Designing and Achieving 100-year Life

by

Siva Venugopalan

Principal Engineer

Siva Corrosion Services, Inc.

Siva@SivaCorrosion.com

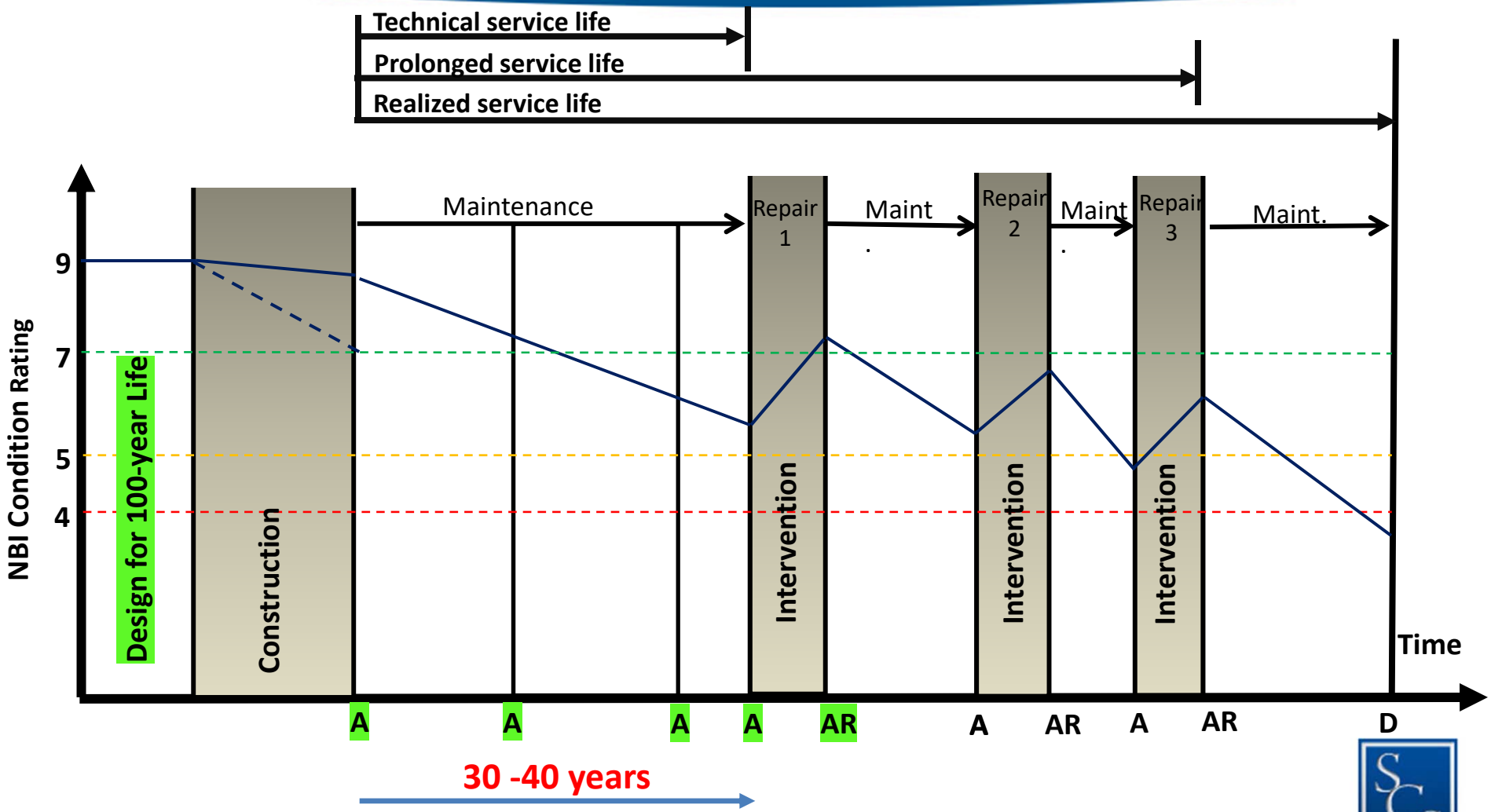
Agenda

- Current State of Practice
- Designing new bridges for a 100-year service life
- Preserving existing bridges beyond 100-year life

Current Practice

- Define the life requirement – 75 years
- Use Epoxy coated rebars
- Use 2.5-inch cover
- Use regular concrete mix or with admixtures
- Avoid using ASR aggregates
- Deemed to satisfy 75-year life

Condition (planned, realized)



A = Assessment AR = Assessment of Repaired Structure D = Demolition

What We Test

- We test/calculate:
  - Compressive Strength
  - Air, Slump, W/C
  - ASR of aggregate
  - Freeze thaw resistance

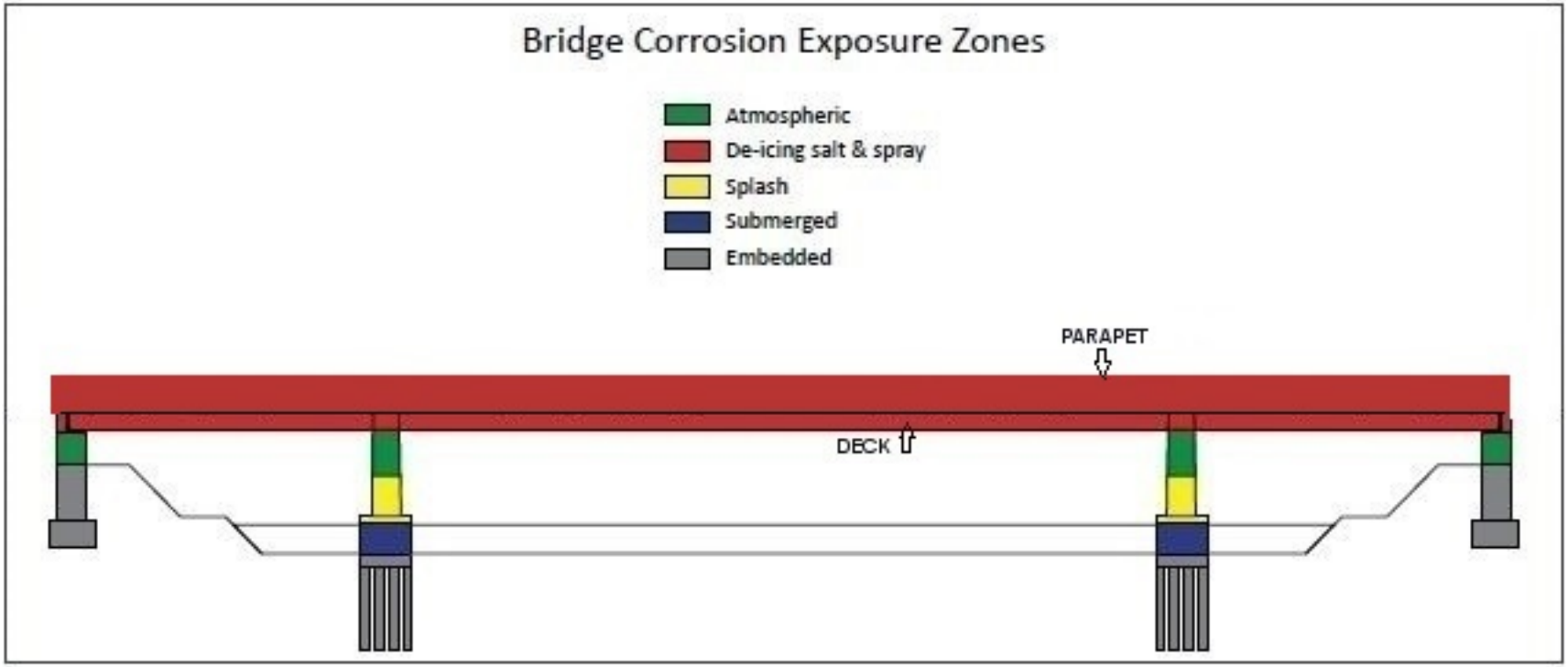
What We Miss

- We do not test/plan:
  - Resistance to chloride penetration
  - Rebar cover variation
  - Chloride loading
  - Temperature Variation

