SIMCO

STADIUM

Comprehensive Durability Modeling for Concrete Structures

Demystifying STADIUM®

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AAPA Webinar
February 18th 2015

Webinar Summary

- Description of STADIUM®
- Using STADIUM® for new structures
- Using STADIUM® for existing structures
- Extending STADIUM® use to asset management

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Who We Are

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SIMCO is an engineering firm
entirely dedicated to the durability
and preservation of concrete structure

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SIMCO Since 1989

- SIMCO is recognized for its integrated solutions that lead to the optimum design and maintenance of concrete structure.
- SIMCO assists owners and managers in the management of the complete lifecycle of their structure assets.

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A Comprehensive Offer

SIMCO's Unique Offer

Software Solutions | **Engineering Services** | **Specialized Lab Services**

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Description of STADIUM®

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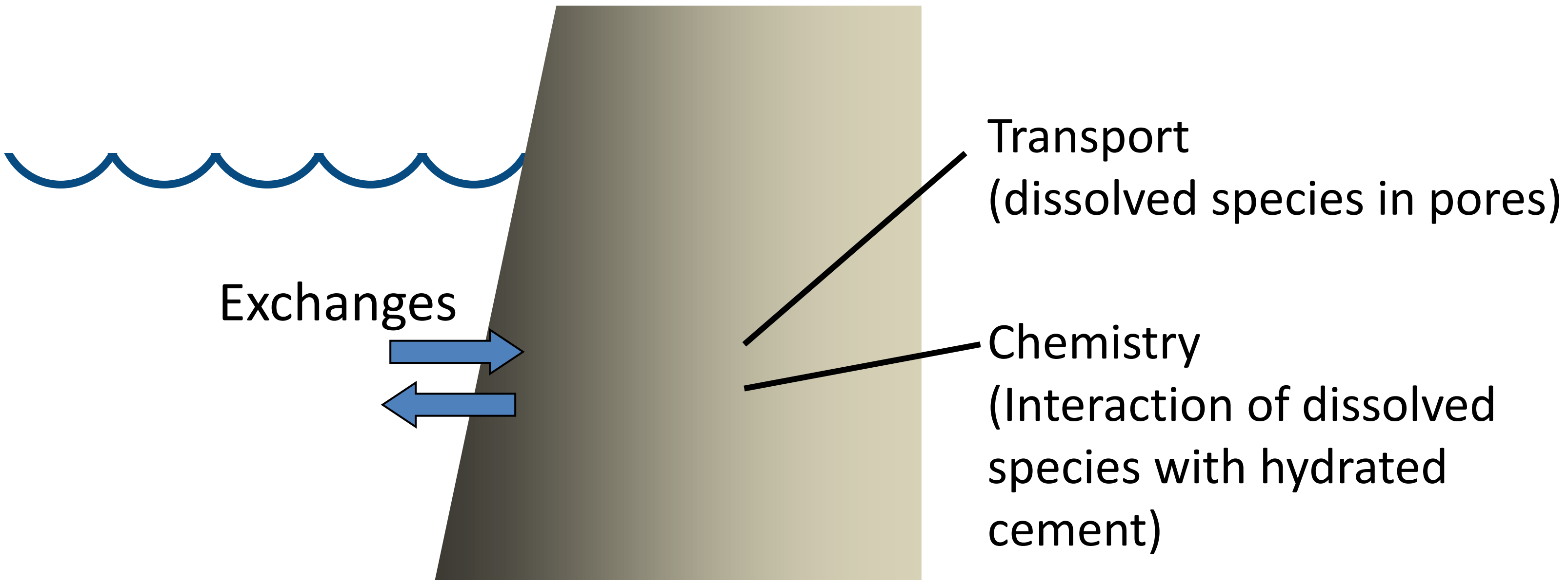
Basic Principle

STADIUM® models the transport of chemical species in cementitious materials resulting from exchanges at the material/environment interface.



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Main features

- Chloride, sulfate, carbonate ingress
- Temperature effects
- Moisture transport (wetting/drying cycles, capillary suction)
- Multiple chemical reactions
- Cement, fly ash, slag chemistry
- Time-dependent exposure conditions.

STADIUM®

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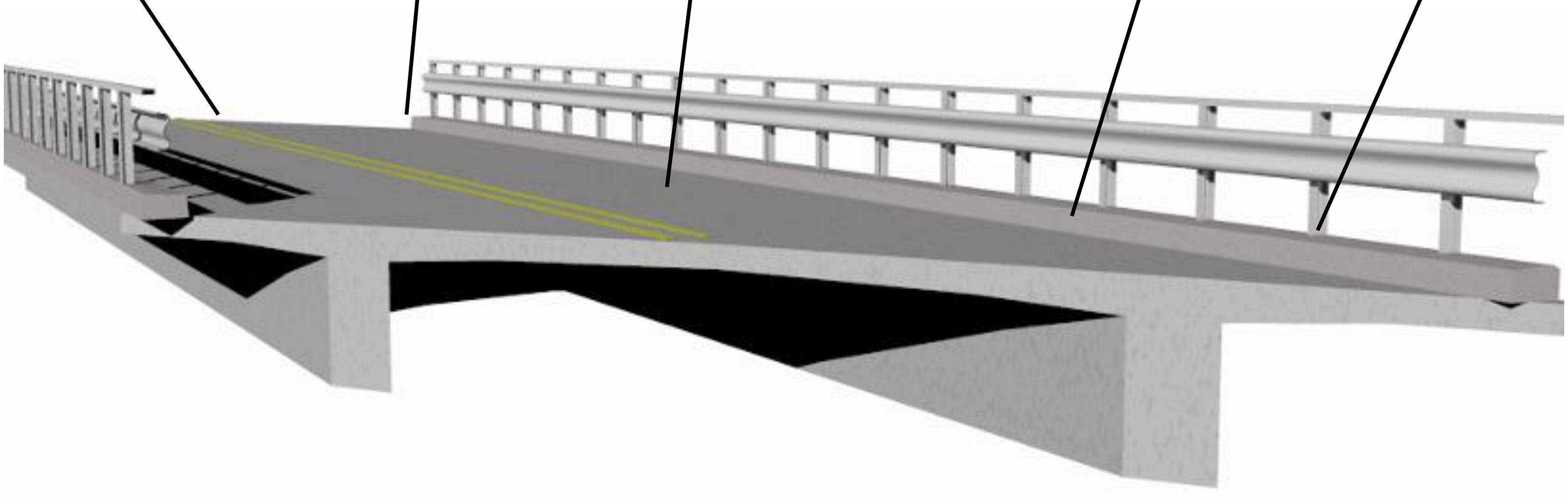
Main features



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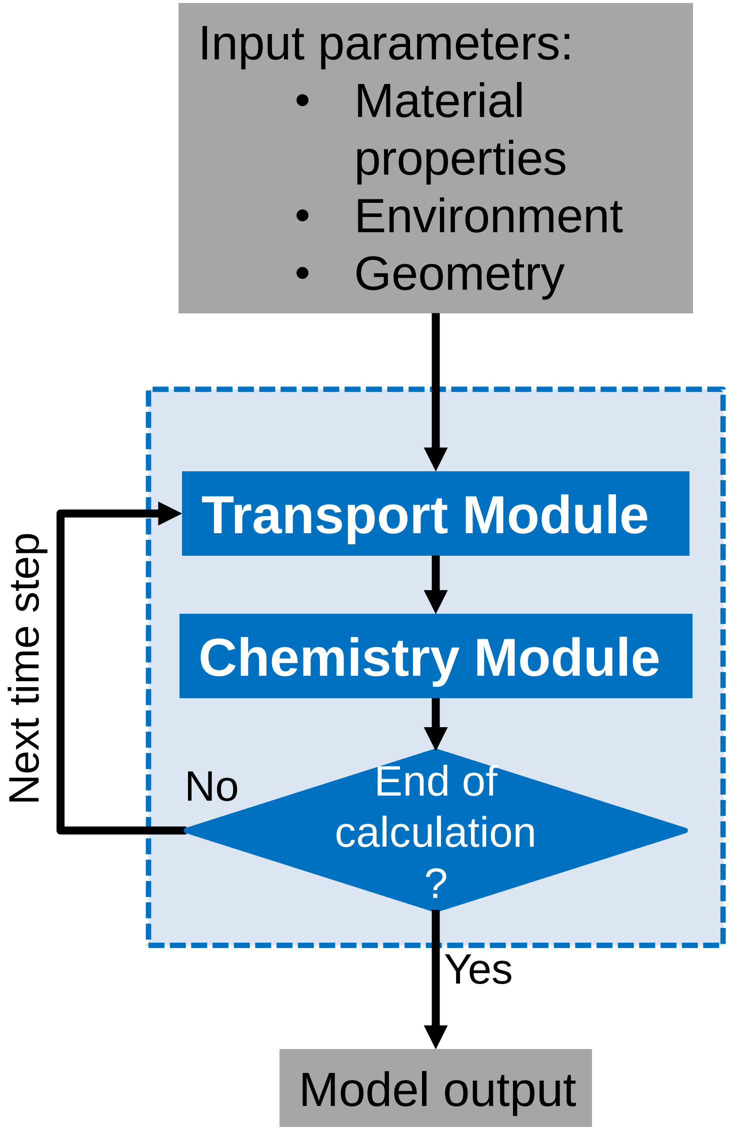
STADIUM® Main Algorithm



The model is divided in 2 main modules:

- The transport module makes the species move during one time step,
- The chemistry module simulates the reactions between species in the pores and the hydrated paste.

