

Correlating Service Life Modeling and Corrosion Deterioration in Industrial Marine Structures

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ABSTRACT

This paper presents the use of service life modeling to describe corrosion deterioration affecting an industrial marine structure in an aggressive environment. Measures taken to prevent and mitigate reinforcement corrosion were taken for the construction of basin and channel elements exposed to a stream of high-chloride concentration water. Furthermore, an impressed current cathodic prevention system was reportedly installed to prevent corrosion deterioration. Nevertheless, severe corrosion deterioration was observed in some structural elements after ten years in service. This study presents the use of service life modeling tools to estimate the initiation of reinforcement corrosion deterioration and predicted the long-term performance of elements 30 years after construction for various scenarios. Based on the modeling results, estimates of the time to corrosion initiation and corrosion propagation are elucidated and correlated with the premature corrosion deterioration.

Key words: Reinforced Concrete, Deterioration, Materials Performance, Environment, Infrastructure

INTRODUCTION

Service life modeling tools for concrete structures are predominantly focused on new structures exposed to chloride penetration. In rare cases, service life modeling tools are used to describe observed corrosion-related distress in existing structures. This paper highlights the possible outcome of using service life modeling as a tool for understanding the deterioration progress in reinforced concrete structures and to ascertain the likely scenarios that led to the observed distress.

Structure Description

An industrial marine structure in the Middle East was affected by severe reinforcement corrosion after 10 years in service, even when significant corrosion mitigation strategies were implemented. The observed corrosion distress led to an investigation of the likely causes and predicted time of failure to match the observed distress. The evaluated elements of this structure include the Transition Channel Receiving Basin, Transition Channel, Discharge Channel, and Outfall of an industrial marine reinforced concrete structure was affected by reinforcement corrosion. The Transition Channel Receiving Basin approximate dimensions (width, length, height) are 100x100x17 m (328x328x56 ft); the Transition

Channel is 100x80x17 m (328x262x56 ft); the Discharge Channels are 100x850x17 m (328x2788x56 ft); and the Outfall is 100x210x17 m (328x689x56 ft). These concrete structural elements were constructed with a concrete mixture containing a corrosion-inhibiting admixture, and an impressed current cathodic protection (ICCP) system to mitigate corrosion over the structure service life. The use of ICCP systems for new construction is often defined as cathodic prevention¹. In 2018, a condition assessment and laboratory testing of concrete properties related to the durability of the structure were conducted. Significant cracking and spalling of concrete was identified at various locations in the structure. Cracks facilitate the ingress of moisture and chlorides that accelerate the initiation of reinforcement corrosion², and may accelerate the rate of deterioration³⁻⁴, and can interfere with the electrical field distribution and effective protection conferred by the ICCP system. Furthermore, it was discovered during the condition assessment that the ICCP system was not functioning properly in portions of the structure. As an extension of the scope of work, an evaluation of the remaining service life of the structure considering the current condition, the partial failure of the cathodic protection system, and a fully functioning CP system.

In addition to the condition assessment, laboratory testing of concrete samples extracted from various locations of the structure was conducted. Compressive strength, chloride penetrability, water permeability, unit weight, water absorption, acid-soluble sulfates, acid-soluble chlorides were measured, and chloride concentrations at different depths from the concrete surface (chloride profiles) were determined.

For the evaluation of the estimated remaining service life, chloride ingress data obtained from different locations of the reinforced concrete structure exposed to atmospheric, splash and submerged conditions were utilized. Other information provided included documents pertaining the concrete mixture proportions, construction of the reinforced concrete elements, ICCP system design and implementation, and reinforcement design and implementation.

MATERIALS & EXPOSURE CONDITIONS

Concrete Mixture Proportions

The reinforced concrete elements subject to condition assessment and service life modeling were constructed using a concrete mixture with proportions shown in Table 1. The cementitious portion of this mixture consisted of 295 kg/m³ of ordinary portland cement (considered to be similar or equivalent to ASTM C150⁵ based on the provided mill certificate), and 105 kg/m³ of pulverized fuel ash (assumed to be similar to fly ash meeting the designation Type F of ASTM C618⁶ based on the provided chemistry). The fly ash replacement level was 26% by mass of cementitious. The design water-to-cementitious materials ratio was 0.37 and the specified design compressive strength was 40 MPa (5800 psi) at 28 days of age.

Table 1 – Reported Concrete Mixture Proportions

Concrete Mixture Constituent	Mass, kg/m ³ (SSD)	Mass, lb/yd ³ (SSD)
Ordinary Portland Cement – ASTM C150	295	497
Pulverized Fly Ash – ASTM C618	105	177
Fine Aggregate – Washed Sand	714	1203
Coarse Aggregate – 20mm	610	1028
Coarse Aggregate – 10mm	535	901
Water - Potable	148	250
Admixture – High-Range Water Reducer (ASTM C494 ⁷ Type F)	8.4	14
Admixture – Corrosion-Inhibiting Admixture (ASTM C1582 ⁸)	~10.0	17

During construction, no issues regarding fresh or hardened properties of concrete were reported. The compressive strength of concrete was reported to exceed 40 MPa at seven days of age. Based on available records, it was not possible to ascertain if laboratory testing of concrete properties related to the concrete resistance to chloride ingress were conducted. No reports of variations in proportions and materials for the purpose were available, but may have occurred during construction in hot weather conditions. Variations in batching water are commonly present if uncontrolled aggregate moisture, ice, or other methods for cooling concrete are utilized. Constructability issues such as poor consolidation, bug-holes or honeycombing have not been reported.

