

HOW TO TREAT CORROSION ?



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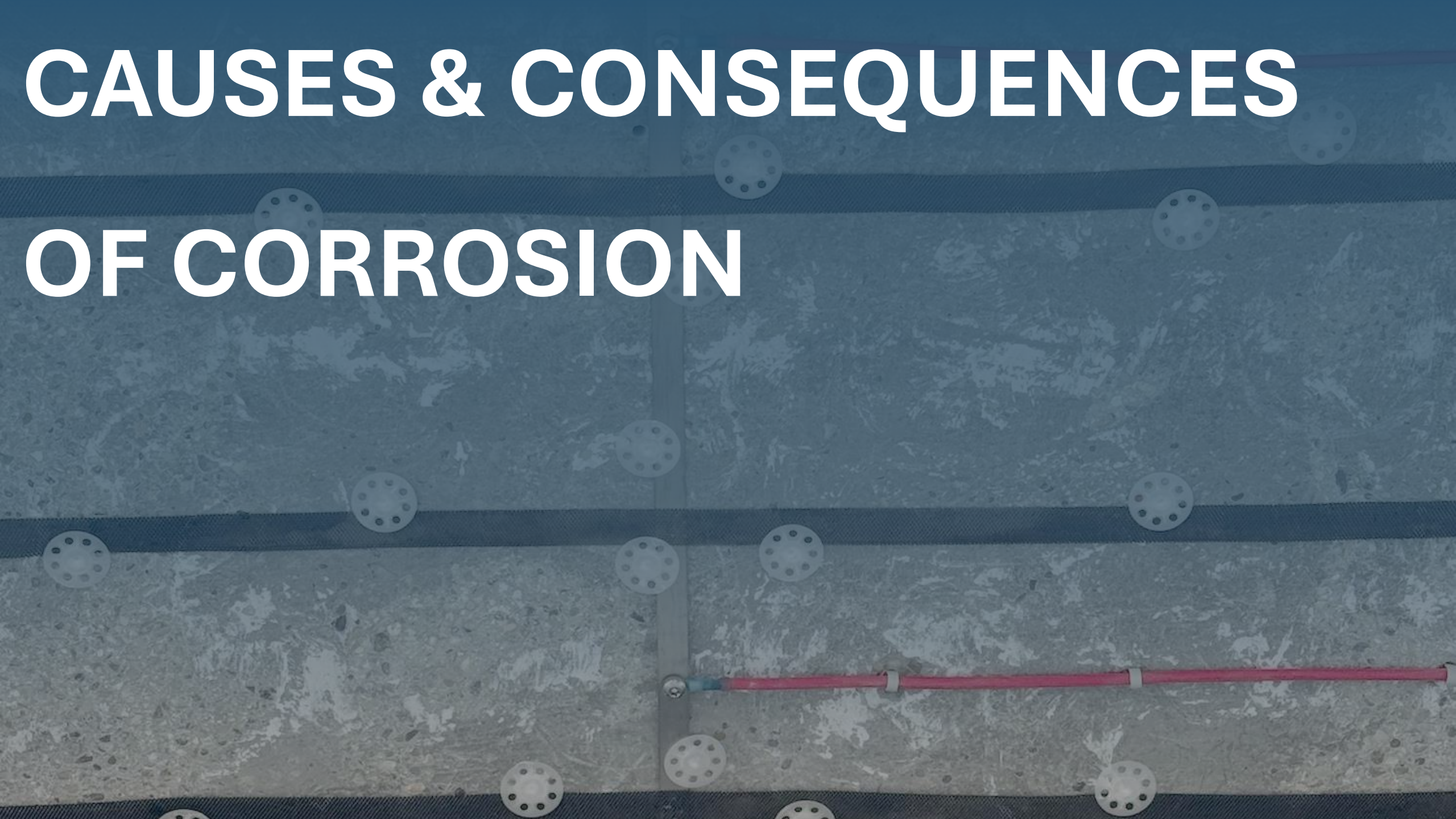
2. Corrosion Diagnostic

3. Corrosion Treatment

4. Case Study



CAUSES & CONSEQUENCES OF CORROSION



NO SECTOR IS IMMUNE TO CORROSION

1st cause of premature ageing for 80% of structures.



CORROSION CAUSES

3 conditions must be gathered



Presence of an electrolyte

- Concrete contains enough water (interstitial solution) to enable the passage of current (even when it seems dry)



Presence of an oxidant

- Dissolved oxygen reacts with electrons released by steel to form rust (iron oxides)



Steel Depassivation

- The protective film (passive) of steel is destroyed by
 1. Carbonation of concrete
 2. Chloride pollution



CORROSION CAUSES

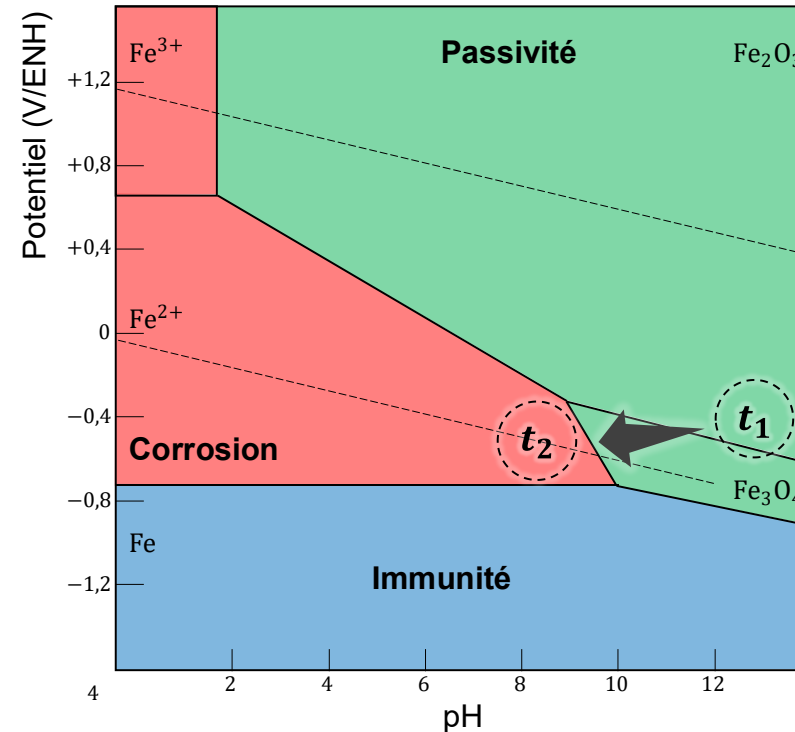
1) Carbonation of concrete

CO_2 penetration by concrete porosity

Decrease of pH (<9) of interstitial solution

Dissolution of the passive film which initially protected the steel.

Carbonated concrete (pH<9)
Corrosion area



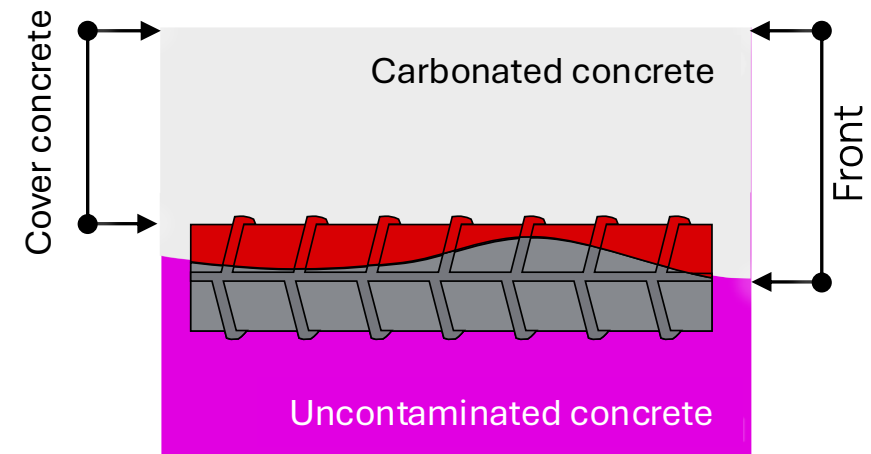
New concrete (pH \approx 13)
Passivation area

CORROSION CAUSES

1) Concrete Carbonation

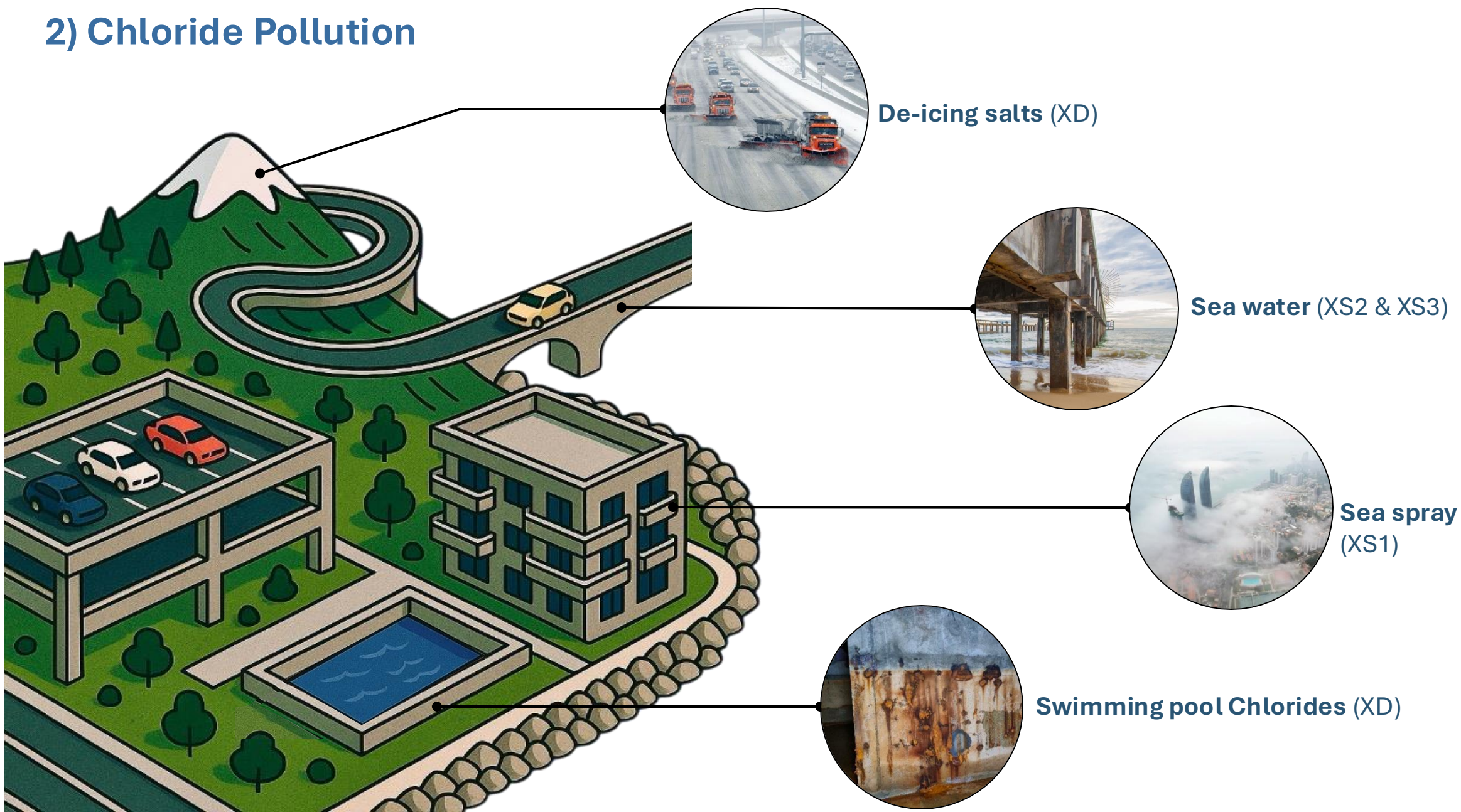
The depth of carbonation can be assessed by spraying a coloured indicator

The phenolphthalein remains **purple in uncontaminated areas** and becomes **transparent in carbonated areas**



CORROSION CAUSES

2) Chloride Pollution



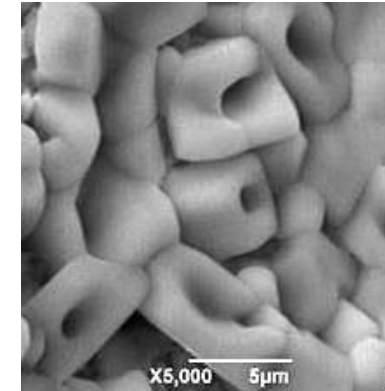
CORROSION CAUSES

2) Chloride Pollution

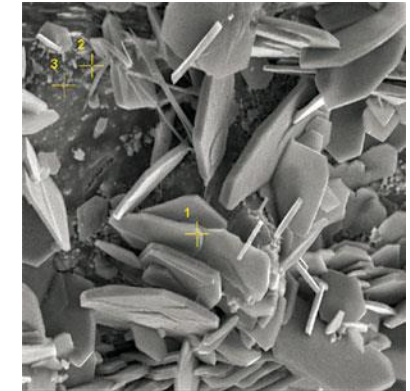
Chloride are present in **2 forms**:

- **Free Chlorides**: present in the pore solution, they are responsible for corrosion initiation.
- **Bound Chlorides**: chemically (Friedel's salt) or physically (adsorption on hydrates)

Free Chloride

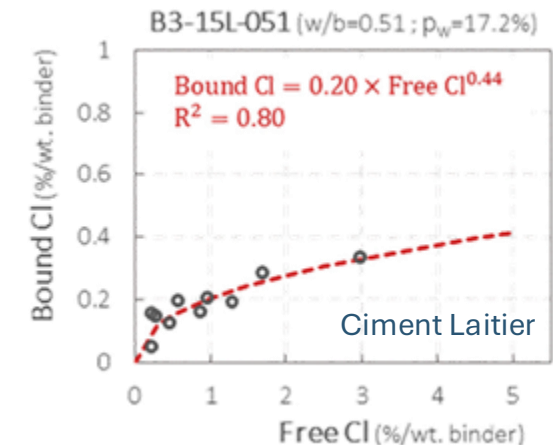
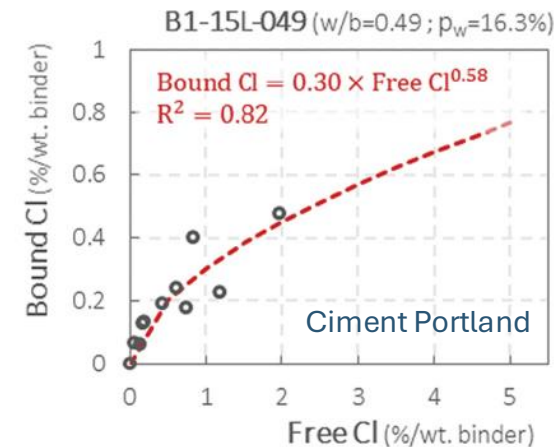


Friedel's salt



The **binding capacity** of the cement matrix (**isotherm**) depends on concrete composition

Binding Isotherm



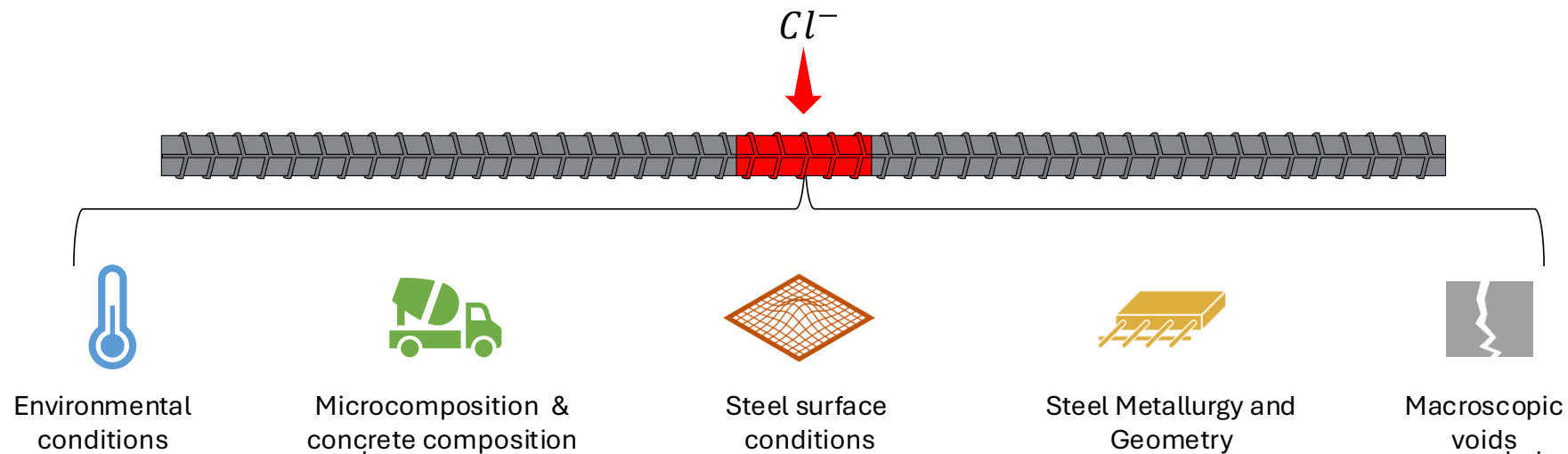
CORROSION CAUSES

2) Chloride Pollution

Chlorides have a **strong oxidizing effect** on steel.

Corrosion initiate when free chlorides reach steel in sufficient quantity in a located area.

