Probabilistic Service Life Modeling: Validation Case Studies

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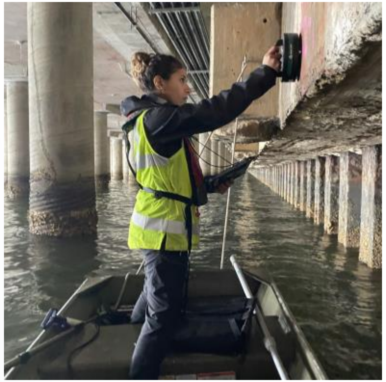
WJE

Outline

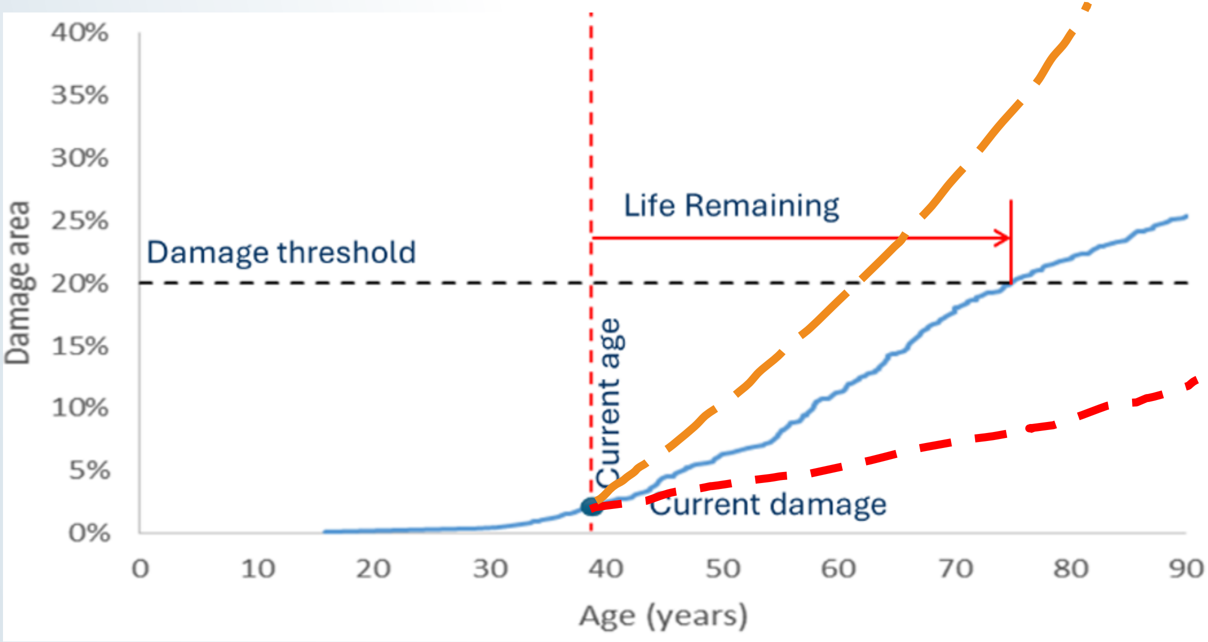
- Service Life Modeling Basics and Validation Needs
- Description of Structures
- In-Depth Corrosion Assessments
- Chloride Diffusion Behavior
- WJE's Service Life Modeling Approach (WJE CASLE™)
- Results from Validation Case Studies
- Conclusions

Corrosion of Reinforced Concrete Structures




Service Life Model Validation Needs



- *Service life model results inform decision making about rehabilitation or replacement needs.*
- *Accuracy of future projections is critical to cost-effective asset management plans.*

Case Studies – Bridges in Midwest Region

S. Garrett, J. Lawler, M. Abdelrahman, and M. Gries, "Diffusion-based service life modeling to predict chloride contamination and damage in bridge decks: Validation case studies," in Proc. AMPP Annu. Conf. + Expo 2025, Nashville, TN, USA, Apr. 2025.

Study Bridges

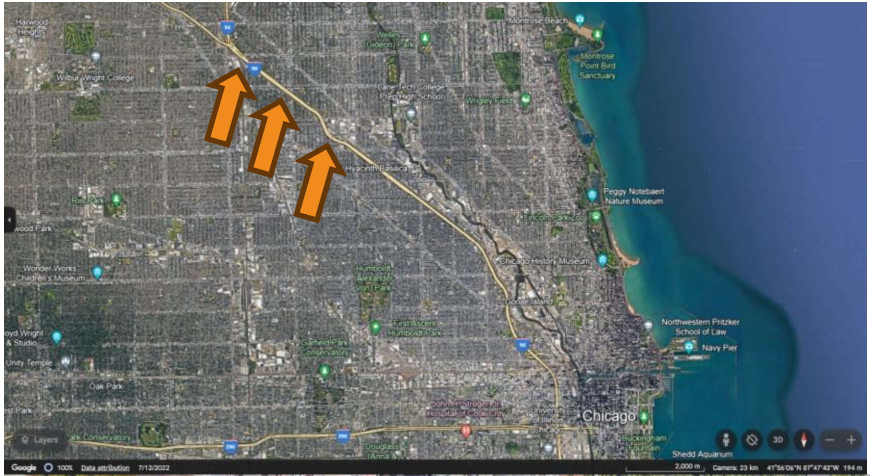
- I-94/I-90 Kennedy Expressway
  - Chicago, IL
  - 2011 and 2023
- Indiana State Route 46
  - Columbus, IN
  - 2013 and 2024

Interstate I-94 (I-94)

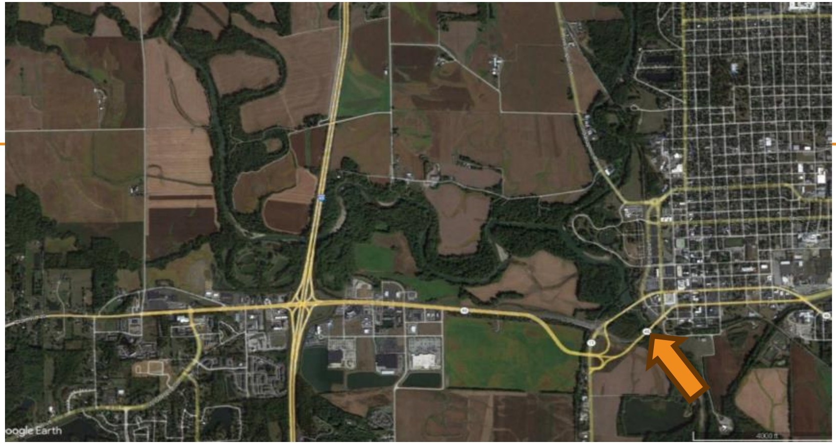
Indiana State Route 46 (SR 46)

