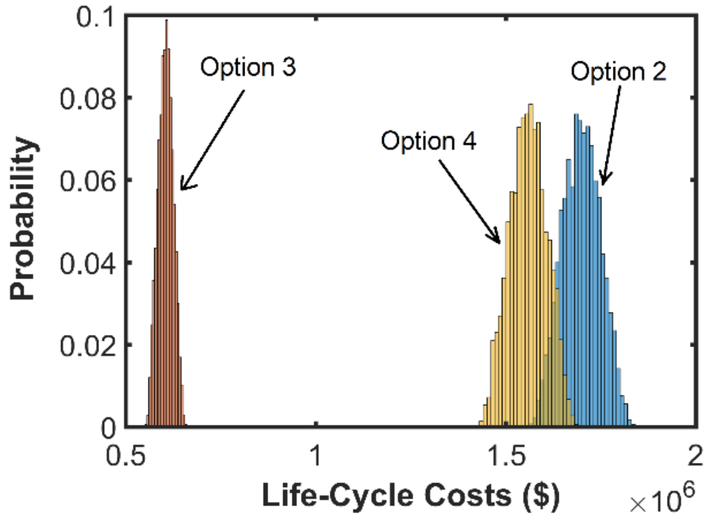
Bridge Life-Cycle Cost Analysis (BLCCA)





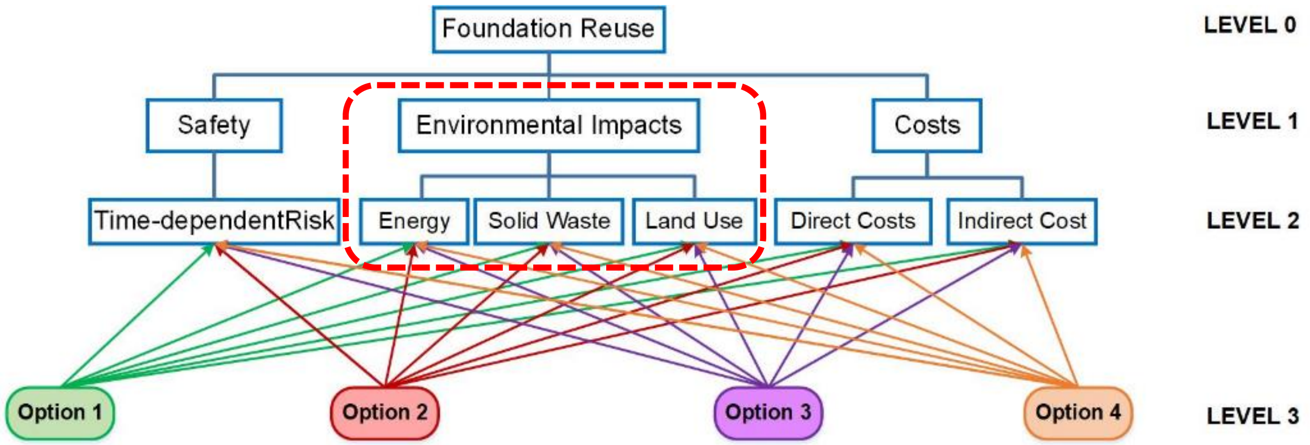






Environmental Impact Assessment

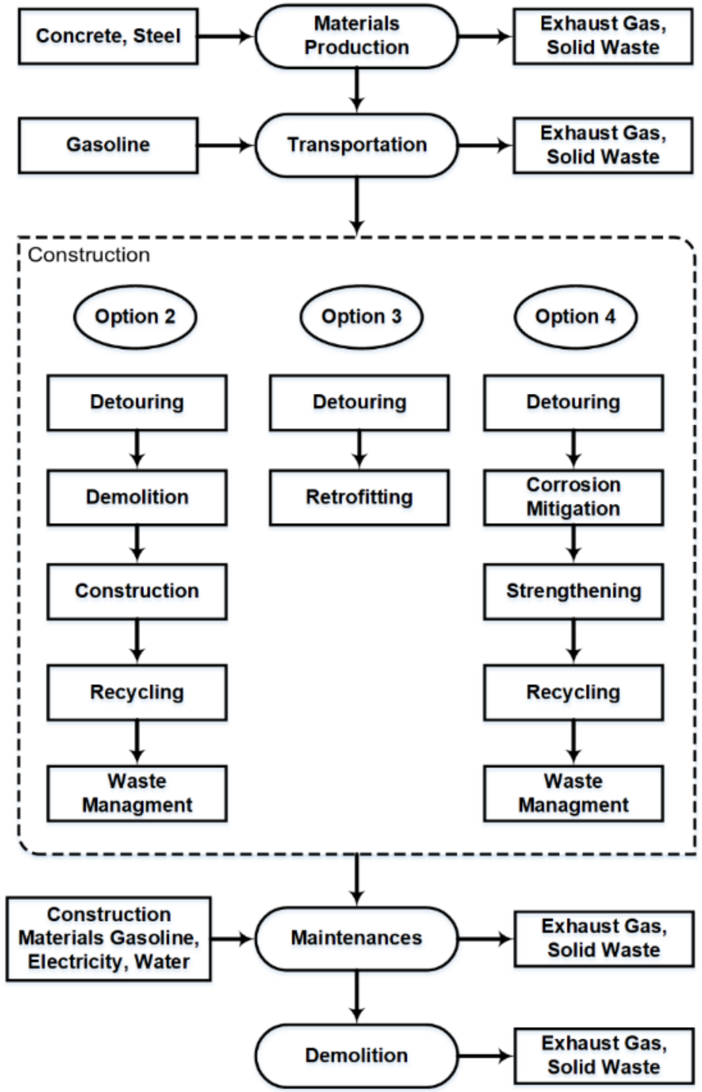
Foundation reuse is likely to have significantly lower environmental impacts than alternatives from Options 1 and 2 through savings of material and labor.



Life-Cycle Environmental Impact Assessment (LCEIA)

The Material and energy consumption can be evaluated in 4 life-cycle phases:

- Manufacturing Phase
- Construction Phase
- Use Phase
- End-of-Life Phase



Questions?

Thank You

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