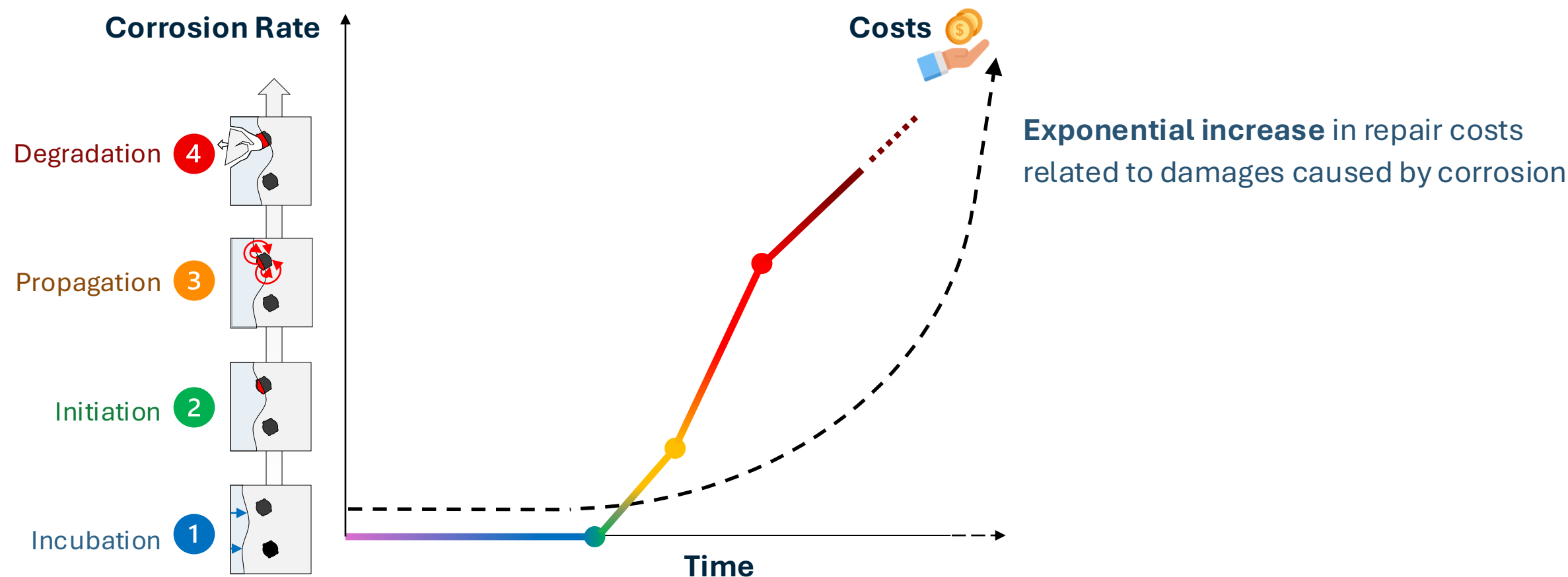
This corrosion initiation threshold depends on **multiple parameters** (Angst & al, 2011)



CORROSION CONSEQUENCES

Service life in 4 periods (Tutti)

Effects of corrosion are similar, whatever its origin (chlorides or carbonation)



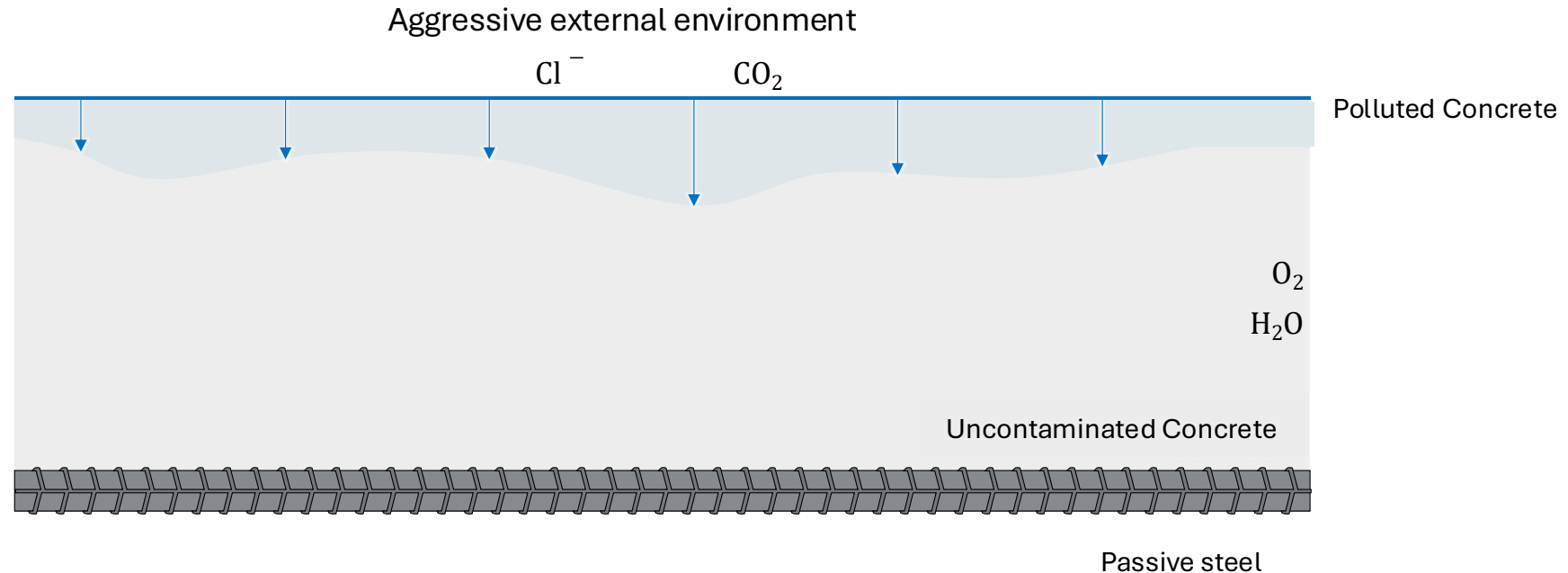
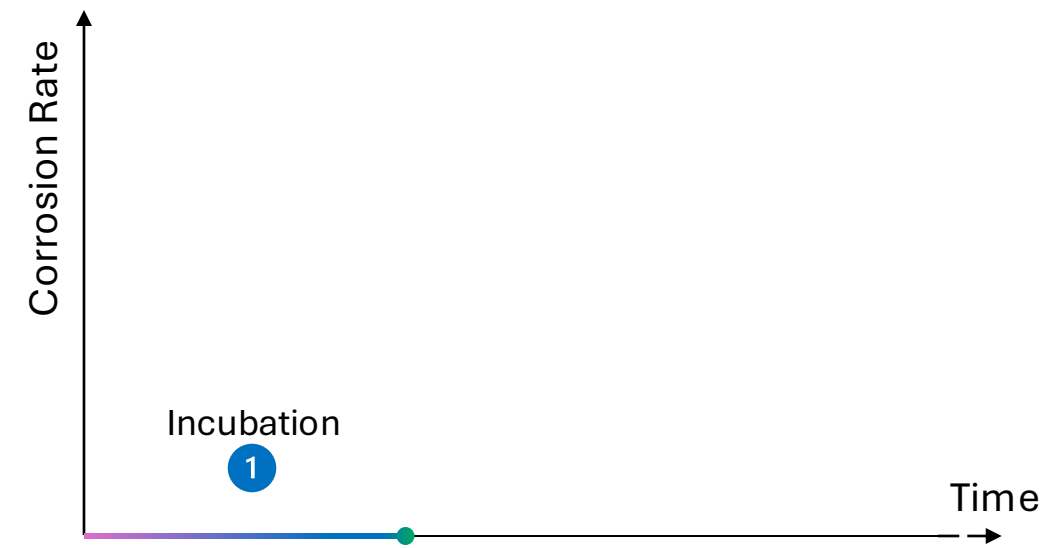
CORROSION CONSEQUENCES

Period 1 : Incubation

Transport of aggressive agents through concrete cover

Duration of the period is variable and function of:

- Exposition
- Concrete cover
- Physicochemical features of the concrete



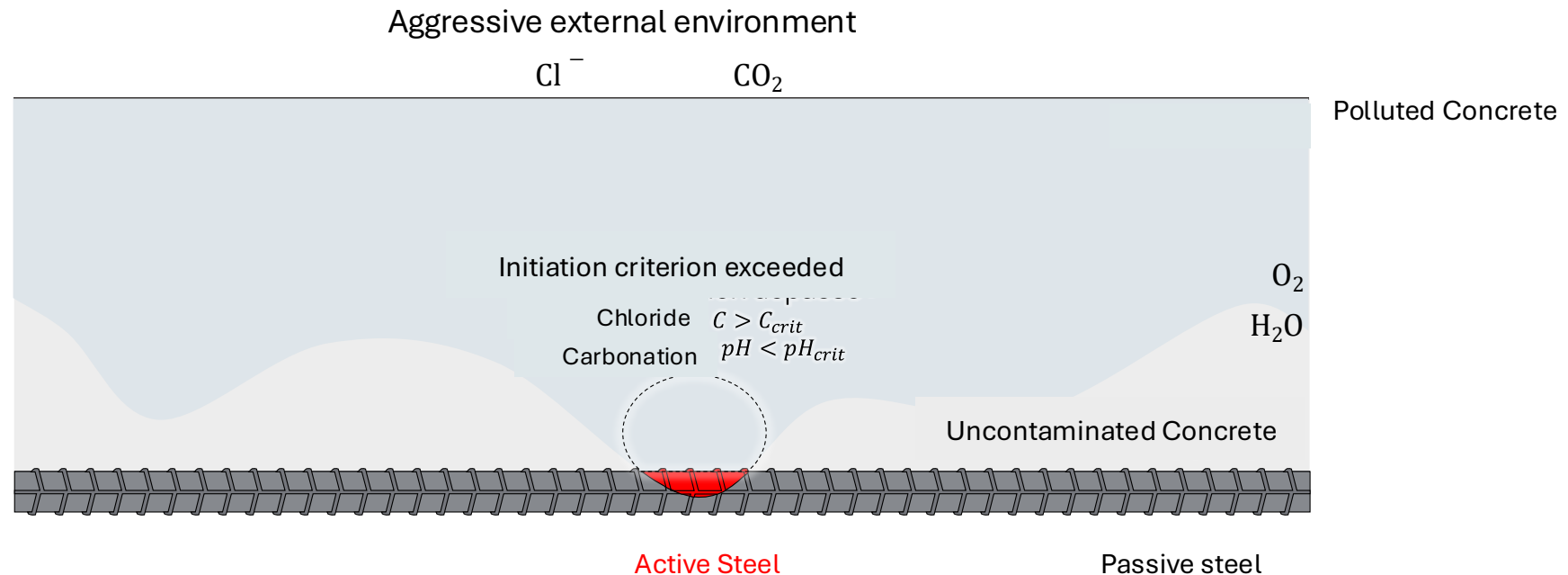
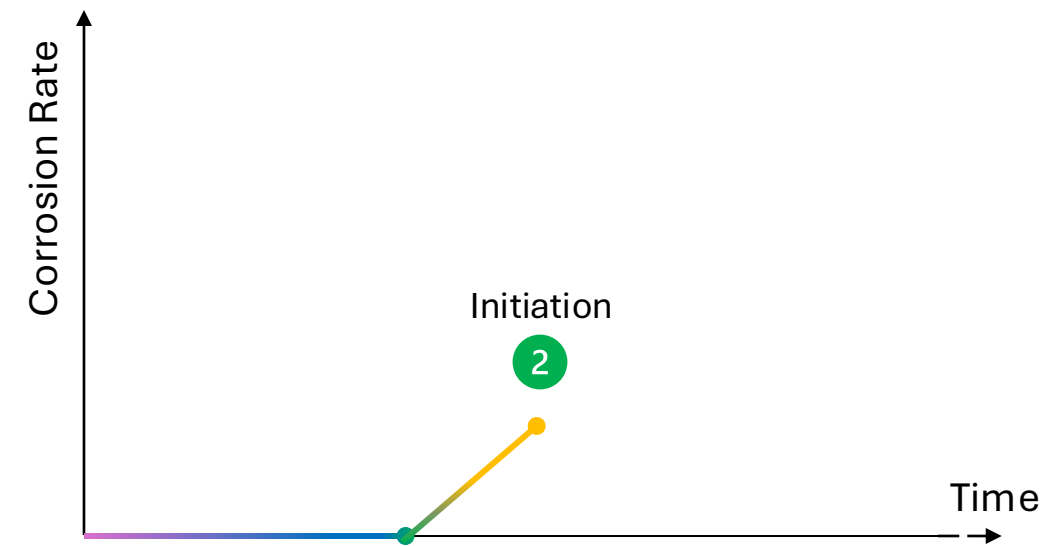
CORROSION CONSEQUENCES

Period 2 : Initiation

Local dissolution of the protective passive layer

Initiation criterion:

- Chloride: chloride concentration $>$ critical concentration (variable)
- Carbonation : $\text{pH} <$ critical $\text{pH} \sim 9$

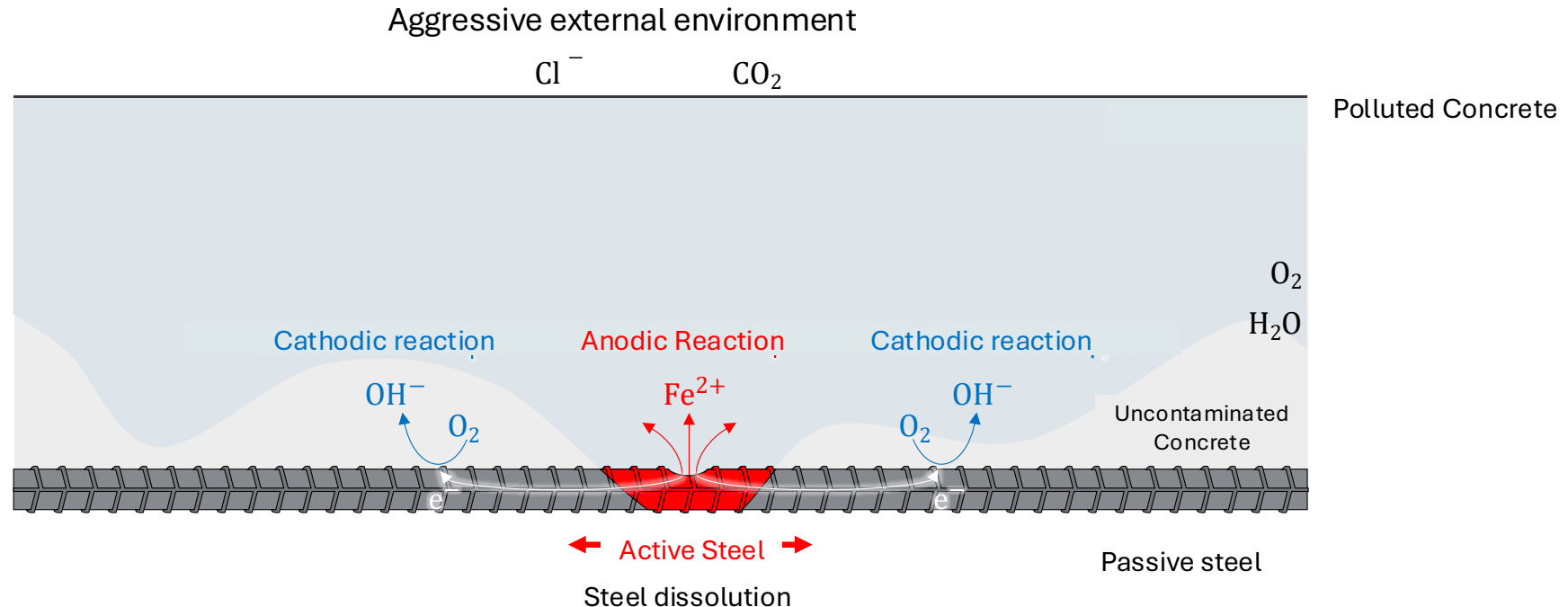
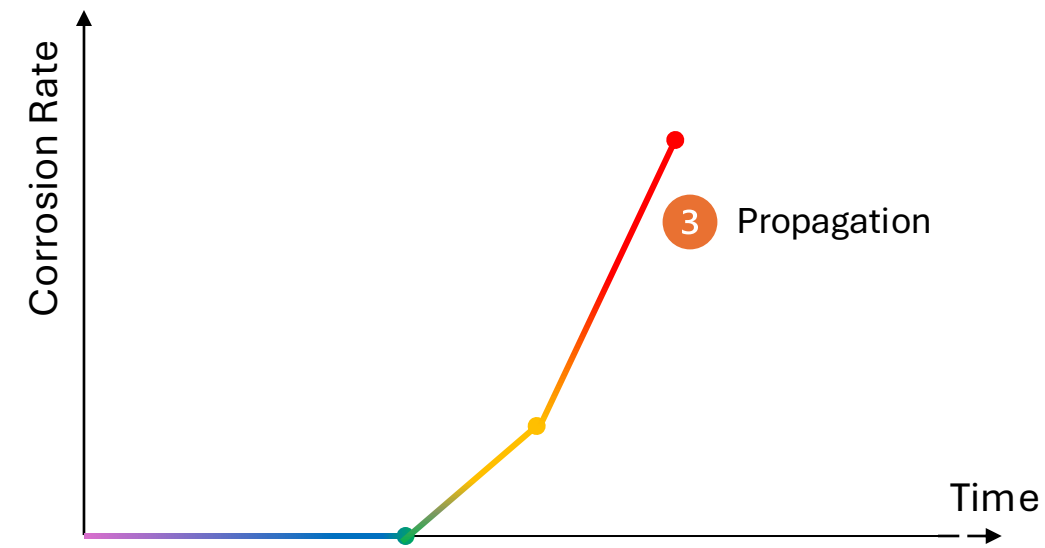


CORROSION CONSEQUENCES

Period 3 : Propagation

Galvanic cell between **active steel** and **passive steel**:

- **Anodic** reaction: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$
- Cathodic reaction: $2 \text{H}_2\text{O} + \text{O}_2 + 4\text{e}^- \rightarrow 4 \text{OH}^-$