I-94 – Kennedy Expressway

- No overlay
- Typical transverse cracking
- Cover varied from 2.2 to 2.8 inches
- 2011 damage ranged from 1 to 5 percent
- 2023 damage ranged from 4 to 21 percent



Indiana State Route 46



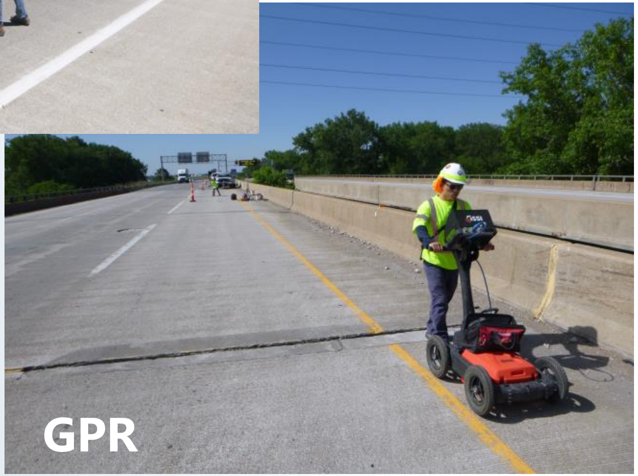
- Post-Tensioned Structure
- Sacrificial Latex-Modified Concrete Overlay (2 inch)
- Nominally 5 inches of total cover
- No widespread cracking
- 2013 Damage - ~ 0%
- 2024 Damage <1%

In-Depth Corrosion Assessments


Chain Drag

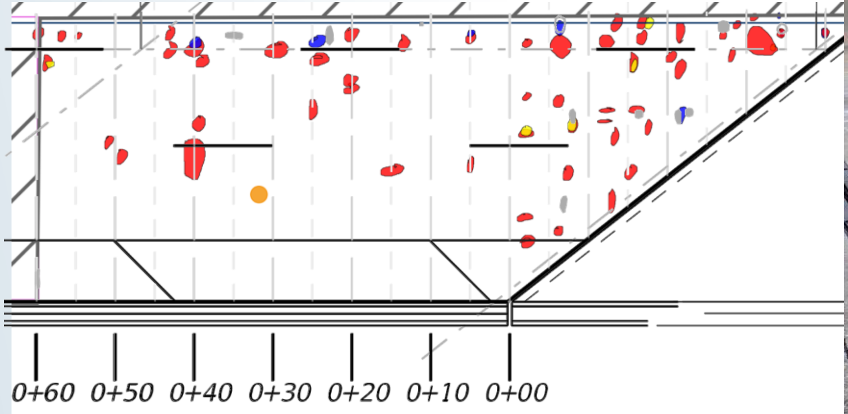
Combination of visual, sounding, and nondestructive evaluation to characterize distress and support material sampling


Resistivity


GPR


Half-Cell

Deterioration Mapping



2011 LEGEND:

- 5 ft. Grid Line
- 10 ft. Grid Line
- Spall
- Delamination

0 5 10 20
Graphic Scale
Feet

2023 LEGEND:

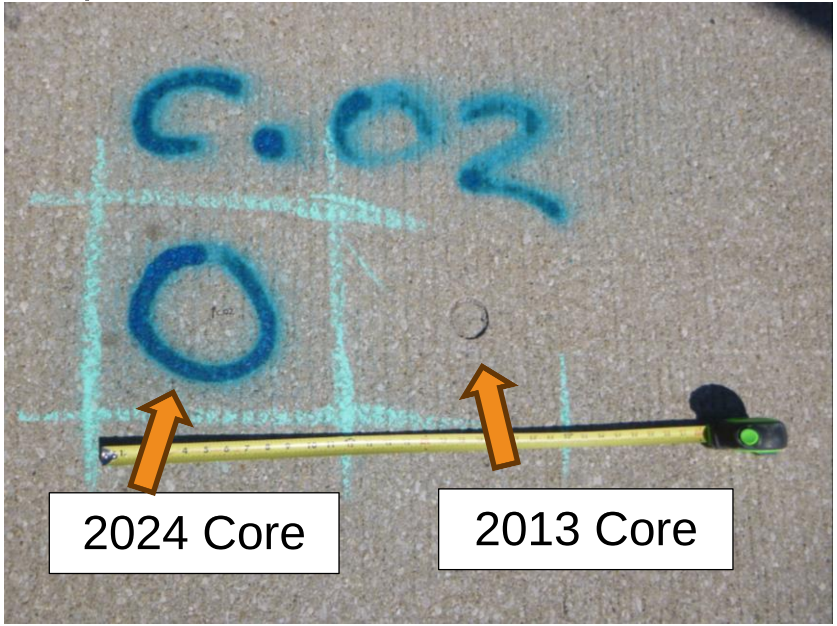
- Delamination
- Spall
- Previous Repair
- Crack