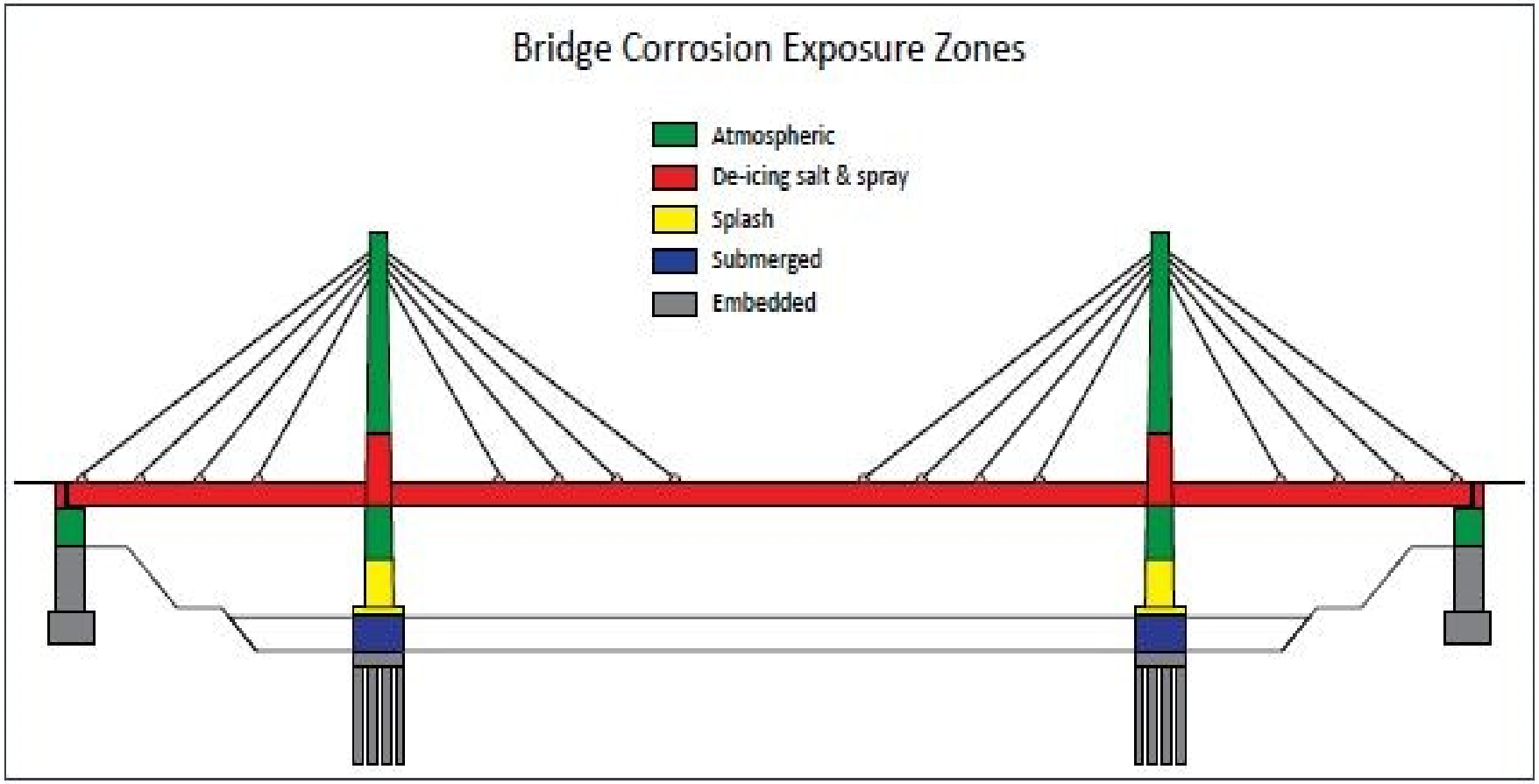
If We Fail to Plan We Plan to ….

- Plan for a 100-year service life based on exposure conditions.
- Use for small/large/complex bridges.
- Plan the type of concrete for various bridge elements.
- Plan the type of steel needed for superstructure/cables/strands/tendons.

Exposure Zones – Typical Bridges



Exposure Zones – Complex Bridges



Changes Currently Considered

- Corrosion Protection Plan for all bridges
- Major Bridges – 100 years, others – 75 years
- Components considered for Service Life
  - Stay Cables, cable protection, cable stay pylons
  - Deck, wearing surface, barriers, and railings
  - Superstructure and substructure (steel or concrete)
  - Footers, piles, caissons, drilled shafts
  - Expansion Joints, bearings, coating systems
  - Access ladders, inspection travelers,

SHRP R19A/fib 34

Design Criteria

Strategy A: Avoidance of deterioration	Strategy B: Full probabilistic approach
Exposure Classes	Probabilistic models: -Resistances -Load/Exposure -Geometry
Design provisions	Limit states

Design / Verifications

Project specification for material selection & execution maintenance plan inspection / monitoring plan

Means of Achieving 100-year Life

- Use of corrosion resistant steel
- Use of durable concrete mix
- Use of sufficient concrete cover
- Testing for concrete mix durability and concrete cover
- Testing for steel quality/thickness
- Testing for coating quality/adhesion/thickness

Service Life Design (SLD)

- Additional thickness for steel members exposed to soil/water
- Type of coating for steel members
- Type of concrete ← Affects Durability
- Plan the type and frequency of maintenance - to achieve the service life of replaceable elements

fib Bulleting 34 – Model Code for SLD

- Avoidance approach for deterioration such as:
  - Carbonation
  - Sulfate attack
  - Delayed Ettringite Formation (DEF)
  - Alkali Aggregate/Silica Reaction (AAR/ASR)
  - Freeze/thaw
- Full Probabilistic approach for chloride induced corrosion

Limit States

- Depassivation of reinforcement - end of service life
- When chloride threshold reached at reinforcement depth
- Serviceability limit state – 90% probability that corrosion has not initiated within the service life
- Corresponds to the reliability factor of 1.3

SHRP – R19A SLD Model based on fib Bulletin 34 Probabilistic Model

$$C_{crit} = C(x = a, t) = C_o + (C_{s,\Delta x} - C_o) \cdot \left[1 - \mathrm{erf}\left(\frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$

$$D_{app,C} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t)$$

Aging function – time dependant - used to calculate chloride diffusion coefficient

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$

Chloride Migration Coefficient (CMC) @ 28 days

SLD – Probabilistic Analysis

- Define exposure zones degradation mechanism
- Select limit state
- Select:
  - Materials
  - Concrete quality
  - Concrete Cover
- Project Specifications
- Testing to qualify concrete mix and approve concrete mix suppliers
- Production testing during construction pours

Degradation Mechanisms

- Temperature range
- Extent of spray zone?
- Chloride surface concentrations?
- Water corrosivity (chlorides, sulfates, pH, resistivity)
- Soil corrosivity (chlorides, sulfates, pH, resistivity)

Designing for 100-year Life

- Use the average and standard deviation from the survey of state bridges to establish surface chloride concentration
- For critical chloride threshold, use the average and standard deviation of 0.6% (by mass of cementitious material) and 0.15, respectively
- Use design cover and typical standard deviation from survey of state bridges
- Use a reliability index of 1.3 that corresponds to 90% probability that corrosion has not initiated before 100 years

Input Parameters for SLM

Input Parameters

fib Bulletin 34, Section B2 - Full probabilistic design method for chloride induced corrosion - uncracked concrete