CORROSION CONSEQUENCES

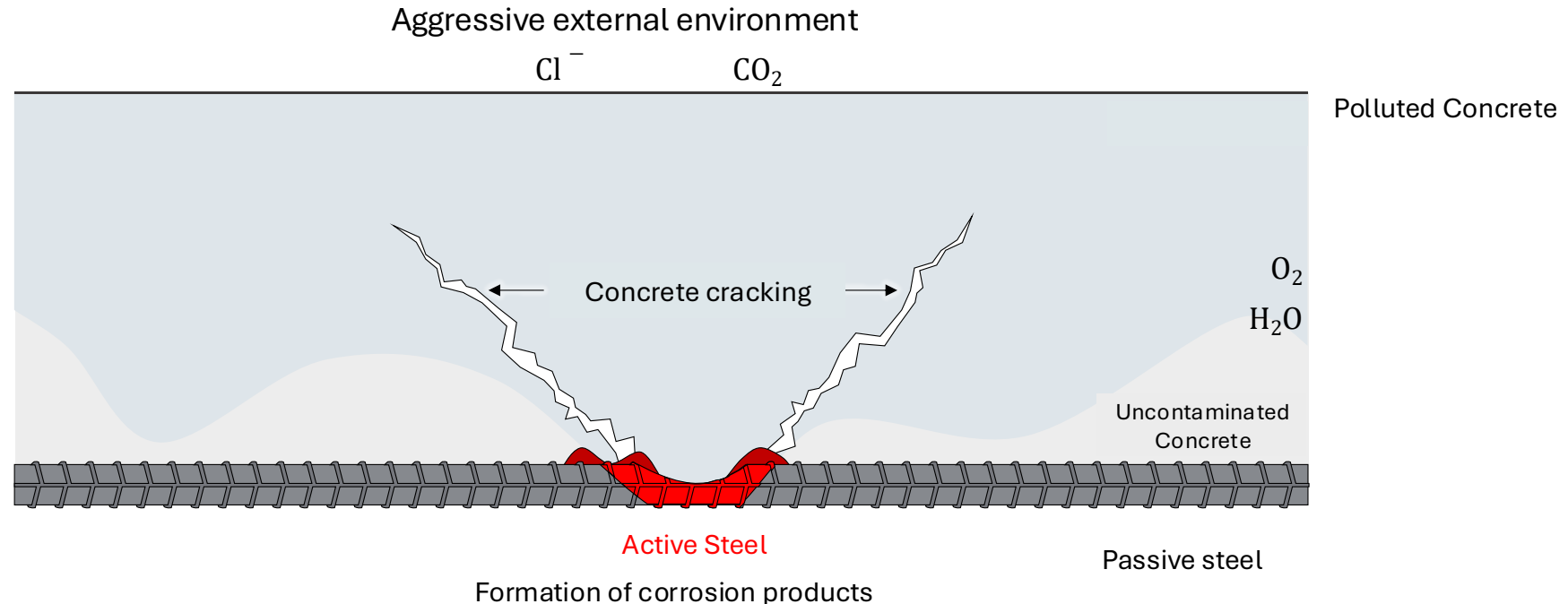
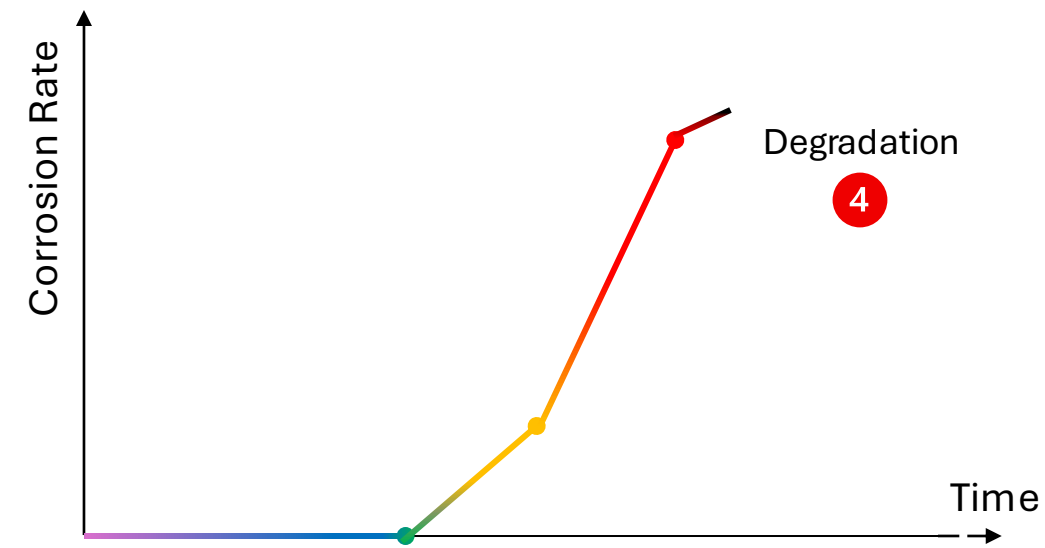
Period 4 : Degradation

Formation of **expansive corrosion products**

Cracking of the concrete cover

First visible signs of corrosion

→ Alert of the project owner



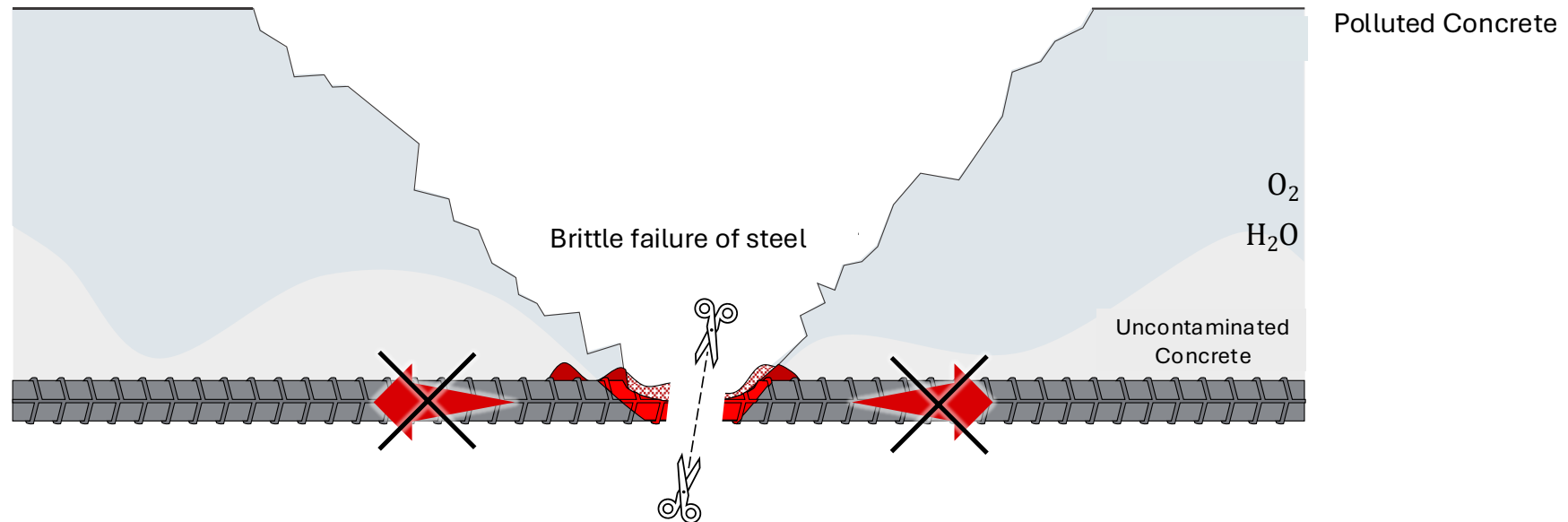
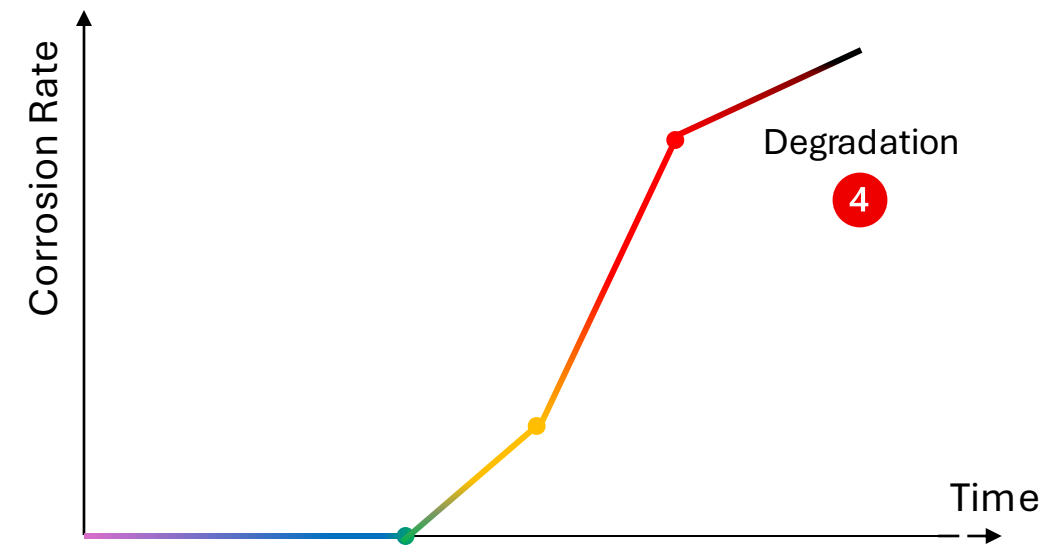
CORROSION CONSEQUENCES

Period 4 : Degradation

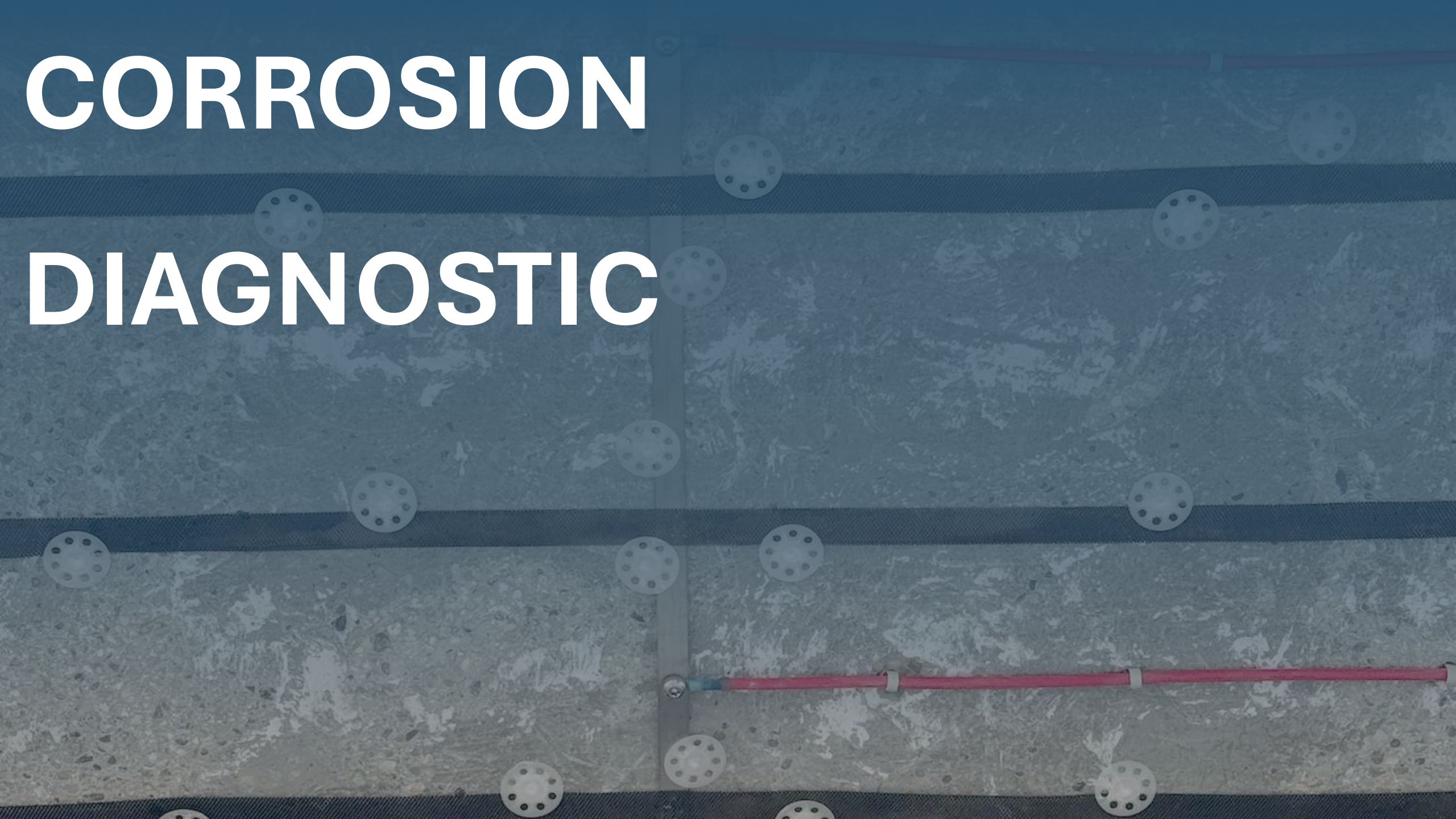
Concrete cover spalling

Loss of load-bearing capacity and ductility

Brittle failure of the structure



CORROSION DIAGNOSTIC



CORROSION DIAGNOSTIC

Principes & Objectifs

Corrosion diagnostic should be able to:

- **Characterize the structure** within its environment
- **Confirme corrosion pathology**
- **Characterize this pathology** (nature, extent and activity)

This **information is essential** to:

- Defining a **monitoring program**
- **Recommending a suitable treatment solution** for the rehabilitation of the structure
- Providing **input data** to the repair and treatment of the structure



CORROSION DIAGNOSTIC

Inspection of the structure



In practice:

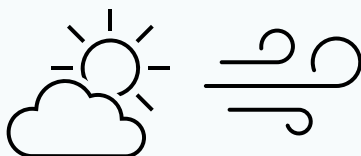
- Directly on the structure
- Televisual
- Drone



Environmental conditions

Exposure of the façade to weathering

Opened or enclosed environment



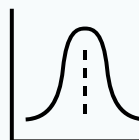
Numerical Representativeness

10% to 20% of the structure according to its dimensions

Example :

10 balconies analysed over a 100 balconies residence

2 columns over a 20 columns garage



Bounding of the sample

At least one area showing visible deterioration (for pathology assessment)

At least one area appearing sound (defining the upper limit of the structure's condition)



CORROSION DIAGNOSTIC

Characterization of steel rebars



In practice

- Spacing and diameter of rebars
- Position (concrete cover)
- Total steel surface



What is it for?

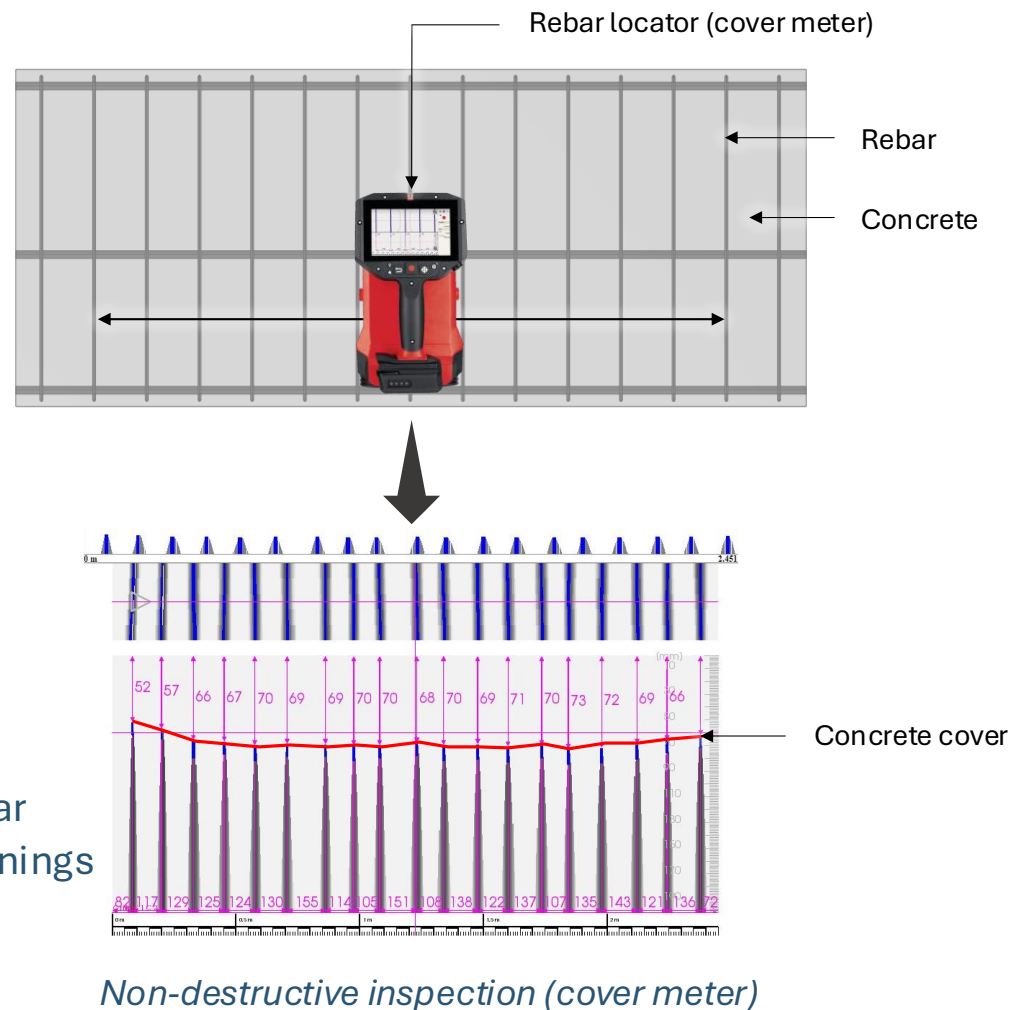
- Assess the extent of the pathology
- Establish the connections to the rebar
- Design cathodic protection
- Reassess the structure



Destructive inspection

TWO METHODS

- Non-destructive: Rebar locator & Radar
- Destructive: localized exploratory openings



CORROSION DIAGNOSTIC

Electrical continuity



In practice

- Reinforcement mapping (rebar locator, radar)
- Exposing and cleaning the reinforcement (concrete chipping)
- Measurement using a **high-impedance multimeter**



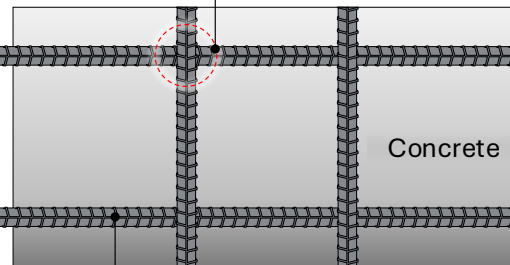
What is it for?