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STADIUM® – Transport Module

The transport module accounts for the following:

Mechanisms	Properties	Lab tests
Electrodiffusion of species	Diffusion coefficient	Migration test
	Porosity	ASTM C642
Moisture transport (liquid & vapor)	Permeability	Drying test
	Moisture isotherm	Drying test
Heat conduction	Thermal conductivity	Estimated
	Heat capacity	Estimated

Notes:

- All equations are coupled to each other (e.g. temperature influences moisture and diffusion),
- The equations are solved using FEM,
- 1D and 2D versions are available.

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STADIUM® – LAB Application

Characterization of concrete mixtures

Evaluation of transport properties – Input to STADIUM®

STADIUM® MTC

Drying test
ASTM C1792

Permeability
Moisture isotherm

STADIUM® IDC

Migration test
Modified ASTM C1202

Tortuosity
Diffusion coefficients

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STADIUM® – Transport Module

Additional features:

- Base species considered: OH^-, Cl^-, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, $H_2SiO_4^{2-}$, $Al(OH)_4^-$, $Fe(OH)_4^-$, HCO_3^-, NO_2^-.
- Possibility of setting time-dependent boundary conditions (exposure solution, temperature, humidity) to better reproduce climate conditions.
- The model accounts for the effect of cement and SCM hydration on transport properties, e.g.: reduction of diffusion coefficients through time due to presence of fly ash.
- The model also accounts for the effect of pore volume variations from chemical reactions on transport properties (feedback effect).

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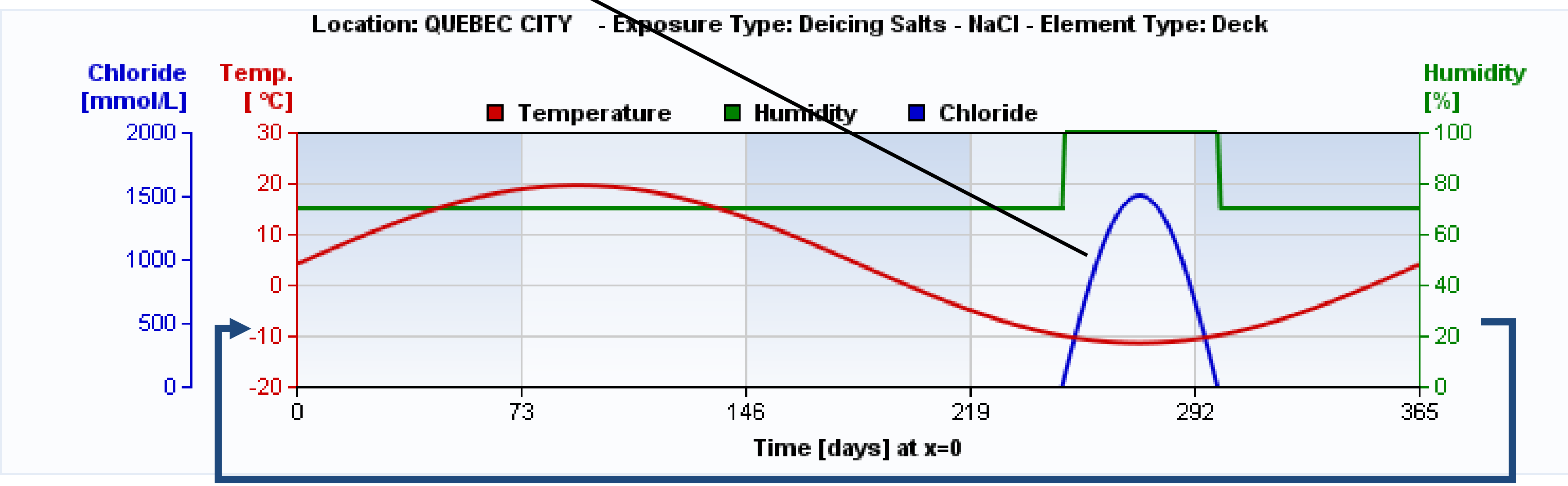
STADIUM® – Exposure Conditions

Time-dependent boundary conditions:

Exposure to deicing salts during winter



After a one-year cycle, the model goes back to the beginning of the year. The cycle is repeated.

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STADIUM® – Chemistry Module

The chemistry module solves the thermodynamic equilibrium relationships between hydrated cement paste minerals and species in the pore solution:

- Excess of some species may lead to the formation of new minerals,
- Conversely, dissolution may occurs when concentration levels of some species is low,
- The module handles the equilibrium of pure minerals (classical law of mass-action),
- The effect of temperature on chemistry is considered.

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STADIUM® – Chemistry Module

INPUT TO CHEMISTRY MODULE

- Mix composition
- Cement chemistry
- SCMs chemistry
- Chemistry database

→

CALCULATED PARAMETERS

- Hydrated cement paste composition
- Pore solution composition

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STADIUM® – Chemistry Module

Handling of chloride binding:

- Chloride binding mostly occurs as the result of chloride in the pore solution interacting with AFm phase (e.g. monosulfates).
- The reaction results in the formation of Friedel's salt.
- Friedel's salt equilibrium is modeled as a solid solution with AFm phases.
- A small portion of chloride binding also occurs due to physical binding with charged pore surfaces. The Langmuir-type model implemented in STADIUM is pH-dependent.

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STADIUM® – Model Output

At the end of calculations, the model provides the following information:

- Space and time distribution of species concentrations,
- Space and time distribution of mineral contents,
- Space and time distribution of temperature and humidity,
- Analysis of the main variables to get: total calcium, sulfur and chloride content.
- Chloride content at specific depth to estimate the time to initiate corrosion for different rebar depths.

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STADIUM IS NOT LIFE-365!

*By all accounts, Fick was a fine gentleman, just not for concrete.

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Back to basics

In order to model chemical species transport in cementitious materials, you need to solve:

$$\frac{\partial c_i^b}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \mathrm{div}\left(D_i w \,\mathrm{grad}(c_i) + \frac{D_i z_i F}{RT} w c_i \,\mathrm{grad}(\psi) + D_i w c_i \,\mathrm{grad}(\ln \gamma_i) + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \,\mathrm{grad}(T) + c_i D_w \,\mathrm{grad}(w) \right) = 0$$

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Back to basics

In order to get to Fick's 2nd law:

$$\frac{\partial c}{\partial t} - \mathrm{div}\left(D^* \,\mathrm{grad}(c)\right) = 0$$

You need to….