Exposure Conditions

Environmental and exposure conditions play a crucial role in the ingress of chlorides into concrete. Most importantly, relative humidity and concentration of chlorides in marine or de-icing environments determine the driving force for chloride ingress. EN 206⁹ defines the exposure conditions for marine environment by their exposure severity as:

- XS1: Atmospheric – when airborne chlorides are present but there is no direct contact with sea water;
- XS2: Submerged – zones where concrete is permanently in contact with sea water;
- XS3: Splash/Tidal – zones where direct contact with sea water is present and periods of wetting and drying are affecting the structure.

The exposure conditions for portions of the structural elements in this structure had zones that ranged from XS1 to XS3.

Cathodic Protection System

Impressed current cathodic protection (ICCP) systems with embedded MMO (mixed metal oxides) ribbon mesh anodes and platinized titanium (Pt/Ti) anodes were installed to protect the structure from corrosion. A total of 492 ICCP zones were designed and implemented. During service, it was detected that a significant number of zones at Receiving Basin, Discharge Channels, Transition Channel and Outfall structure were not functioning properly. Failure of the ICCP system included the following:

- Failure to meet on depolarization criteria suggested in NACE SP 0290¹⁰
- Failure of anode cables at anode termination, cable joints and at areas of damaged insulation, both in direct-buried and in concrete covered cables runs.
- Anode to cathode short circuit
- Reference electrodes failure
- Design deficiencies in terms of number of anode feeder cables with respect to design current and other factors such as 300 mV maximum voltage drop in anode circuit, maximum current carrying capacity of used conductor bar etc.

The ICCP system was divided into different zones across the elements at the Receiving Basin, Transition Channel, Discharge Channel and part of the Outfall structures. Prior to and during the condition assessment, it was detected that progressively these ICCP zones were failing to provide the design protection. Consequentially, the failure of CP system may have resulted in active reinforcement corrosion. Table 2 shows a summary of the current efficiency in protection offered by ICCP at various locations subject to condition assessment.

Table 2 – Evaluated Efficiency of ICCP Protection at Selected Locations

Cathodic Protection Efficiency	Locations
100%	L1, L2, L12, L3
25%	L5, L6, L7, L8, L9, L10, L11
0%	L3, L4

CONDITION ASSESSMENT

An evaluation of the concrete transport properties was performed using chloride penetration data obtained from several locations at various structural elements exposed to atmospheric, splash/tidal, or submerged chloride exposure. The input information included concrete mixture proportions, chloride ingress profiles, age of the structure at which the profiles were extracted, and concrete cover depths.

Chloride Ingress Profiles

Sampling for determining the chloride ingress was conducted at an age of ten years after construction. Concrete cores were extracted from 13 selected areas from different structural elements. Acid-soluble chloride (ASTM C1152¹¹) concentrations were determined at 30 mm (~1.2 in.) increments, up to a depth of 240 mm from (~10 in.) the concrete surface. Subsequently, an analysis of the chloride ingress data was conducted to determine the surface chloride concentration (C_s) and the apparent diffusion coefficient (D_{app}) using a least square regression analysis as required by ASTM C1556¹². Figures 1 through 3 show the measured and calculated chloride ingress profiles in concrete samples extracted from atmospheric (Figure 1), splash (Figure 2), and submerged (Figure 3) exposure conditions.

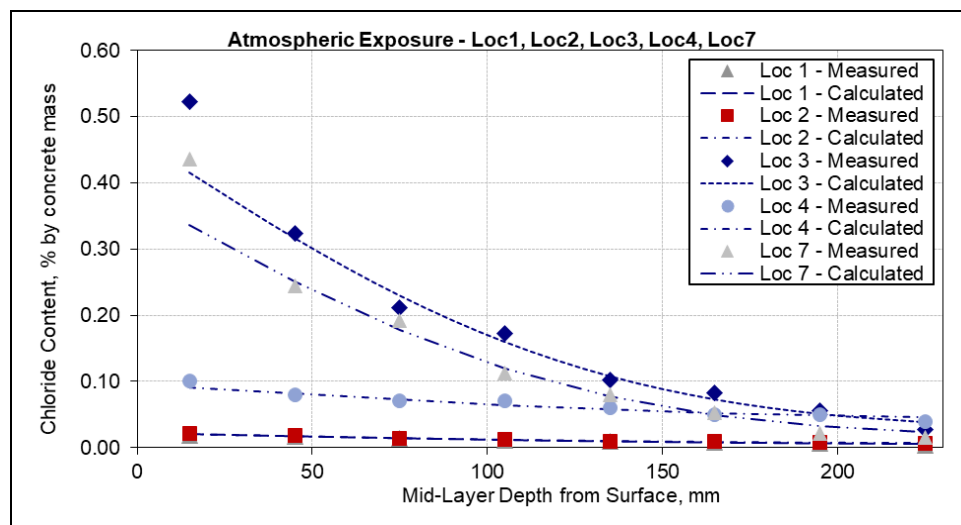


Figure 1: Chloride Ingress Profile for Zones exposed to Atmospheric Conditions.