- Perform **potential mapping surveys**
- The proper functioning of **cathodic protection**

Multimeter



Metallic contact



Rebar



Exposure of steel and connection with an alligator clip

3 METHODS :

- Indirect: with a reference electrode
- Direct: between two points
- Polarization: current injection

Potential mapping



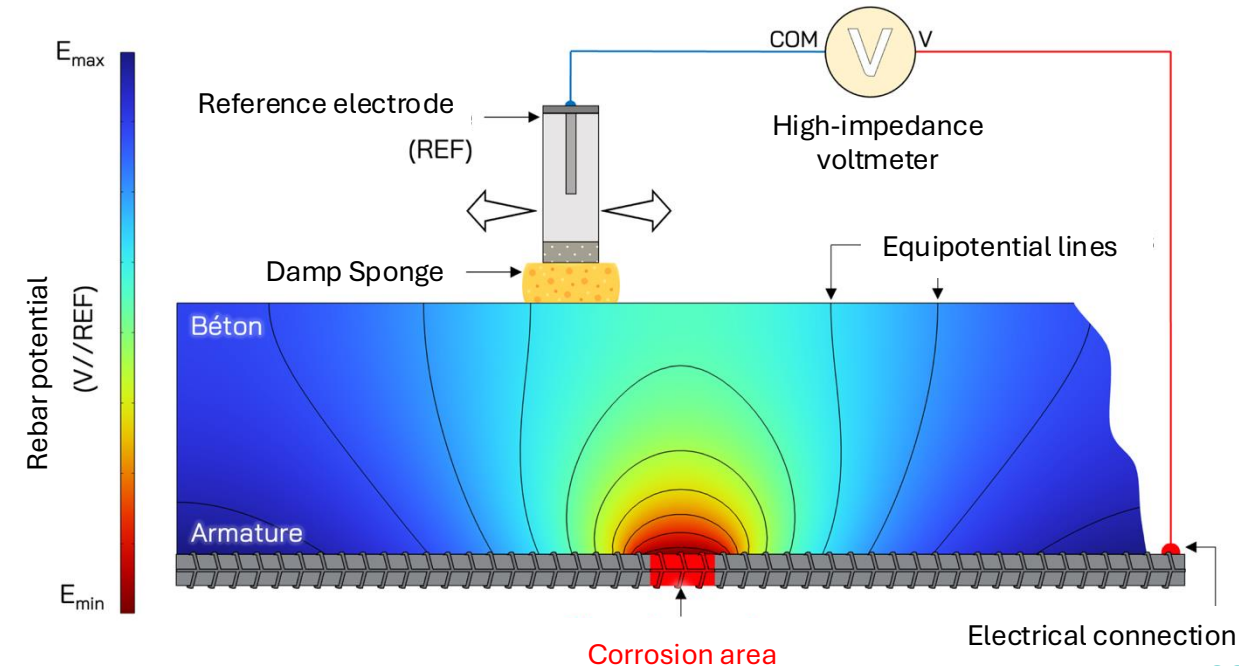
In practice

- Measurement of the potential between the rebar and an external electrode.
- Preparing the area: bare concrete, damp, non-dripping
- Orthogonal mesh, post-processing using a specific software.



What is it for?

- Assess and locate the pathology
- Identify the sampling (origin/pathology activity)
- Potential gradients (pathology activity)
- Exclusion of the uncontaminated areas



CORROSION DIAGNOSTIC

Potential mapping



In practice

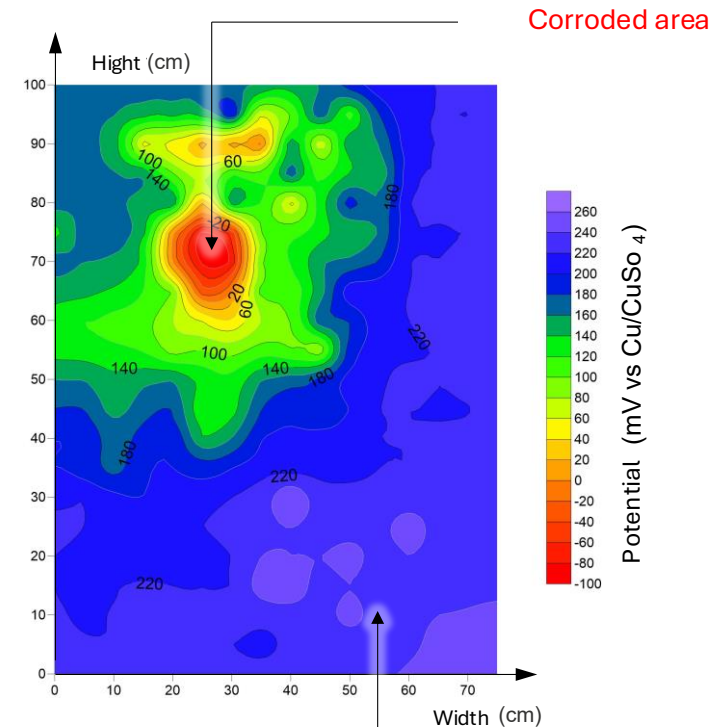
- Measurement of the potential between the rebar and an external electrode.
- Preparing the area: bare concrete, damp, non-dripping
- Orthogonal mesh, post-processing using a specific software.



What is it for?

- Assess and locate the pathology
- Identify the sampling (origin/pathology activity)
- Potential gradients (pathology activity)
- Exclusion of the uncontaminated areas

Core Sampling



Uncontaminated area

CORROSION DIAGNOSTIC

Depth of carbonation



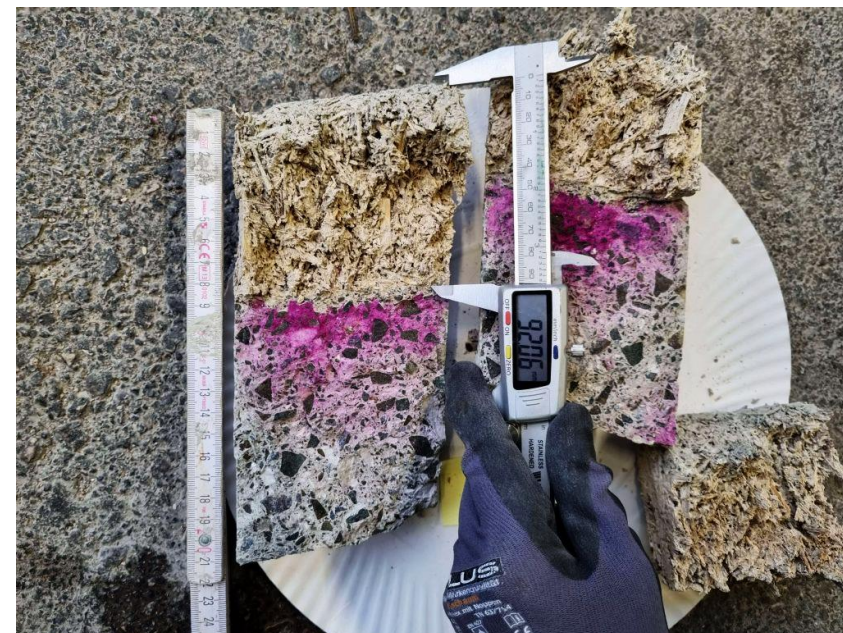
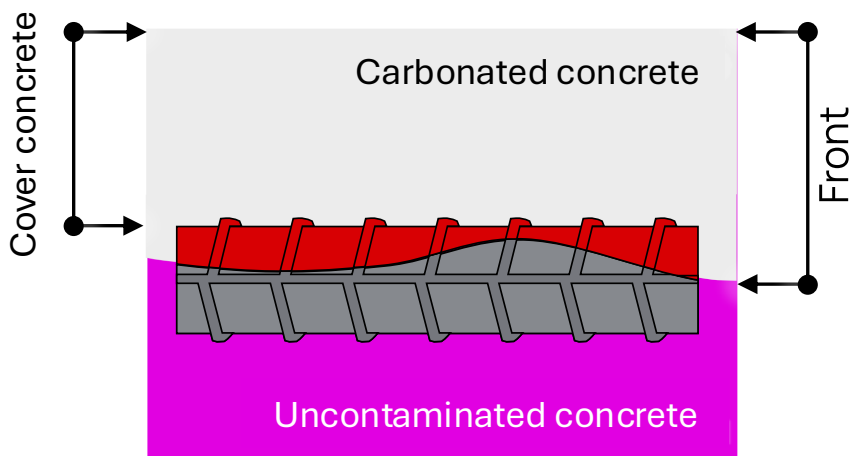
In practice

- Measurement on a fresh, cleaned fracture surface or on a core sample
- Measurement of the depth of carbonated concrete (coloured indicator)
- Comparison of this depth to the concrete cover of the reinforcement



What is it for?

- Acidification of concrete: $\text{pH} < 9$
- All areas in the uncoloured area are carbonated
- Informs us about the **origin** and the **activity** of the pathology



Coloured indicator	Acid form Carbonated Concrete	Transition range (pH)	Basic form Non-Carbonated Concrete
Phenolphthalein	colourless	8,2 to 10,0	pink
Thymolphthalein	colourless	9,3 to 10,5	blue

CORROSION DIAGNOSTIC

Determination of chloride content



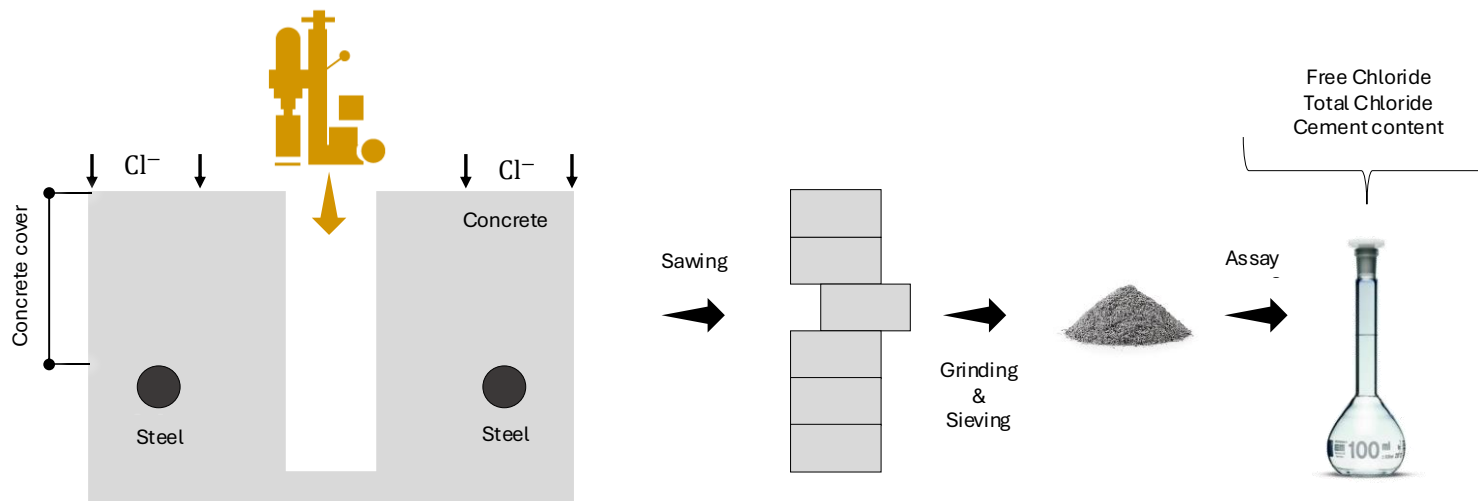
In practice

- Measurement of the chloride concentration profile (free & bound chloride)
- Comparison of the profile to the critical threshold



What is it for?

- The initiation threshold varies, in particular, with the type of cement
- Indicates the presence and origin of Cl^- (endogenous, exogenous)
- Provides information on the **origin** and **activity** of the pathology



Sea spray and sea water




De-icing salts




Salts & Chlorine of swimming pools

CORROSION DIAGNOSTIC

Other measurement: Concrete resistivity

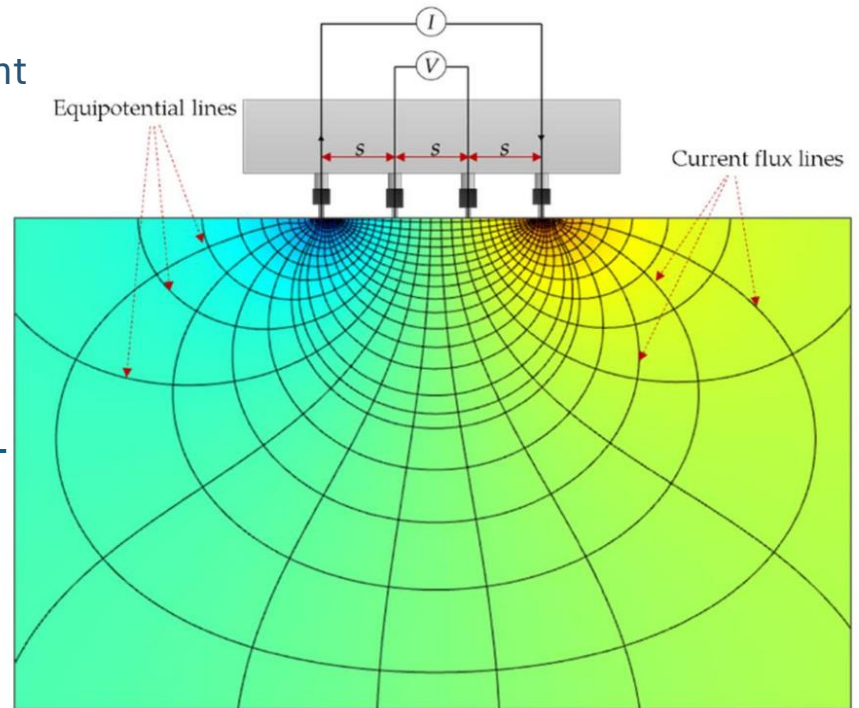
-  **In practice**
- Injection of a current and measurement of a difference in the potential
 - Resistivity describes the opposition of the concrete to the flow of the current

-  **What is it for?**
- Part of the diagnostic **evidence**
 - Allows structural elements to be grouped during zoning
 - Essential for the **design** of the treatment



TWO METHODS

- Onsite: Wenner method
- In laboratory: on core samples



CORROSION DIAGNOSTIC

Other measurements: Vibration analysis



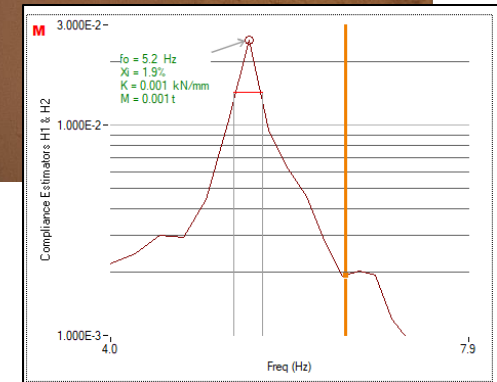
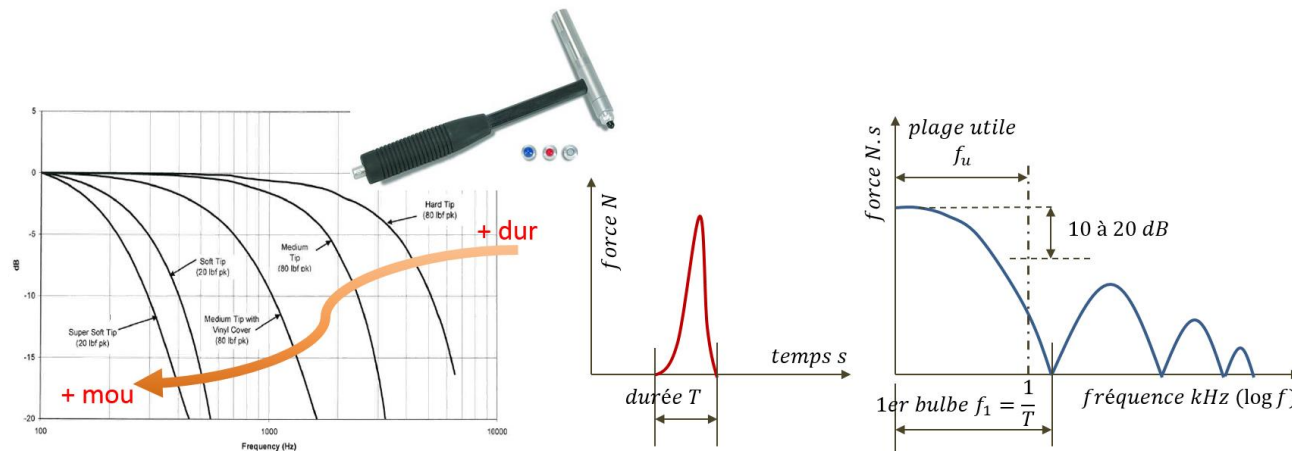
In practice

- Vibrational excitation of the balcony using an impact hammer
- Recording the vibrational response followed by dynamic analysis



What is it for?

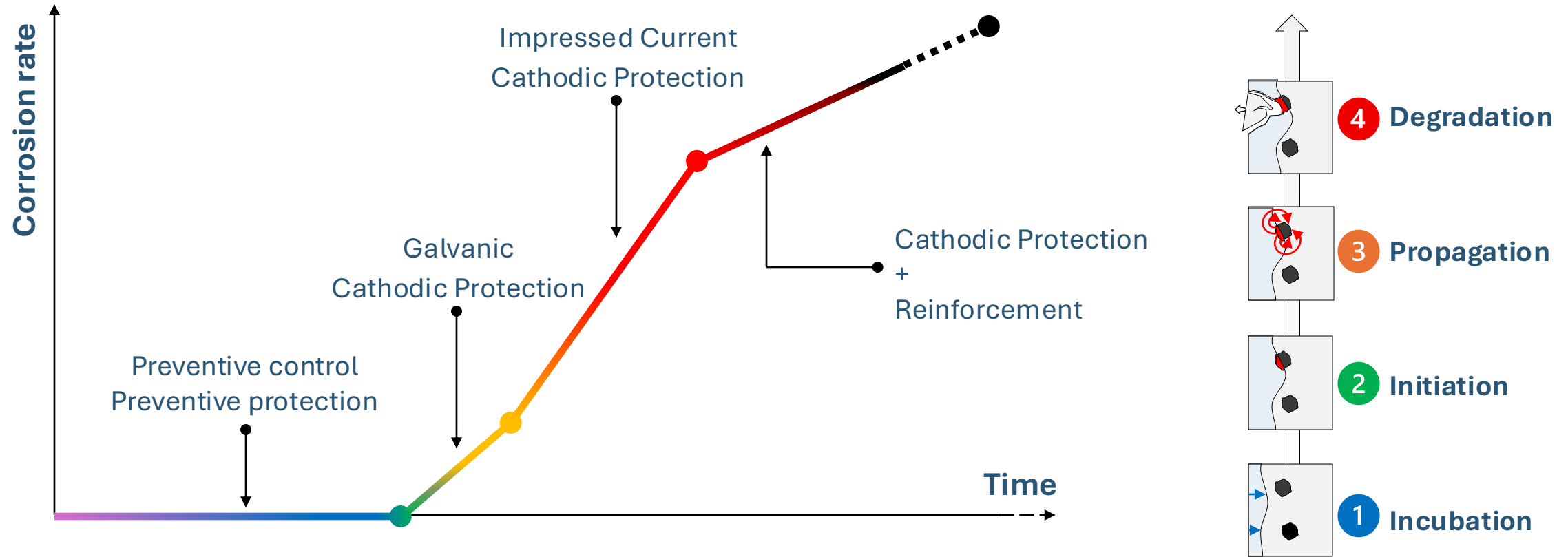
- Corrosion degrades the mechanical connections (flexibility)
- Distinction between sound and degraded balconies
- High-efficiency method: under 15 minutes per balcony



CORROSION DIAGNOSTIC

Recommendations

The whole set of measurements performed enables to recommend the **most suitable treatment**.