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Back to basics

…neglect moisture transport coupling:

$$\frac{\partial c_i^b}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \text{div}\left(D_i w \,\text{grad}(c_i) + \frac{D_i z_i F}{RT} w c_i \,\text{grad}(\psi) + D_i w c_i \,\text{grad}(\ln \gamma_i) \right.$$
$$\left. + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \,\text{grad}(T) + c_i D_w \,\text{grad}(w) \right) = 0$$

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Back to basics

…neglect temperature effects:

$$\frac{\partial c_i^b}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \operatorname{div}\left(D_i w \operatorname{grad}(c_i) + \frac{D_i z_i F}{RT} w c_i \operatorname{grad}(\psi) + D_i w c_i \operatorname{grad}(\ln \gamma_i) + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \operatorname{grad}(T) + c_i D_w \operatorname{grad}(w) \right) = 0$$

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Back to basics

…neglect electrodiffusion coupling and chemical activity:

$$\frac{\partial c_i^b}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \operatorname{div}\left(D_i w \operatorname{grad}(c_i) + \frac{D_i z_i F}{RT} w c_i \operatorname{grad}(\psi) + D_i w c_i \operatorname{grad}(\ln \gamma_i) \right.$$
$$\left. + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \operatorname{grad}(T) + c_i D_w \operatorname{grad}(w) \right) = 0$$

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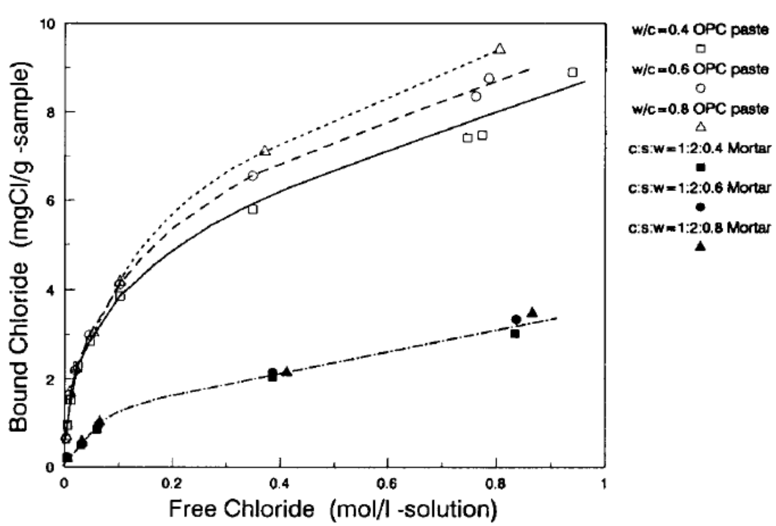
Back to basics

…and most of all, assume linear chloride binding:

$$\frac{\partial c_i^b}{\partial t} + \frac{\partial (w c_i)}{\partial t} - \mathrm{div}\left(D_i w \,\mathrm{grad}(c_i) + \frac{D_i z_i F}{RT} w \,\mathrm{grad}(\psi) + D_i w c_i \,\mathrm{grad}(\ln \gamma_i) + \frac{D_i c_i \ln(\gamma_i c_i)}{T} w \,\mathrm{grad}(T) + c_i D_w \,\mathrm{grad}(w) \right) = 0$$



Data show that chloride binding is always nonlinear!!

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Using STADIUM® for new structures

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Performance specifications

- Performance specification language is commonly incorporated in durability requirements for new concrete structures.
  - ✓ E.g.: 100-year service-life (time before major repairs)
- We are still in a transition phase: performance specifications are still mixed with prescription requirements.
  - ✓ E.g. RCPT values (1000 Coulombs)
- Long-term service-life often associated with corrosion initiation.
- Reliable modeling is needed to make a convincing case.

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UFGS Methodology

- The U.S. Department of Defense recognizes STADIUM® as the only accurate numerical solution for the prediction of long-term behavior of reinforced concrete structures exposed to marine environments.
- Since 2010, STADIUM® is specified in the Unified Facilities Guide Specifications (UFGS).
- The service-life requirement is 75 years before major repairs, 65 years before corrosion initiation.
- US Navy, USACE, USAF, NASA

Specified by the
US NAVY
UFGS-03 31 29

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UFGS Methodology

Characterization of lab mixes

Mix selection: service-life requirements

Production: QA/QC

STADIUM®

Specified by the US NAVY

UFGS-03 31 29

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UFGS Methodology

SIMCO's test methods are part of the UFGS protocol:

- Volume of permeable voids (porosity): ASTM C642
- Diffusion coefficients: modified ASTM C1202 (migration test)
- Moisture permeability: ASTM C1792 (drying test)

Specified by the US NAVY UFGS-03 31 29

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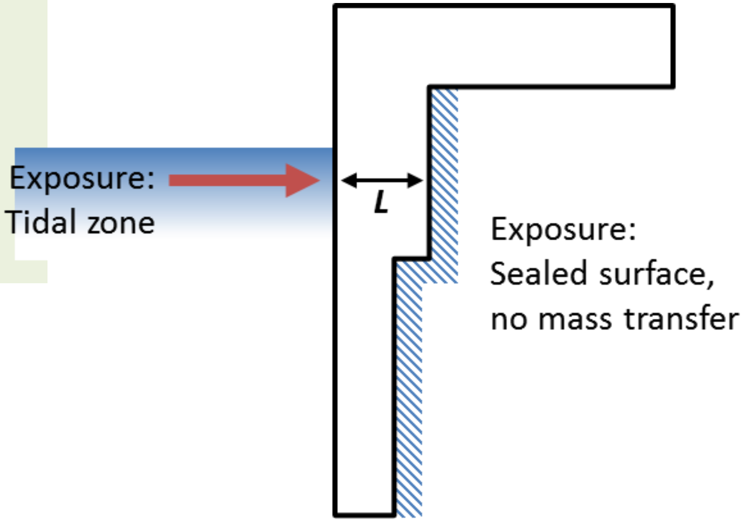
Example – mix qualification

MIX A	MIX B
▪ 0.35 w/b ▪ 20% Fly Ash Type C ▪ D_{Cl} (28d): 2.44e-12 m^2/s	▪ 0.35 w/b ▪ 35% GGBFS ▪ D_{Cl} (28d): 1.70e-12 m^2/s

ADDITIONAL INFO

- Location: Norfolk, VA (Temp., RH)
- Salinity: 34 ppt
- Tidal zone
- Rebar depth: 4 in. (100 mm)



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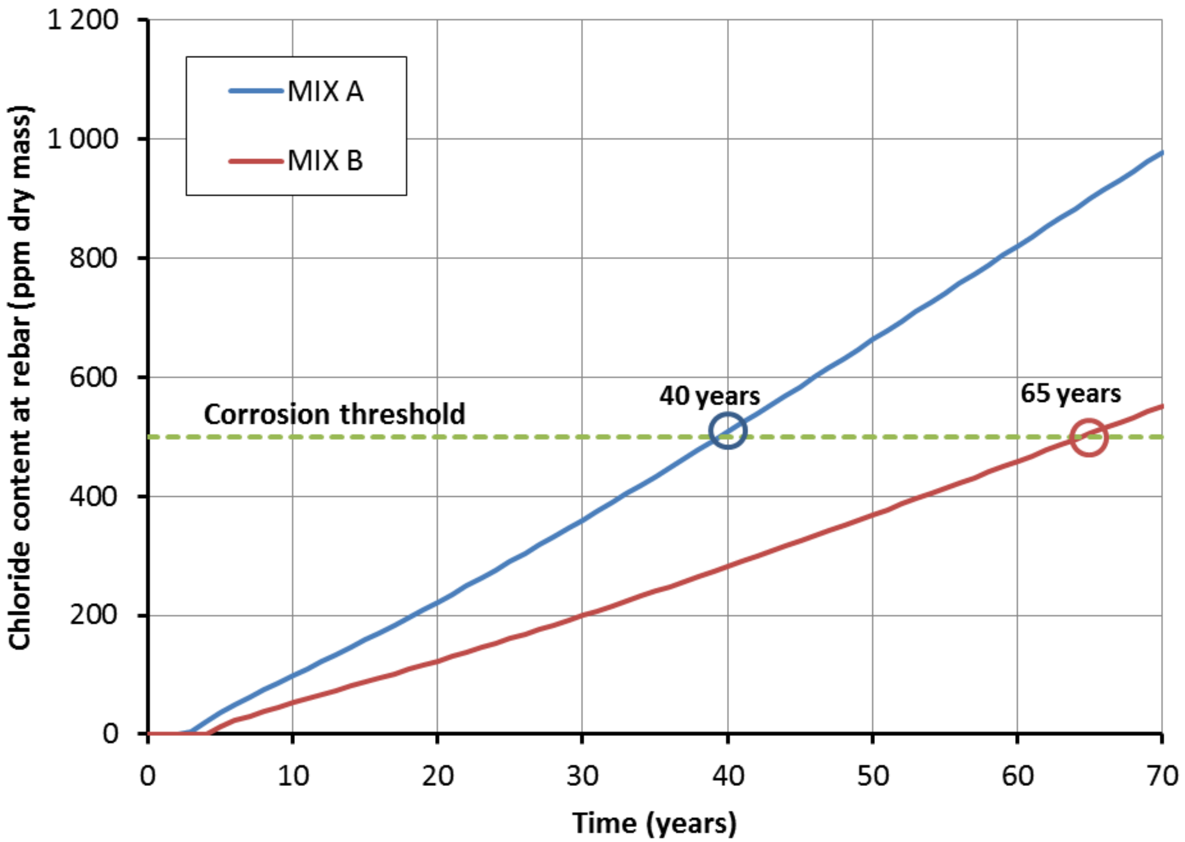
Example – mix qualification