Irving Park
2011 Data: 1%
2023 Data: 4%

Material Sampling & Replicate Cores

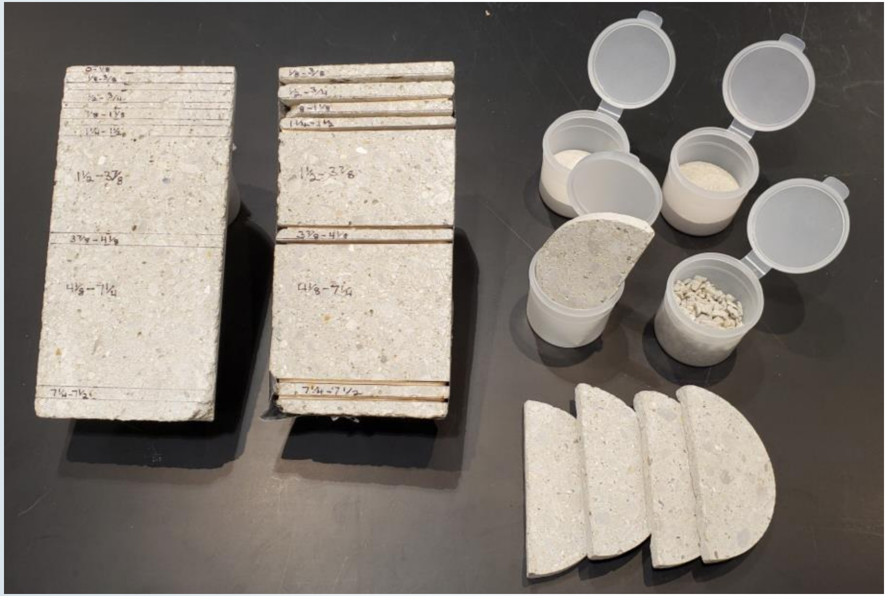
Replicate Cores (I-94)

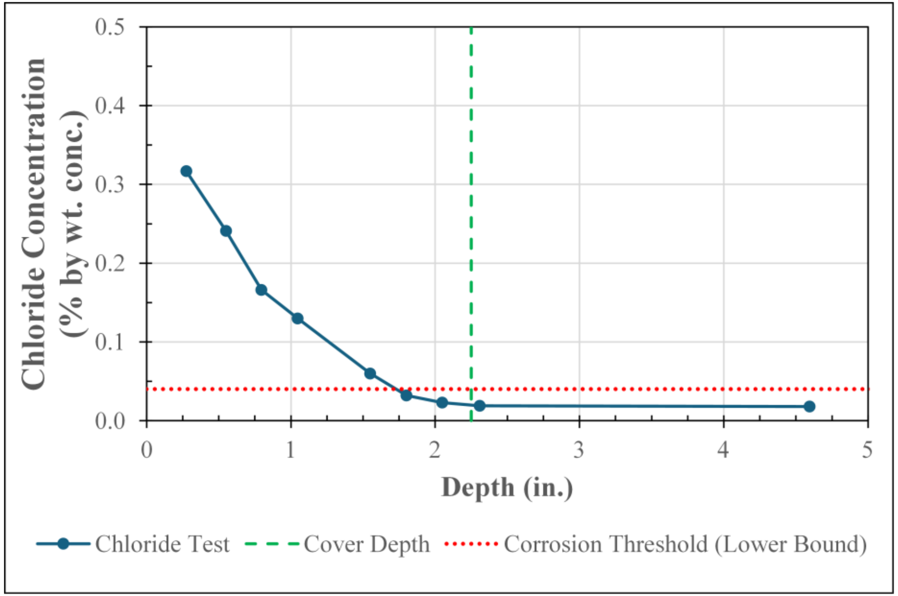
Replicate Cores (SR 46)



