CORROSION PROTECTION FOR LA FONTAINE TUNNEL

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Paper prepared for the session Transportation Structures
2024 Transportation Association of Canada (TAC) Conference & Exhibition
Vancouver, British Columbia

ABSTRACT: The Louis-Hippolyte-La Fontaine tunnel-bridge complex, as its name implies, is divided into two sections: the tunnel part of a length of 1.4 kilometer, linking the Island of Montreal to Île- Charron, and the bridge part that connects Île-Charron to Longueuil over a length of 457 meters. The Tunnel is considered a very important submerged tunnel in Canada and opened in 1967. It is managed by the MTQ and allows 120,000 vehicles to cross the St. Lawrence River daily. The initial construction cost was $75million.

The Tunnel has deteriorated over the 50+ years of its existence due to chloride-induced corrosion. A major refurbishment of the tunnel began in 2020, which is to be completed in 2025. The Tunnel is one of top 50 largest infrastructure projects in Canada with total project value of $2.1 billion. The tunnel includes service tunnel, southbound and northbound tunnels.

The main objectives of corrosion protection are to provide a minimum of 20 years corrosion protection by galvanic anodes and ensure the sustainability of the infrastructure, including the goal of operating without major long-term obstacles for 40 years. Galvanic cathodic protection provides an effective low maintenance option for engineers and owners of infrastructure. The service tunnel has been patch repaired and protected with discrete galvanic anodes, while the traffic tunnels will be refaced and protected with distributed galvanic anodes.

This presentation includes the studies of different corrosion protection options, design and implementation of corrosion protection system.

1 CORROSION OF REINFORCED CONCRETE

Corrosion of reinforcing steel is recognized as the major cause of the deterioration of reinforced concrete structures. Exposure to de-icing salts, seawater and chloride-containing set accelerators, play a significant role in reinforcing steel corrosion (Figure 1). When the chloride content at the rebar level exceeds the threshold for initiation of corrosion, the passivation protective film on the rebar surface is destroyed and a corrosion cell can form either on the same piece of rebar with anodic and cathodic sites adjacent to each other, or a macro-cell between two different layers of reinforcement. Long-term exposure to carbon dioxide is also cited as a contributor to the corrosion of steel in concrete as well. Figure 2 illustrates both the local corrosion cell on the top rebar and the macro-cell between the top and bottom rebars. Table 1 shows the probability of corrosion according to ASTM C876 in relation to the half-cell readings. According to the result of a literature survey, the chloride threshold for initiation of corrosion ranges from 0.025% to 0.075% by mass of concrete.

Figure 1. Pier Corrosion Due to Chloride from Leaking Joints and Roadside Splash

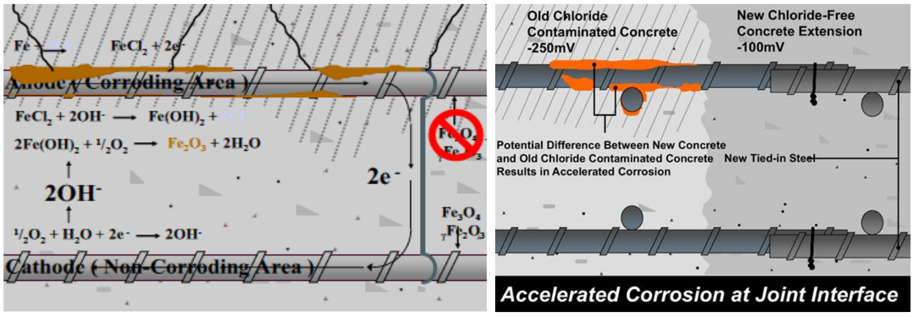


Figure 2. Corrosion Cell in Reinforced Concrete, Accelerated Corrosion at Construction Joints

