Case Study: 17 years of Corrosion Prevention for a Reinforced Concrete Bridge

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ABSTRACT

Chloride-induced corrosion can have a severe impact on the integrity of reinforced concrete structures and can dramatically shorten their service life. Cathodic prevention technology has been an effective electrochemical method used to prevent the initiation of corrosion in reinforced concrete structures in marine environments.

In 2005, a cathodic prevention system was installed during construction at the Sea Cliff Bridge along Lawrence Hargrave Drive (LHD) in New South Wales, Australia.

The bridge is located in an unusually severe marine environment as it faces the open ocean and is subject to splashing in high sea swells, putting it at high risk of chloride-induced corrosion.

This paper will present the theory of cathodic prevention and will include a performance summary of the system after nearly 17 years of operation.

Keywords: cathodic, prevention, concrete, corrosion, Sea Cliff Bridge

1. INTRODUCTION

1.1 What is Cathodic Prevention?

Cathodic prevention (CPrev) was applied for the first time in Italy in 1989 as “a method of preventive maintenance for new structures that are expected to become affected by chloride contamination in the future” and to emphasize that the “aims, operating conditions, throwing power, and effects (particularly those regarding hydrogen embrittlement) of CPrev, as well as many of the engineering and economic aspects of the design, construction, monitoring and maintenance of CPrev are different from those of normal cathodic protection”, so the name of cathodic prevention was proposed [1,2].

Cathodic prevention is an electrochemical technique that involves the application of a small electrical current using anodes that have been embedded in the concrete during construction. This system can be applied to an entire structure or to selected elements of a structure with the aim of preventing reinforcement corrosion when chloride penetration from the environment takes place during the service life of the structure. The basic philosophy of cathodic prevention is that a much smaller cathodic prevention current is required to prevent pitting corrosion compared to the higher current requirement to suppress ongoing corrosion. Another distinction is that the cost of the application of cathodic prevention is substantially lower than the cost of the application of cathodic protection.

In reinforced concrete structures, steel embedded in alkaline-free chloride concrete is in a passive condition. This passivity breaks down when the level of chloride exceeds the threshold and pitting corrosion can initiate.

The conditions for pitting initiation and propagation were pointed out by Pourbaix who during the 1970’s introduced the concept of “imperfect passivity” and “perfect passivity” intervals. The different domain of potentials is shown in Figure 1. As can be seen in the graph, for cathodic prevention, a modest lowering of the steel potential can produce a significant increase in the critical chloride level. The free corrosion potential of steel ranges from –200 mV to 0 mV when measured against a saturated calomel electrode (SCE). Pitting corrosion can take place if the chloride level exceeds 0.4 %W/W of cement.

If a cathodic prevention current is applied to steel in chloride-free concrete, this will allow the steel to remain passive even when the chloride reaches a considerably high content. The cathodic prevention current produces hydroxide ions at the steel surface and causes the chloride ions to move toward the anode and away from the steel.