Chloride Diffusion Behavior

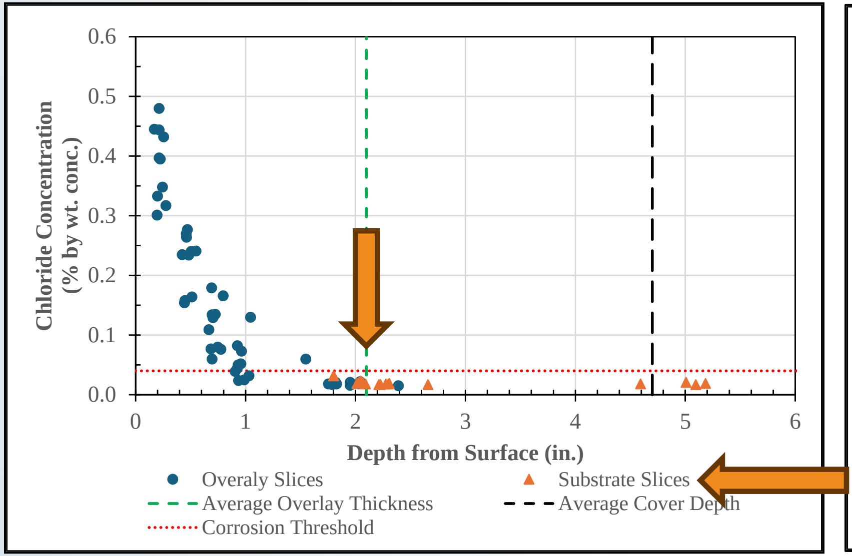
Chloride Diffusion Behavior



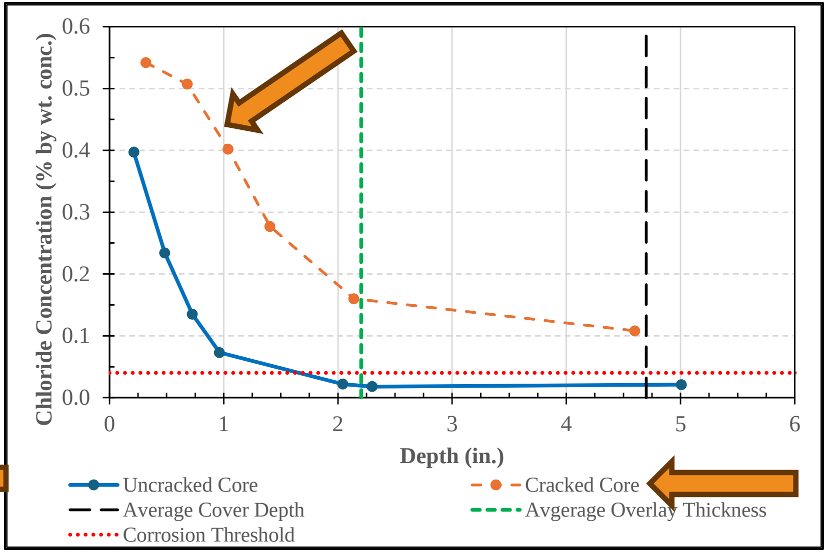


Chloride Diffusion Behavior

Effective Overlay at SR 46

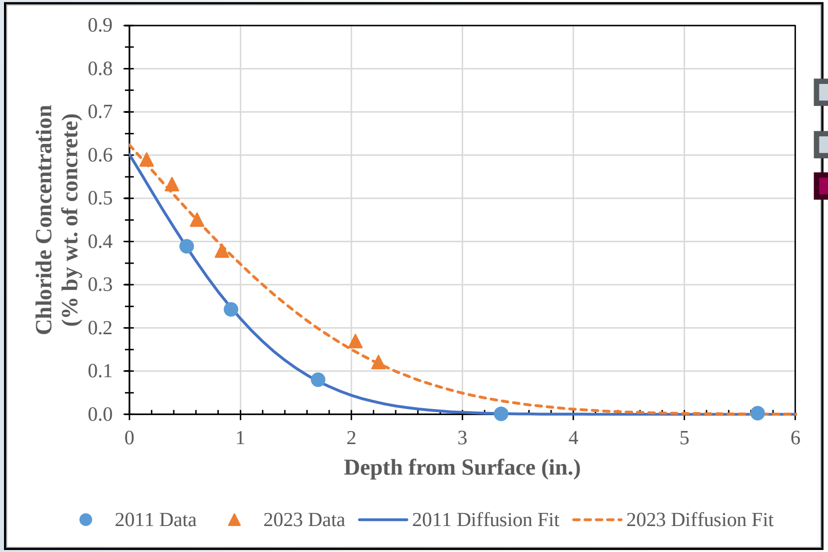


Cracking substantially impacts chloride ingress and durability

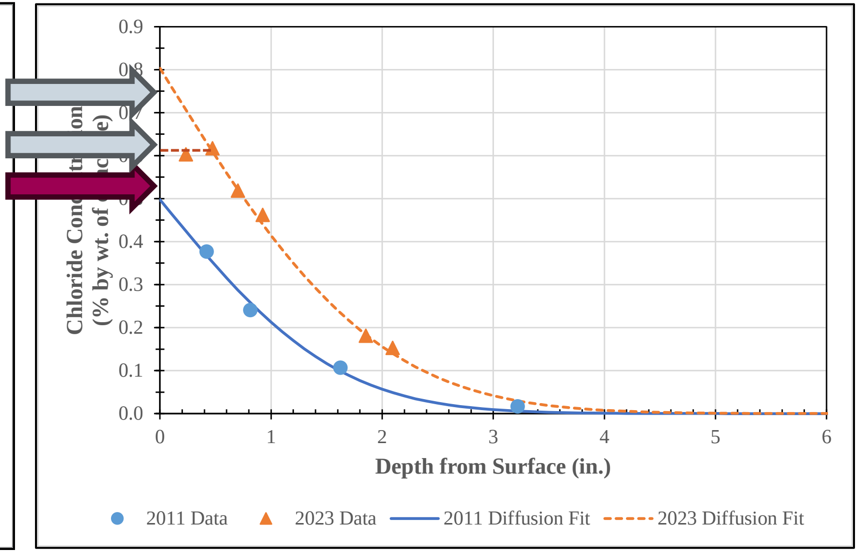


Diffusion Behavior at "Replicate Cores"

Consistent Surface Exposure



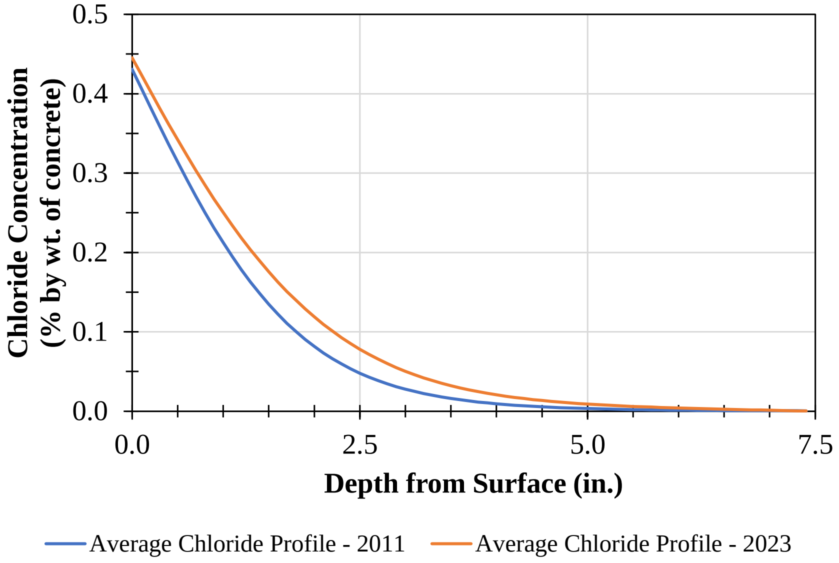
Apparent Exposure Variability



Global Chloride Diffusion Behavior

- Local behavior was variable
- On average, similar exposure over the ~ 10 years between studies
- Total chloride levels increased over the ~ 10 years:
  - *18 percent at SR 46*
  - *24 percent at I-94*