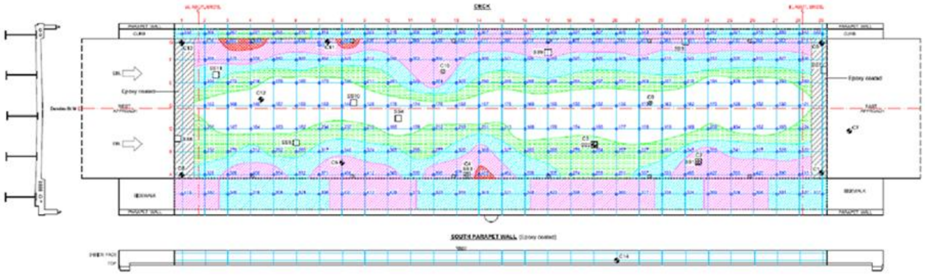


Figure 3: Typical Bridge Deck Corrosion Potential Map

Table 1. Corrosion Potentials

Reading (Cu/CuSO4 Half-cell)	*Corrosion Condition*
>-200 mV	Low (<5% probability of corrosion)
-200 to -350 mV	Uncertain (50% probability of corrosion)
<-350 mV	High (>95% probability of corrosion)

Figure 2 shows a construction joint where some old concrete is removed and new concrete is cast onto the remaining concrete, such as patch repair, through slab repair, deck widening or barrier wall replacement. Typically the old concrete with high corrosion potentials or high chloride content is removed, the remaining chloride contaminated concrete may have a corrosion potential of -250mV, which is in the uncertain range. The new concrete typically has a low corrosion potential, for example -100mV. The difference in corrosion potentials between these two concrete areas will make the remaining concrete an anode, which will corrode to protect the cathode - the steel in new concrete. This will lead to the premature failure of the older concrete at the construction joint if no proper protection is put in place.

One option is to apply cathodic protection to prevent and control localised corrosion in high corrosion risk areas. Cathodic protection system has been shown to be effective in mitigating corrosion damage and reducing the rate of the delamination per year to 0.04% from the average 1% per year for unprotected structures (Gulis, Lai & Tharmabala 1997)

2 GALVANIC ANODE FOR CORROSION PREVENTION AND CORROSION CONTROL

Since corrosion of steel reinforcement is an electro-chemical process, it can be mitigated by electro-chemical means such as cathodic protection. While impressed current cathodic protection system is typically used to provide general corrosion protection over the entire deck surface, galvanic cathodic protection system can be used in targeted areas where there is elevated risk due to higher content of chloride. Embedded galvanic anodes (Figure 6) have been used for patch repairs to address patch-accelerated corrosion (Figure 5) since late 1990s.

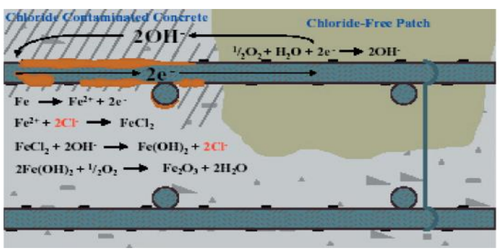


Figure 5. Patch Accelerated Corrosion Cell

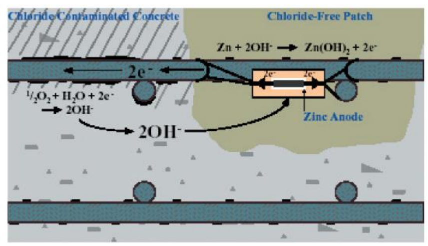
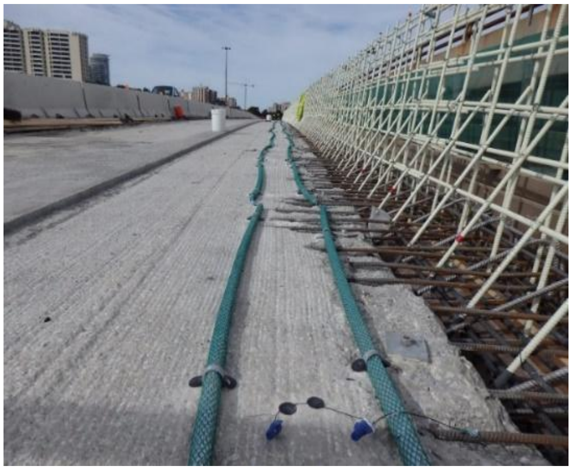


Figure 6. Patch Containing discrete Galvanic Anodes

The anode was produced from zinc metal encased in a specially formulated porous cementitious mortar saturated in a highly alkaline environment. Such an environment maintaining a constantly high pH, which is corrosive to the zinc and protective to the steel, was shown to sustain the zinc in an active condition producing soluble zinc corrosion products that do not stifle the corrosion process of the metal.

