APPLICATION OF CATHODIC PREVENTION TO SEA CLIFF BRIDGE, LAWRENCE HARGRAVE DRIVE

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Abstract

Chloride-induced corrosion can have severe impacts on the integrity of reinforced concrete structures and can dramatically shorten their service. Cathodic Prevention (CPrev) is an effective electrochemical method used to prevent the initiation of corrosion in reinforced concrete structures in marine environments. Sea Cliff Bridge is a recently constructed two-lane bridge between Clifton to Coalcliff along Lawrence Hargrave Drive (LHD), 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 a very high risk of chloride-induced corrosion. This paper discusses the design and application of Cathodic Prevention to the Sea Cliff Bridge including the state-of-the-art remote control and monitoring technology installed.

Keywords: cathodic, prevention, concrete, corrosion

Introduction

A section of Lawrence Hargrave Drive between Clifton and Coalcliff, north of Wollongong, was closed for repair in July 2004 due to geological instability of the area. The A$49 million, 665 metre Sea Cliff Bridge was constructed to bypass this section of road. The bridge was opened in December 2005 and is located offshore, curving about 45 metres to the east of the cliff face. The bridge is 41 metres above sea-level at its highest point.

Sea Cliff Bridge consists of two sections, GD2 and GD3 bridges, which were constructed by different methods. GD2 Bridge is a 455 metre long balanced cantilever bridge supported by a reinforced concrete substructure of four piers. GD2 joins the 210 metre long incrementally launched GD3 Bridge. GD3 Bridge is supported by a reinforced concrete substructure of seven piers.

Figure 1: Sea Cliff Bridge – Aerial View (with GD2 on left and GD3 on right)

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. It is well documented that concrete structures in such environments are particularly prone to chloride-induced corrosion of the steel reinforcement. This can eventually lead to expensive repair works and significantly reduce the life of the structure.

Figure 2: Sea Cliff Bridge during construction. CPrev applied to pier columns and pilecaps

Cathodic Prevention (CPrev) is a proven electrochemical technique used in reinforced concrete structures to prevent the onset of corrosion caused by environmental chloride contamination. CPrev is used to improve the durability and service life of the structure and reduce maintenance costs. It may be used with other compatible advances in concrete technology such as high performance concrete mixes, to further increase the durability of the structure in severe environments.

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 concrete surface area protected is 4,890 m^2. A total of 16.5 km of ribbon anode was used in this installation.

The following sections detail CPrev background theory, design assumptions, concept design, system monitoring, protection criteria, and installation.

Cathodic Prevention Theory

In the presence of chlorides, for example on bridge decks where de-icing salts are spread, or in splash zones of marine structures, additional preventive corrosion measures must be used to guarantee a service life of even a few decades.

In addition to the use of good quality concrete with increased cover, some of these measures used include corrosion inhibitors, coatings, stainless steel reinforcement and cathodic prevention. Each of these options was evaluated for this project in terms of suitability, technical issues, lead times, effectiveness and cost implications, and cathodic prevention was selected as the preferred option[15]. Cathodic prevention was applied for the first time in Italy in 1989 as "a method of preventive maintenance of 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[3,4].

This technique is based on the principle that the critical chloride threshold increases as the potential of steel decreases. The decrease of reinforced steel potential is obtained through the application of a direct current, which flows through the concrete from an anode applied on the concrete surface to the reinforcement.

To understand how cathodic prevention works it is important to consider the corrosion and protection conditions, which are shown in Figure 3. If environmental conditions belong to region (A), pitting corrosion is possible. In order to gain protection the potential must be brought to region (B) where pitting does not initiate but can propagate or to region (C) to stop even active pits.