Fick's 2nd Law

$$C_{crit} = C(x = a, t) = C_o + (C_{s,\Delta x} - C_o) \cdot \left[1 - \mathrm{erf}\left(\frac{a - \Delta x}{2\sqrt{D_{app,C} \cdot t}}\right)\right]$$ Equation (B2.1-1)

$$D_{app,C} = k_e \cdot D_{RCM,0} \cdot k_t \cdot A(t)$$ Equation (B2.1-2)

$$k_e = \exp\left(b_e\left(\frac{1}{T_{ref}} + \frac{1}{T_{real}}\right)\right)$$ Equation (B2.1-3)

$$A(t) = \left(\frac{t_o}{t}\right)^{\alpha}$$ Equation (B2.1-4)

Parameter	Description	Units	Distribution Function	Normal Distr Coefficients: Mean, μ	Normal Distr Coefficients: Std Dev, σ	Normal Distr Coefficients: Coeff of Variation, σ/μ	Log-Normal Distr Coeffs: $\ln\mu - \ln((\sigma/\mu)^2 + 1)/2$	Log-Normal Distr Coeffs: $\sqrt{\ln((\sigma/\mu)^2 + 1)}$	Beta Distr Coeffs: Lower Bound, a	Beta Distr Coeffs: Upper Bound, b	Beta Distr Coeffs: α	Beta Distr Coeffs: β
$D_{RCM,0}$	Chloride Migration Coefficient (from Nordtest NT Build 492 - results are given in m²/sec)	in²/yr	Normal	0.420	0.084	0.20						
		mm²/yr		271.0	54.2							
		m²/sec		8.59E-12	1.72E-12							
b_e	Regression variable, (limited to 3500 °K to 5500 °K)	°K	Normal	4800	700							
T_{real}	Temperature (from Local Weather Data)	°F	Normal	52.0	14.0							
		°C		11.1	7.78							
		°K		284.26	7.78							
T_{ref}	Standard test temperature	°F	Constant	67.6								
		°C		19.8								
		°K		292.9								
k_e	Environmental transfer variable	n/a	n/a									
k_t	Transfer parameter	n/a	Constant	1.0								
α	Aging exponent - PCC w/ ≥ 20% Flyash	n/a	Beta	0.6	0.15				0	1	5.80	3.87
t_o	Reference point of time (28 days = 0.0767 yrs)	yrs	Constant	0.0767								
A(t)	Aging function	n/a	n/a									
C_o	Initial Chloride Content of Concrete	mass% of binder	Normal	0.10	0.00	0.001						
C_s or $C_{s,\Delta x}$	Chloride Concentration at surface, or at substitute surface Δx	mass% of binder	Log-Normal	2.50	1.25	0.50	0.8	0.47				
Δx	Transfer function - splash/spray zone	in	Beta	0.35	0.22	0.629			0	1.97	1.90	8.77
		mm		8.90	5.60				0	50	1.90	8.77
cover, a	Concrete cover	in	Log-Normal	2.00	0.15	0.075						
		mm		50.80	3.81		3.93	0.07				
C_{crit}	Critical chloride content (plain reinforcing)	mass% of binder	Beta	0.60	0.15	0.25			0.2	2	5.31	18.58
t_{SL}	Design service life	yrs	n/a	25								
β	Target Reliability	n/a	n/a	1.3								

Designing and Checking – 100 year Service Life

Monte Carlo Trial Results

Trial Results of Randomly Generated Values of Input Parameters to Fick's 2nd Law

Trial	$D_{RCM,0}$ (mm^2/yr)		b_e (°K)		T_{real} (°K)		k_e	α		$A(t_{SL})$	$D_{app,C}$ (mm^2/yr)	C_o (mass% of binder)		$C_{s,\Delta x}$ (mass% of binder)		Δx (mm)		cover (mm)		C_{crit} (mass% of binder)		$C(x=cov,t_{SL})$	Pass (1) /Fail (0)
	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT		rand 0-1	RESULT			rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	rand 0-1	RESULT	RESULT	
1	0.456	264.93	0.135	4028	0.690	286.0	0.7	0.180	0.507	0.0263	4.99	0.38	0.10	0.199	1.800	0.761	0.000	0.796	55.9	0.895	0.797	0.23	1
5000	0.766	310.30	0.036	3543	0.621	284.7	0.7	0.877	0.825	0.0027	0.59	0.37	0.10	0.427	2.459	0.621	0.000	0.232	46.0	0.372	0.538	0.10	1
SUMMARY																							
Computed Mean		272.01		4746		282.7	0.6		0.65	0.02	2.93		0.10		3.00		0.00		50.89		0.60		
Input Mean		270.97		4800		282.7			0.65				0.10		3.00		0.00		50.80		0.60		
Max		450.38		5500		307.75	2.41		0.97	0.32	72.93		0.10		16.35		0.00		82.30		1.17		
Min		78.86		3500		257.08	0.09		0.16	0.00	0.05		0.10		0.45		0.00		29.37		0.24		
																		Total Passing			4521		
																		Total # of Trials			5000		
																		Reliability			0.90		
																		P_f, Probability of failure			0.10		
																		β, Reliability Index (calculated)			1.306	Passes	
																		β, Target Reliability Index			1.3		

- Realiability Index Calculated > Target Realibility Index
  - The concrete mix will provide 100 year life
- Realiability Index Calculated < Target Realibility Index
  - Adjust concrete mix, cover until target reliability is exceeded

Model Defined Chloride Migration

fib34 Trial No.	Concrete Element	Required Design Service Life	Surface Chloride (mass% binder)		Concrete Mix	Chloride Migration Coefficient (in^2/yr), Max. Allowed*		Concrete Cover (in)		Model Service Life
			Mean, μ	Std Dev, σ		Mean, μ	Std Dev, σ	Mean, μ	Std Dev, σ	
1	Deck (Full Depth)	100	2.50	1.25	Class H w/ >20% FA	0.420	0.084	2.75	0.15	100
2	Deck (Wearing Surface)	25	2.50	1.25	Class H w/ > 20% FA	0.420	0.084	2.00	0.15	25
3	Deck Underside	100	1.00	0.50	Class H (Any Type)	0.320	0.064	1.00	0.15	100
4	Deck Underside	100	1.00	0.50	Class H (Any Type)	0.420	0.084	1.25	0.15	100
5	Barriers (Interior Face)	40	2.50	1.25	Class H w/ >20% FA	0.320	0.064	2.00	0.15	40
6	Barriers (Interior Face)	40	2.50	1.25	Class H w/ >20% FA	0.420	0.084	2.25	0.15	40
7	Barriers (Exterior Face)	40	1.88	0.94	Class H w/ >20% FA	0.180	0.036	1.50	0.15	40
8	Barriers (Exterior Face)	40	1.88	0.94	Class H w/ >20% FA	0.420	0.084	2.00	0.15	40
9	Abutments (Exp. Joint)	100	1.88	0.94	Class B w/ >20% FA	0.240	0.048	2.00	0.30	100
10	Piers (No Joint)	100	1.00	0.50	Class B (Any Type)	0.500	0.100	2.00	0.30	>100

Note: CMC must be tested at 28 days per NT build 492.