The first monitored application of the embedded anodes was completed at the Leicester Bridge, UK, in 1999. As verification for the performance of the anodes in actual structures, a total of 12 commercial anodes were installed in an otherwise conventional patch repair on spalled and cracked areas of a beam section of the bridge. The performance of these anodes was monitored with time. Each monitored anode generated up to 400-600µA of current during hot periods and less than 100µA during cold spells. The mean current density ranged between 0.6 mA/m^2 and 3.0 mA/m^2 with an overall mean of around 1.4 mA/m^2, generally within the suggested range for cathodic prevention. According to these results, a range between 24 years and 37 years service life can be achieved for 60g zinc mass. This is confirmed by the assessing the removed anodes from the repair, which lost about 25 to 30% of the zinc metal and were still active. Corrosion Prevention strategy can be used in various applications including structural extension or widening, new construction and patch repairs (Lai, Langendeon, & Liao 2018).



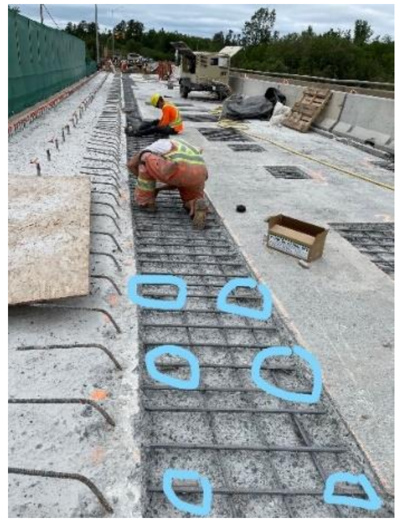


Figure 7. Distributed Anodes installed at the edge of existing deck for the parapet wall replacement to prevent corrosion from initiating, Toronto, Canada

Figure 8. Highway 622, Atikokan, Discrete anodes for patch repairs

3 DRILLED-IN FUSION ANODES FOR CORROSION CONTROL/CATHODIC PROTECTION

Anodes can be installed in drilled holes in the following applications.

- Sound concrete with high corrosion potentials and high chloride concentration, in which delamination and spalling are expected as results of the corrosion (Figure 9).
- Chloride contaminated prestressed concrete where concrete removal is not desired

Fusion anode is a two-stage anode system, combining the performance of an impressed current electrochemical treatment (Stage 1) with the long-term maintenance-free capabilities of an alkali-activated galvanic anode (Stage 2). As illustrated below, this modular corrosion protection system provides two stage corrosion protection. During the first stage, this system utilizes a self-powered impressed current cathodic protection anodes to perform an electro-chemical treatment to halt corrosion and passivate the steel. These two stage anodes then automatically switch over to provide maintenance free galvanic anodes to maintain the steel passivity for the life of the system. This switch occurs automatically without the need for external monitoring or human intervention. Each anode includes both the impressed current cathodic protection and galvanic protection components and is connected to steel using a single wire (Whitmore, Liao, Simpson & Sergi 2019).