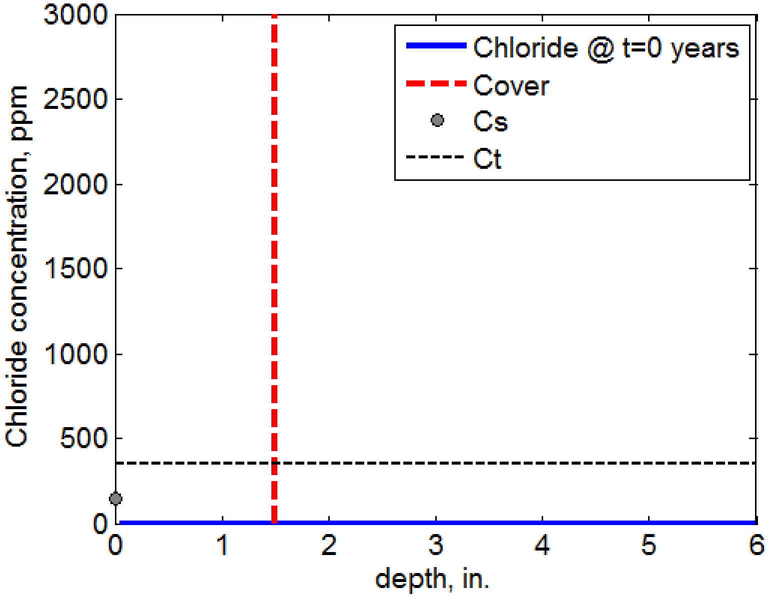
I-94 Average Chloride Profiles



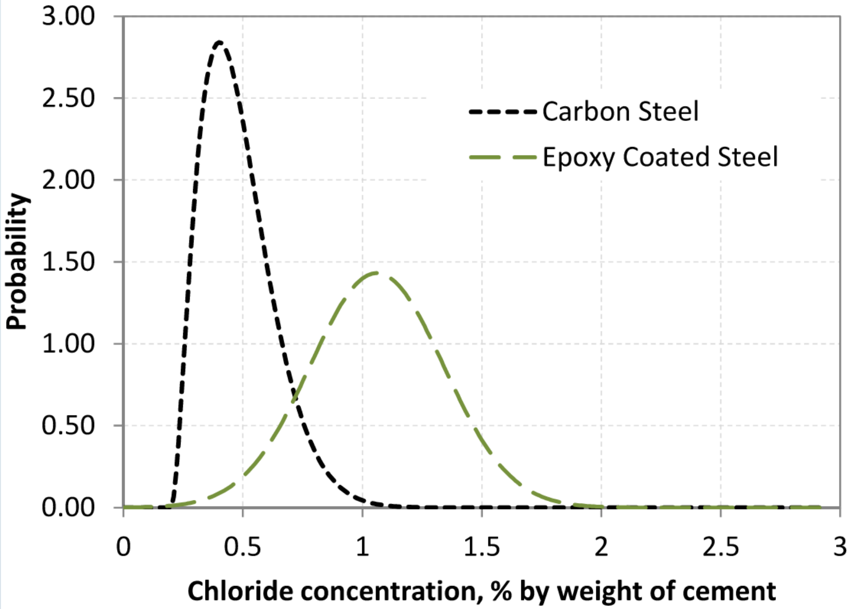
WJE's Service Life Model Approach (WJE CASLE™)

Service Life Modeling for Existing Structures

- Fick's 2nd Law of Diffusion
- Considerations
  - *Time for surface build-up*
  - *Time for chloride diffusion to rebar*
  - *Chloride concentration to initiate corrosion ("Chloride Threshold")*
  - *Time for corrosion product to build up and cause damage*



Chloride Thresholds



- **Uncoated Rebar:**
  - Beta Distribution
  - Mean – 0.48 % by wt. cement
  - Lower bound value – 0.2 % by wt. cement
- **Epoxy-Coated Rebar:**
  - Normal Distribution
  - Mean – 1.06 % by wt. cement
  - Based on Field Studies
- *Rebar type also affects propagation time*

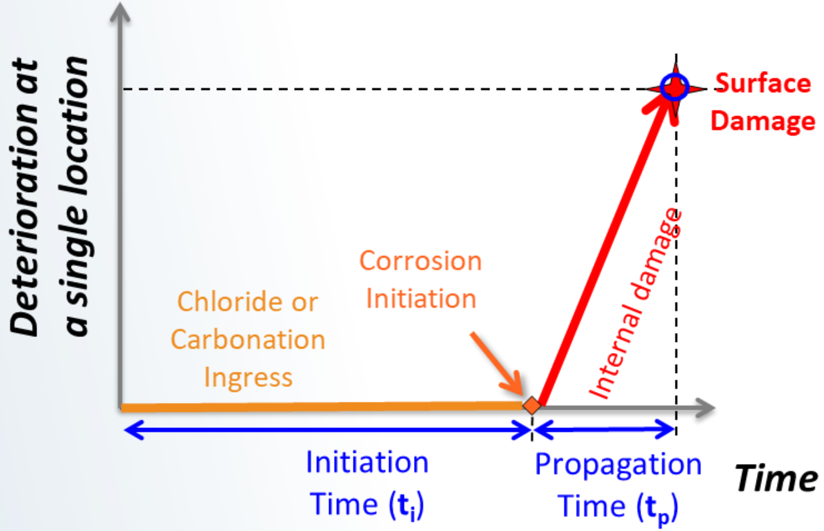
J. Lawler, et. al. "Statistical Distributions for Chloride Thresholds of Reinforcing Bars". ACI Materials Journal. March 2021. p. 13 to 20.