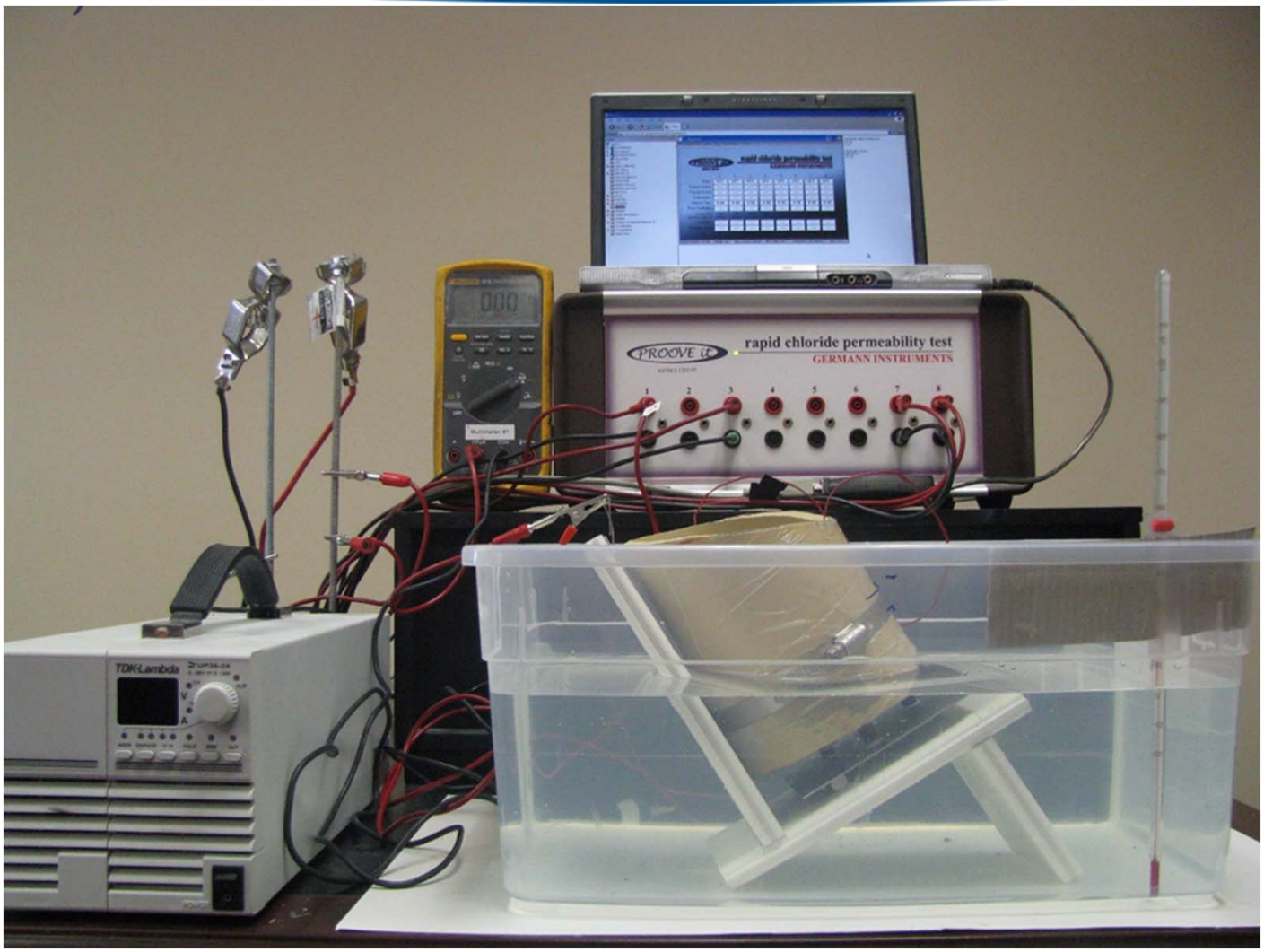
Critical to verify before & during construction

Critical to verify after construction – rerun model to confirm SLD

Pre-construction Testing

- Fib Model Code – based on NT Build 492 test
  - To measure chloride migration coefficient at 28 days (similar to coulombs test except it allows one to calculate the service life)
  - Direct input parameter to the probabilistic model
  - Project specification must define frequency of testing during production stage

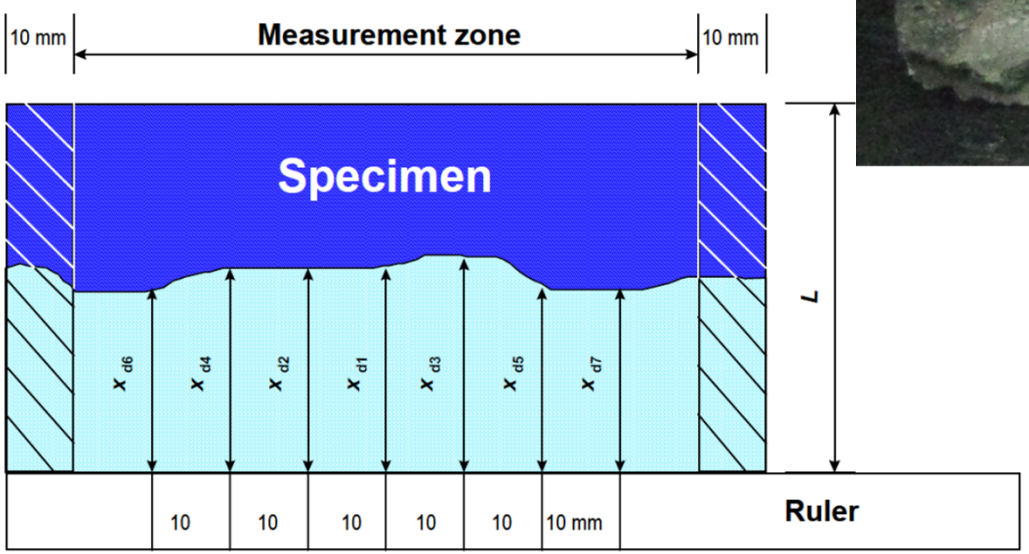
NT Build 492 in Progress (Oregon Bridge)

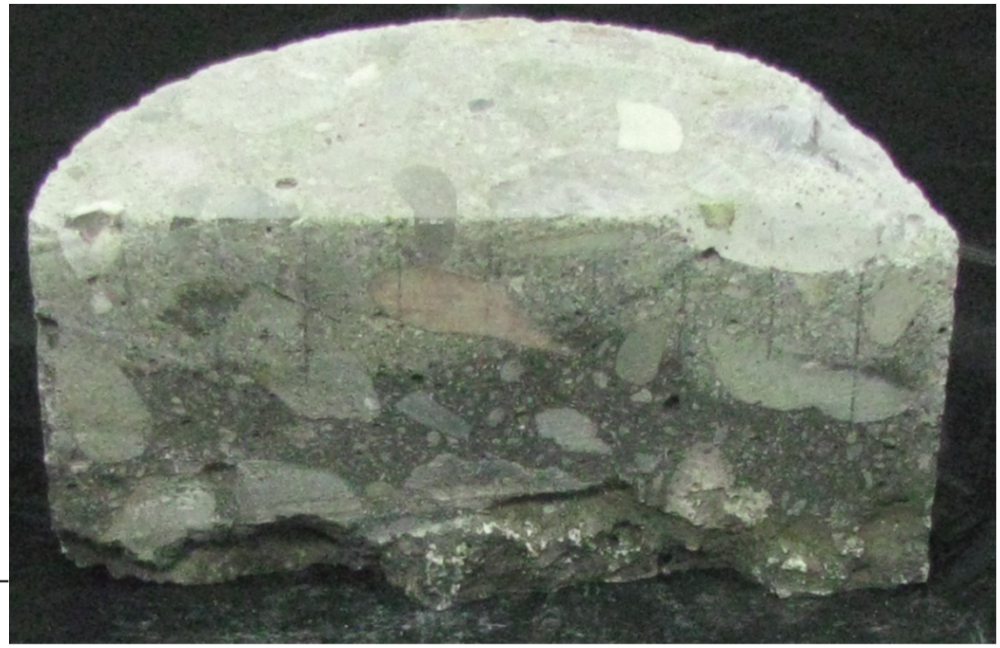


NT Build 492

- After the test – core split in half
- Silver nitrate solution sprayed on broken surface
- Document the depths of chloride penetration
- Calculate the Chloride migration coefficient
- One test – requires three cylinders

NT Build 492 - Chloride Penetration





NT Build 492 Test

Siva Corrosion Services, Inc.