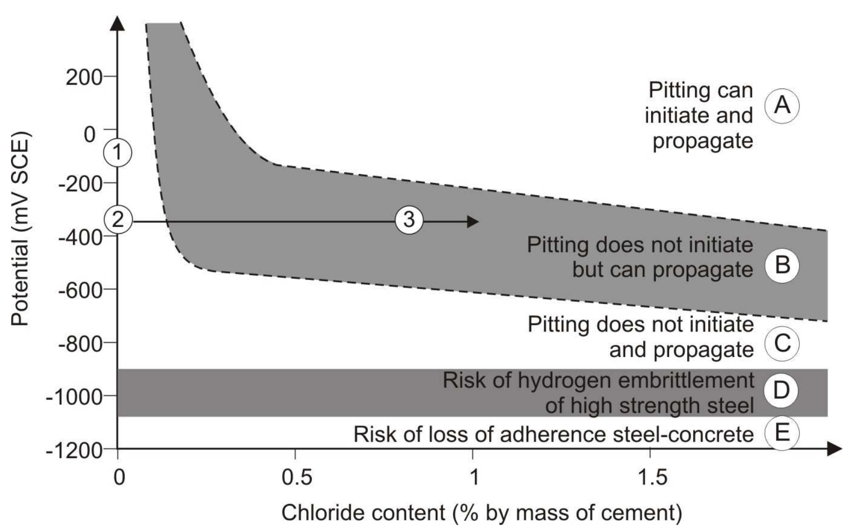

Figure 3: Evolution path of cathodic prevention[5]

In the same Figure 3 the typical evolution path (①②③) in terms of potential and chloride content of cathodic prevention is shown. Lowering the potential of new passive steel allows passivity to be maintained even when chloride content becomes higher than the critical content for non-polarized structures.

Such polarisation leads to conditions of imperfect passivity where pitting corrosion, although it cannot initiate, can propagate. It should therefore be emphasised that cathodic prevention has to be applied before corrosion initiates and must be maintained throughout the entire service life of the structure.

Design Assumptions

In order to design a CPrev system, certain design assumptions need to be made, as there is usually no opportunity to perform a trial before construction of the structure begins.

Some of the assumptions for this design are as follows:

- Current density requirement of 10mA/m^2 of steel reinforcement. AS2832.5[6] mentions in the 'informative' Appendix section that typical current densities for cathodic prevention range between 0.2 mA/m^2 and 2 mA/m^2. These figures are based on laboratory tests and field experiences mainly referring to cathodic prevention of steel reinforcement in atmospherically exposed concrete, in particular decks and piles of bridges and viaducts.[9-12] Other field experiences in more severe marine environments, such as the Sydney Opera House underbroadwalk, indicate higher current densities are required, typically within the range of 2 to 5 mA/m^2.[1] There is generally very limited experience and information available from field studies, and therefore, without the benefit of a pilot trial, a current density of 10mA/m^2 of steel surface area was used in this system.
- For current distribution requirements, anode spacing was limited to a maximum of 300mm centres. It is known that due to the resistivity of concrete, the spacing of anodes is crucial to ensure adequate distribution of current to the steel reinforcement. Without the benefit of a trial this maximum spacing was adopted based on past experience, and was considered practical in terms of the steel geometry.

Design Concept

The design of the system was completed in accordance with relevant standards, including AS 2832.5-2002[6].

Mesh ribbon anode LIDA® Grid (activated mixed metal oxide Titanium) was used as the anode material, to be embedded in the concrete during construction. The anode was specially manufactured to provide a 100 year design life operating at 110mA/m^2. The specifications of the mesh ribbon anode are as follows:

- Width: 23.7mm
- Thickness: 1.3mm
- Current output: 5.28mA/m

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

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

The zoning of a typical pier is illustrated in Figure 4 and is described in Table 1.

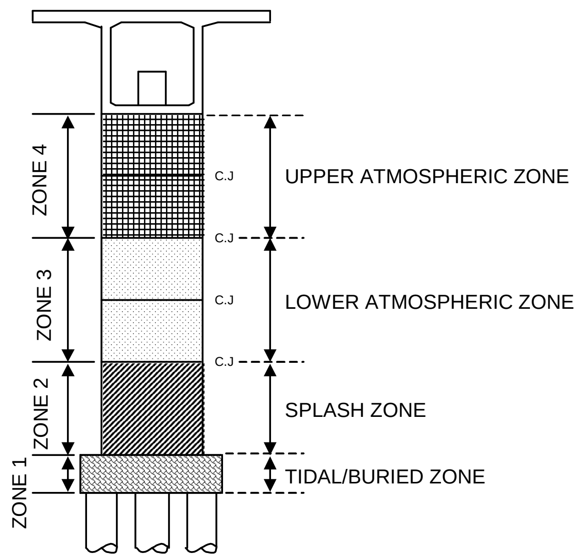

Figure 4: **Typical Pier Electrical Zoning**

Table 1: Electrical Zoning of Sea Cliff Bridge

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

One control unit was installed for each bridge. Within each control unit, there is a sufficient number of separately controllable rectifiers for supply of DC current to each zone.