CORROSION TREATMENT



Repair, but how?

The **intervention strategies** generally recommended by **inspectors**...



**Traditionnal
Repair**



**Corrosion
Inhibitors**



**Dechlorination
& Realkalination**



**Cathodic
Protection**



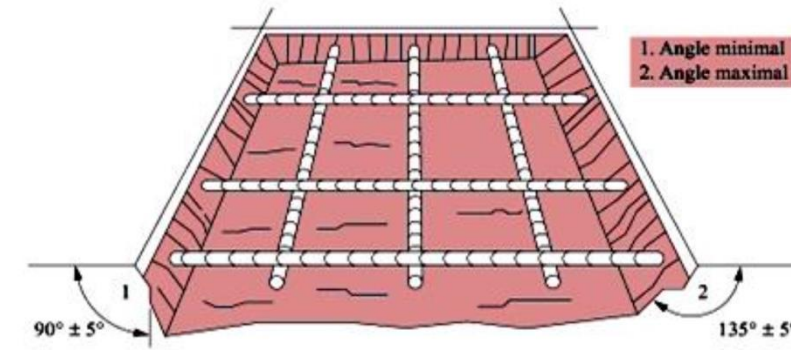
CORROSION TREATMENT

Traditional repair



Methodology

- Removal of deteriorated concrete (hammering, chipping tool, hydrodemolition)
- Replacement of severely corroded rebars (EC2 lap splice length)
- Cleaning of rebars - Application of a passivating primer
- Reconstitution of the concrete cover with a repair mortar (NF EN 1504)



Concrete Repair
(source: NF EN 1504-10)



What sustainability?



Rebar section loss needing steel
addition



Application of a passivating primer on the
rebars

CORROSION TREATMENT

Traditional Repair



Induced anode effect

Repaired area

- New concrete, high pH
- Steel rebar re-passivation

Adjacent area

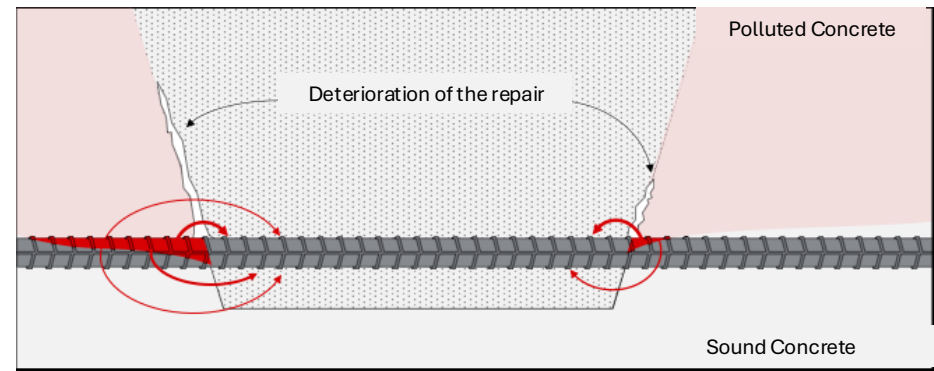
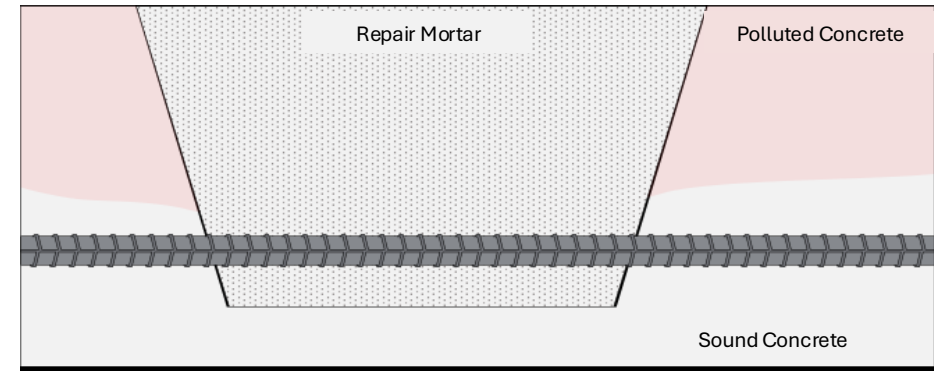
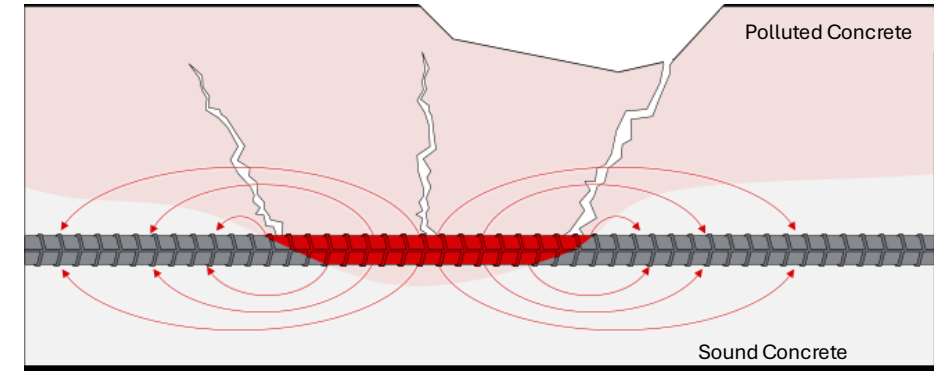
- Still carbonated or polluted by chloride concrete
- The reinforcement stays active

Electrochemical imbalance

- Repaired area = cathode
 - Degraded area = anode
- A current flows, initiating a new corrosion

Consequence

Corrosion **moves** on the periphery of the repairs,
The phenomenon can accelerate: **corrosion is quicker that before**



< 5 years after repair

Traditional repair



Induced anode effect



< 5 years after repairs

CORROSION TREATMENT

Traditional repair



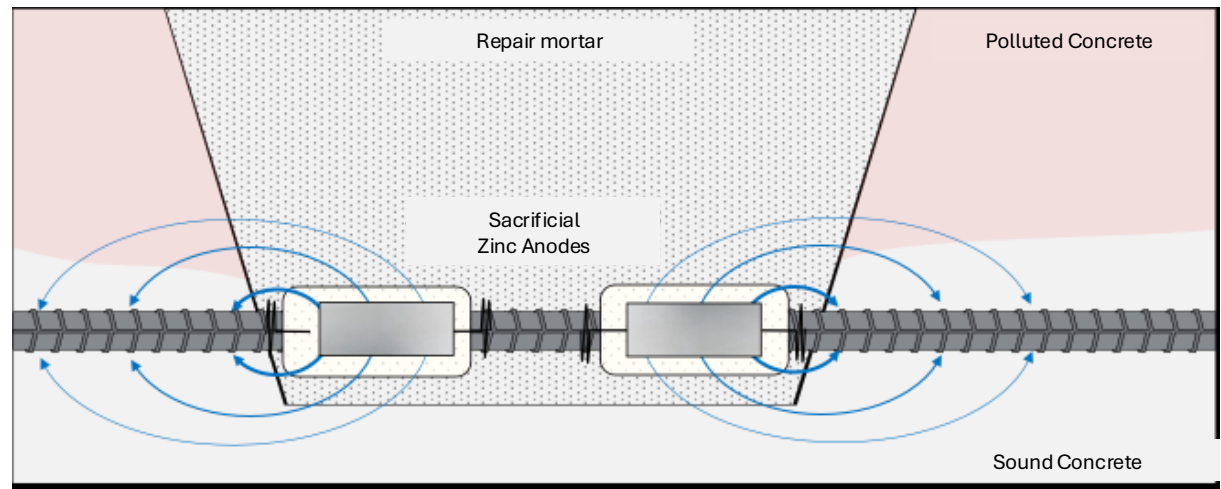
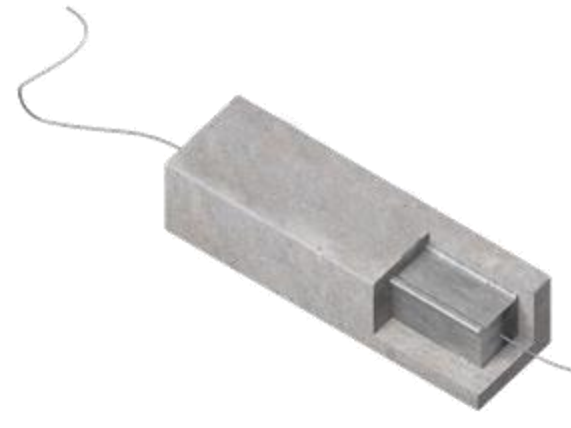
How to avoid this consequence?

Sacrificial anodes tied to the reinforcement:

- Sacrificial zinc core activated by a lithium enriched mortar
- Enlarge lifespan of the repair up to 10 years
- Works without any external power source



But there are several limits...

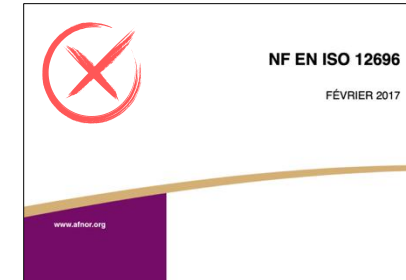


Traditional repair



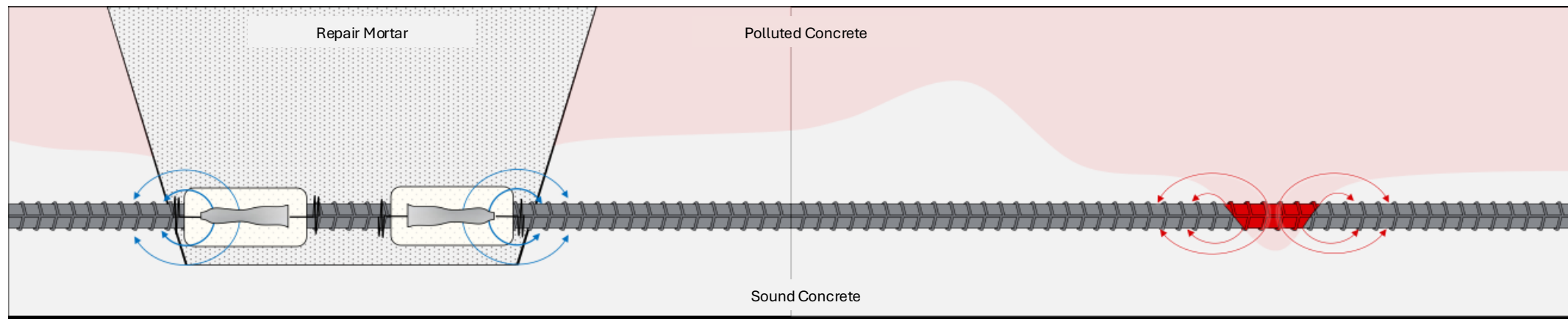
Limits of sacrificial anodes

1. This solution is **NOT** cathodic protection
(No monitoring system)



2. **Loss of anodes' efficiency**
(Passivation of zinc & Increase of the resistance)

3. **Initiation of new corrosion clusters**
(Out of reach for the anodes in non-repaired areas)



Corrosion inhibitors

3 mechanisms:

1. Anodic → reinforce the passivation layer
2. Cathodic → slow down dissolved oxygen reduction
3. Pore blockers → limit penetration of aggressive agents

Expected outcomes:

- Delay initiation of corrosion (extend of period 1 incubation)
- Reduce corrosion rate during propagation (delay of period 4 degradation)



What is the actual efficiency?

CORROSION TREATMENT

Inhibiteurs de corrosion

New limits:

- **Passive** chemical solution, **non-adjustable** in time
- **Non-guaranteed et variable** performance depending on the formulation, dosage and environment
- **No measurable long-term benefit** (FHWA RD-01-097 study)
- **Secondary effects:** Alteration of the cement matrix (porosity, resistance, rheology)

3. The corrosion inhibitors did not provide any protection against corrosion in the environments in which they were evaluated.



Kessler & al, 2007
Liu & al, 2024
FHWA RD-01-097, 2002



Figure 2-1. General view of the Elmwood Avenue bridge over NY Route 198, Buffalo, NY.

Re-alkalisation & Dechlorination

Operating procedure:

- Fixation of a metallic anode on the surface of facing
- Application of a cellulose soaked in an alkaline solution
- Connection of the rebar to the (-) terminal and the anode to the (+) terminal
- Application of a current ($\sim 1 \text{ A/m}^2$ steel) during several months
- Regular sampling
- Performance assessment (coloured indicator/ Cl^- determination)

Expected outcomes:

- Restauration of concrete pH: Realkalisation
- Extraction of chloride: Dechlorination



What is the actual efficiency?

Realkalination & Dechlorination



A lot of limits:

- **Limited protection**
 - Temporary Protection – corrosion resumes after 10/15 years
 - Treatment limited to the concrete cover of the first reinforcement layer
 - No electrochemical protection of the reinforcement (which can corrode)
- **Too high current:**
 - Hydrogen release et damage of steel/concrete interface
 - Does not apply to prestressed structures (risk of brittle failure)
- **Reaction of concrete:**
 - Formation of expansive compounds resulting from the reaction of alkalis with reactive aggregates



Nilsson & al, 2006
Siegwart & al, 2005
Bertolini & al, 2004
Andrade & al, 2001
Bennett & al, 1993

CORROSION TREATMENT

Cathodic Protection

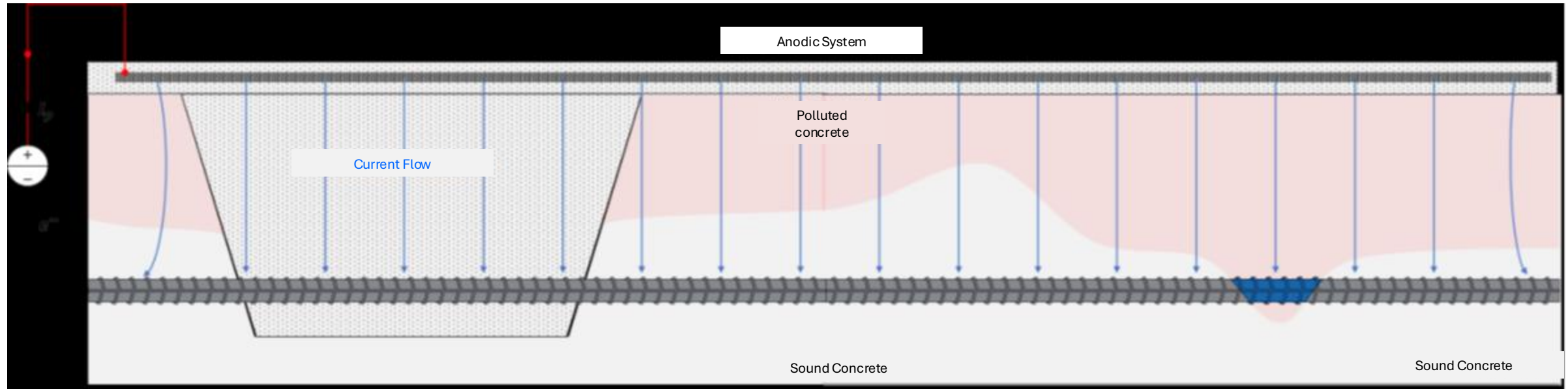


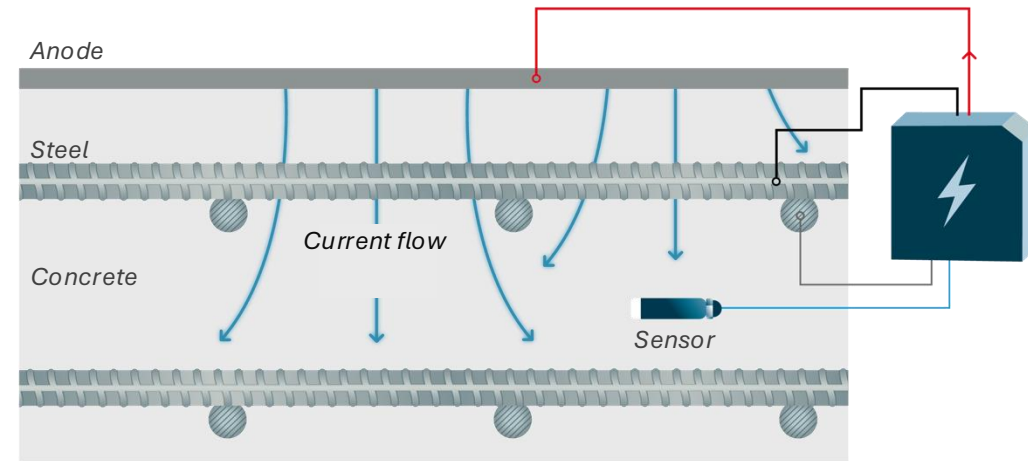
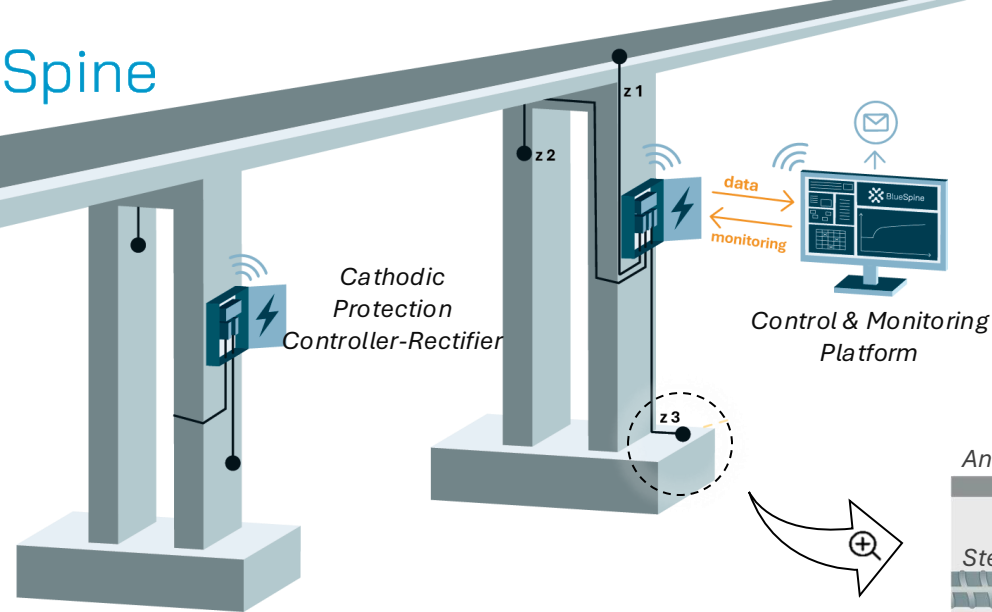
Then, how can we treat corrosion sustainably?