1313 Wilmington Pike
Suite 2B
West Chester, PA 19382
(610) 692-6551
www. SivaCorrosion.com

Date: 12/28/2015

Report # 100103-01-4

Client:
Andrew Blower
Oregon DOT
4040 Fairview Industrial Drive, SE MS-4
Salem, OR 97302

Concrete Cores From:
Hooker Creek
Tim Whitehall
Quality Control
(541) 389-0981

Date Core Arrived at SCS: 12/7/2015
Concrete Type: Class HPC 4000 Standard with Novamesh 950 Fiber
Test Date: 12/22/2015
Age at Test Date (days): 28
Test Method: NT Build 492

Core Number	Core #1	Core #2	Core #3
Core Length, mm	202	202	202
Core Diameter, mm	102	102	102
Test Sample Thickness, mm	48.36	50.78	49.37
Test Sample Diameter, mm	102	102	102

Test Result

Applied Voltage, Volts	30	30	25
Test Duration, Hours	24	24	24
Initial Current, mA	57.5	56.7	53.2
Final Current, mA	76.8	81.5	69.3
Initial Temperature, °C	23	23	23
Final Temperature, °C	22	21	21
Average Temperature, °C	22.5	22	22
Average Chloride Penetration Depth, mm (see table below for calculation)	27.55	27.86	24.58
Non-stady State Migration Coefficient, 10^{-12} m^2/s	12.56537	13.29287	13.62545

Average Non-stady State Migration Coefficient, 10^{-12} m^2/s	13.16123

SCS Capabilities

- Test concrete mix for durability
- Qualify concrete mix suppliers
- Test durability of concrete (placed in service)
- Back test actual service life achieved versus proposed
- Take action at the early stage to address any issues regarding durability

Benefits of Service Life Design

- Performance and design requirements that owners can use
- Scientific approach to designing structures
- Design methods use scientific probabilistic approach instead of a subjective “durability”
- Environmental loading and material resistance
- Defined durability requirements for various components
- Project specification – based on applicable deterioration mechanisms, available materials, and work methods

What about Existing Bridges?

- Can we predict the remaining service life of existing bridges?
- Proactively address deterioration when it is minimal and less expensive
- Can I target/minimize testing and sampling and still predict future deterioration?

Inspection and Analysis

- Deck inspection and sampling recommended at 20-25 years (before visible damage occurs)
- Pre-stressed beams inspection and sampling recommended at first signs of cracking or corrosion
- Substructure inspection and sampling recommended after visible delamination and spalls occur

Data Analysis

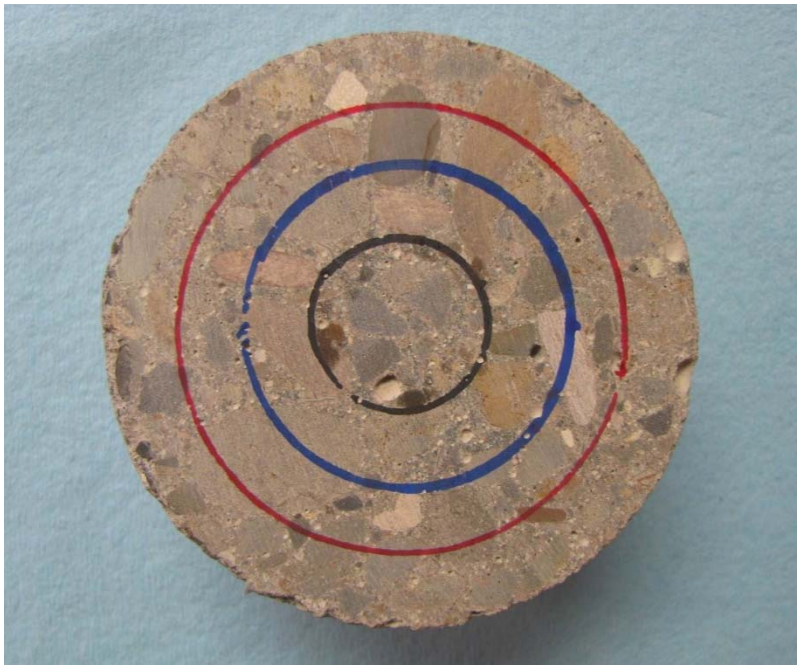
- Corrosion Data Analysis:
  - Rebar cover statistics
  - Damage quantities (delam, spall, patches) in ft^2 and percentage
  - Chloride Content (profile, diffusion, percentage over threshold at rebar level)
  - Service Life Model (NCHRP 558)
  - Life Cycle Cost
  - Selecting simpler & Cost Effective Repair Option

Repair/Mitigation

- Identify viable options that address current damage, projected future damage, and service life goals
- Calculate Life Cycle Cost of each option
- Compare options and costs (repair vs. replacement)
- Select option based on cost, service life, and/or maintenance requirements

Importance of Sampling Size

Chloride cores shall be 4-inch diameter – similar to compressive strength cores



A smaller core or powder samples can lead to significant variation in chloride level

Black Circle – 1” diameter – mostly aggregate (possibly low chlorides) or paste (very high chlorides)

More sampling locations will not reduce variability

Full circle – 4” diameter – good representation of concrete and the chloride concentration at a particular depth

Chloride Testing Method Refinement

Photos Courtesy Siva Corrosion Services, Inc.

Chloride Testing Method Refinement

Photos Courtesy Siva Corrosion Services, Inc.

Chloride Testing Method Refinement

Photos Courtesy Siva Corrosion Services, Inc.

Chloride Ingress Modelling

Table 1
Summary of Chloride Content for Bridge #02071A

No.	Core ID	Sample Depth (in)	Sample Number	Chloride Content, % Cl by mass concrete	Comments
1	BR02071A D2	0.25	Depth 1	0.192	Surface
2		0.75	Depth 2	0.108	
3		1.25	Depth 3	0.063	
4		1.75	Depth 4	0.029	
5		2.25	Depth 5	0.011	
6	BR02071A D3	0.25	Depth 1	0.187	Surface
7		0.75	Depth 2	0.134	
8		1.25	Depth 3	0.066	
9		1.75	Depth 4	0.043	
10		2.25	Depth 5	0.023	
11	BR02071A D4	0.25	Depth 1	0.184	Surface
12		0.75	Depth 2	0.143	
13		1.25	Depth 3	0.102	
14		1.75	Depth 4	0.047	
15		2.25	Depth 5	0.020	
16	BR02071A D5	0.25	Depth 1	0.243	Surface
17		0.75	Depth 2	0.113	
18		1.25	Depth 3	0.042	
19		1.75	Depth 4	0.028	
20		2.25	Depth 5	0.010	
21	BR02071A D6	0.25	Depth 1	0.220	Surface
22		0.75	Depth 2	0.187	
23		1.25	Depth 3	0.088	
24		1.75	Depth 4	0.052	
25		2.25	Depth 5	0.014	
26	BR02071A D7	0.25	Depth 1	0.103	Surface
27		0.75	Depth 2	0.086	
28		1.25	Depth 3	0.056	
29		1.75	Depth 4	0.041	
30		2.25	Depth 5	0.021	

Chloride Test Results
ASTM C1152

Siva Corrosion Services, Inc.
SCS Project # 100109-01
Page 1 of 2

- Chloride testing is reported in ½" (13mm) depth increments from the surface.
- A chloride profile is created and a curve fit is used to determine effective surface concentration and diffusion coefficient.