An important part of the design process was the selection of the optimum location for the system components. The junction boxes, conduit, cabling and control units were specifically located to allow relatively easy future maintenance, whilst ensuring the components are not visible to the public (for aesthetic purposes) and are protected from potential vandalism.

Monitoring

The performance of the system is monitored by a combination of Silver/Silver Chloride (Ag/AgCl) reference electrodes with a design life of 20 years and activated MMO Titanium pseudo reference electrodes with a design life of 100 years. The reference electrodes were installed during 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.

The Silver/Silver Chloride reference electrodes can be used to measure the absolute potential of the steel reinforcement and for potential decay measurements. They allow the system to be assessed according to all the protection criteria in the Standard[6], and therefore allow the monitoring engineer to make informed decisions on current output required to maintain protection levels. This is especially critical during the first few years of system operation. However, as their design life is limited, and the structure itself is designed for at least 100 year service life, it is important to include references that will monitor the system past the first 20 years. Activated MMO Titanium pseudo reference electrodes can be used very effectively for potential decay measurements, which allows the engineer to assess the system based on the 100mV decay criterion.

Control System

A remote control and monitoring system was selected for this project. Computer control systems have some major advantages over manual locally-controlled systems, including the following:

- Remote access ensures the system can be checked regularly and very easily to confirm the system is continually operating. Any faults can easily be identified with alarm functions and rectified as soon as possible. Manual systems are sometimes only monitored 6-monthy or yearly, and therefore there is a risk that the system could be off for an extended period of time due to faulty electronics or blown fuses.
- Computer control systems allow monitoring data to be continuously logged which allows the engineer to view historical data and ensure the system is stable.
- Computer control systems have specific cathodic protection/prevention testing functions, which ensures monitoring is done easily and effectively, reducing the margin for error. For example, when performing a 24 hour depolarisation monitoring survey with a manual system, data is taken at the beginning of the survey and then at the end of the 24 hour period. This ignores any potential fluctuations that may have occurred over the 24 hour period, and can provide some very misleading results which is used to adjust the system outputs. This is especially an issue when monitoring tidal zones. A computer control system with graphing capabilities allows data to be logged and viewed over the whole 24 hour period and therefore better judgements on system adjustment can be made.

The RECON® computer control system was installed for this project to power, monitor and control the system. This control system has the following features:

- Online real-time data display
- Rectifiers that utilise Pulse Width Modulation technology, which provides high efficiency and low ripple (<1%)
- Constant current, constant voltage and potentiostatic modes
- Remote control facility and local control
- Graphical user interface which allows for trend plotting current, voltage and reference electrodes IR free potential for each circuit.
- Automatic data logging with user selectable data saving intervals
- Adjustable current interrupter to undertake interference testing
- Automatic depolarisation tests with user selectable depolarisation periods (e.g. 4 hours, 24 hours or 72 hours)
- Automatic measurement of CP ON and CP Instant OFF potentials using potential measurement channels with high input impedance (>500 MΩ) and high accuracy (± 1mV).
- Potentiostatic mode that can be set to control the system based on an IR free potential
- Alarm functions
- Historical data analysis, including graphing of a selected date and time interval
- Heavy-duty modular components which allows simple replacement of parts.
- Password protected access which provides security.
- Function which allows all data to be exported to a spreadsheet program
- Remote access via GSM network.