Cathodic Protection

Principle: Provide a direct electrical current through anodes to **cathodically polarize the steel**

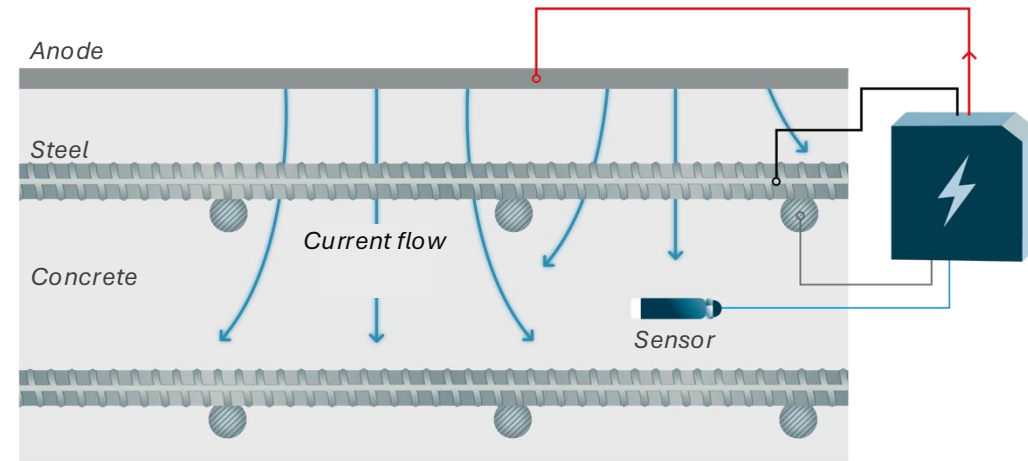
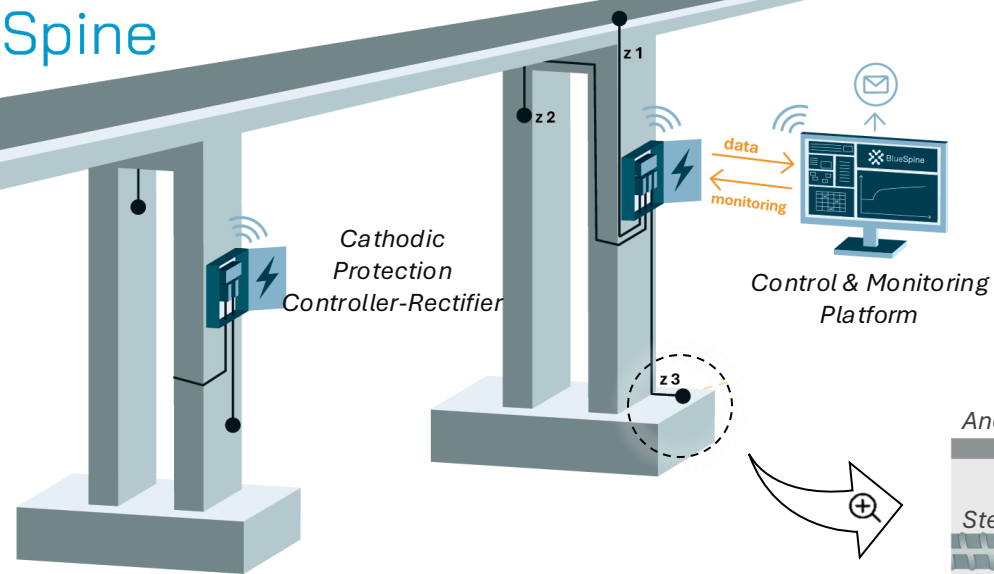
2 methods : Galvanic Protection (GCP) or Impressed Current Protection (ICCP)



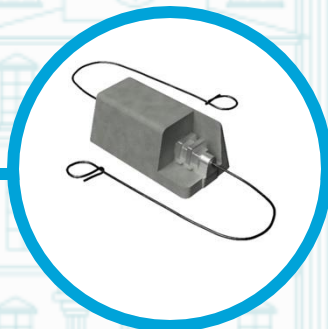


3 main benefits:

1. **Lower steel potential** under a threshold when **corrosion kinetics becomes neglectable** ($< 0,01 \text{ mm/an}$)
2. **Chlorides move toward the anode** under the effect of electric field \rightarrow it lowers the concentration around the rebars
3. **Formation of OH^- ions** by cathodic reaction, which **progressively increases the pH** \rightarrow it **restores steel passivation**



2 solutions depending on the needs of the structure



+10 years

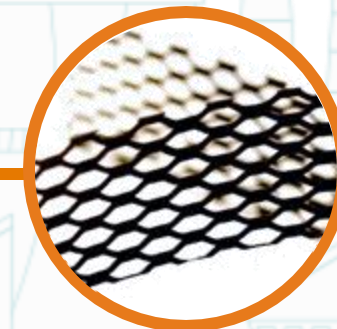
Galvanic

Zinc anodes
Metal consumption

Impressed current

Titanium anodes
Connection to the power grid

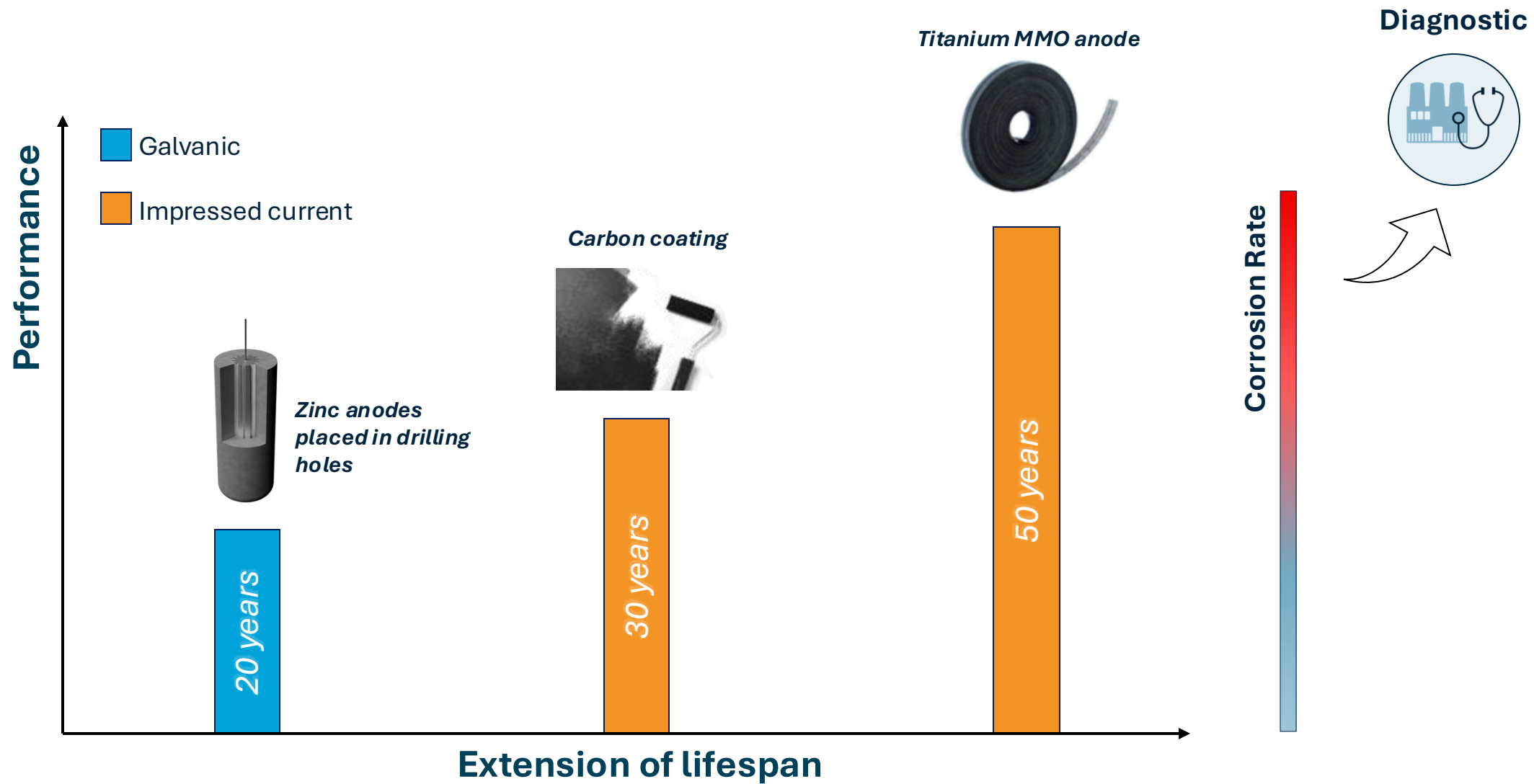
+20 years



+50 years

CORROSION TREATMENT

Cathodic Protection



CORROSION TREATMENT

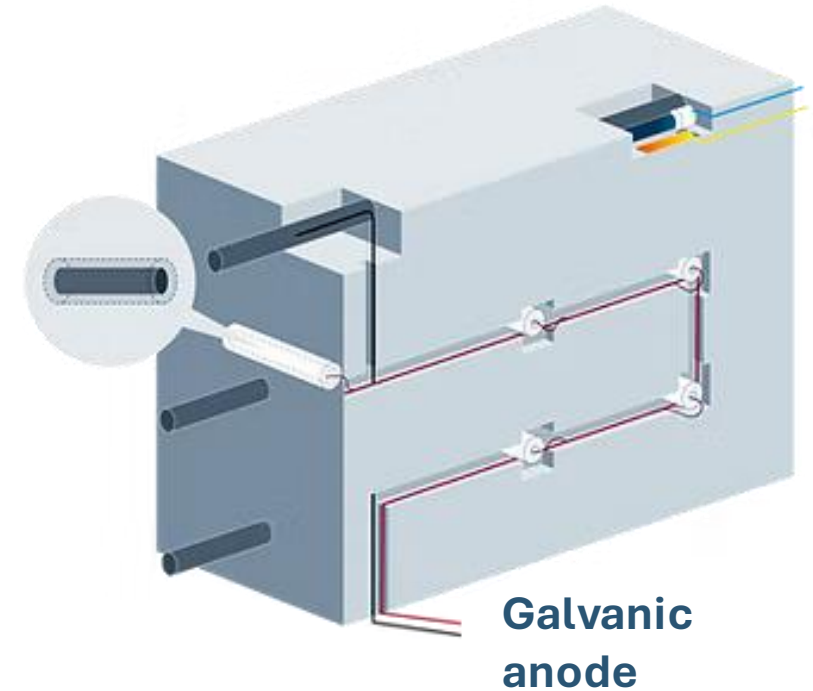
Galvanic Protection

The current comes from a **galvanic cell** with a less noble metal:

- Anodic reaction: metal oxidation (Zinc)
- Cathodic Reaction: oxygen reduction

The current generated by the anodes **is not controllable** and **depends on numerous factors**:

- Form and surface of the anode
- Ageing of the anode (Passivation)
- Exposition conditions (Temperature, Oxygen...)
- Concrete resistivity
- Reinforcement density



CORROSION TREATMENT

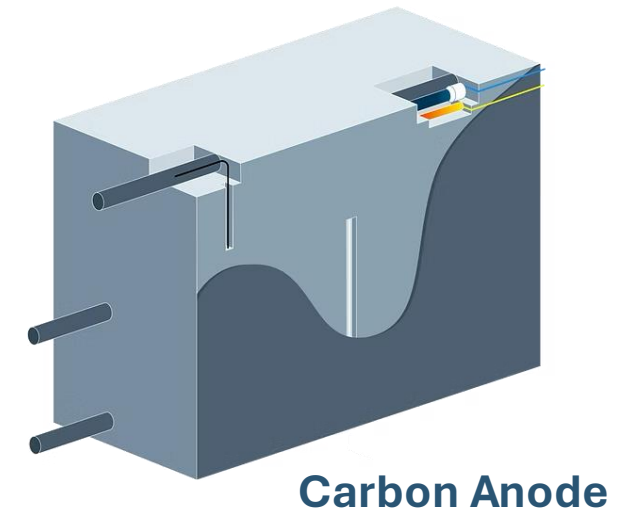
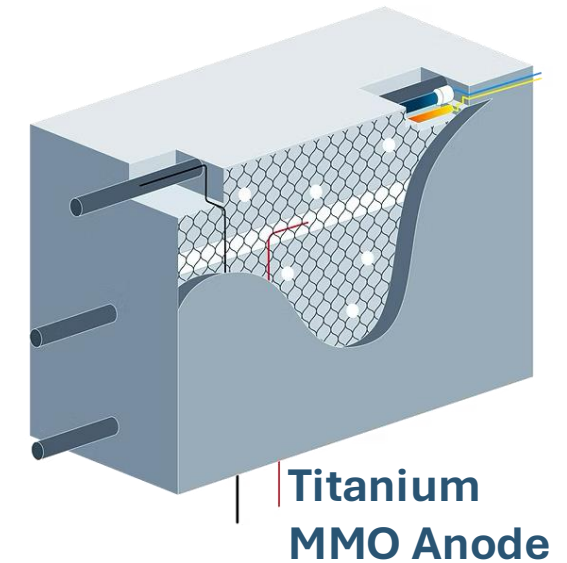
Impressed Current Protection

The **current** is provided and controlled:

- A **direct current generator**
- An **inert anode** (Titanium MMO or Carbon) which catalyses the **oxidation reaction of the water (terminal +)**
- The reinforcement which catalyses the **reduction reaction of oxygen (terminal -)**
- **Medium power consumption = a Refrigerator**

The **current is stable (impressed)** but the **voltage of the generator vary** depending on:

- Form and surface of the anode
- Resistivity of concrete
- Reinforcement density
- Exposition conditions (Temperature, Oxygen...)



Standard referential

Cathodic protection is governed by **2 standards ISO** :

- **EN ISO 12696** specifies performance requirements and design provisions
- **EN ISO 15257** sets out staff competence requirements (5 levels)



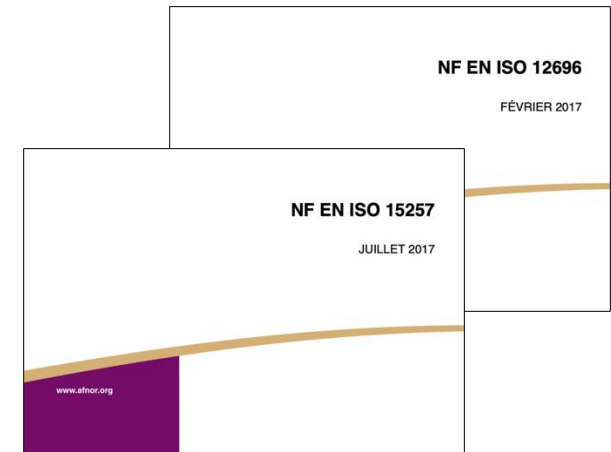
Work & control (N2)



Studies (N4) & performance assessment (N3)

EN ISO 12696 is a performance standard which defines **3 performance criterion**

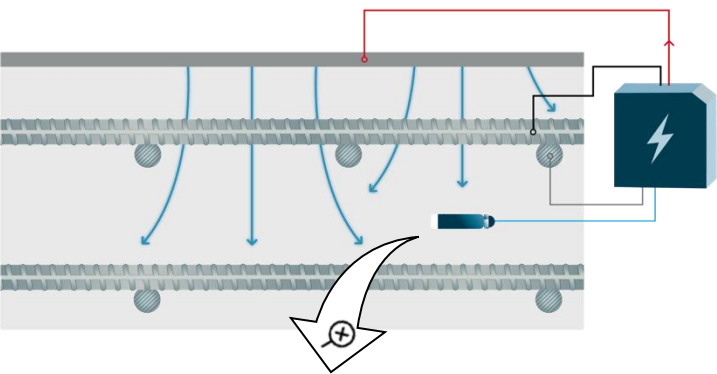
Any cathodic protection installation must have **a monitoring system**