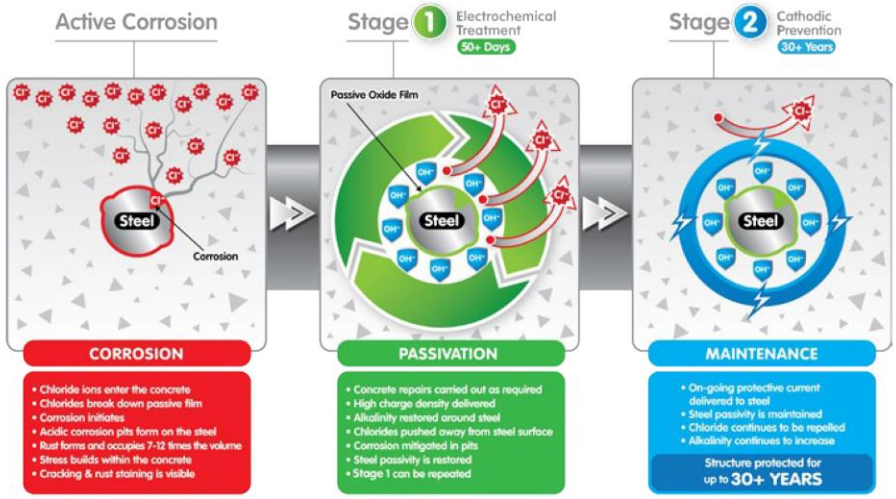


Figure 9. Illustration of Fusion Anodes

Corroded steel is protected by a two-stage corrosion protection system. Stage 1 passivates the steel, produces a shield of hydroxyl ions and repels chlorides. Stage 2 maintains the steel in passive condition

4 DISTRIBUTED GAVANIC ANODES FOR LONG TERM GLOBAL CORROSION PROTECTION

The 20-year monitoring data of distributed galvanic anodes are able to generate high initial current output and very healthy long term current output to achieve 100mV or more polarization, and provide long-term protection (Liao 2022). This type of anode has been used for long term global protection in many different structural components, including abutment refacing, concrete deck overlay, concrete jackets for columns, piers, tunnel and marine piles.

Figure 10. First Trial of DAS Anodes in Bridge Deck Overlay, Ontario, Canada, in 2003

Figure 11. Distributed anodes in pier overbuild and abutment refacing

5. CORROSION PROTECTION FOR LA FONTAINE TUNNEL

The tunnel includes service tunnel, southbound and northbound tunnels. The Tunnel has deteriorated significantly over the 50+ years of its existence due to chloride-induced corrosion. The main objectives of corrosion protection are to provide a minimum of 20 years corrosion protection by galvanic anodes and ensure the sustainability of the infrastructure, including the goal of operating without major long-term obstacles for 40 years. Galvanic cathodic protection provides an effective low maintenance option for engineers and owners of infrastructure. The service tunnel has been patch repaired and protected with discrete galvanic anodes, while the traffic tunnels are being refaced and protected with distributed galvanic anodes.

