Repair and Maintenance of Marine Structures by Cathodic Protection

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Abstract

Marine structures such as bridges, wharves, jetties and mooring dolphins are required to function in an aggressive environment for many years. Maintenance expenditure is sometimes sporadic and the required service life may be increased as the structure ages, with the result that many marine substructures deteriorate to the extent that major repairs are needed.

The technology available for repair and maintenance of reinforced concrete structures has grown in recent years and electrochemical treatments, such as cathodic protection, are now becoming common for marine structures. This paper indicates the range of cathodic protection systems and hardware in current practice, with reference to the treatments applied to port structures in Victoria, Queensland, New South Wales and Tasmania. Their different methods of contract delivery are also indicated.

1. REINFORCED CONCRETE IN MARINE ENVIRONMENTS

Steel and concrete have been used effectively together in civil construction for over 100 years. Their combination has been commonly used because of its versatility, durability, fire resistance and low cost. However embedded steel reinforcement frequently corrodes and this corrosion can cause significant deterioration of the structure.

1.1. The Corrosion Process

During construction a protective oxide film forms on the surface of reinforcing steel as the cement hydrates. The film is formed due to the high alkalinity (pH 12.6-15.5) of the hydrating cement and it will continue to protect the steel against corrosion while the high alkalinity is retained.

Concrete is a microporous material and therefore susceptible to the permeation of gases and diffusion of ions, such as chlorides, in solution. Penetration of chloride ions in the concrete microstructure will occur where elements are exposed to seawater and salt spray.

In most cases the laws of diffusion can approximately predict the rate of chloride ingress. Salt water is rapidly absorbed by dry concrete through the initial mechanism of suction. Chloride ions then move through the concrete pores through diffusion. When in sufficient concentration, the presence of chlorides at the steel surface can initiate corrosion. Once the layer is destroyed the chlorides are not consumed in the reaction but act as a catalyst in the ongoing corrosion process.

Corrosion is an expansive process because rust products occupy a much larger volume than the original steel. This leads to cracking, delamination and finally spalling of the concrete cover to the steel. Once exposed to the atmosphere, the steel reinforcing will then continue to corrode at an accelerated rate.

In low oxygen conditions, such as in buried or submerged areas, the corrosion rate is reduced due to the limited availability of oxygen. Corrosion under these conditions is slower and usually results in a partially soluble and less expansive ‘black rust’.

Chloride ingress is the principal cause of extensive and severe corrosion of embedded steel reinforcing in concrete structures at coastal locations. The implementation of remediation measures is usually left until the presence of chlorides is widespread with high concentrations of chlorides at or beyond the level of steel reinforcement. At this stage, cathodic protection is often the most appropriate technique to prevent further deterioration.

1.2 Cathodic Protection of Reinforced Concrete

Cathodic protection of metals against corrosion was first demonstrated in the early nineteenth century and it is now used in a wide variety of applications to slow corrosion of metals including pipelines, ships’ hulls, underground storage tanks and offshore structures.

Since the 1970s this technology has been applied to effectively stop corrosion of embedded steel reinforcing within concrete structures. The anodes used in cathodic protection systems for buried and immersed concrete structures are well established but the technology of the anodes for atmospherically exposed concrete structures is still evolving. Over the past ten years cathodic protection is being used more frequently as a cost-effective solution to control corrosion of steel reinforcing in atmospherically exposed concrete structures.

Cathodic protection controls the corrosion process by altering the thermodynamics and kinetics of the affected steel and is achieved by forming an electrical circuit with an introduced anode using the concrete as an electrolyte and the protected steel as the cathode. Cathodic protection can be driven either by galvanic means or an impressed current.

2.0 CATHODIC PROTECTION SYSTEMS

Galvanic and impressed current cathodic protection systems can both be used to protect embedded steel reinforcing in atmospherically exposed concrete structures from corroding.

2.1 Galvanic Cathodic Protection

Galvanic (also known as sacrificial) anodes are the oldest form of cathodic protection with their use dating back to the early 1800s. They are based on the principle of dissimilar metal corrosion and use metals that are further down the electrochemical series than iron (such as zinc, aluminium and magnesium) to protect the steel by preferential consumption of the anode.