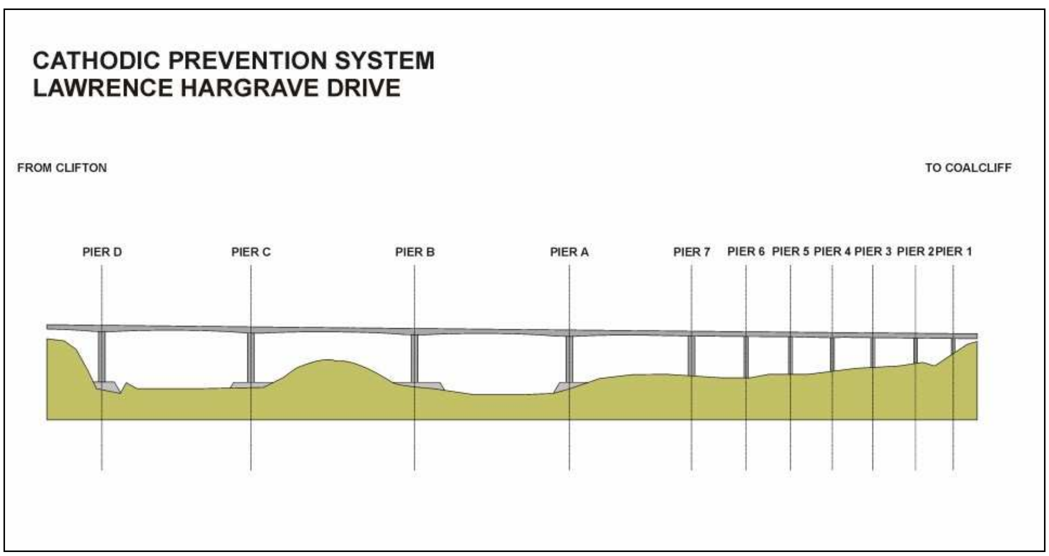

Figure 5: Recon control system software RLmon main page - displays overall layout of bridge

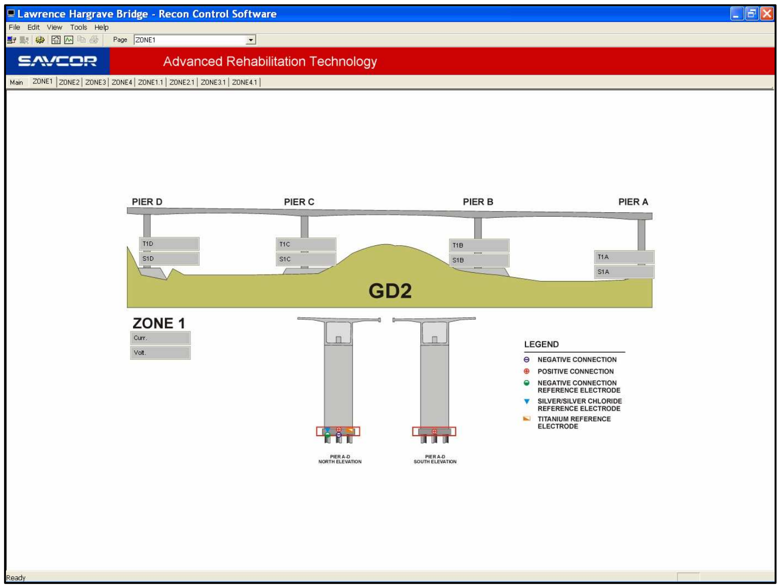

Figure 6: Recon control system software RLmon - graphically displays a specific zone with system measurements

Protection Criteria

The system was designed to satisfy the currently accepted protection criteria as outlined in Australian Standard AS2832.5[6] for cathodic protection of steel in concrete structures. The criteria for Cathodic Prevention is considered to be the same as for cathodic protection, except in the case of the "Absolute passive criterion", as the steel is already assumed passive before CPrev is applied.

The protection criteria is as follows:

No instant off steel/concrete potential shall be more negative than –1100 mV with respect to Ag/AgCl/0.5M KCl for plain reinforcing steel.

Subsequent system adjustment shall be based on meeting one of the following criteria:

(a) A potential decay criterion. A potential decay over a maximum of 24 h off at least 100 mV from instant off.

(b) Extended potential decay criterion. A potential decay over a maximum of 72 h of at least 100 mV from the instant off potential subject to a continuing decay and the use of reference electrodes (not potential decay sensors) for the measurement extended beyond 24 h.

(c) Absolute potential criterion. An instant off potential more negative than –720 mV with respect to Ag/AgCl/0.5M KCl.

Installation

Prior to the installation of the CPrev system, the electrical continuity of the steel reinforcement was tested in accordance with AS2832.5[6]. Where discontinuity was identified, the adjacent steel was welded to establish adequate continuity. All of the cages were tack welded for construction purposes, and therefore continuity was generally found to be satisfactory.