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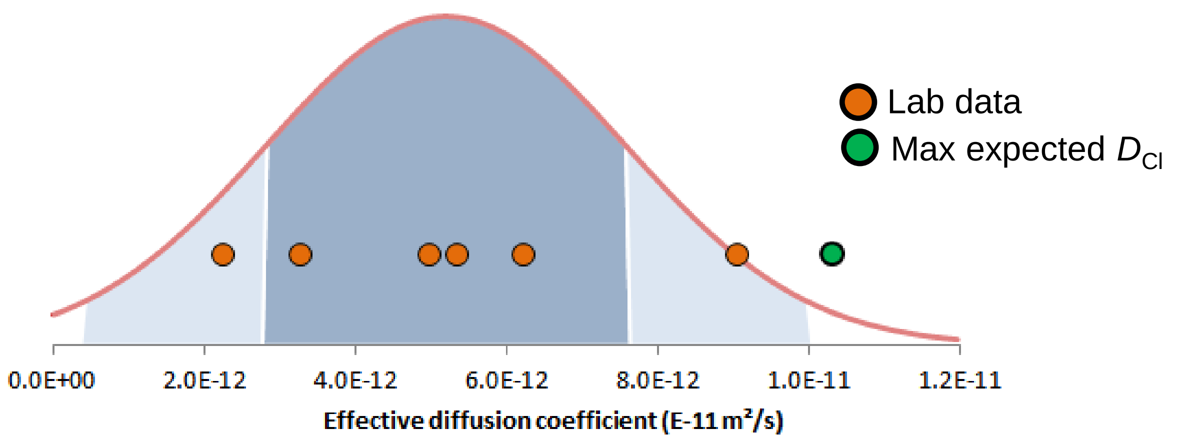
UFGS Update

Introduction of variability language

- Lab testing: 3 or more batches
- Calculation of tolerance limit: max expected diffusion coefficient
- Value that will not be surpassed in more than 1 in 10 batches at 90% confidence level
- This value must clear durability requirements



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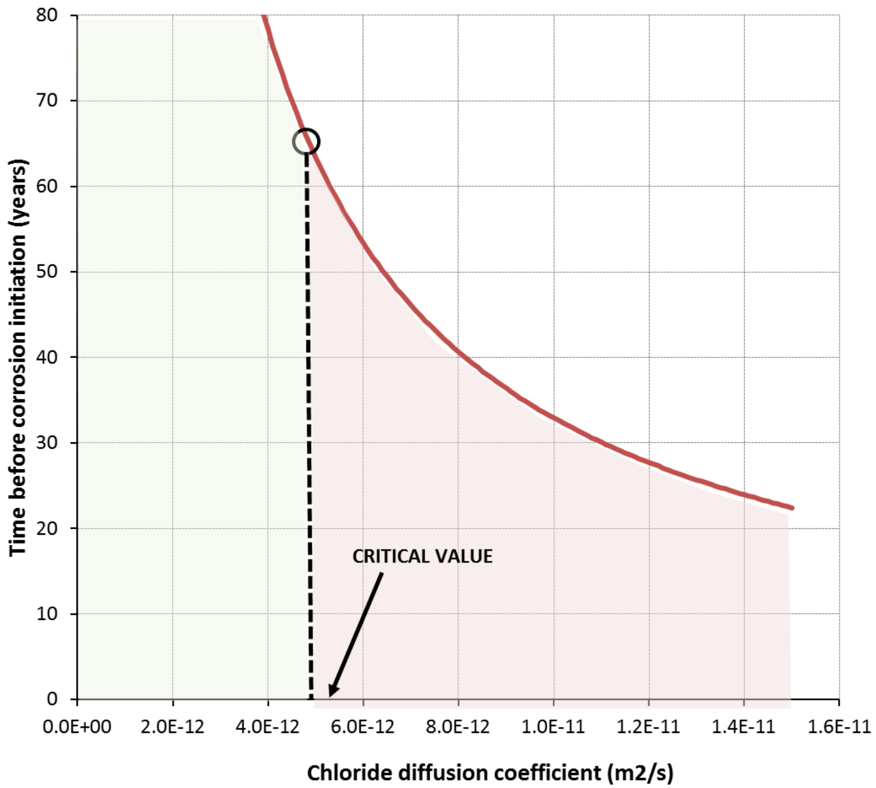
UFGS Update

Calculation of critical value

- Max value of diffusion coefficient that allows reaching durability requirements
- Used for QA/QC validation



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Using STADIUM® for existing structures

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Existing structures

Similar test protocol

- Data obtained from cores instead of lab cylinders.
- Additional benefit: chloride profiles can be measured.
- Missing information: mix proportions, cement chemistry.
- Petrographic analyses can provide some missing information.

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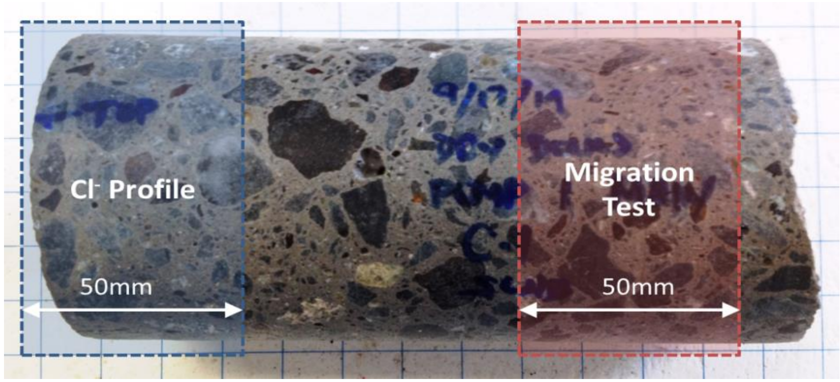
Concrete Characterization

TEST SERIES

- Absorption test (ASTM C642)
- Migration test (ASTM C1202 mod.)
- Drying test (ASTM C1792)
- Chloride profiles (ASTM C1152)
- Petrographic analysis

MODELING PARAMETERS

- Volume of permeable voids (porosity)
- Diffusion coefficients (tortuosity)
- Water permeability, moisture isotherm
- Chloride load (exposure cond.)
- Mixture composition



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Simulation procedure

Concrete characterization

Verification of current contamination level

Prediction of future behavior

STADIUM®

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Case study

Bridge in Southern Florida

Case study

Analysis of the central section:

- No signs of corrosion could be observed in the middle span.
- The objective was to estimate the time to corrosion in that part of the structure.
- The bridge was 26 years-old at the time of the study.