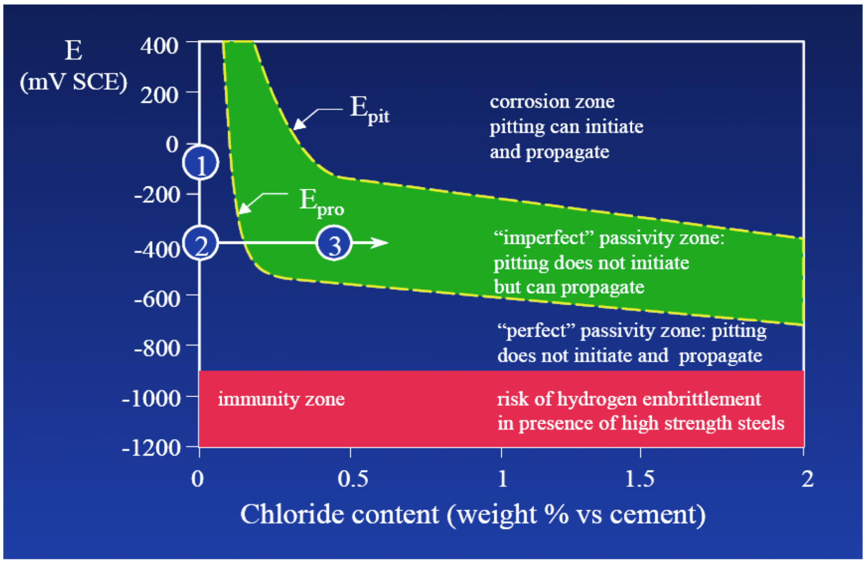


Figure 1 – Cathodic Prevention

When cathodic prevention is applied, the initiation of new pits is prevented however pitting corrosion can still propagate. For this reason, cathodic prevention needs to be applied before corrosion initiates and must be maintained throughout the service life of the structure. If pitting corrosion has been initiated, the current capacity typical for cathodic prevention will no longer be sufficient and cathodic protection current would be required.

The use of cathodic prevention for prestressed steel will eliminate the risk of hydrogen evolution because a lower current is required to prevent the initiation of pitting corrosion. The theoretical operating current for cathodic prevention ranges from 1-2 mA/m² of steel. The cathodic prevention design current density is normally 10 mA/m² of steel surface.

2. Corrosion Prevention Measures

Beside cathodic prevention, the general corrosion prevention measures to improve the durability and service life of concrete structures in harsh marine environments include:

- Modifying the concrete mix design, provision of adequate cover for the steel reinforcement and coating.
- The use of corrosion-resistant reinforcement.
- Addition of inhibitors to fresh concrete mix.

2.1 Mix Design, Concrete Cover and Coating Application

The quality of concrete is of major importance in determining the durability of reinforced concrete structures. Although concrete is a dense material, it contains pores and many of these pores are interconnected to form a network of channels that allow water and oxygen (both important to steel corrosion) to penetrate into the concrete. For this reason, a low water to cement ratio will lead to either a lower number of pores, or smaller pores in the concrete, both of which can lead to a reduction in concrete permeability and conductivity of the concrete. In addition to selecting a lower cement ratio for the concrete, the selection of the cement type and the addition of mineral admixtures such as silica flume, fly ash and slag can play a significant role in reducing the corrosion rate of reinforcement in concrete.

An adequate layer of concrete to the first layer of reinforcing steel may, under some circumstances, delay the ingress of chloride ions. The adequate depth of concrete cover is normally stated in various standards, subject to the exposure conditions of the structure. The minimum depth of concrete cover must be adjusted to allow for tolerances caused by construction practices.

For dense, high-quality concrete with adequate concrete cover, carbonation induced corrosion of the embedded steel is not considered to represent a major problem. However, for concrete structures in marine environments, irrespective of the quality of the concrete and the thickness of the concrete cover, it has been evident that it is only a matter of time before detrimental amounts of chloride reach the embedded steel through the concrete cover or cracks, leading to reinforcement corrosion and concrete spalling.

The penetration of chloride takes place through uncracked concrete mainly by capillary absorption and diffusion. When a relatively dry concrete element is exposed to salt water, the concrete will absorb the salt water relatively fast, and wetting and drying of the concrete (especially in tidal zones) can accelerate the accumulation of salt concentrations in the concrete. Furthermore, similar concrete elements with similar exposure conditions will exhibit variations in the concrete deterioration process as it is difficult to ensure homogeneity of concrete after being placed.

Coating the external surfaces of concrete may, in some circumstances, assist in delaying the onset of reinforcement corrosion. In marine environments, especially in the tidal and splash areas, it is unlikely that such measures will be effective in preventing reinforcement corrosion.

2.2 Corrosion Resistant Reinforcement

The final and most important line of defense against corrosion is the reinforcing steel itself. As a measure for preventing the corrosion of steel in concrete, various types of corrosion resistant reinforcement have been used in the past.