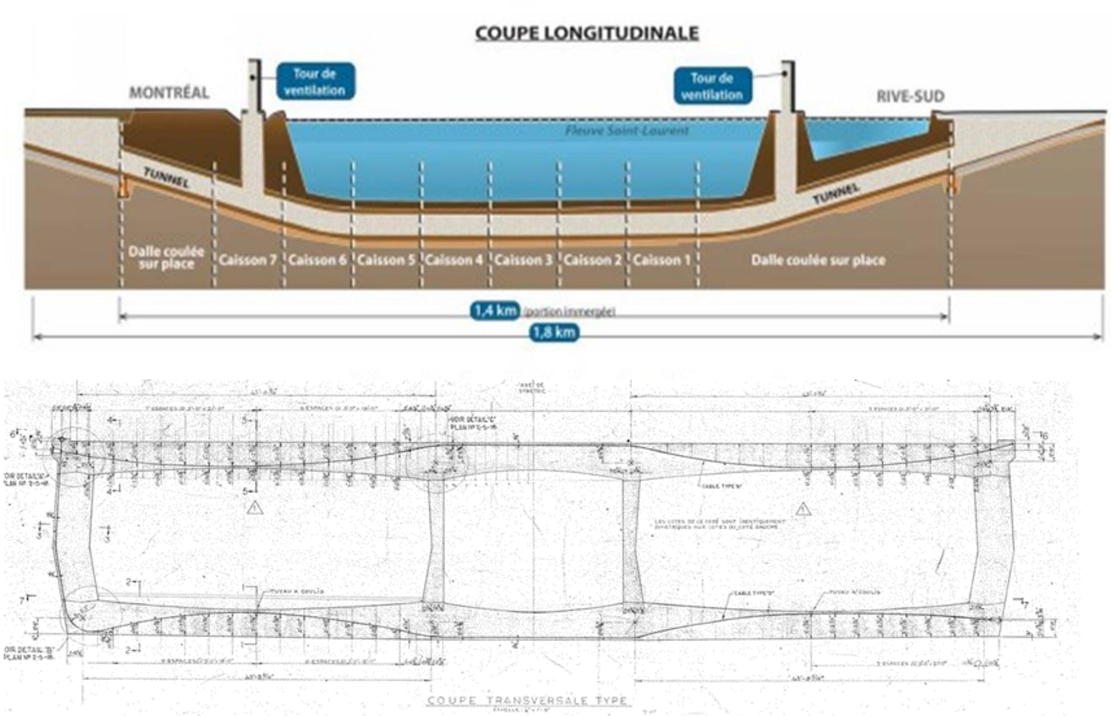


Figure 12. Sections

5.1 Preliminary Design of Corrosion Protection

At the preliminary stage, a high level corrosion protection strategies were developed by National Research Council, the requirements include:

1. Install zinc-based sacrificial anodes to protect the structures
2. Use discrete anodes for patch repairs and line anodes for overbuild/refacing
3. Impressed current cathodic protection is NOT permitted due to the possibility of hydrogen embrittlement of the post-tensioning steel
4. In patch repairs, design the protection with sacrificial anodes in such a way as to prevent corrosion of the reinforcement located around the repaired areas due to an electrochemical incompatibility between the reinforcement in the new repair concrete and that in the existing concrete, for a minimum Life of twenty years
5. In overbuild, design the linear sacrificial anodes to control on-going corrosion in the existing concrete for a minimum life of 20 years.
6. The design should be done by a galvanic protection expert with at 10 years of experience in concrete structures
7. The design parameters include chloride contents, steel density ratio, and the current corrosion activity in the existing concrete
8. Galvanic anodes alone should be able to protect the concrete for a minimum of 20 years without considering coating or corrosion inhibitors.
9. Install anodes according to ACI RAP Bulletin 8 "Field Guide to Concrete Repair Application Procedures - Installation of Embedded Galvanic Anodes"
10. Submit calculations and drawings for all the galvanic corrosion protection
11. Install 8 monitoring stations to verify the performance

The protection scope include:

- Traffic tunnels
- Service tunnel
- Approach retaining walls
- Ventilation towers

5.2 Design of Corrosion Protection

At the design and build tendering stage, with the considerations of the high level corrosion protection strategy developed by national research Council, the steel density in each area of each structural components were calculated, chloride contents were tested, and then the current density requirements are determined. Based on this information, the anodes were selected and spacings were designed.

Different sections have different rebar layout so the tunnels and the retaining walls were divided into a few areas (Figures 13 and 14). Chloride tests were sampled at different heights and along the chainages as well (Figure 15 and 16).