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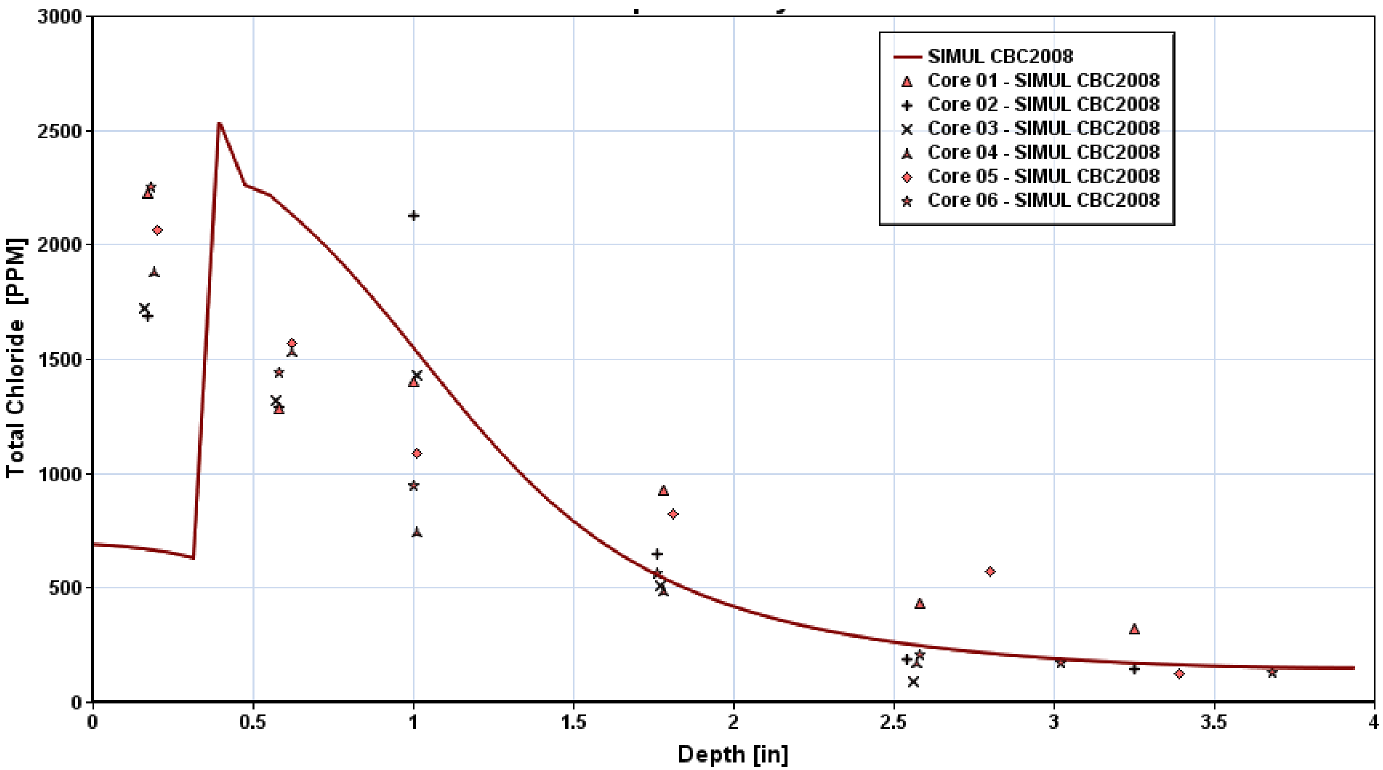
Case study

Modeling of current conditions:



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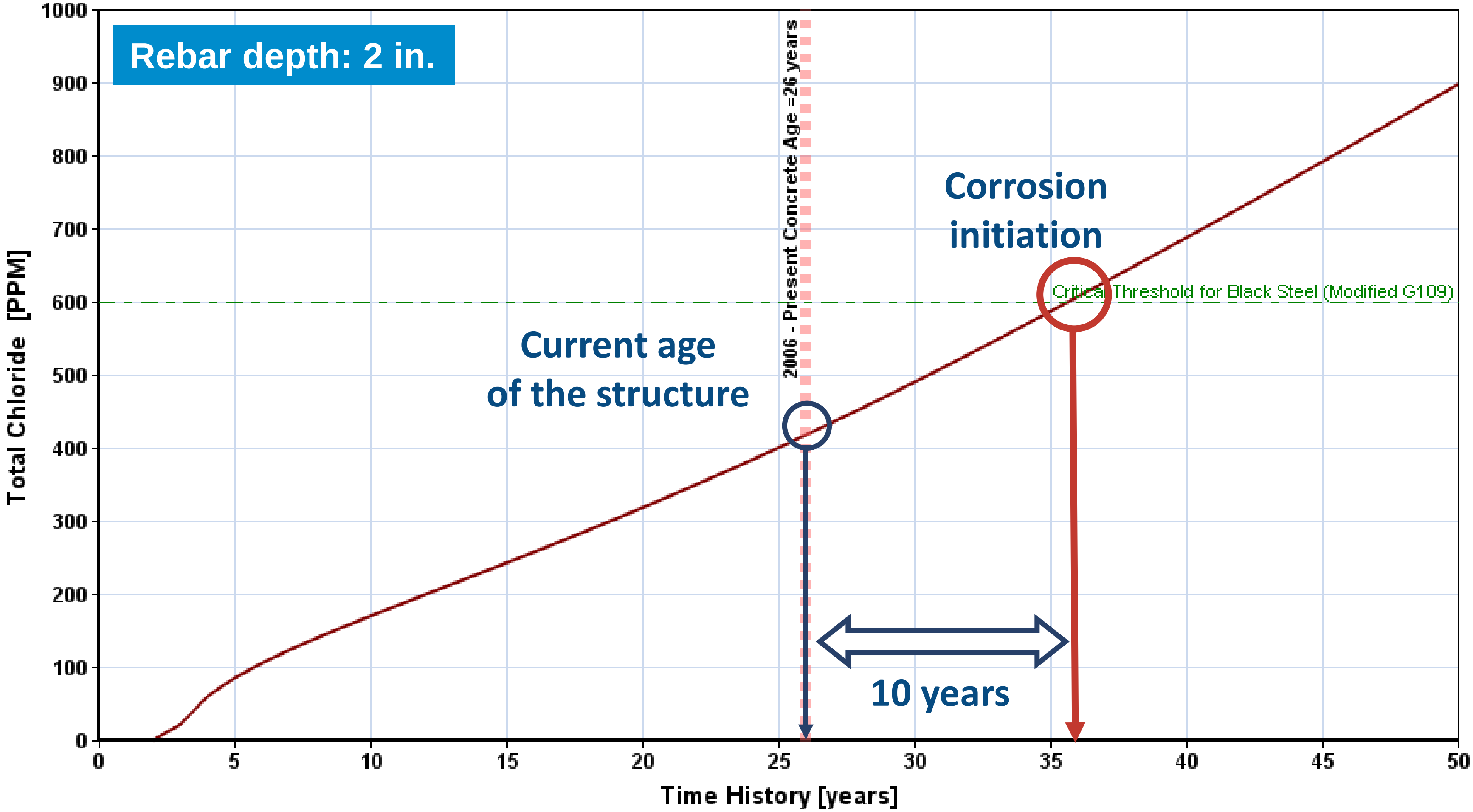
Case study

Remaining service-life – Time to corrosion initiation



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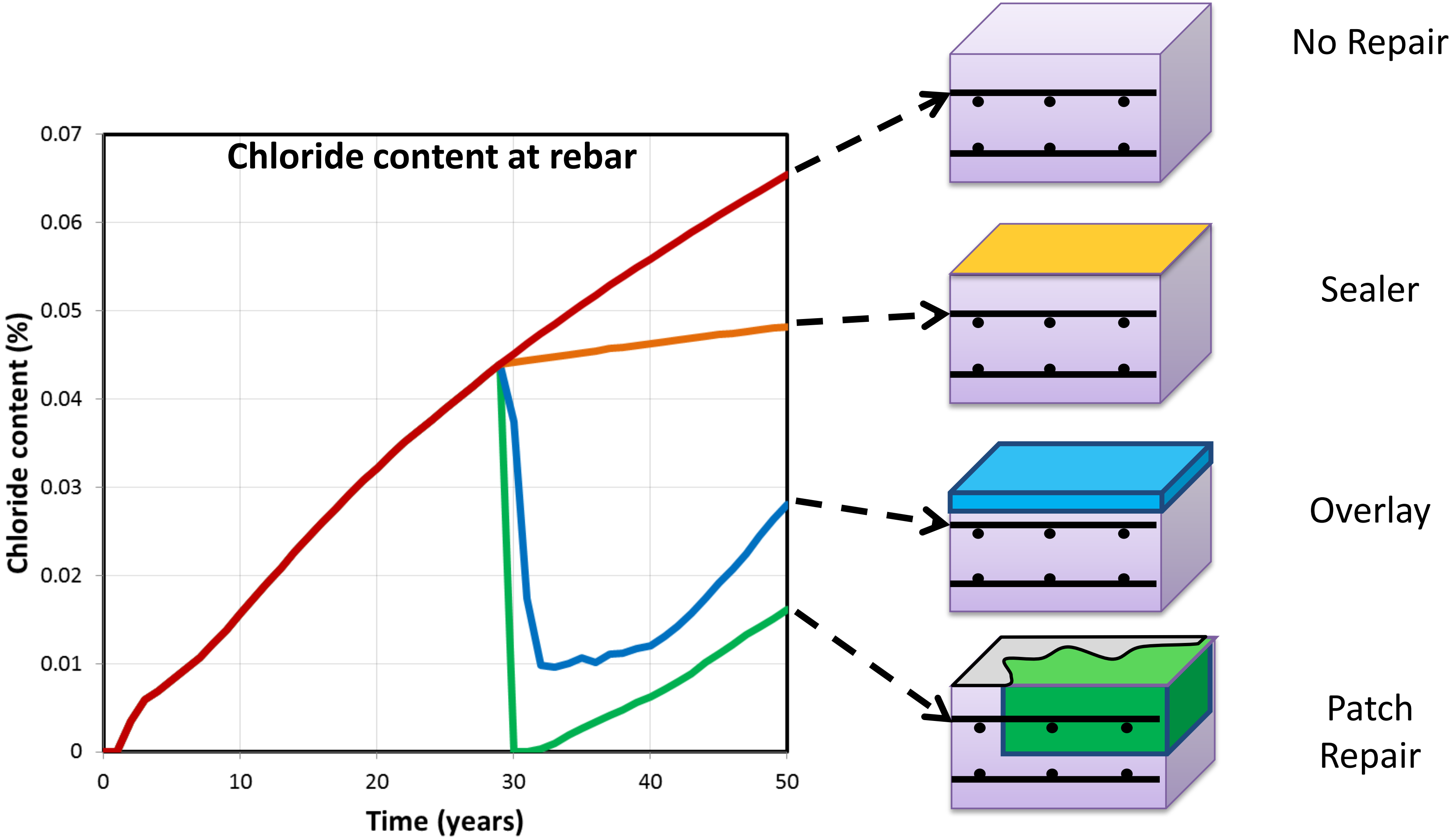
Case study