2.2.1 Epoxy Coated Reinforcement

Epoxy coated reinforcing bars are carbon steel coated with stable organic coatings (epoxies) to serve as a barrier for isolating the steel from moisture, chloride ions and oxygen to prevent corrosion.

Epoxy coated rebar was introduced in the mid-1970s in the United States as means of extending the useful life of reinforced concrete bridge components by minimising concrete deterioration caused by corrosion of the reinforcing steel. The epoxy coatings are intended to prevent moisture and chlorides from reaching the steel.

There are various documents regarding this subject with some of the documents showing favourable performance of epoxy coated rebar especially when used in areas of low corrosion risk.

When epoxy coated rebar was used in substructures that are exposed to a severely corrosive environment, the epoxy coated bars did not perform well. Significant premature corrosion of the epoxy coated bars was observed in many structures 5-10 years from the date of construction.

The main reasons for the failure of the epoxy coated bars are:

- Under-film corrosion because of the migration of water, oxygen and chlorides through the concrete and epoxy to the steel surface.
- Wet adhesion loss resulting in the separation of the coating from the substrate.
- Disbondment of the epoxy coating from the reinforcing steel which starts as coating defects.

It is the author's opinion that the use of epoxy coated rebars for corrosion prevention should not be considered for corrosion prevention. In areas of low corrosion risk, the use of carbon steel with high performance concrete and good concrete cover is sufficient to prevent corrosion from occurring. If the oxide layer which forms around the steel is not damaged due to carbonation or chloride ingress, there should be no issues with corrosion. For the areas of high corrosion risk in marine environments, the use of epoxy coated rebars is unlikely to provide the adequate corrosion prevention to extend the life of the structure.

2.2.2 Galvanised Steel Reinforcement

Hot-dipped galvanised coatings for reinforcing bars have been used over the last fifty years in many countries to improve the service life of concrete structures. Steel reinforcing bars can be protected with a coating applied by dipping prepared steel bars into a molten bath of zinc.

Galvanising constitutes a means to extend the service life of reinforcement in concrete structures that will be subjected to carbonation. A substantial increase in the service life of the structure can be achieved by using galvanised steel.

For marine structures, where the primary problem is chloride-induced corrosion, the increase in service life could be too short to justify the extra cost for the use of galvanised reinforcement. Rapid corrosion will occur when galvanised and black steel is used in the same structure and is electrically connected in chloride-contaminated structures.

2.2.3 Stainless Steel Reinforcement

The term stainless steel refers to a group of corrosion resistant steels containing a minimum of 12% chromium. Various alloying additions (eg. nickel, titanium, nitrogen) can be added to provide different mechanical and corrosion properties. The use of stainless steel in concrete is related to its capacity to resist corrosion in chloride-contaminated structures.

Stainless steel reinforcement has been used in various countries in structures that are located in aggressive environments. Stainless steel has been used in construction joints or critical gaps between columns and decks. There is no extensive performance data available for long-term use of stainless steel as reinforcement in concrete.

Because of the high cost of stainless-steel reinforcement, it is unlikely that the entire reinforcement for a large marine structure would be made from stainless steel. A more likely use of stainless steel would be for the outer layer of rebar in a reinforced concrete element in the tidal/splash zone. Galvanic corrosion in this case between stainless steel and carbon steel should be investigated.

2.3 Corrosion Inhibitors

Corrosion inhibitors are chemicals that can be added to the concrete to decrease the corrosion rate. The inhibitors can be subdivided into three categories, anodic inhibitors, which are used to reduce the anodic reaction rate, cathodic inhibitors, which are used to reduce the cathodic reaction rate, and mixed inhibitors which are used to reduce cathodic and anodic reaction rates.

The inhibitors are used as a preventive measure for new reinforced concrete structures in aggressive marine environments with a known future risk of chloride-induced corrosion. Corrosion inhibitors are marketed separately as admixtures, or they may be present in repair products used for conventional patch repair.