In submerged or buried areas discrete zinc anodes are positioned adjacent to the structure where the low resistivity of the soil or water allows the current to pass readily from the anode to the steel reinforcing. In atmospherically exposed concrete it is necessary to distribute the zinc anode more closely in the areas to be protected, as the resistivity of concrete is substantially higher than soil or water.

Spraying zinc in atmospherically exposed areas has been common practice in the US over the past ten years. In Australia, VicRoads installed similar systems on four coastal bridges along the South Gippsland Highway some five years ago. The zinc was applied by heating and then spraying it onto exposed surfaces. The thickness of the zinc after application was approximately 0.5mm. Provision was made for interrupting the circuit between the anode and steel reinforcing and measuring permanent reference electrodes within an enclosure adjacent to each structure. These cathodic protection systems have been regularly monitored since energising and are still performing satisfactorily.

More recently, proprietary discrete zinc anodes have been developed for extending the life of patch repairs in chloride-saturated concrete. Encased in porous mortar plugs and fixed to the reinforcing steel at intervals around the perimeter of each patch, the units are designed to prevent the formation of incipient anodes in the adjacent unrepaired concrete. The zone of effectiveness of each unit is about 500mm and their expected lifespan is up to ten years. Trials of these sacrificial anodes have been conducted within the last year on two wharves in Queensland.

The service life of galvanic cathodic protection systems is governed by the quantity of anode used. In buried/submerged situations it is common to design for a 30-year service life and a 10 to 15-year service life in exposed atmospheric situations.

2.2 Impressed Current Cathodic Protection

Impressed current cathodic protection systems have been used to protect steel reinforcing in atmospherically exposed concrete structures for more than 25 years. These systems consist of the following fundamental components:

- A direct current power supply
- An anode system
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- Cables to create a circuit between the anode and reinforcing steel

There are a number of different types of anode that are available in varying geometric forms, but activated titanium or conductive ceramics anodes are most commonly used in marine applications.

2.2.1 Activated Titanium Anodes

The anode comprises a titanium product with an electro-catalytic coating containing oxides of rare earth elements (such as platinum, iridium, etc). Activated titanium anodes may be operated at current densities of up to 400mA/m^2 of anode surface area for short periods, but at this density acid attack of the surrounding concrete can occur.

For this reason it is recommended that the anode current density is limited to a long-term maximum of 110mA/m^2 of anode surface, but for short-term periods (ie months) current densities of up to 220mA/m^2 may be permitted. At these operating levels the anodes have an effective service life of at least 75 years. The anodes are commonly available as open expanded mesh (in wide rolls), narrow strip ribbons (which may also be in expanded mesh form), or small-diameter rods.

The open mesh is usually fixed to the concrete surface and covered by a sprayed low-resistivity, cementitious overlay about 25mm thick. In some cases, the mesh can be fixed to the inside face of formwork and incorporated in a poured repair mortar (this can also be used for 'cathodic prevention' in new concrete structures). It should be noted that an overlay increases the dead weight of the structure by 50-80kg/m^2, and careful quality control must be implemented to prevent it from debonding from the substrate.

Ribbon anodes are usually recessed into the cover concrete in sawn grooves and backfilled with a cementitious grout of moderately low resistivity. The ribbon is usually between 12mm to 25mm in width and approximately 1mm thick. The anode slots are typically spaced 150 to 300mm apart and the depth of cover to the reinforcing steel dictates their depth and orientation. In some applications, ribbon anodes can be fixed to the reinforcing steel with insulating clips before pouring the repair mortar or new concrete.

Activated titanium rods have been used as an internal anode system when installed in holes drilled into the concrete to depths of around 100 to 200mm, or even deeper if remote layers of reinforcing are also to be protected. The spacing of the anodes is determined by the distribution of reinforcing steel and the location of corrosion activity. One such internal system, which has been used on a number of Australian bridges since 1990, uses 3mm diameter mixed metal oxide coated titanium rods, backfilled with a conductive graphite-based paste or gel. The graphite is consumable due to gas generation at the anode and is estimated to have an effective service life of 10 to 15 years.