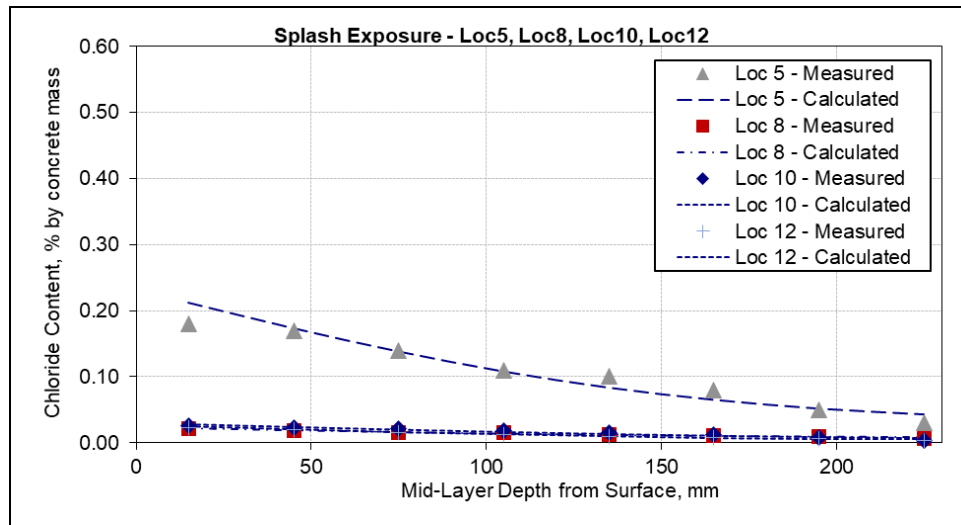


Figure 2: Chloride Ingress Profile for Zones exposed to Splash Conditions.

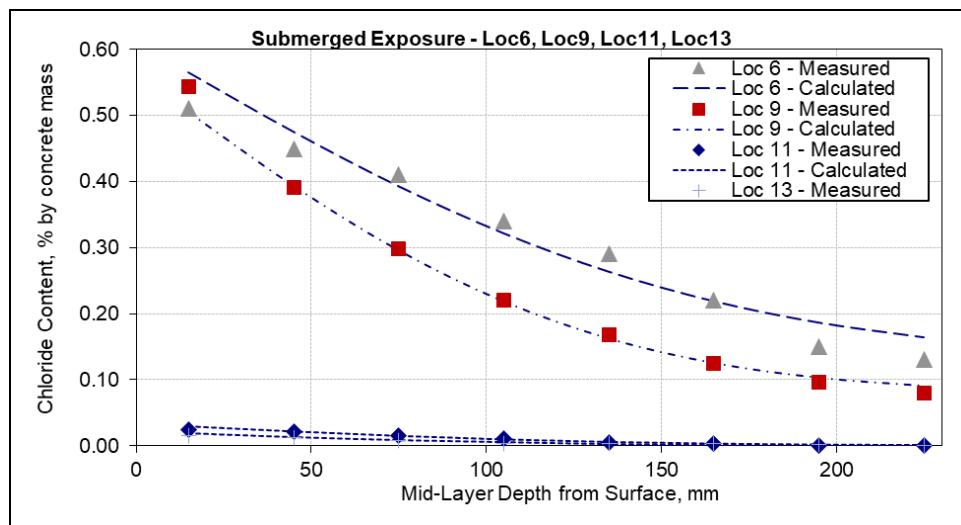


Figure 3: Chloride Ingress Profile for Zones exposed to Submerged Conditions.

Upon review of the condition assessment data, it was determined that the chloride ingress profile found in zones without ICCP protection was significantly higher than in zones in which ICCP was functioning properly. For example, chloride ingress profiles obtained from locations L1 and L2 are significantly different from those obtained from locations L3 and L4 as shown in Figure 1, even though the exposure conditions are assumed to be comparable. The difference in calculated C_s and D_{app} , was therefore assumed to be influenced by the performance of the ICCP system since the system was found to be fully operational at locations L1 and L2 whereas the CP system failed to provide sufficient protection at L3 and L4 locations.

The performance of the ICCP system at the splash conditions was found to be fully (L12) or partially effective (L5, L8, L10, L12). Elements exposed to submerged conditions were found to have partially effective CP systems (L6, L9, L11, L13). Although the chloride ingress in these exposure zones was expected to be higher than in the atmospheric zone.

Table 2 shows the calculated maximum surface chloride concentration and apparent diffusion coefficient of concrete for each exposure condition. Results show that the calculated surface chloride