Chloride Ingress Modelling

Field Test Data

X[Depth, in]	0.25	0.75	1.25	1.75	2.25
Cf [Chloride Concentration, %]	0.192	0.108	0.063	0.029	0.011

Calculated Values

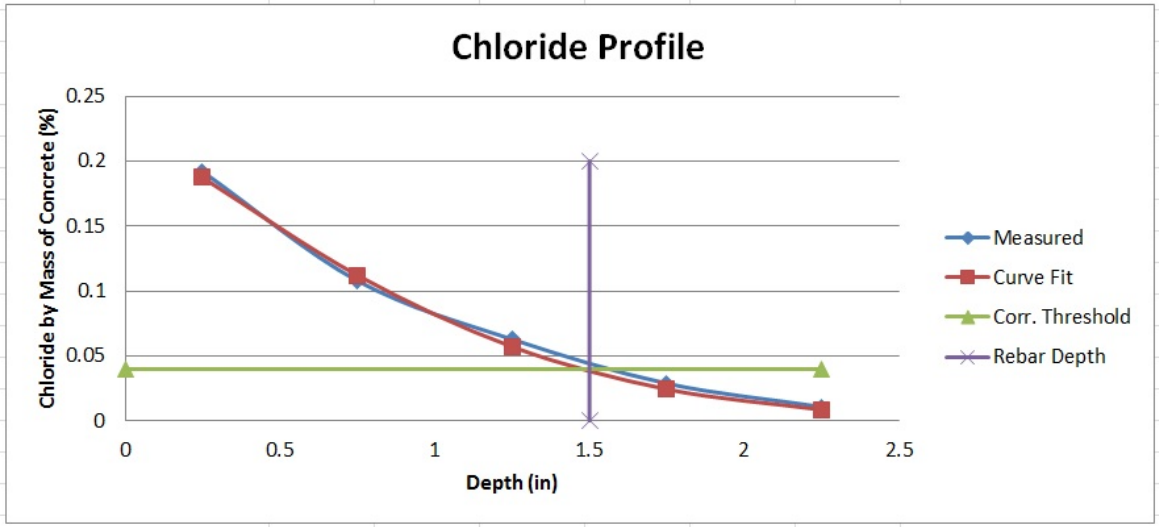
C(x,t) [Chloride Concentration, %]	0.187331	0.112226	0.057252	0.024571	0.008793

Sum of Least Squares

(Cf-C(x,t))^2		1.79E-05	3.3E-05	1.96E-05	4.87E-06	
Sum[(Cf-C(x,t)^2]						7.54E-05

User Input Data

t[time, yr]	48
Diffusion Coefficient [Dc, in^2/yr]	0.0123
Surface Concentration [Cmax, %]	0.229



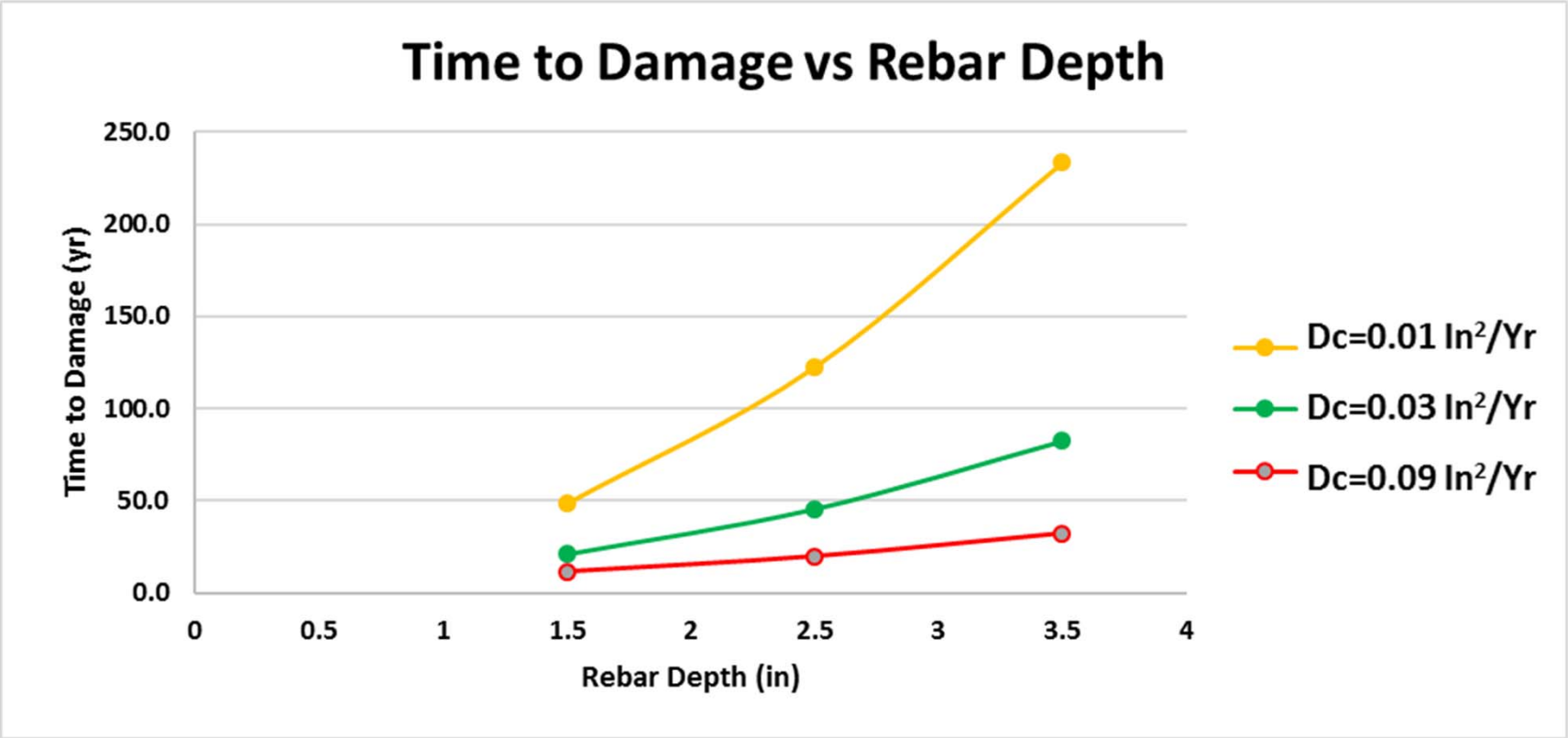
Time to Corrosion Initiation

Use Diffusion Equation:

$$C_{x,t} = C_o \left[1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right]$$

- **Using**
  - Cover of 1.5”, 2.5”, and 3.5”
  - Average surface chloride for deck, substructure, and piles in marine environments
  - Chloride at the rebar = 400 ppm
  - Diffusion coefficients (in^2/yr.) of:
    - ✓ 0.01 in^2/yr. – Excellent durability,
    - ✓ 0.03 in^2/yr. – Good to fair durability,
    - ✓ 0.09 in^2/yr. – Poor Durability