2.2.2 Conductive Ceramic Anodes

Conductive ceramic anodes comprise a ceramic tube that is electrically conductive and corrosion resistant that encapsulates a titanium core. Ceramic anodes can be operated at up to 900mA/m^2 of anode surface however it is more usual for the anode to operate at around 400mA/m^2. At these operating levels there is the possibility of anodic gases being generated and therefore the anodes are supplied with a dedicated gas venting system to allow any gases to dissipate.

They are installed via holes drilled from the exposed surface, then backfilled with a cementitious material. Unlike their titanium counterparts they are not required to be backfilled with a conductive paste or gel and at normal operating levels are expected to have a service life in excess of 50 years.

Conductive ceramic anodes were developed in the UK some eight years ago and have been used widely in Australia over the past five years. The discrete anodes are available in different lengths and diameters but are usually from 18mm to 28mm in diameter and 150mm to 270mm in length. They are typically installed between 300mm and 600mm apart.

2.2.3 Choice of Impressed Current System

The extended service life required for marine structures is often greater than 30 years and in these situations impressed current cathodic protection systems are usually more appropriate than the shorter-lived sacrificial ones.

Within the variety of systems outlined above, there are a number of different proprietary anodes presently available. Selection is usually dictated by the geometry of the structure and the distribution and corrosion activity of its embedded reinforcing steel, as well as cost and logistical issues, such as access for installation.

Experience suggests that activated titanium ribbon strips are usually chosen where protection of reinforcing steel is required in the surface of wide elements such as deck slab soffits and walls. Where protection of the steel reinforcing in more than one face is required (for example columns and beams, as well as thick slabs and walls) the use of discrete anodes may be more cost-effective by permitting installation from one face only.

Ribbon anodes are often used in overhead applications such as the soffits of beams. This may be the only face accessible if it is necessary for the wharf to continue operating during repair work. Crane beams at container berths in Brisbane and Newcastle, for example, are protected by ribbon anodes for the length and width of the beam soffit. Anode spacings vary from 140mm to about 300mm, depending on the density of reinforcement. The methods used on these structures to fix the anode include embedding in a sprayed overlay, grouting in sawn slots and embedding in the sprayed repair.

A mixture of anode types is often used to optimise the performance and cost of a cathodic protection system. An example is the rehabilitation of a large wharf in Portland, Victoria. The main beams, typically 840mm wide by 690mm deep, were protected on their sides and soffit by seven ribbon anodes. The 600mm thick, heavily reinforced fender wall was protected on both sides by a pattern of discrete anodes, installed from one side at 300 to 450mm spacings.

A further example of anode variety is in the repair and protection of two wharves at Townsville, Queensland. Patch repairs were made to isolated areas of deck slab and ribbon anodes were fixed to the steel in each patch in order to prevent the formation of incipient anodes beyond it. Repairs were also made to some of the large, circular columns; these were protected by discrete anodes installed in their centres.

Discrete anodes are often utilized where access to one face of a concrete structure is not possible. An example of this is the protection of reinforcing steel in the soffit of berthing dolphins at Port Giles in South Australia. In this case the clearance between the water level and the soffit of the dolphin was too small to allow installation of anodes from below. As a result, discrete anodes were installed in holes up to 1400mm long drilled from the top and sides of each dolphin.

3.0 CATHODIC PROTECTION FEASIBILITY AND DESIGN

Prior to the implementation of remediation measures the available technology together with life cycle costing should be evaluated to ensure the most effective solution is selected. In order to assess the feasibility of cathodic protection the condition of the structure and deterioration mechanisms should be determined as well as establishing the following:

The reinforcement is continuous. For cathodic protection to be effective the reinforcement must be electrically continuous.

The current requirement, which is usually based on 20mA/m2 steel surface area.

The design life of the cathodic protection system, which is usually between 10 and 50 years.