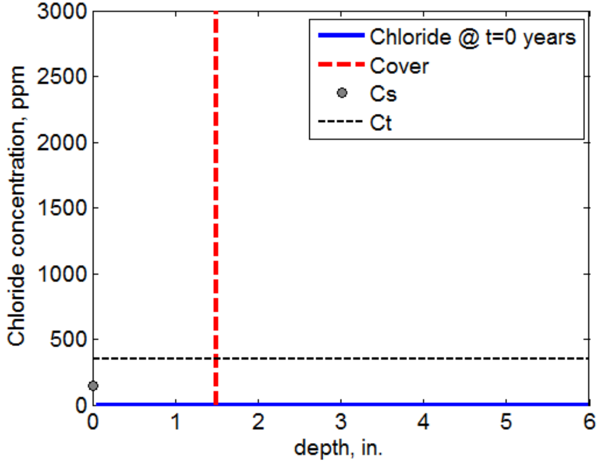
Corrosion Initiation and Propagation

Time to damage

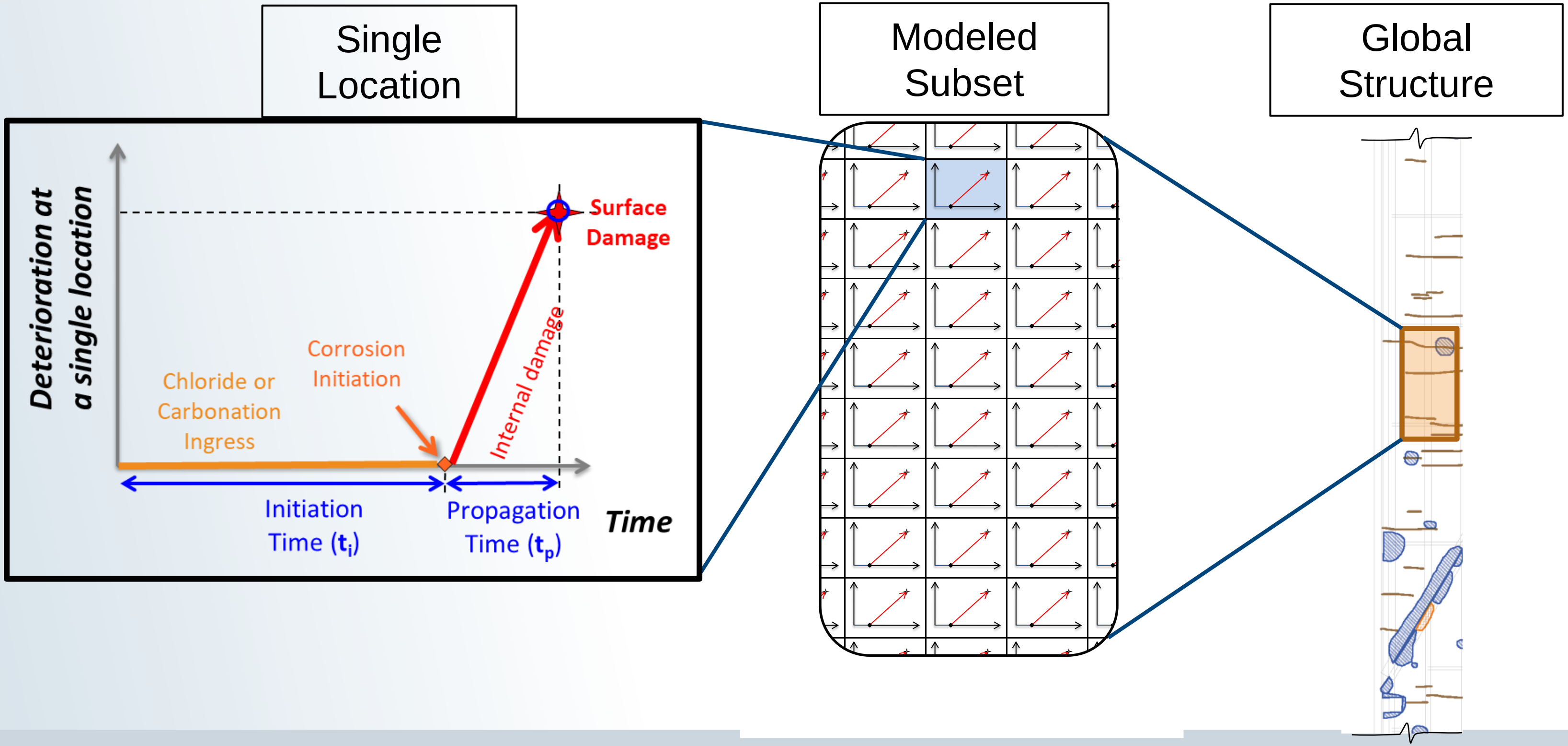
=

$t_i + t_p$



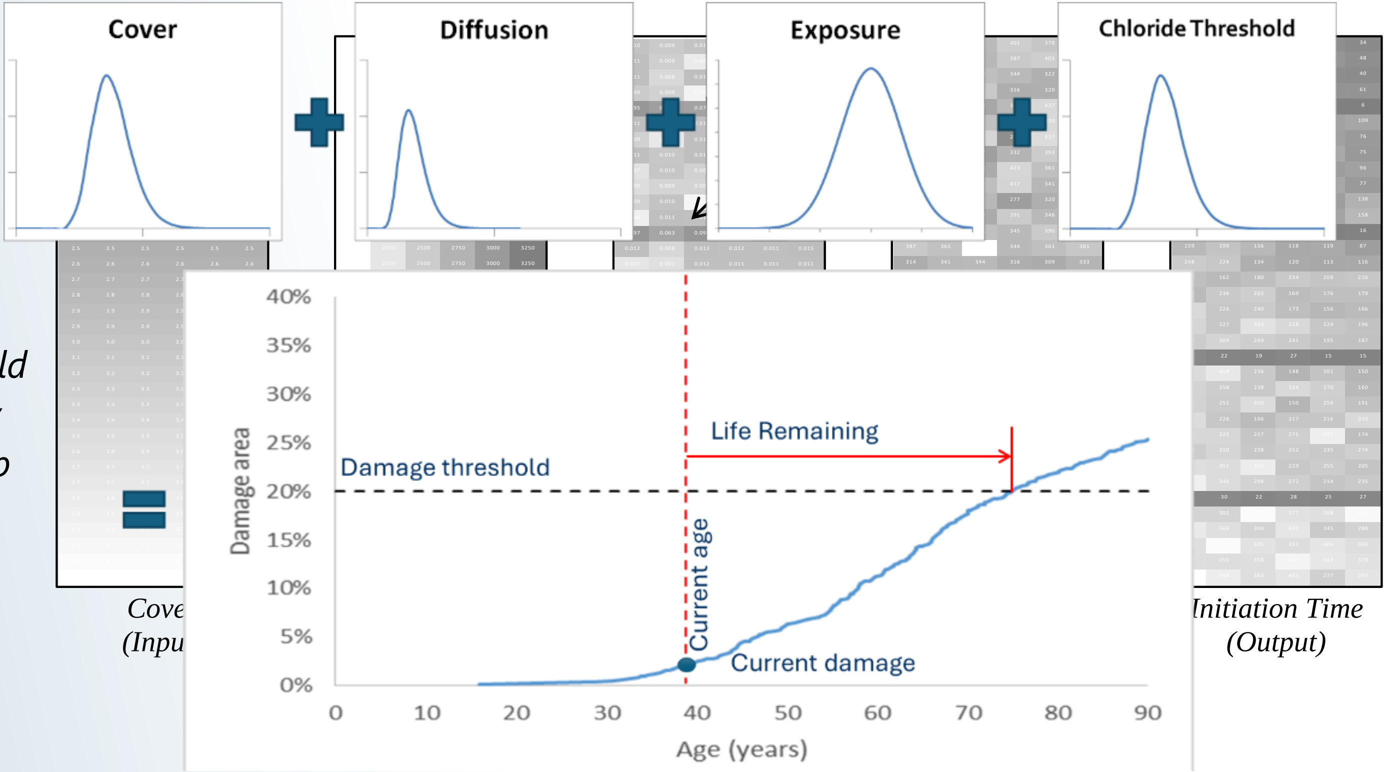


Model Discretization



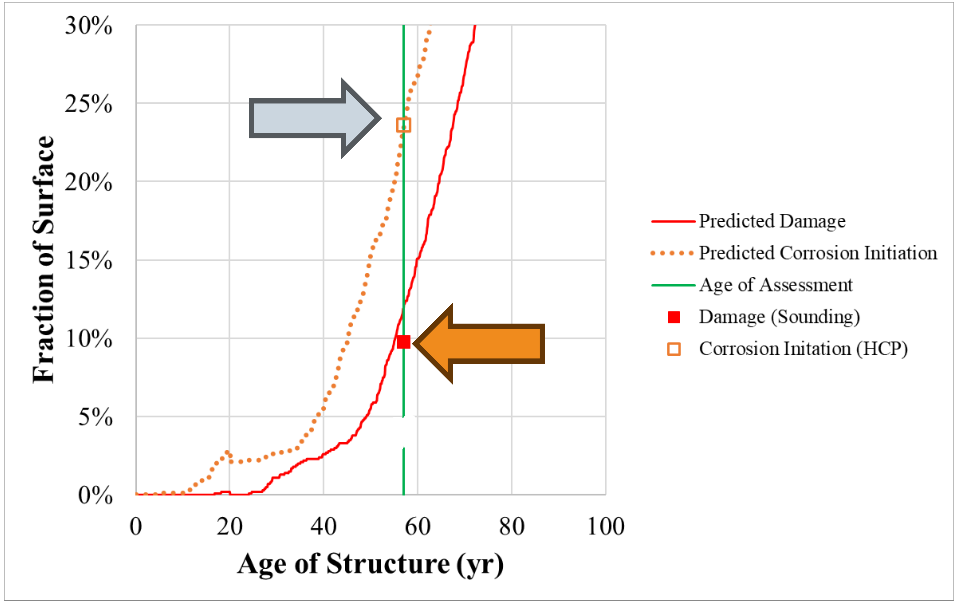
Model Discretization

Synthesis of field and laboratory data to develop and "calibrate" model



Results from Model

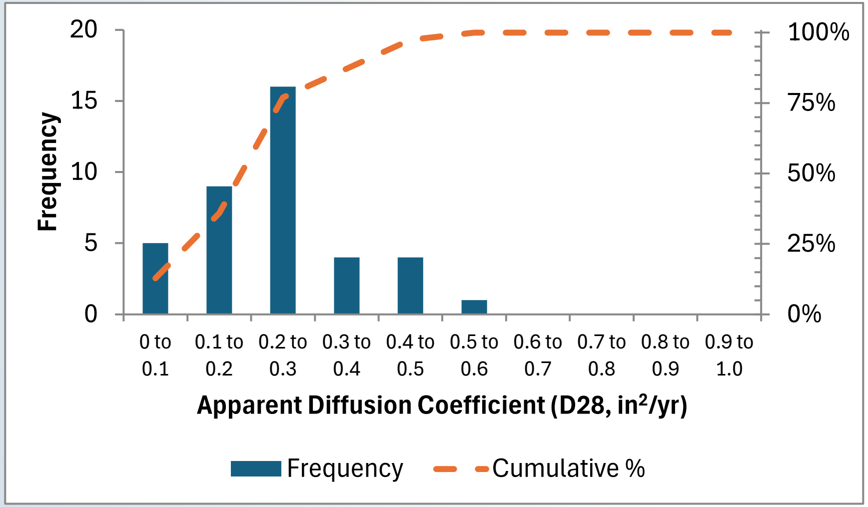
- Model predicts corrosion initiation and propagation