The steel reinforcement cages were constructed in two halves in an area near the bridge construction site. Once each half of the cage was completed the CPrev components were installed and fully tested. Following this, each half of the cage was lifted by crane to the location of the bridge pier where it was welded to the adjacent connecting sections of the structure. The CPrev components were adjusted as required and final testing undertaken. Following final inspection and acceptance of test results, concrete was poured into this section. Cathodic prevention technicians were present during all stages of the works including the concrete pour and vibration, to ensure no damage would occur to the CPrev components.

Figure 7: Anode installation on column steel reinforcement cages

Reference electrodes were installed at the designated locations. All cables were embedded in concrete and terminated in a junction box above each pier. The four junction boxes for GD2 Bridge were installed in the service tunnel. The seven junction boxes for GD3 Bridge were fully concealed in the barricades adjacent to the pedestrian walkway. All junction boxes are relatively easily accessible for future maintenance and protected from vandalism for long term durability. The cables from each junction box were then terminated in the appropriate GD2 and GD3 control units in the service tunnel.

Figure 8: Cables and junction boxes for GD3 installed within the concrete barricades

The installation was fully integrated into the bridge construction, and does not affect the bridge aesthetics.

A comprehensive testing schedule was implemented for this project, to ensure all components were installed in accordance with the specification. These tests included short circuit tests between anode ribbon and steel reinforcement, continuity checks of all connections, thorough inspections prior to concrete pour and temporary energising of each section following concrete pour. One of the most essential steps in the installation process was the final inspection prior to concrete pour to ensure no short circuit could occur during the concrete pour or vibration of the concrete. This included cutting or folding back any tie wire that could potentially move during this process and ensuring every anode and conductor bar strip is adequately fixed.

Conclusions

There are some difficulties associated with installing a CPrev system during construction, mainly associated with ensuring no components are damaged during the concrete pour and subsequent bridge construction, and that no short circuit occurs. The installation at Sea Cliff Bridge proved to be very successful with all components installed satisfactorily and no damage occurring to any component including cable. No short circuits of the anode to steel reinforcement occurred in any of the pours. All reference electrodes were stable and measuring satisfactorily. This was achieved only through a rigorous inspection and testing schedule, and cathodic protection/prevention technicians and engineers competent and experienced in this type of work. The risks associated with inexperienced personnel undertaking this type of work can be high.

Temporary energising of the system indicated all reference electrodes will achieve the protection criteria, with almost all of the references shifting between 50-250mV in the negative direction instantly. At the time of writing this paper there was no permanent power yet installed to the structure to enable longer-term testing.

There are advantages and disadvantages with installing a CPrev system during construction of a bridge as opposed to later completing repair works and retro-fitting a cathodic protection system.

A comparison is shown below, assuming that cathodic prevention is installed during construction, and retro-fitting a cathodic protection system is done after significant corrosion damage has already occurred (as is typically done):

	Cathodic Prevention	**Concrete repair and Retro-fit Cathodic Protection**
Advantages	Lower life-cycle maintenance costs	Can be installed to reduce corrosion only if it is diagnosed as a serious problem for a particular structure
	Lower current density = less anode required	Lower initial cost
	Prevents initiation of corrosion	
	Aesthetically better	
	Increase design life of structure	
	Operates at more noble potentials – much lower risk of hydrogen embrittlement	
Disadvantages	Higher initial capital cost	Higher life-cycle maintenance costs
		Potential closure of structure during maintenance works
		Structural weakening due to corrosion
		Continuity of steel may not be adequate
		Unsightly repair works and slot cutting
		Possible risk of grout deterioration due to method of installation in tidal zone

This installation has shown that Cathodic Prevention can be installed successfully during major construction works by experienced personnel. When considering the durability of a marine structure to be constructed, serious considerations should be given to the applicability of installing a Cathodic Prevention system. Major maintenance works that cause closure of a structure in the future may be prohibitive. As was seen with Lawrence Hargrave Drive, closure of the previous roadway was a major problem for local communities and businesses. A life cycle analysis can be undertaken to estimate the long-term cost effectiveness of CPrev, especially when expecting a reasonable design life for the structure.

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