Extension of service-life



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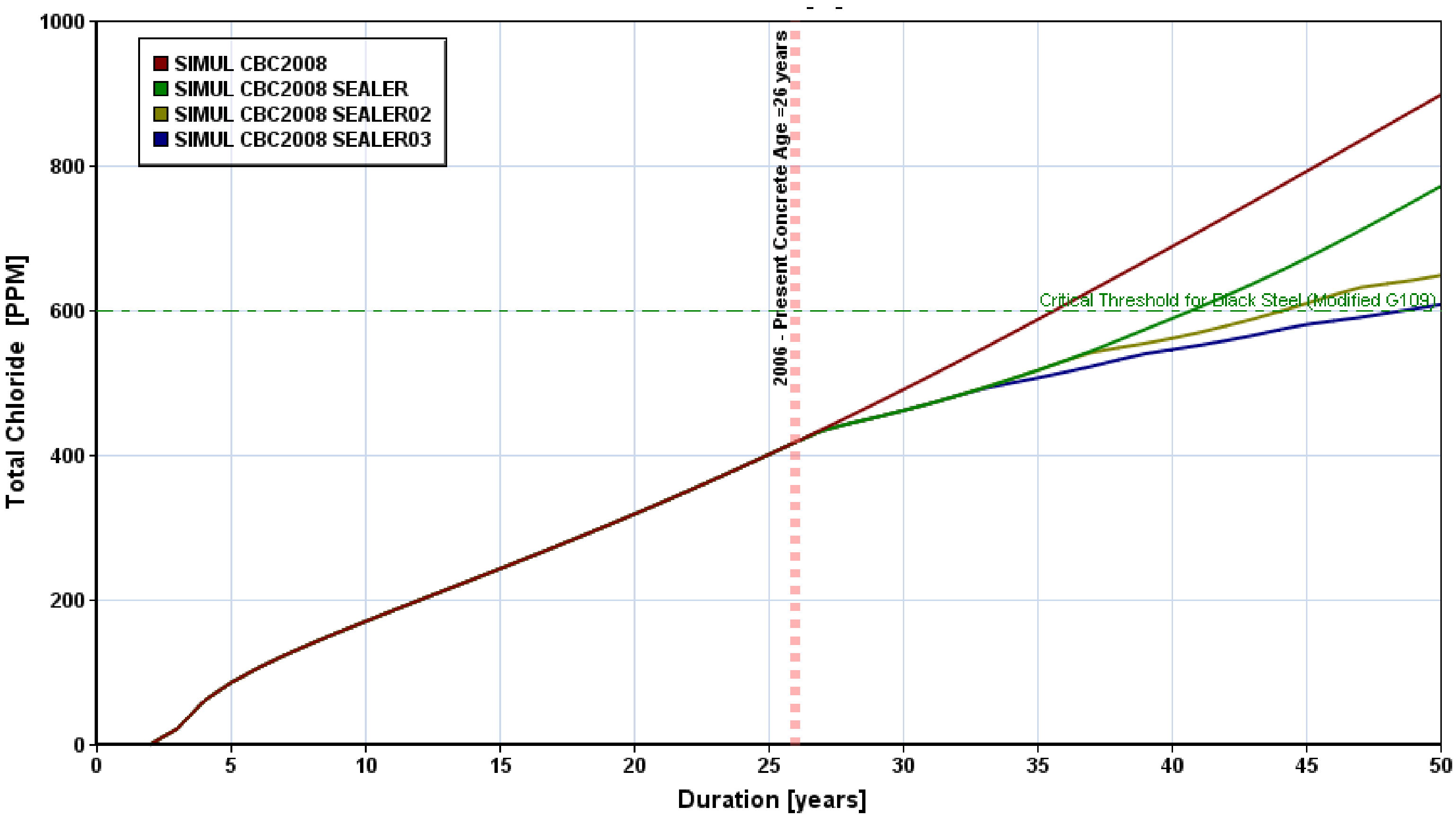
Case study

Extension of service-life



No sealer

Applied once

Every 10 years

Every 6 years

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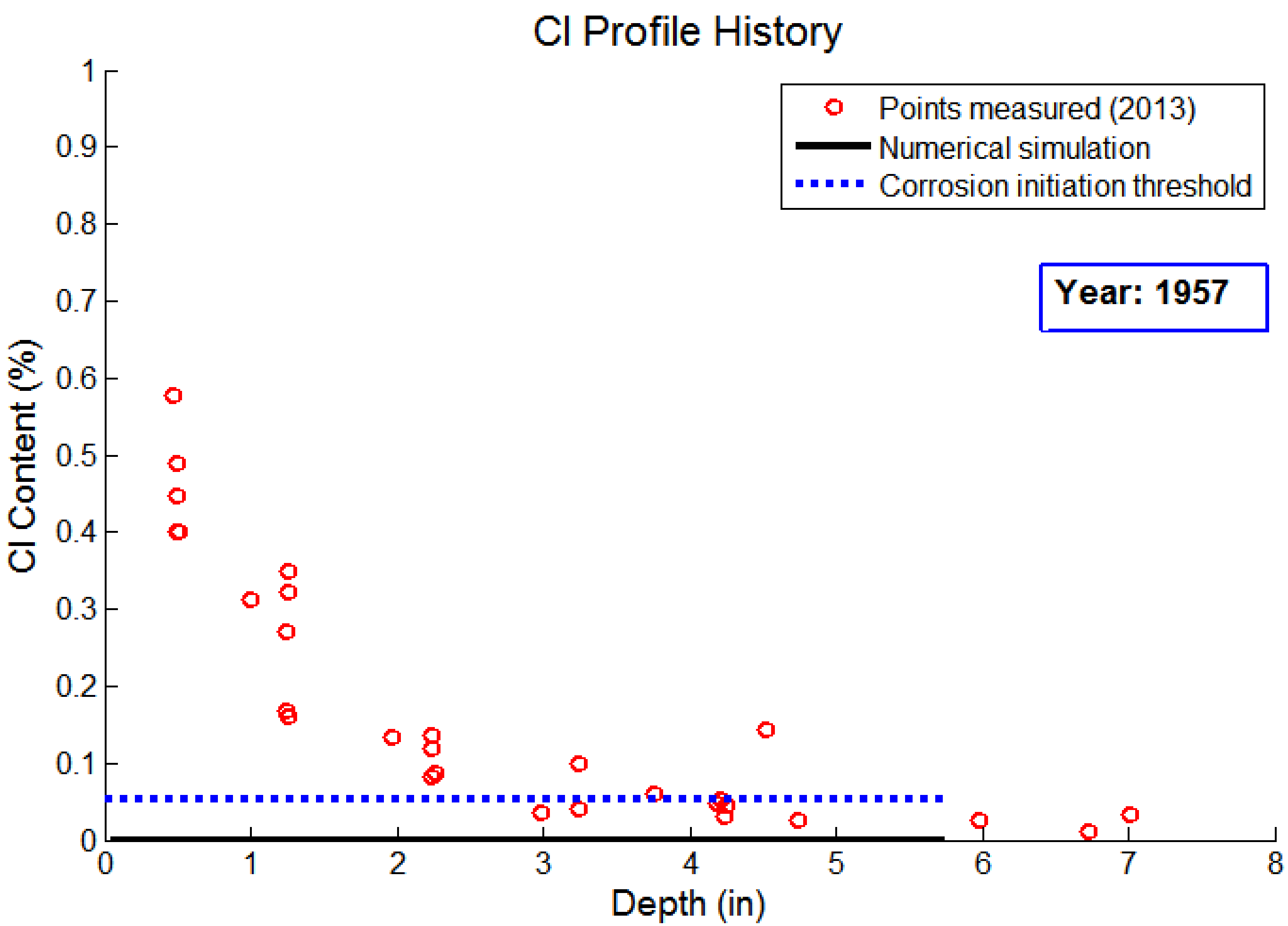
Past Repairs