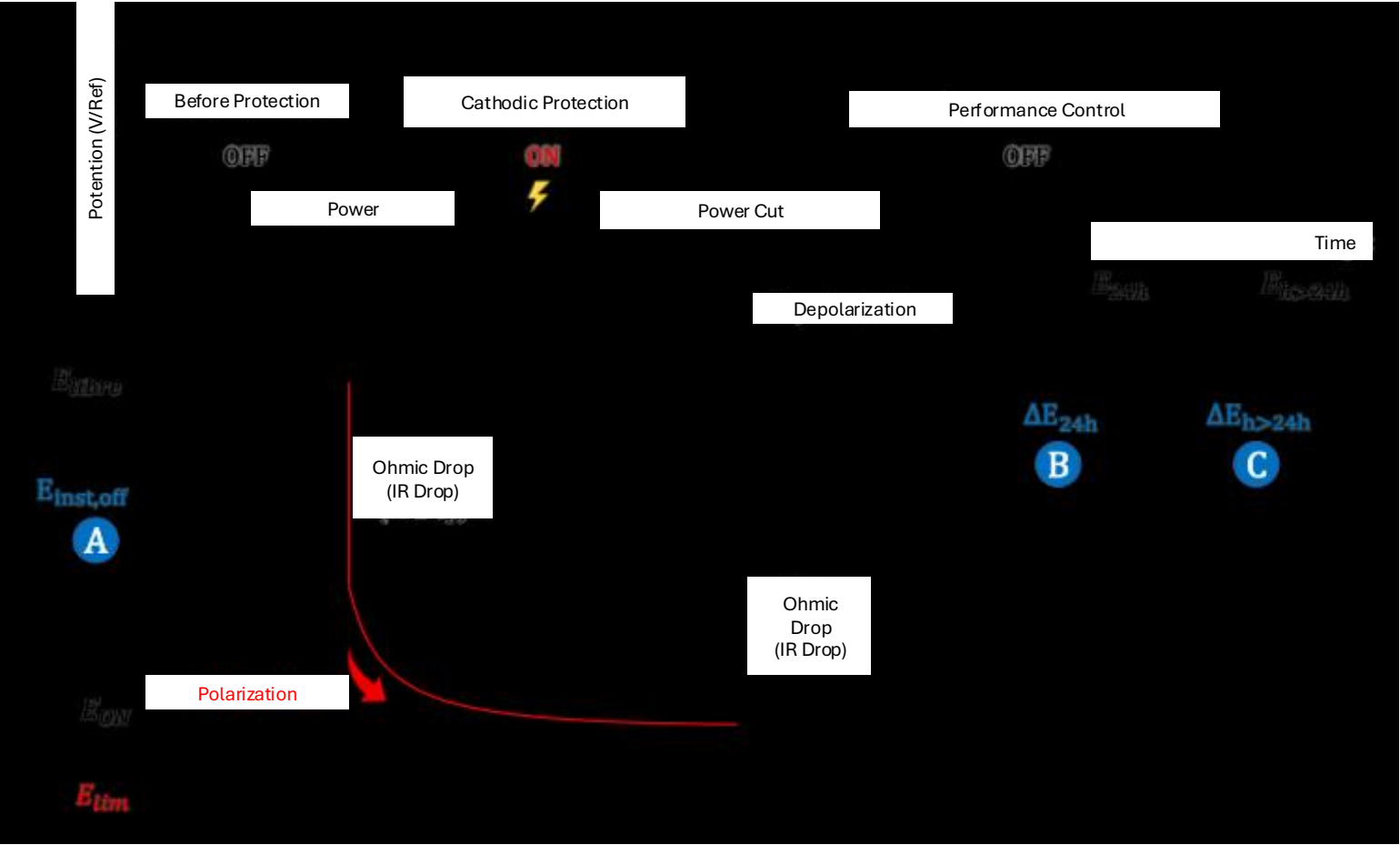
CORROSION TREATMENT

Cathodic Protection Monitoring

3 performance criterion assessed after a power cut with an imbedded reference electrode



Reference electrode Mn/MnO₂



The background of the slide is a photograph of a concrete wall. It features a grid of circular metal anchors or bolts. A red pipe runs horizontally across the lower portion of the wall, secured with metal brackets. The text is overlaid on the left side of the image in a white, bold, sans-serif font.

CASE STUDY

ICCP MEYLAN CAR PARK

FACILITY

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Presentation of the structure

- Construction: 1993
- Diagnostic: 2024
- ICCP Treatment: 2025



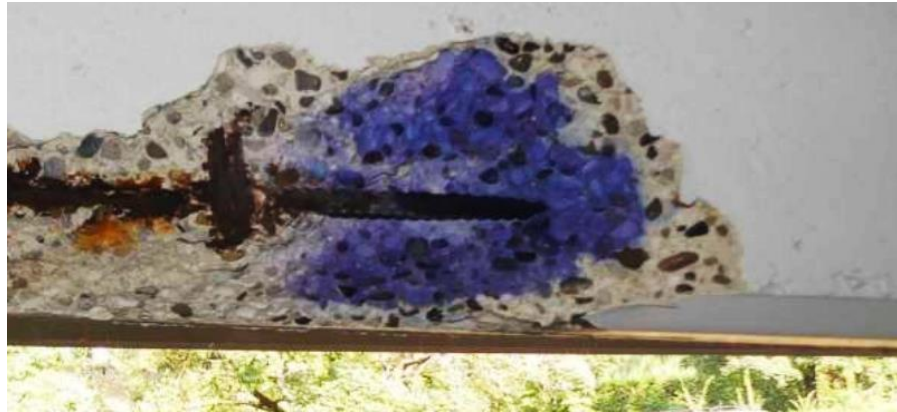
CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

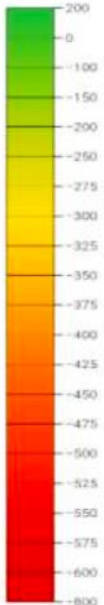
Corrosion Diagnostic

Sample Number	Element	Minium concrete cover (mm)	Depth of investigation (mm)	Cl- Content (% of concrete weight)
Po1	Beam showing a significant cracking	55	0 – 30 mm	0.071
			30 – 50 mm	0.081
D2	Soffit of the slab near a wastewater pipe penetration	45	20 – 40 mm	0.038
D3	Soffit of the slab showing a significant cracking	45	0 – 40 mm	0.431
D4	Sound soffit of the slab	45	0 – 30 mm	< 0.01
			30 – 40 mm	< 0.01

Acceptable content (<0.03%) / Excessive content (>0.03%)



Low probability of corrosion



High probability of corrosion

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Conception Study

Gathering Input Data

Defining the current demand

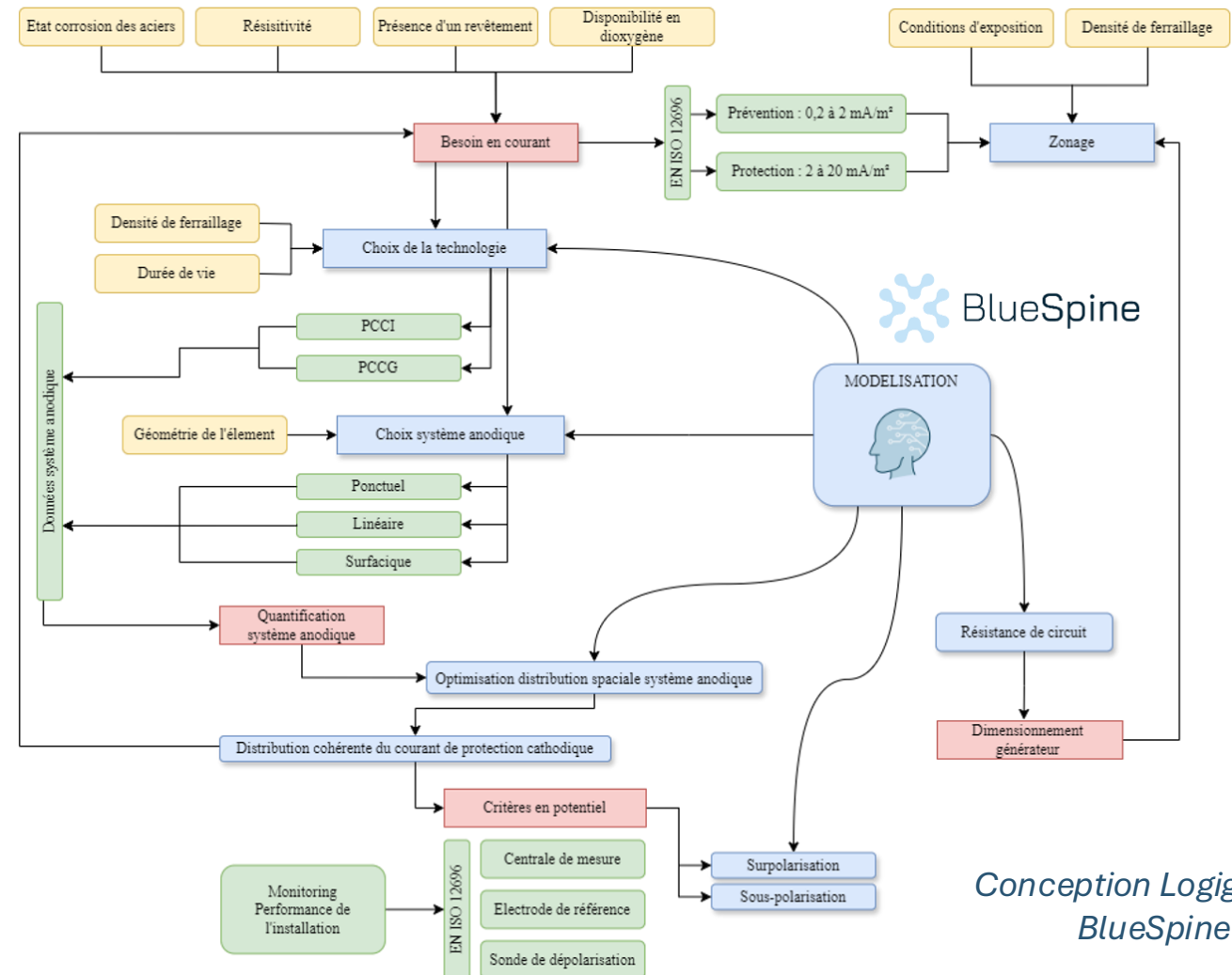
Initial Zoning

Anodic system selection

Digital design and optimization

Power and resistance calculations

Final Zoning and constructive dispositions



Conception Logigram of
BlueSpine

ICCP Shopping Center Car Park – Meylan (38)

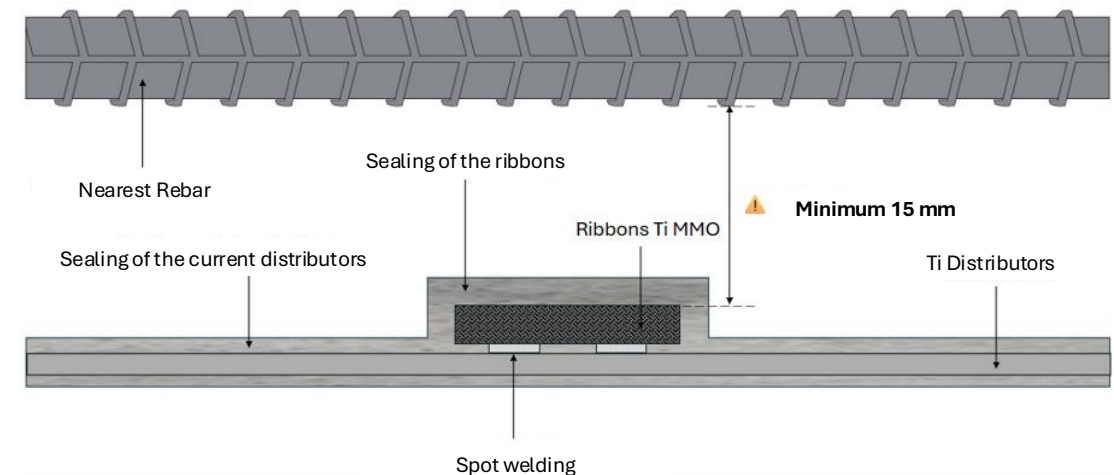
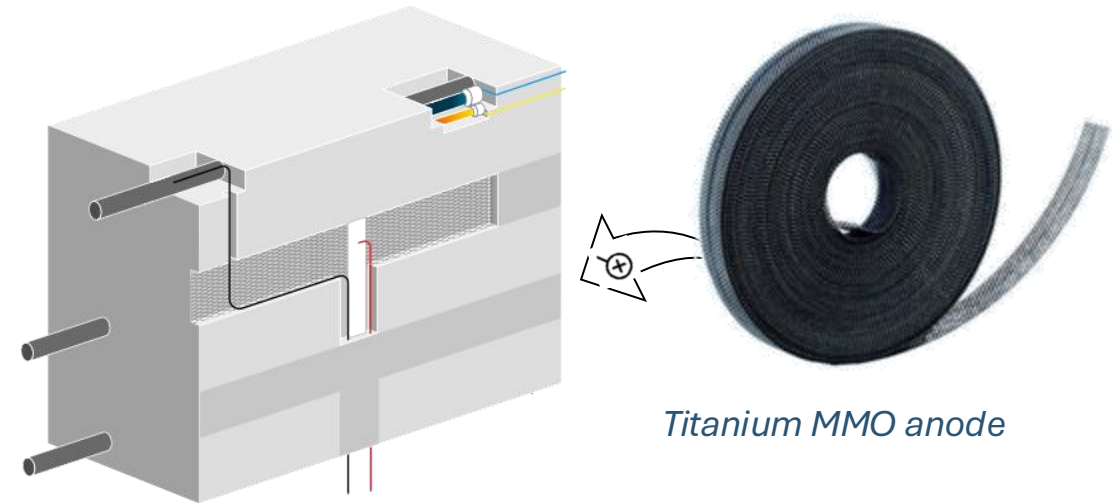
Conception Study

Hypotheses of design

- **Pathology:** Active corrosion by chloride
- **Current demand:** 20 mA/m²
- **Suitable anodic system:** Titanium MMO ribbon

Protection perimeter

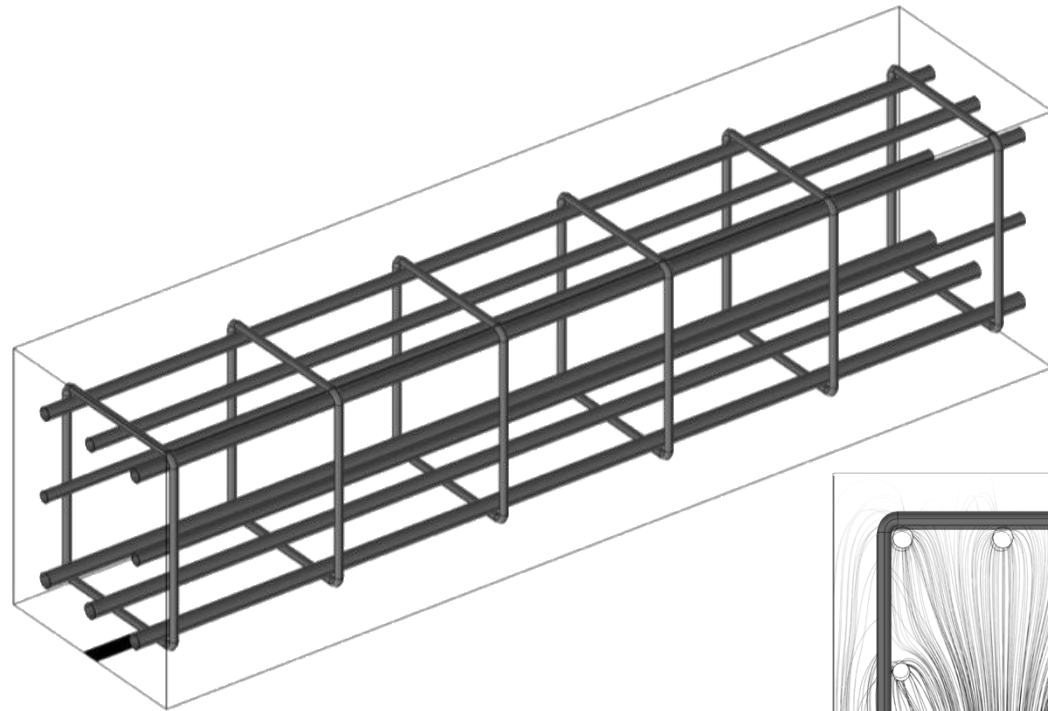
- Standard columns
- Column-head corbels
- Beams
- Tie beams
- Prestressed hollow-core slabs



CASE STUDY

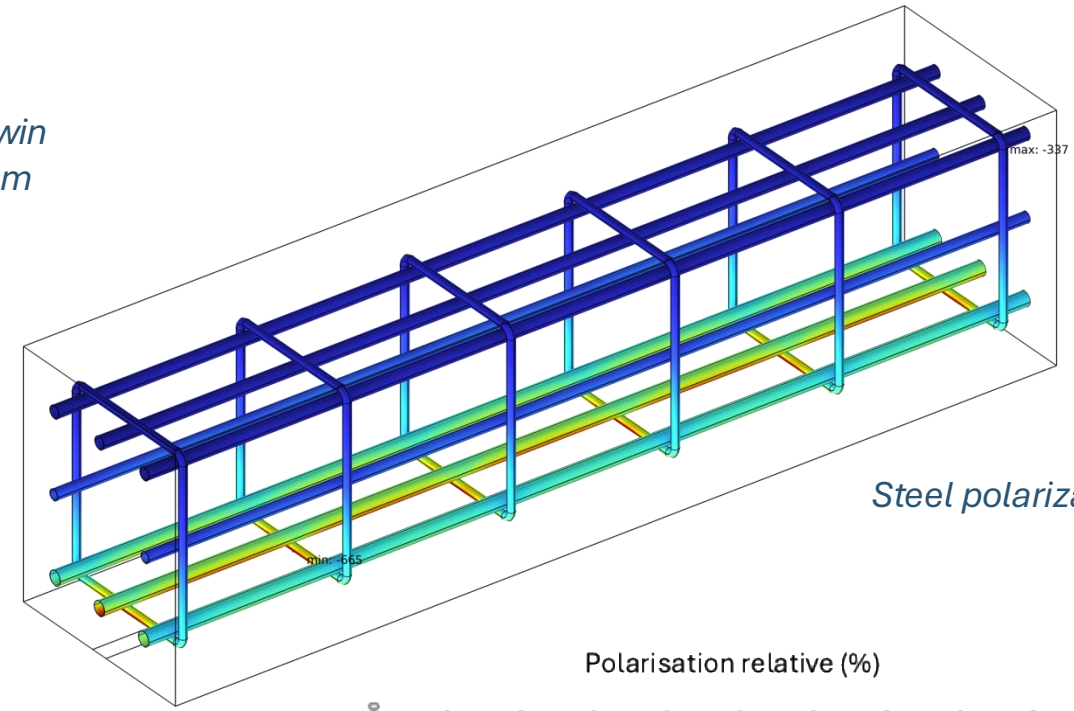
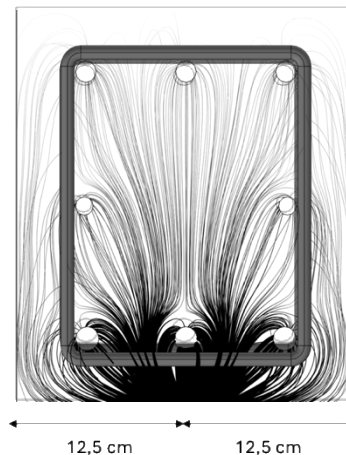
ICCP Shopping Center Car Park – Meylan (38)