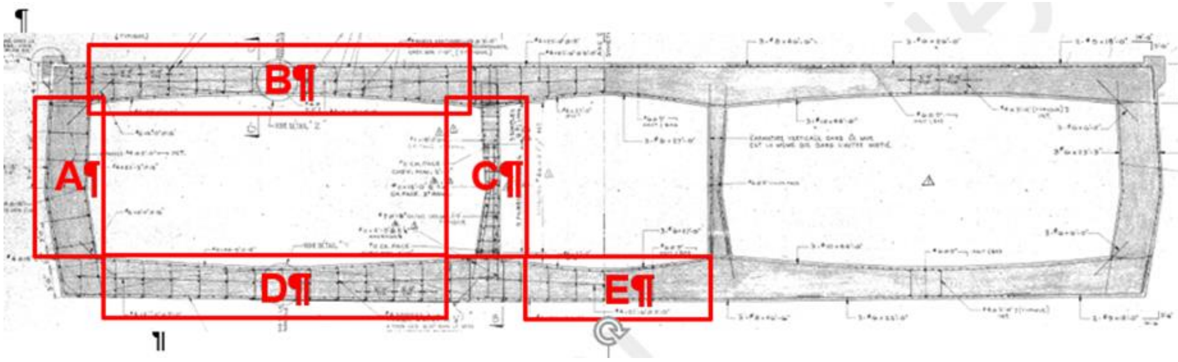


Figure 13. Tunnel Sections for Steel Density Calculations

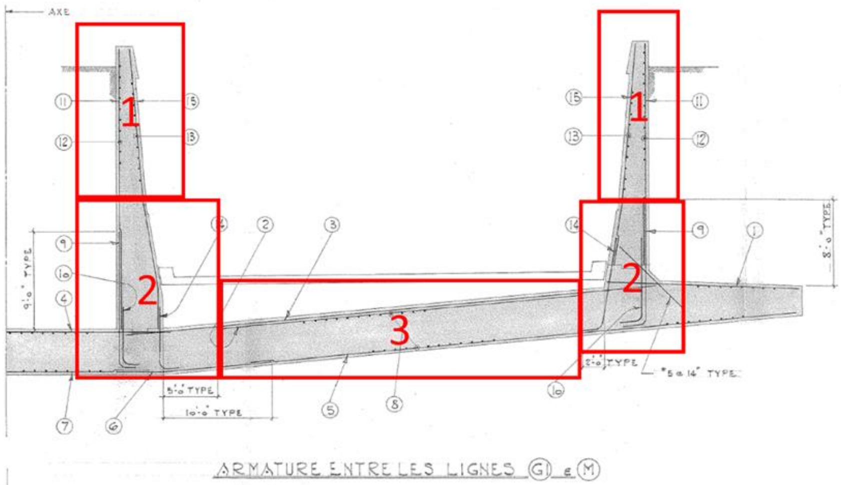


Figure 14. Retaining Wall Sections for Steel Density Calculations

Chloride contents were considered in each area in terms of elevation and chainage.

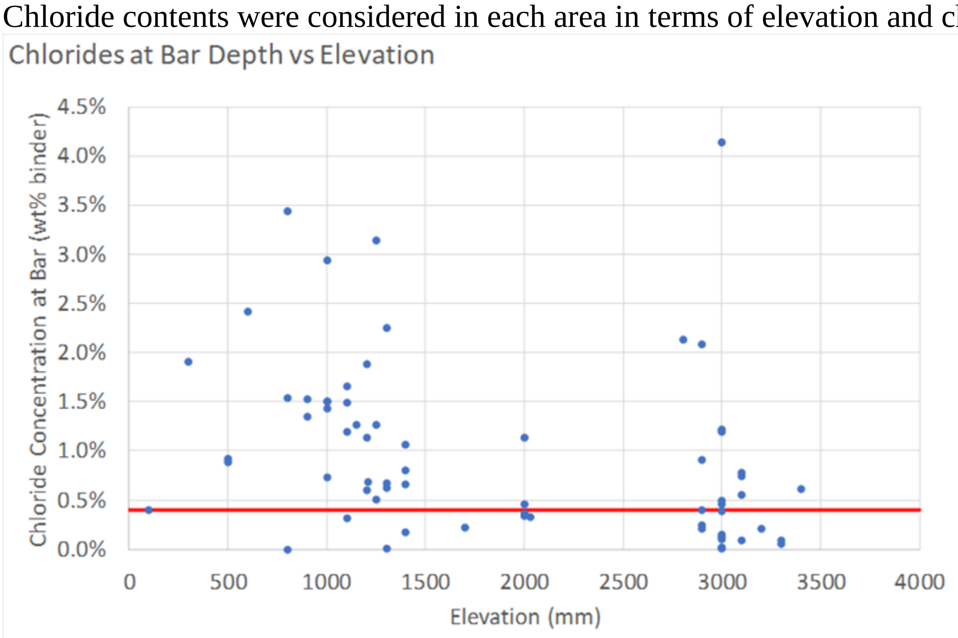


Figure 15. Chlorides at reinforcing depth vs. elevation. Red line shows lower bound corrosion initiation threshold of 0.4 wt.% cement.