- Single-point verification can be used with data at current age
  - *Half-cell data can compare to corrosion initiation*
  - *Sounding data can compare to model predicated damage*
- Ideally, model validation would occur at multiple points in time



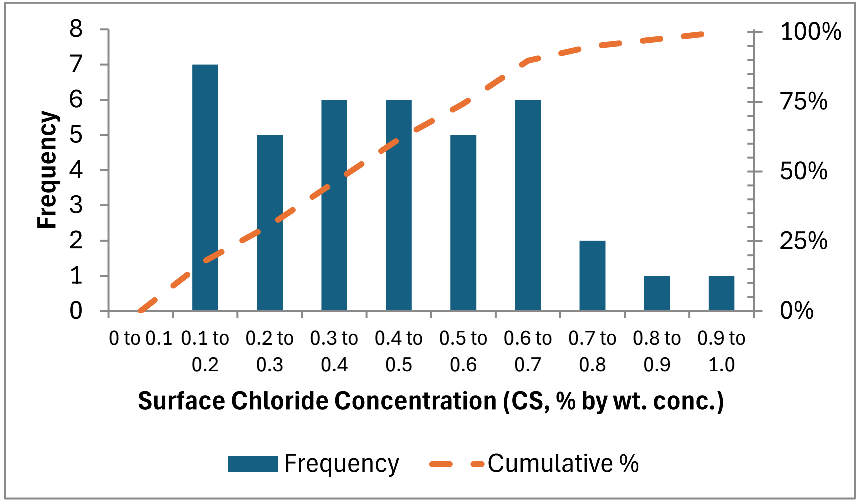
Results from Service Life Modeling Validation

Service Life Inputs – Chloride Diffusion Fitting Parameters

"Apparent Diffusion" (I-94)



"Chloride Surface Exposure" (I-94)