Conception Study

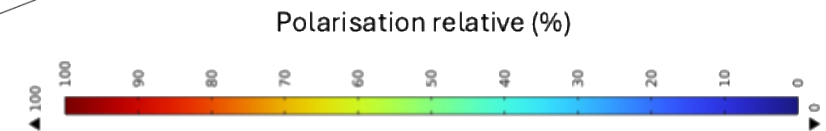


3D Digital twin
of a Tie Beam

Current lines
distribution



Steel polarization

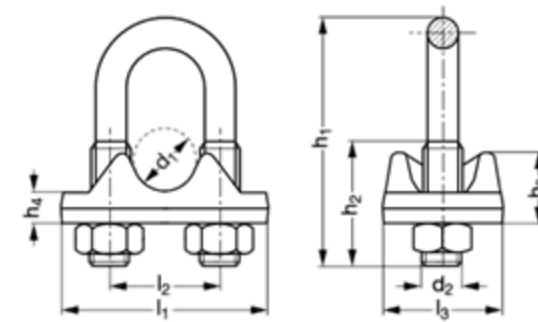


ICCP Shopping Center Car Park – Meylan (38)

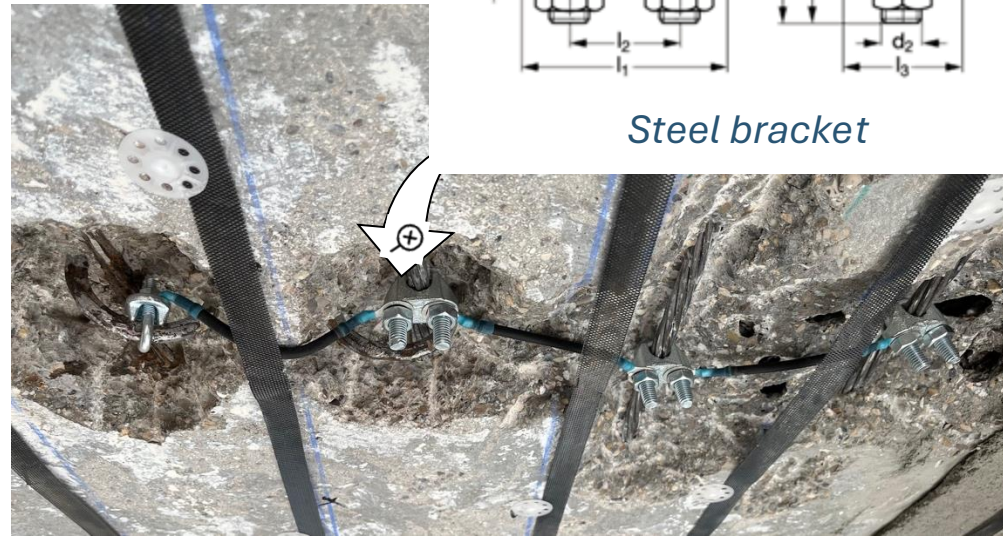
Rebar continuity verification



Standard compliant measurement 4 cables
(EN ISO 12696)
Performed with BlueSpine Q-Box



Steel bracket



Restoration of continuity between the prestressing
strands

ICCP Shopping Center Car Park – Meylan (38)

Anodic system installation



Cutting grooves in the various structural elements



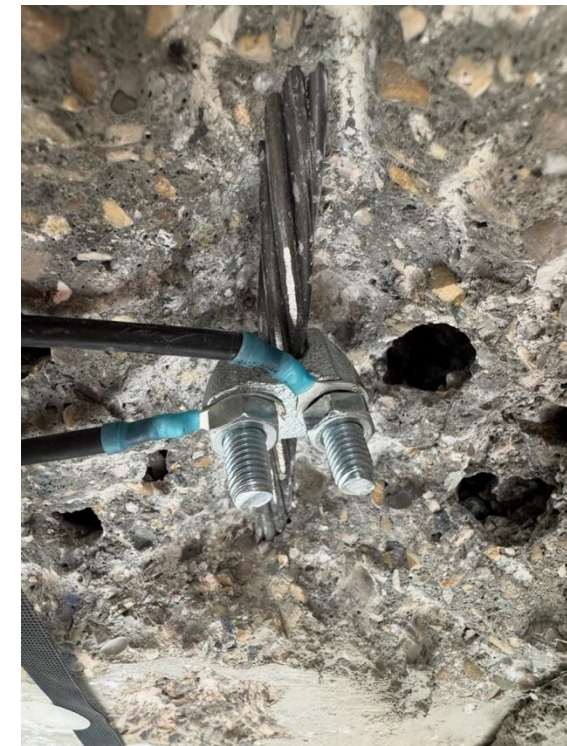
Ribbon installation in the cutting grooves

ICCP Shopping Center Car Park – Meylan (38)

Anodic & cathodic connections



Anodic connections (+) with titanium connectors



Cathodic connections (-) with steel connectors

ICCP Shopping Center Car Park – Meylan (38)

Anodic & cathodic wiring



Installation of anodic cables (red) and cathodic cables (black) in the cutting grooves or at the surface of the facing



*Doble sheath XLPE-XLPE
Cable*

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Sensors : Reference electrodes & Depolarization probes



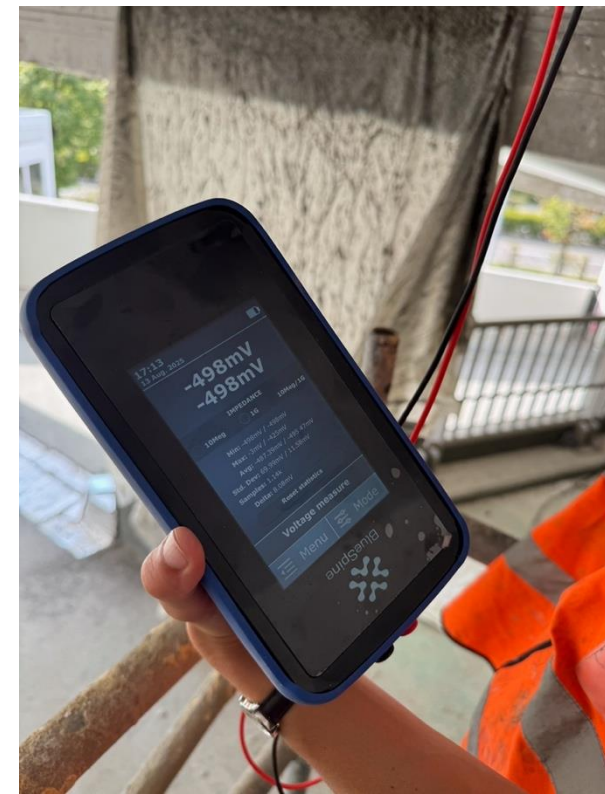
Installation of the pre-embedded sensors



Reference electrodes
 Mn/MnO_2



Depolarization probes
Ti MMO

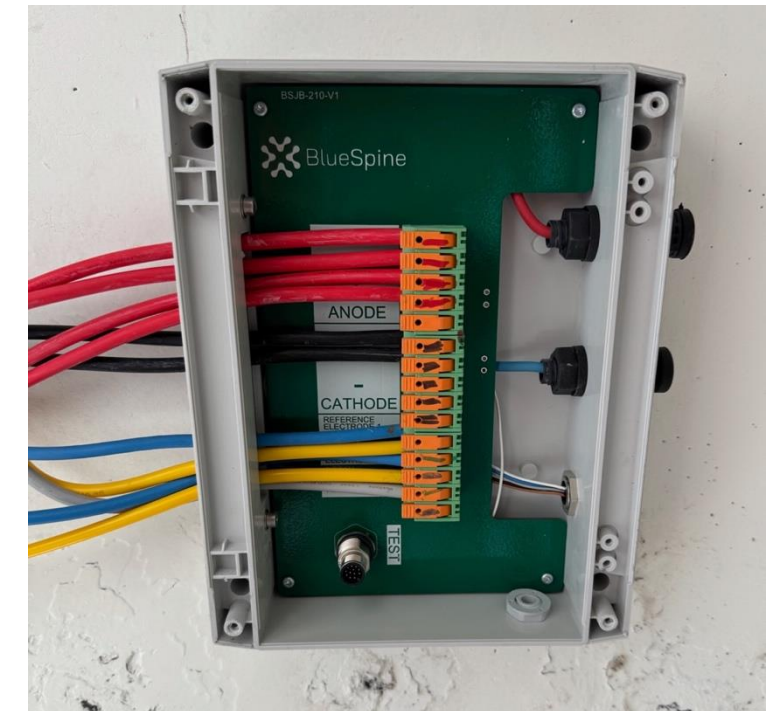
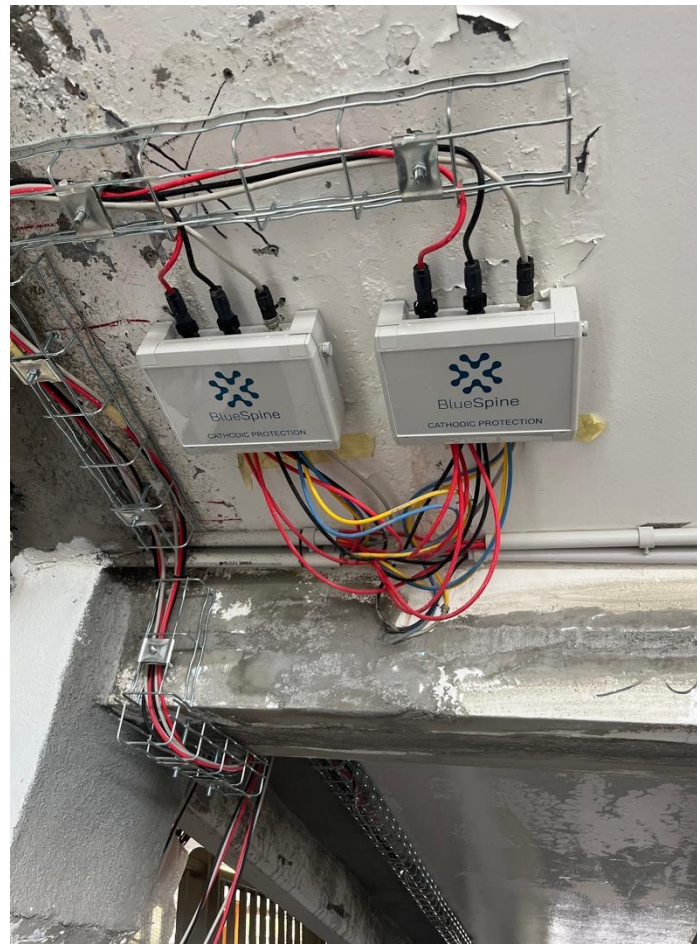
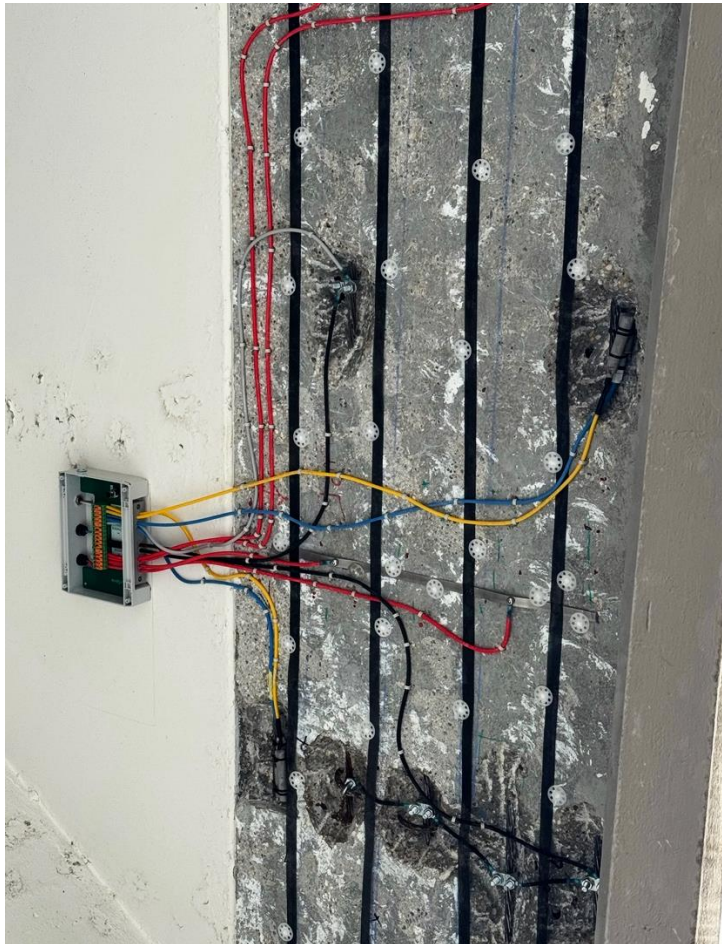


Verification of the sensor's installation by double impedance measurement performed with BlueSpine Q-Box

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Connection to the junction box

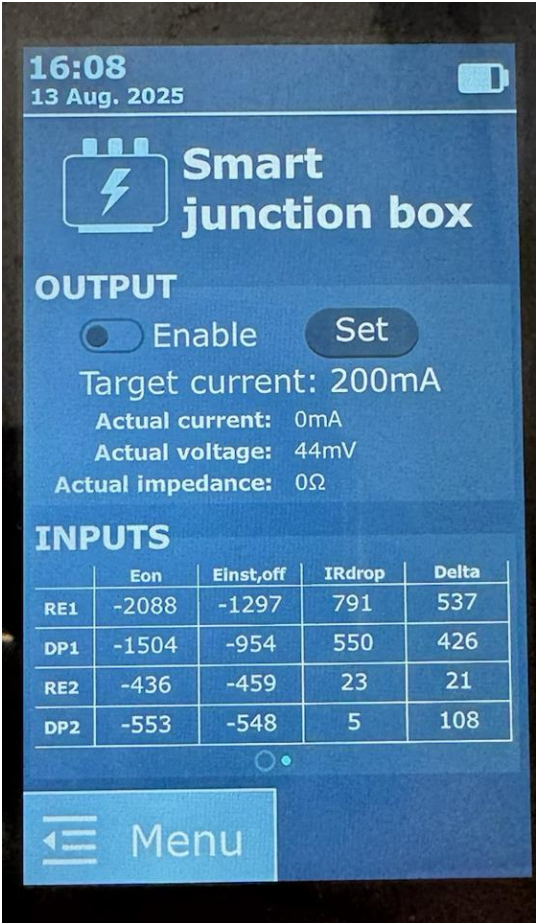


*BlueSpine waterproof junction boxes
with integrated circuit for quality
control*

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Temporary commissioning



Current injection with BlueSpine Q-box
BlueSpine to check the fonctionment
of the area

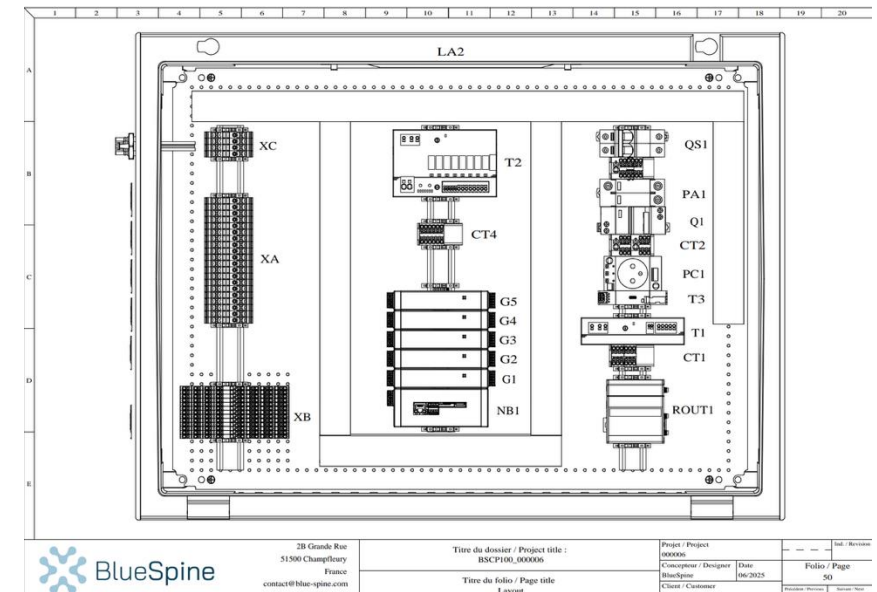
CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Connection to the controller



*Multi-zone controller
with generators
(3A-20V)*

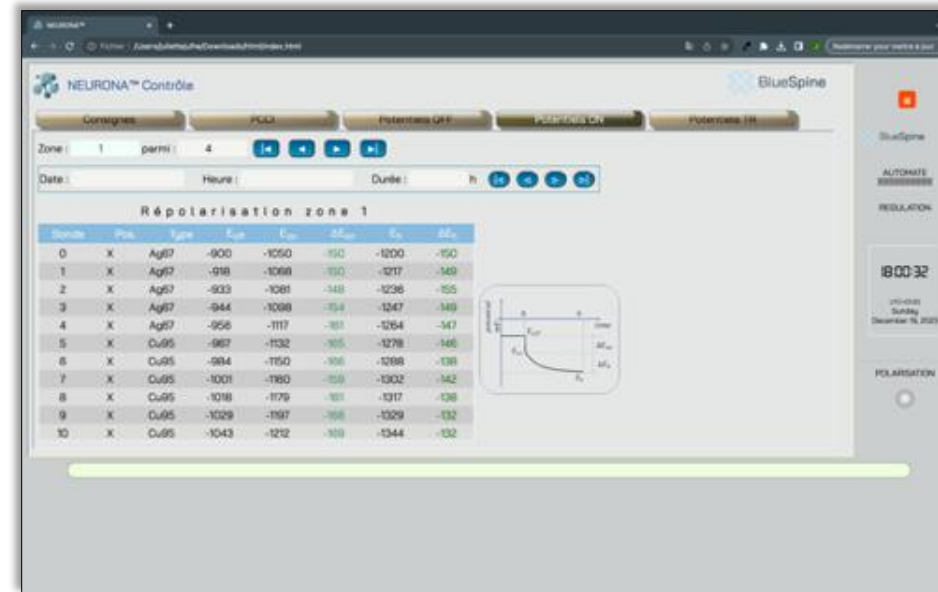


Controller plan

CASE STUDY

ICCP Shopping Center Car Park – Meylan (38)

Installation commissioning & monitoring



BlueSpine Neurona Interface for cathodic protection installation Monitoring