There are various questions related to the application of corrosion inhibitors as admixtures to reinforced concrete. Some of these questions are related to the long-term experience with corrosion inhibitors, the effect of corrosion inhibitors on concrete properties, the acceleration of corrosion when the corrosion inhibitors are used in inadequate dosage, and other issues such as the leaching out and evaporation of the inhibitors from the concrete.

In general, it appears that if inhibitors are used in suitable concentrations, they may delay the initiation of corrosion, however there is no established evidence that the commercial inhibitors available at present are able to reduce the corrosion rate after the initiation of corrosion.

2.4 Corrosion Prevention selection

For Sea Cliff bridge, the options for consideration were the use of stainless-steel reinforcement or the use of cathodic prevention.

Cathodic prevention was the selected method for this bridge to improve the corrosion resistance of reinforcement and increase the life of the bridge with minimal maintenance. To the best of our knowledge, the cost of a cathodic prevention system was substantially lower than the cost of using stainless steel reinforcement.

3. CATHODIC PREVENTION CASE STUDY

The 665-meter Sea Cliff Bridge was constructed in 2004 and was opened for traffic in December 2005. The bridge consists of two sections, GD2 and GD3, which were constructed using different methods. GD2 bridge is a 455 m long balanced cantilever bridge supported by a reinforced concrete substructure of four piers. GD2 joins the 210 m long incrementally launched GD3 bridge. The GD3 bridge is supported by a reinforced concrete substructure of seven piers.

The Sea Cliff Bridge is situated in a harsh marine environment as it directly faces the open ocean and is subject to splashing from high sea swell.

During the construction of the bridge, a CPrev system was incorporated into the pile caps and columns of GD2 and GD3 in order to prevent corrosion of the embedded steel. These elements of the structure were considered to have the highest future risk of corrosion.

The total surface area on the bridge to be protected was 4,890 m^2. A total of 16.5 km of ribbon anode was used in the CPrev system installation.

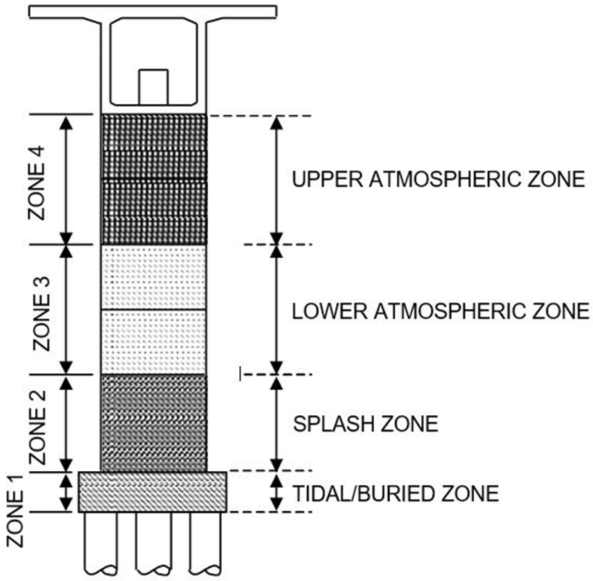
3.1 Design Concept

The design of the system was completed in accordance with the applicable Australian Standard at the time of construction AS 2832.5-2002[3]. Special mesh ribbon activated mixed metal oxide Titanium anodes with a design life of 100 years were used as the anode material. Cementitious spacers imported from Italy were used to provide separation between the ribbon anodes and the steel reinforcement of the bridge. The system components were embedded in concrete including anode connections, steel connections and reference electrodes. All cables from the bridge structure were terminated in junction boxes and a control system located at the end of the bridge.

The pile caps and pier columns were divided into multiple electrical zones to account for the following variables of the structure:

- Environmental exposure conditions
- Construction stages
- Geometry of the structure
- Maximum current output of the power units
- Current distribution

The zoning of a typical pier is illustrated in Figure 2.