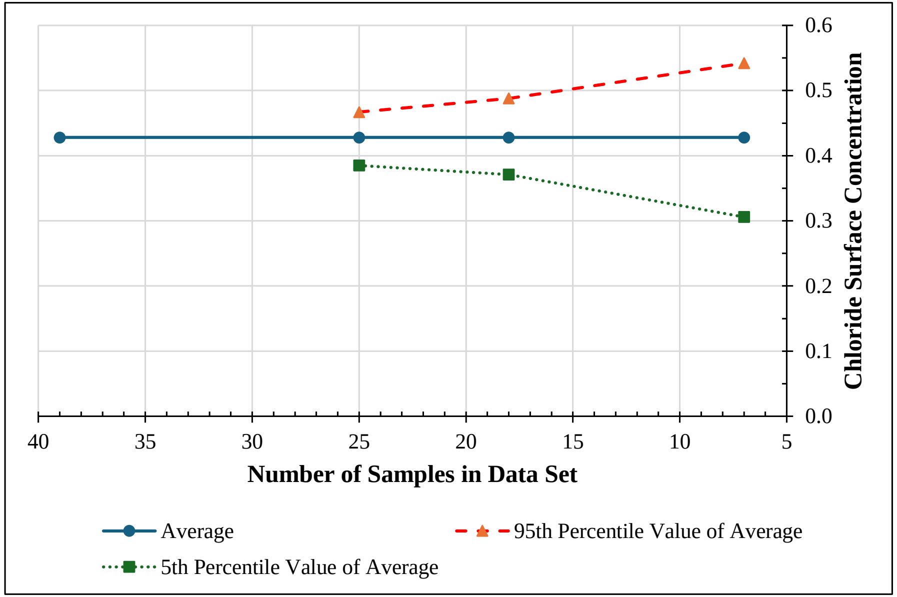


Often modeled as Normal Distributions but others can be used (e.g., Lognormal, Beta, Weibull, etc.)

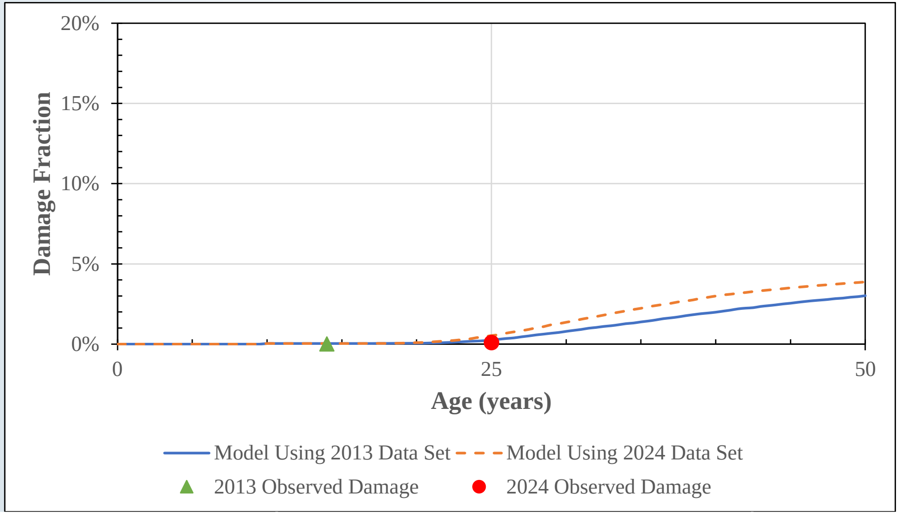
Number of Core Samples

- **I 94** – Seven Bridges, ~40 uncracked cores
- Through a random down-sampling, we can see change in average for smaller data sets
- This shows the need for a sufficiently large sample set to characterize variability in exposure and concrete properties

Chloride Surface Exposure



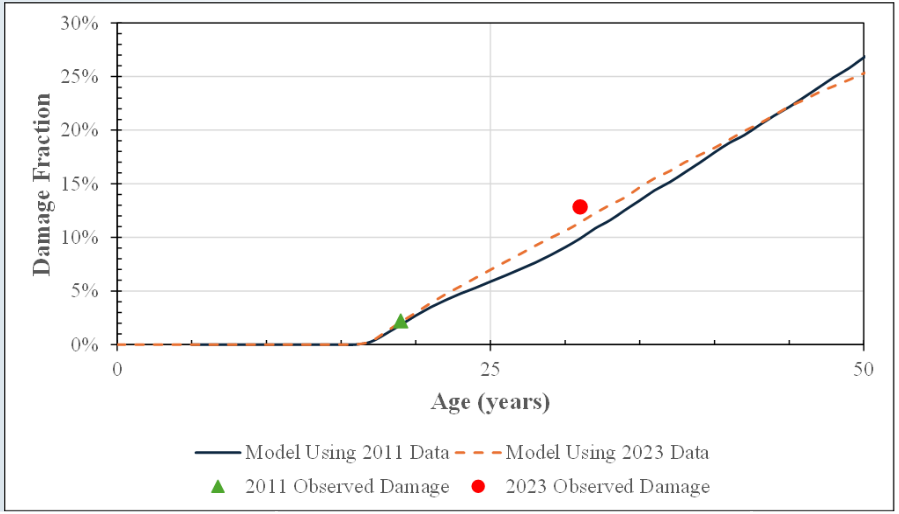
Model Results – Indiana State Route 46



- Strong correlation at both 14 and 25 years
- Behavior controlled by cracking
- Negligible chloride contamination in substrate below sound/uncracked overlay

Age (years)	Field Observed Damage	Model Predicted Damage (Using 2013 Data)	Model Predicted Damage (Using 2024 Data)
14	0.0%	0.0%	0.0%
25	0.1%	0.3%	0.5%

Model Results – I90/I94 Kennedy



- Strong correlation at both 19 and 31 years (3 percent or less difference)
- Behavior controlled by cracking, but also influenced by bulk diffusion through cover concrete

Age (years)	Field Observed Damage	Model Predicted Damage (Using 2011 Data)	Model Predicted Damage (Using 2023 Data)
19	2.2%	1.8%	2.1%
31	12.9%	9.9%	11.4%

Conclusions *(1 of 2)*

- A finite-difference solution to Fick's second law of diffusion is an appropriate representation for chloride ingress in concrete bridge decks exposed to deicing salts.
- Based on probabilistic modeling, projections of surface area damage differed by 3 percent or less from the observed damage in the two reported case studies.
- Predictions based on initial investigations in 2011/2013 were validated against observed damage during follow-up investigations in 2023/2024 (roughly ten years apart).

Conclusions *(2 of 2)*

- As observed in these studies, surface chloride concentration ("chloride exposure") and associated chloride ingress ("diffusion behavior") can vary widely between closely spaced locations within a bridge deck.
- Investigations in support of service life analysis need to be carefully planned and executed.

Thank you!
Questions?

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