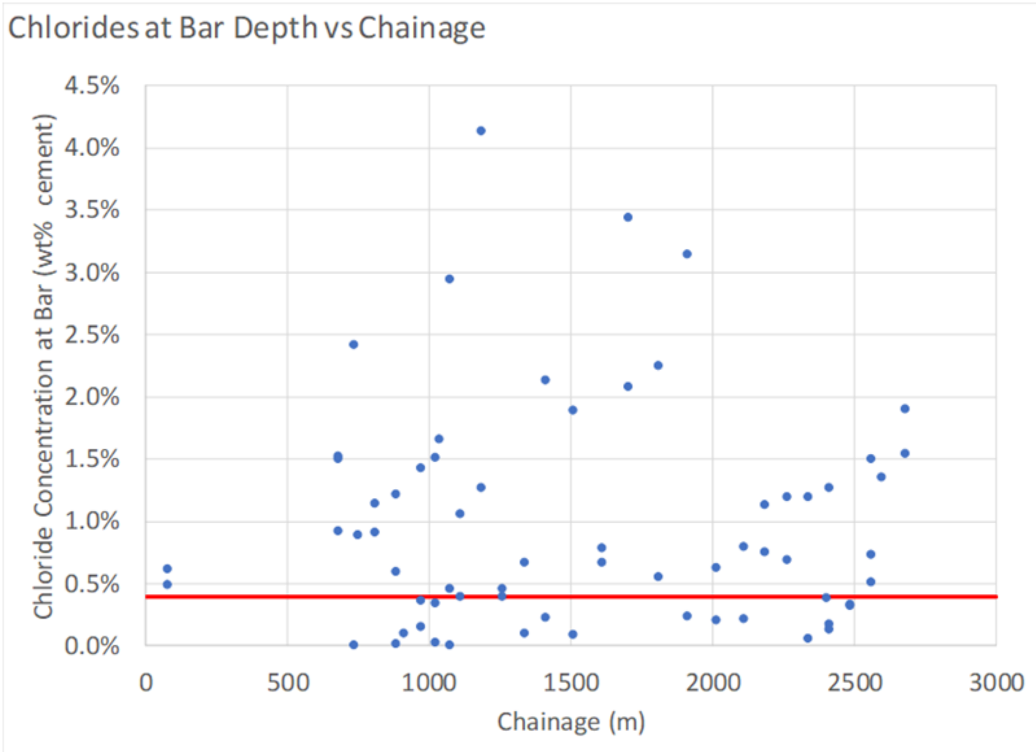


Figure 16. Chlorides at reinforcing depth vs. chainage (0 at kilometer 5). Red line shows lower bound corrosion initiation threshold of 0.4 wt.% cement.

Design assumptions in this project include:

- In the patch repairs of the service tunnel, the objective is to provide protective currents to mitigate the risk of incipient anode microcell corrosion of the adjacent parent concrete at the perimeter of repairs.
- In the refacing/overbuild of the traffic tunnels, the objective is to provide protective currents to mitigate the on-going corrosion since chloride contaminated concrete remains.
- A minimum anode design life of 20 years
- Current density requirements: 0.4 mA/m2, 0.8mA/m2 and 1.6mA/m2 for the chloride contents of less than 0.8%, between 0.8% to 1.5%, and greater than 1.5% by weight of cement.
- The anodes must be embedded in a mortar or concrete with bulk resistivity of 500 ohm-m or less, providing a bridge between the anode in the patch and the parent concrete.

Design requirements for the anodes:

- The anodes shall be zinc-based
- The zinc anodes shall be alkali-activated with a pH greater than 14.
- The anode unit shall contain no constituents that are corrosive to reinforcing steel such as chlorides, bromides, or other halides.
- The anode unit shall be supplied with an integral stainless steel wire
- 20 years of proven track record of the anode technology showing satisfactory field performance with a minimum of three projects of similar size and application

- The current output of the anodes shall be monitored to verify the performance.
- In order to obtain current measurements, an electrical connection between anode and steel should be made external to the concrete. Wires from both anode and steel may be routed to a junction box to facilitate testing. Current may be measured by placing a digital ammeter between wire leads, or by measuring the voltage across a calibrated shunt/resistor installed between anode and steel, using a digital voltmeter.