Zone	Description
1	Pile caps and pad footings
2	Columns: lower two sections
3	Columns: middle two sections
4	Columns: upper two sections

Figure 2 – Zoning of a typical pier

3.2 Monitoring

The performance of the CPrev system was monitored using a combination of Silver/Silver Chloride (Ag/AgCl) reference electrodes with a design life of 20 years and activated Mixed Metal Oxide (MMO) Titanium pseudo reference electrodes with a design life of 100 years. The reference electrodes were installed during the construction of the piers in representative locations throughout the structure to obtain a comprehensive set of data for future monitoring. This included ensuring some reference electrodes were close to and remote from the positive connection to monitor for over and under protection.

3.3 System Performance

A remote-control system was installed for monitoring the cathodic prevention system. Since commissioning, routine testing of the system included functional checks and system testing and adjustment at regular intervals which has been carried out as per TfNSW’s requirements.

The total cathodic prevention current delivery to the structure based on the latest testing was 31.2 Amps. Based on the protected concrete surface area of 4890 m^2, the average current delivery to achieve the protection criteria based on the applicable standard is 6.38 mA/m^2 of concrete surface. Based on an average of 1.5 m^2 steel surface area in 1 m^2 of concrete, the current requirement per 1 m^2 of steel surface area to maintain protection is 4.25 mA. This is well above the theorical assumption of 0.2-2 mA/m^2 of steel surface area and in line with our experience from the operating cathodic prevention systems at the Sydney Opera House [4,5]

Based on the operating system data, the operating current for cathodic prevention systems is 2-5 mA/m^2 of steel surface area.

4. CONCLUSIONS

Work on the construction of the Sea Cliff bridge was completed in December 2005, at an overall cost of 52 million Australian dollars. The cost of incorporating cathodic prevention into the critical elements of the bridge was estimated at approximately 1.5% of the total cost of bridge construction. The original installed control system is still operational and the maintenance and monitoring cost over the past 17 years is estimated at less than 0.3% of the original construction cost.

Based on the system's operational data, the cathodic prevention system is providing full corrosion prevention to all embedded rebar and is maintaining full passivity of the steel reinforcement in the critical elements of the bridge based on the applicable standards.

For reinforced concrete structures that are built in harsh marine environments, cathodic prevention can be considered as an effective low-cost corrosion prevention measure that can be incorporated during the construction phase.

This cathodic prevention installation is a typical example of how innovative technology was used to extend the life of infrastructure assets.

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6. BIOGRAPHIES

Atef Cheaitani is the Managing Director of Remedial Technology Pty Ltd. Atef's expertise is in the assessment and development of rehabilitation solutions for reinforced concrete structures using electrochemical applications. Atef has pioneered the introduction of cathodic prevention technology to Australia, China and India and has been involved in the development of various patented technologies associated with cathodic protection of concrete structures.

Samir Cheytani is the Operations Manager at Remedial Technology Pty Ltd. Samir has comprehensive experience in the condition assessment of concrete structures affected by steel reinforcement corrosion. He has been involved in investigative site work including concrete testing, electrochemical testing, extraction of samples, data analysis and the development of rehabilitation solutions and reporting. Samir has completed a Bachelor of Property Economics degree (BpropEc) in 2005 from the University of Technology, Sydney (UTS), and a Master of Philosophy (MPhil) in Material Science and Engineering in 2020 from the the University of New South Wales (UNSW).

Martin Cheytani is the Technical Manager of Remedial Technology. Martin has completed a Bachelor of Construction Project Management degree (BCPM) in 2014 from the University of Technology, Sydney (UTS), a Master of Philosophy (MPhil) in Material Science and Engineering in 2017 from the University of New South Wales (UNSW), and a PhD from the University of New South Wales. Martin's areas of expertise are in grout acidification associated with ribbon anode ICCP systems, the impact of concrete resistivity on electrochemical protection systems and the development of new generation control systems for electrochemical applications.