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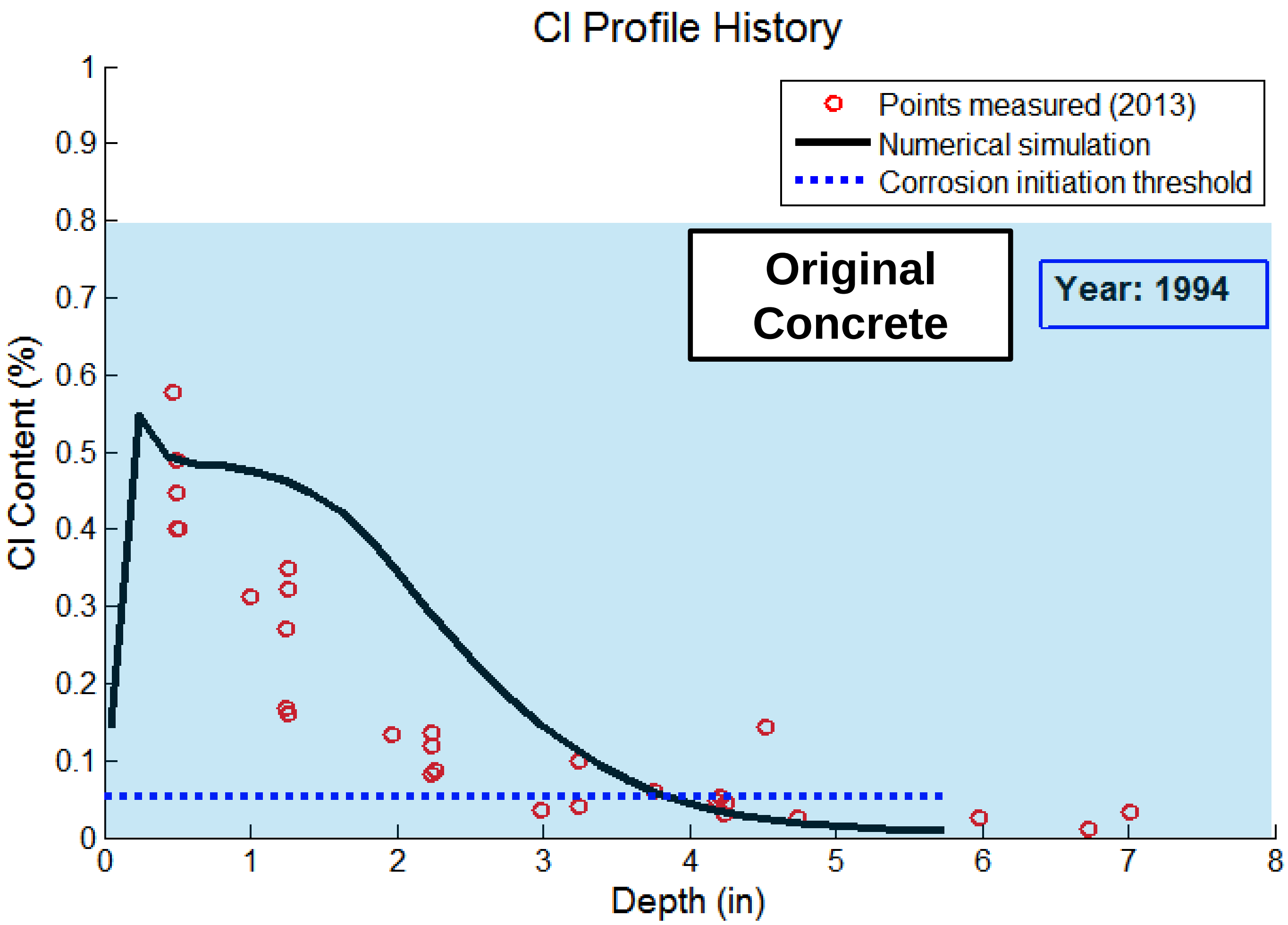
Past Repairs



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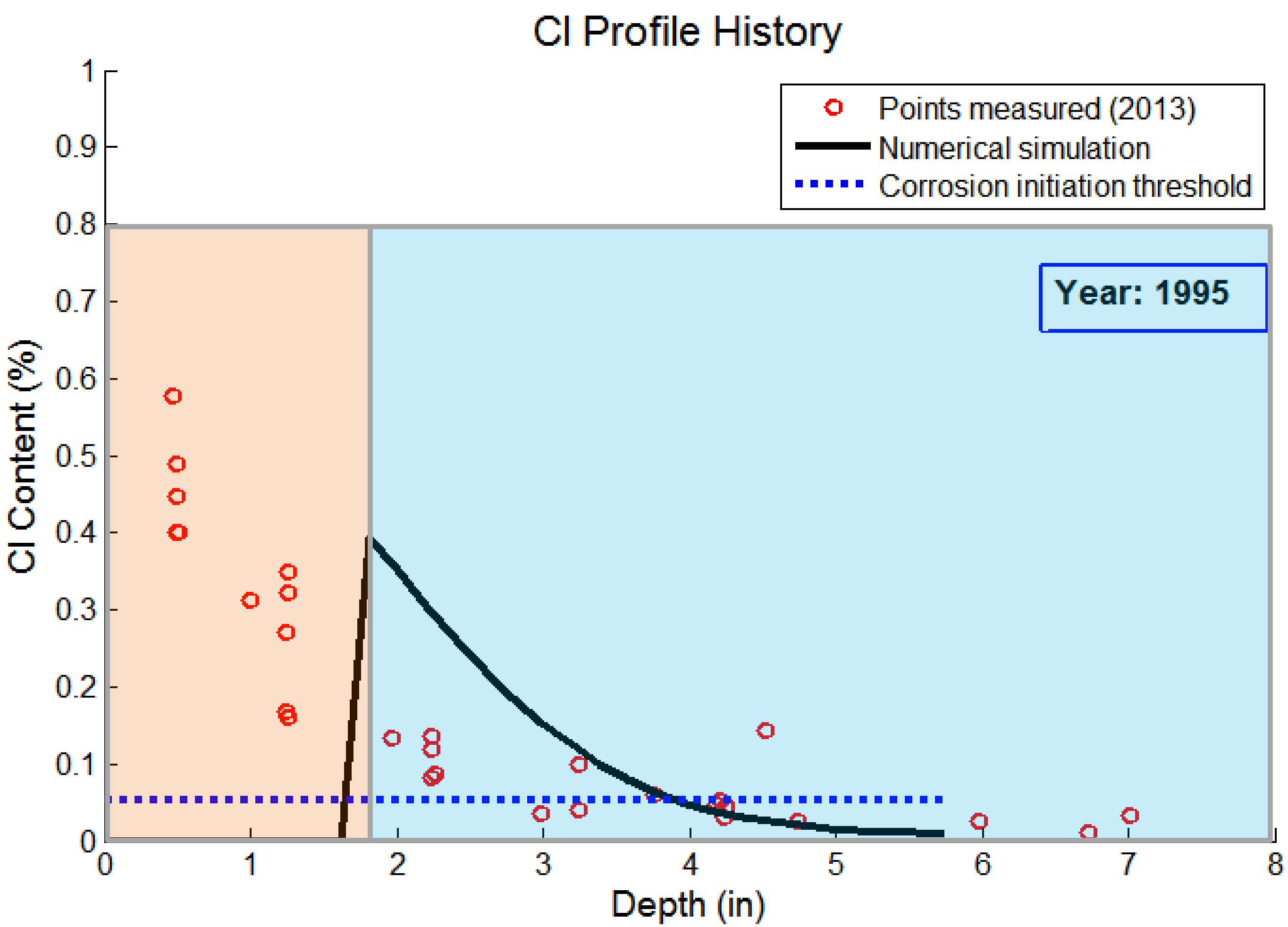

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Extending STADIUM® use to asset management

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Asset management

Extend single structure protocol to clusters of concrete elements

- Prioritize intervention.
- Plan intervention.
- Optimize maintenance operations.
- Optimize costs.