3.1 Remediation Strategies

For smaller concrete structures such as mooring and berthing dolphins, the use of a single remediation technique is often appropriate. However, for larger structures, such as wharves and jetties, the extent and rate of deterioration observed could vary with the different micro-environments that can exist. In these cases, a combination of treatment techniques may be used so that the overall cost, both initially and in future years, best meet the needs of the owner.

A common solution is to apply cathodic protection in areas where the chloride concentration of the concrete at the level of steel reinforcement is high, and protective coatings (eg silane) where chloride ingress has not yet penetrated to the level of steel reinforcement and corrosion damage has not started. The silane requires replacement every ten years or so.

If re-casting of concrete is necessary, mesh, ribbon or discrete anodes can be installed prior to placing of the concrete. Where chloride ion ingress is localized the incorporation of discrete galvanic anodes within the patch repairs can prevent the occurrence of incipient corrosion to provide a more durable solution. Hot spots of local corrosion can be similarly treated with isolated anodes.

3.2 Cathodic Protection Design and Standards

The design of a cathodic protection requires identification of different anode zones for control purposes and to ensure provision of uniform protection levels. These zones are usually based on areas with similar characteristics, such as concrete resistivity and environment. Other issues that should be considered include monitoring requirements, cable routing and protection, positioning of the control and monitoring unit as well as the power source.

Guidance on the design, installation and monitoring of cathodic protection systems for atmospherically exposed structures is outlined in the draft Australian Standard 'Cathodic Protection of Metals

: Part 5 Steel in Concrete Structures' (to be AS 2832.5).

3.3 Performance Monitoring

Performance monitoring of cathodic protection systems is carried out periodically to ensure adequate protection is being achieved over the whole structure. Relevant cathodic protection criteria for steel in atmospherically exposed concrete structures are detailed in the draft Australian Standard (to be AS 2832.5). In summary the cathodic protection is usually demonstrated by achieving at least one of a number of criteria. These are based on changes in electrochemical potentials of the reinforcement during operation of the cathodic protection system and immediately following its temporary disconnection. The criteria are designed to ensure that the steel is adequately but not excessively protected.

Galvanic cathodic protection systems are self-regulating. Monitoring usually consists of a hammer-tapping and/or half-cell potential survey.
With impressed current cathodic protection systems there is the risk of over-protection causing hydrogen generation at the reinforcing steel surface and the possibility of embrittlement particularly in pre-stressed steel. To eliminate this risk permanent monitoring devices are installed together with the cathodic protection system.

Silver/silver chloride/0.5M potassium chloride gel (Ag/AgCl/0.5M KCL) reference electrodes embedded in the cover concrete are commonly used for this purpose. Other sensors including potential decay electrodes have also been used in conjunction with reference electrodes. It is also usual practice to monitor current and voltage outputs to the various zones to ensure the operating limits of the anode are not exceeded.

Permanent reference electrodes should be installed to take into account areas that have the following characteristics:

(a) particular sensitivity to under-protection (at least 500mm away from any anodes),

(b) particular sensitivity to over-protection (less than 250 mm away from an anode);

(c) high corrosion risk or activity (area with a steel/concrete potential more negative than -350 mV Ag/AgCl); and

(d) low corrosion risk or activity (area with a steel/concrete potential more positive than -150 mV Ag/AgCl).

Recent developments in computer and communication technology have introduced the option for remote monitoring and control of cathodic protection systems. The incorporation of a remote system can be particularly cost effective where access to the structure is difficult, or it is distant from major urban areas. It is also appropriate for owners of a number of structures protected by impressed-current systems.

4.0 CONCLUSIONS

Marine and coastal concrete structures are exposed to one of the most aggressive environments, with older structures often suffering extensive and severe deterioration. It is common practice to extend the original service life of these structures and this has been successfully achieved by applying cathodic protection.

Recent developments in anode technology for use in atmospherically exposed concrete structures have resulted in a wide selection of products available. This offers added versatility to the technology in the implementation of both short- and long-term solutions to control steel reinforcing corrosion in deteriorating concrete structures.

The application of enhanced communication facilities as well as more widespread use of computers can also be harnessed so that asset managers can remotely monitor and control the protection of their structures.