One of the main considerations when determining the appropriate spacing for galvanic anode units is the steel density ratio. It is the ratio of steel surface area over concrete area.

Steel density ratio = surface area of steel / surface area of concrete

This can be calculated by estimating the steel surface area in one square meter of the concrete area. A sample table lists the steel density ratio in different areas.

Table 2. Sample Table of Steel Density Ratio

Tunnel Section	Drawing No. (current)	Steel Density Ratio ($m^2_{steel}/m^2_{concrete}$)			
		Interior Wall		Exterior Wall	
	Elevation from Road:	Below 800 mm	Above 800 mm	Below 500 mm	Above 500 mm
T1					
T2 - T4	PO-65-01538-49	1.77	1.47	0.52	0.39
T5 - T6	PO-65-01538-49	1.70	1.44	0.55	0.42
T7 - T8	PO-65-01538-49	1.95	1.56	0.55	0.42
T9 - T10	PO-65-01538-49	2.22	1.70	0.45	0.32
T11 - T12	PO-65-01538-49	2.13	1.81	0.45	0.32
T13 - T14	PO-65-01538-49	2.33	1.94	0.45	0.32
T15 - T16	PO-65-01538-49	2.57	2.11	0.45	0.32
T17 - T18	PO-65-01538-49	2.74	2.22	0.47	0.34

If present, Post-tensioning duct will add more surface area and increase the steel density ratio.

After the chloride contents were tested and steel density ratio calculated, the anode spacing can be determined.

Table 3. Sample Table of Anode Spacing

Tunnel Section	Max. Spacing (mm)							
	Interior Wall				Exterior Wall			
	Below 800 mm		Above 800 mm		Below 500 mm		Above 500 mm	
	Away from duct	Near duct	Away from duct	Near duct	Away from duct	Near duct	Away from duct	Near duct
T1								

T2 - T4	290	270	315	290	530	435	615	480
T5 - T6	295	275	320	295	515	425	590	465
T7 - T8	275	260	305	285	515	425	590	465
T9 - T10	255	245	295	275	570	455	675	505
T11 - T12	265	250	285	265	570	455	675	505
T13 - T14	250	240	275	260	570	455	675	505
T15 - T16	240	230	265	250	570	455	675	505
T17 - T18	230	220	255	245	560	450	660	500

5.3 Implementation

Four components are essential for a galvanic corrosion protection system to function:

- An anode
- A cathode (steel reinforcing)
- Metallic connection between the anode and cathode, which can be achieved by tying the anodes to the cleaned rebar with anode wire.
- Ionically conductive path between anode and cathode. If the anode is fully covered with high resistivity material such as epoxy mortar, the ionic path will be lost.

After the concrete removal and surface preparation are completed, electrical continuity of the rebar within the repair area should be confirmed with the use of an appropriate meter prior to anode installation. When checking electrical continuity DC resistance of 1 ohm or a potential difference of 1 mV or less is acceptable. Discontinuities can be corrected by wiring the “unconnected” bar to adjacent bars using standard steel tie wire.

The anodes should be securely installed to rebars according to its design spacing. The concrete cover of 20mm or more should be allowed for the anodes. Once installed, electrical continuity between the anode tie wires and the rebar should be confirmed using an appropriate meter.

Repair material must have a resistivity below 50,000 ohm•cm to allow the ion transfer. In this case, the electrical resistivity of the repair mortar is between 40,000 to 50,000 ohm•cm, it is recommended to install the anodes within 50mm from the repair perimeter.

6. CONCLUSIONS

With the consideration of chloride contents and steel density ratio, galvanic systems in project can be designed to protect the tunnel components for 20 years or longer.

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