Time to Concrete Damage for Various Rebar Depth

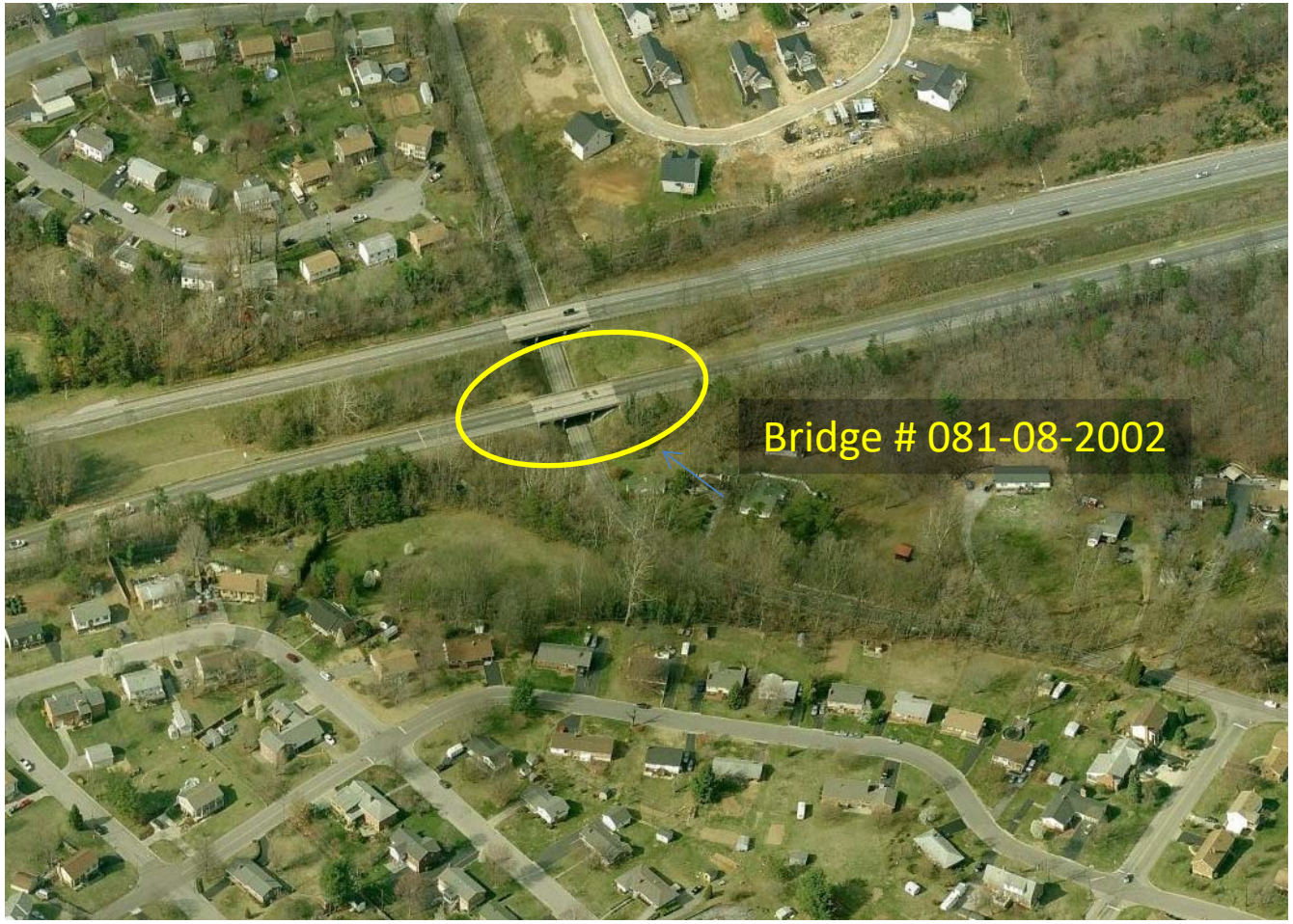


Time for Chloride Sampling

- Plan when to collect chloride samples - based on Age, chloride penetration, rebar cover, and the concrete quality.

Corrosion Evaluation of 2002 Substructure – Roanoke, VA

Bridge Information



Bridge Information

- Bridge # 081-080-2002 (NBI # 14859)
- Location: I-81 NB over Route 641 (Texas Hollow Road), Salem, VA.
- Built: 1962
- RCC Substructure, 3 Spans, 2 piers, 2 abutments
- GRC: Deck = 6, Super = 5, Sub = 4 in the 2015 NBI inspection

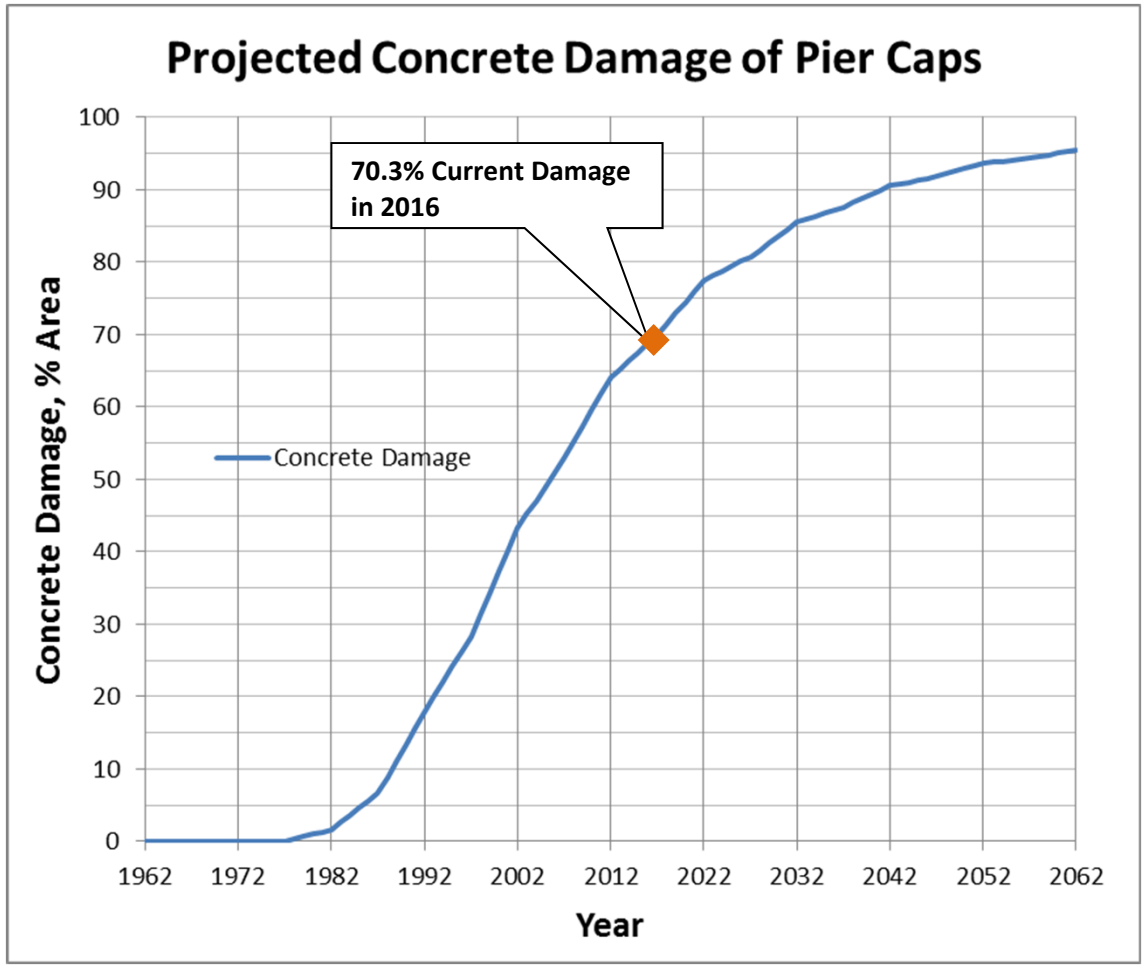
SCS Approaches

- Visual/delamination survey
- Concrete cover
- Chloride profile analysis
- Petrographics and carbonation
- Service life modeling
- Life Cycle Cost analysis