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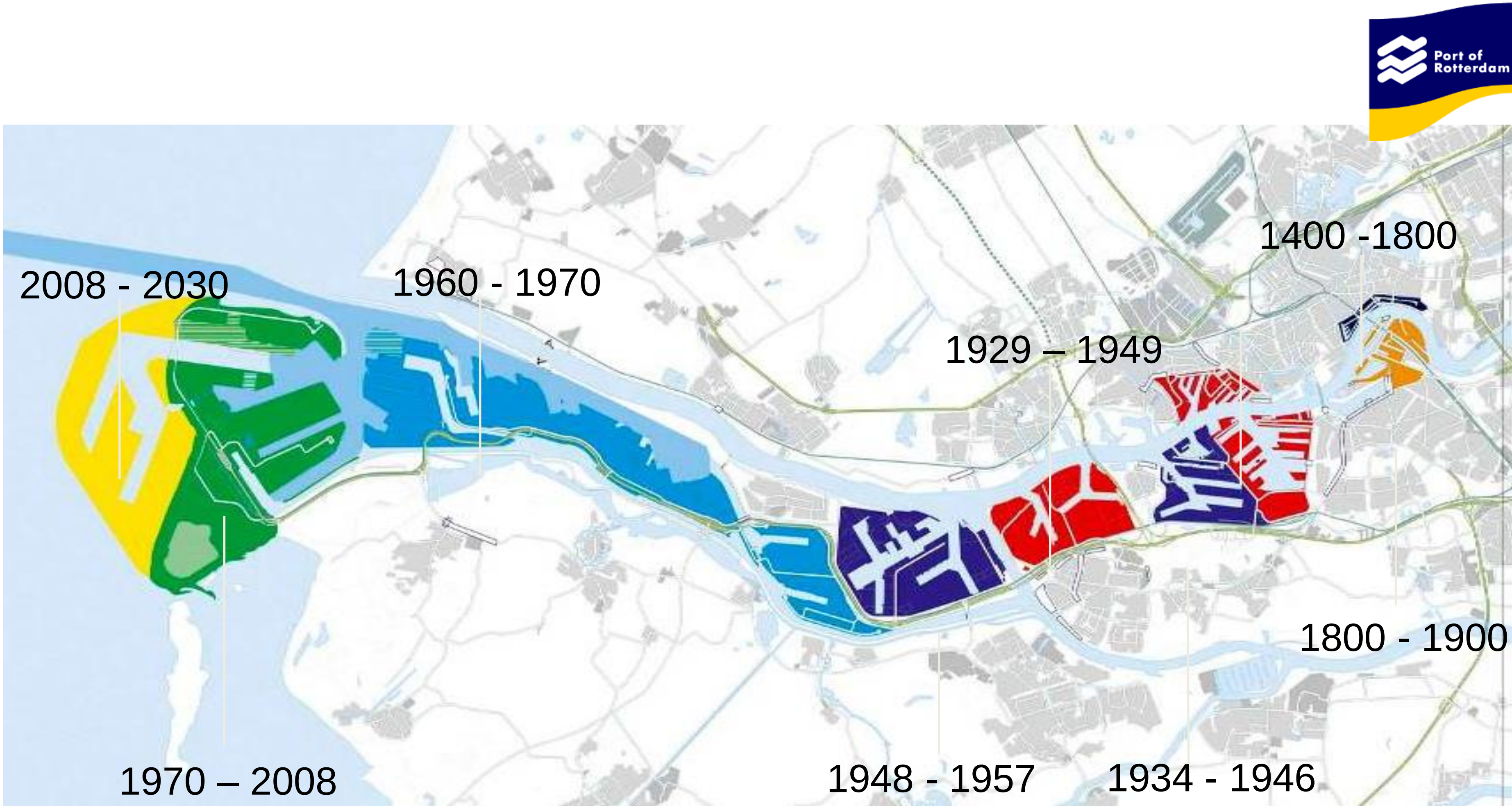
Asset Management – PoR experience



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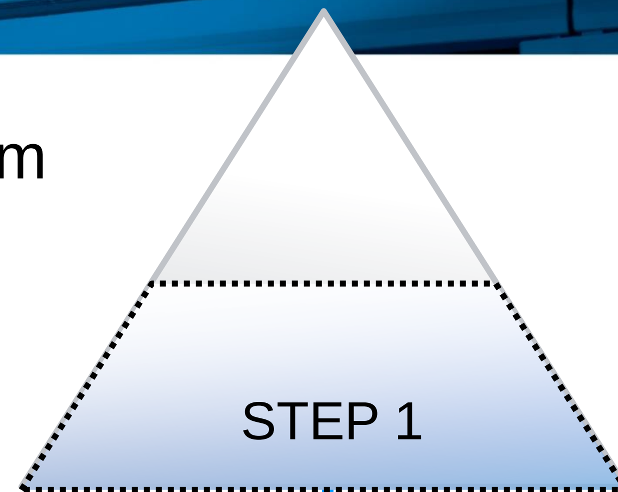
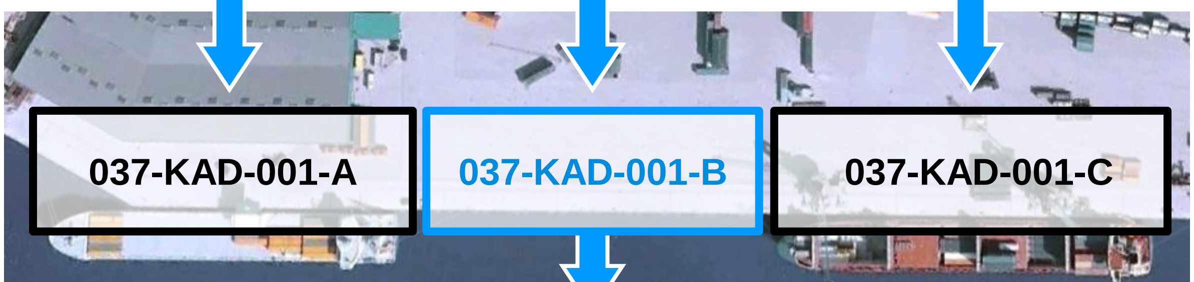
Asset Management – PoR experience

KMS - Kademuren Modellering Systeem





Inspection Request

- **Concrete**
  - Coring
    - Mechanical Testing
    - STADIUM® Testing
  - Visual Inspection
- **Steel**
  - Corrosion Measurements
  - Pitting Evaluation

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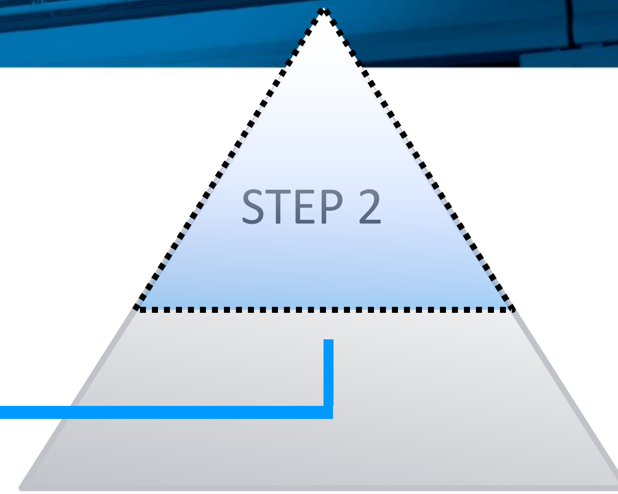
Asset Management – PoR experience

KMS - Kademuren Modellering Systeem



Degradation Analysis per Zone and Element
Evaluate Degradation with STADIUM®

Post Treatment Analysis

For each Zone/Element combination → Select the most critical Zone/Element combination

- Schedule Next Inspection
- Close Monitoring Required
- Repair

→ Critical Year (Trigger/Intervention)

→ Maintenance Proposal

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THANK YOU!

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