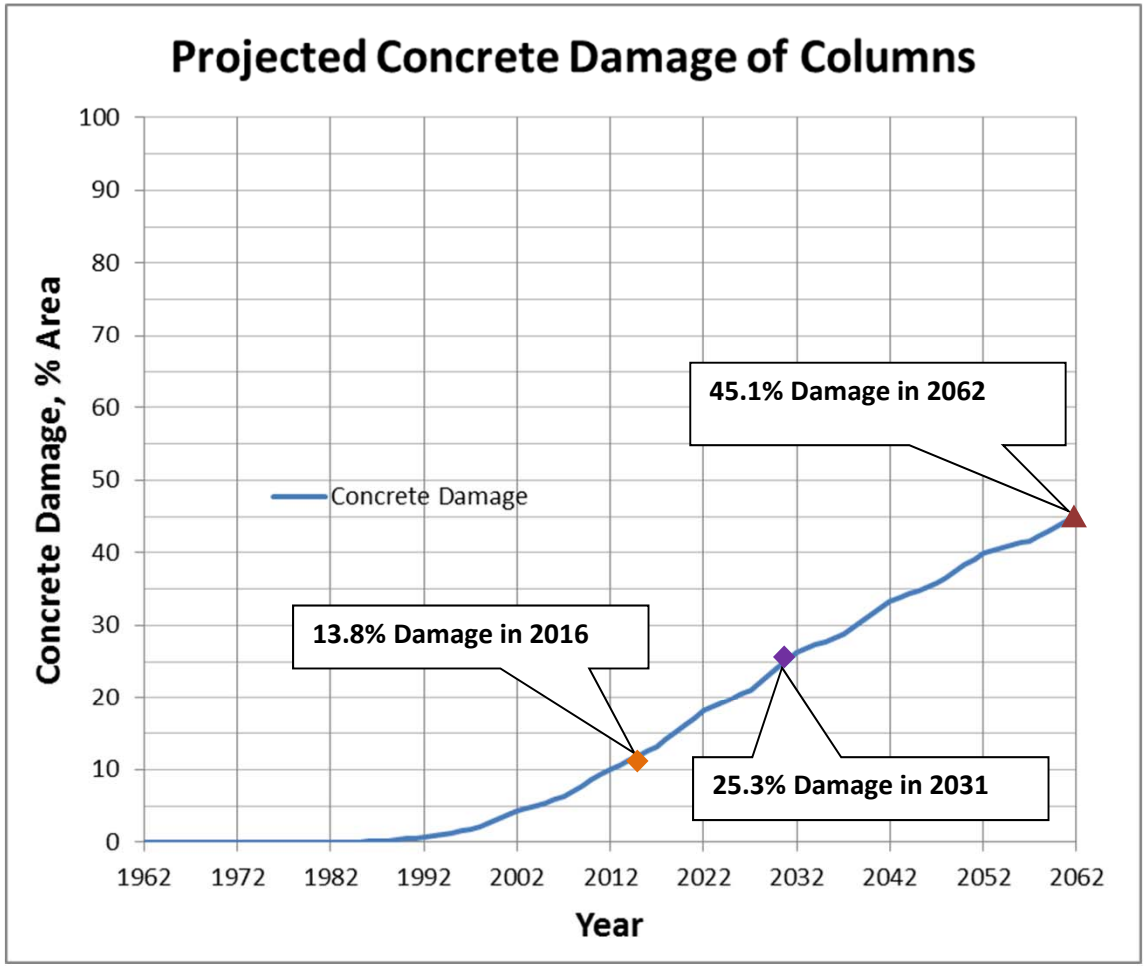
Inspection Findings

Element	% Damage	Avg. Cover (in)	95% Cover (in)	Cl% over 1000 ppm	Cl% over 500 ppm	Avg. Diffusion Coeff. (in^2/yr)	Carbonation Depth (in)	Petro. Analysis
Pier Caps	70.3%	1.90	1.22	0.0%	83.3%	0.050	0.75	Generally good quality concrete
Pier Columns	13.8%	1.70	0.97	0.0%	25.0%	0.019	0.75	
Abutments	0.1%	2.87	1.29	25.0%	100.0%	0.064	0.64	

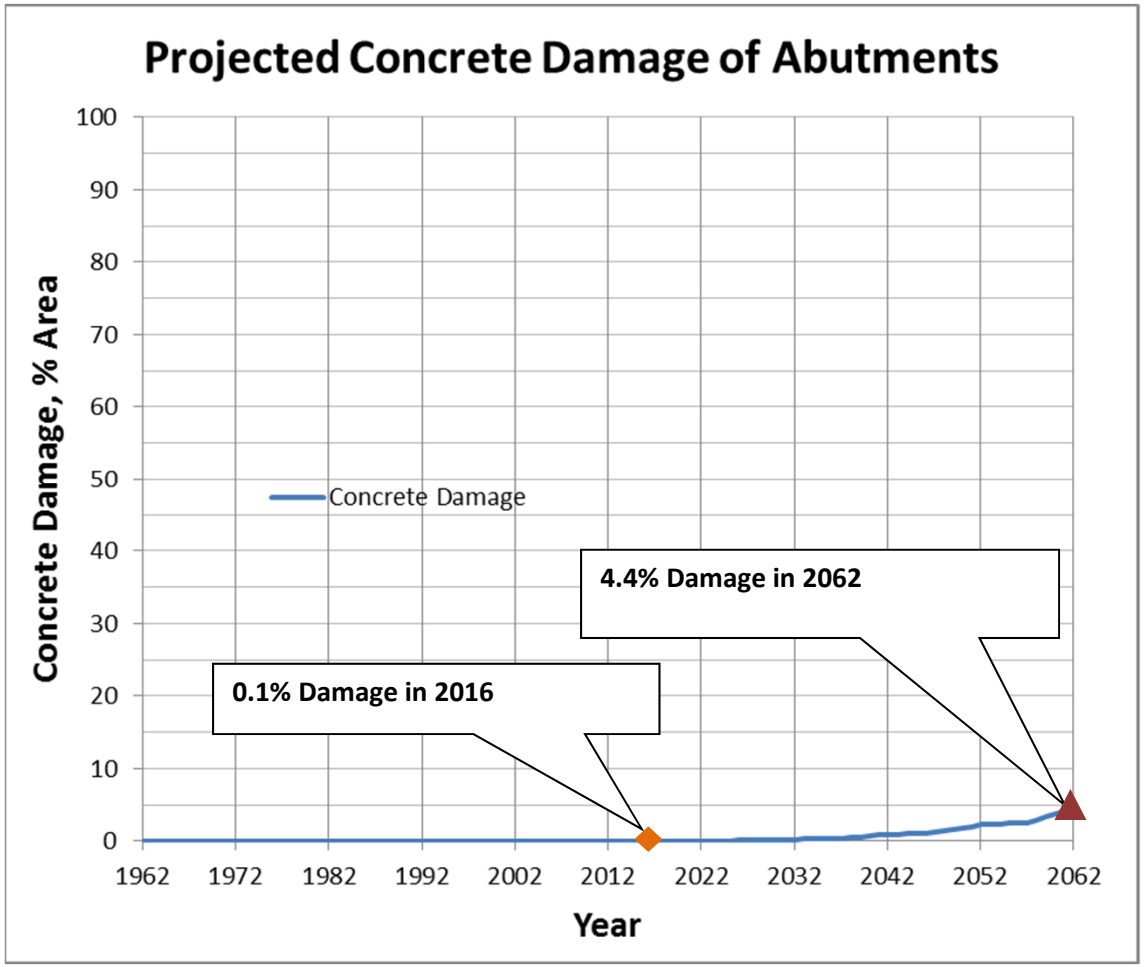
Service Life Processing – Pier Caps



Service Life Processing – Pier Columns



Service Life Processing – Abutments



Life Cycle Cost Estimate

Bridge Element	Description	Initial Cost	Additional Repair Cost (50 years)	Additional MOT Cost (50 years)	Total
Pier Caps	Patch + ICCP	$63,366	$22,820	$5,664	$91,850
Pier Columns	Patch + ECE + Seal	$41,612	$13,042	$5,664	$60,318
Abutments	Patch + Anodes + Seal	$431	$1,101	$0	$1,533
Subtotals		**$105,409**	**$36,963**	**$11,328**	**$153,700**

Questions?

Thank you!