REPAIR AND CATHODIC PROTECTION OF SUBURBAN CONCRETE BRIDGES

- Case study of rehabilitating two concrete bridges over tidal estuaries in NSW
- Design aspects – what to repair, what to protect, and how to do it
- Construction aspects – access, condition of structures, methodologies, environment

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An increasing number of suburban concrete bridges are affected by chloride-induced corrosion of their reinforcing steel. Traditional patch repair of the damaged areas of concrete is recognised to be a short-term solution because it does not prevent further damage. Cathodic protection is now widely used to extend the life of such structures by arresting the corrosion in all areas that are at risk, in conjunction with repairing whatever has already been damaged. This paper reviews two similar bridges in the Illawarra, and demonstrates how different environmental and structural conditions affect the design and construction methods required for the repair and protection of each.

1. INTRODUCTION

Brooks Creek Bridge

Fairy Creek Bridge

Brooks Creek Bridge is a three-span, two-lane suburban concrete bridge built in the late 1960's in Kanahooka, south of Wollongong. It spans a tidal creek that empties into Lake Illawarra a short distance away.

The piers and abutments consist of headstocks, 600mm deep and 900mm high, each supported by seven precast piles (300mm x 300mm). The upstream pile in each pier has a protective reinforced concrete jacket extending 1.5m below the headstock. The deck consists of precast, prestressed girder beams with an in-situ RC topping.

Fairy Creek Bridge is a five-span, two-lane suburban concrete bridge built in the early 1960's in Fairy Meadow, to the north of Wollongong. It spans a tidal creek that empties, via a large lagoon and a sand bar, into the sea about 1km away.

The structural elements of the Fairy Creek Bridge are very similar, in type and dimension, to those of the later Brooks Creek Bridge, although there are some significant differences that will be discussed further.
Both bridges showed evidence of reinforcement corrosion damage in the form of spalling and cracking to the cover concrete in exposed parts of the substructure. An investigation by CTI Consultants in 2004 concluded that the main cause of the deterioration was chloride ingress, and an impressed-current cathodic protection ('CP') system was recommended as a solution.

In 2008 Wollongong City Council invited tenders for a design-and-construct contract for concrete repairs and installation of a Cathodic Protection system, augmented by silane treatment, to the two bridges. The performance specification was provided by Connell Wagner. The installation contract was awarded to Marine and Civil Maintenance.

The contract programme required Brooks Creek to be completed before work started on Fairy Creek.

2. DESIGN

Marine & Civil Maintenance engaged Corrosion Control Engineering to carry out the detailed design of the Cathodic Protection system, and monitor and adjust its performance over the two-year maintenance period required by the contract.

1.1 Design Requirements

The performance specification required the repair and protection of all piles above and below water, and all headstocks, including exposed surfaces of the abutments. Four independently operated and controlled zones were required for the Cathodic Protection system:

- Submerged or buried
- Tidal
- Splash
- Atmospheric

The Cathodic Protection system design life was required to be at least 30 years, and the specified minimum current density to be applied to the reinforcing steel in all zones was 20mA/m^2. Design was to be based on AS2832.5 (Cathodic Protection of Metals – Steel in Concrete) as well as other international standards. Protection criteria were as defined in the Standard.

Other aspects of the Cathodic Protection performance specification included the required number of reference electrodes for monitoring each zone, the maximum current density for each likely anode type, the maximum driving voltage for the titanium components (conductor bar), and the minimum acceptable experience of the Cathodic Protection designer.

While the tidal, splash and atmospheric zones were required to be protected by an impressed-current Cathodic Protection system, the submerged and buried zone was permitted to be protected by sacrificial or impressed-current anodes.

Multiple connections were required, in order to provide redundancy.

Concrete repairs were specified to be made with a proprietary repair mortar and the procedures for breaking out the concrete, treating the exposed steel and curing the repairs were defined.

A silane impregnation or protective coating was specified for all exposed surfaces of the substructure that were less contaminated by chlorides and were not protected by the Cathodic Protection. This included the precast deck soffit and the vertical sides of the bridge.

2.2 Design Concept

Based on the performance requirements outlined in Section 2.1, the Cathodic Protection design concept was that all anode zones were to be driven by impressed current, and the optimum configuration was

- Ribbon mesh anodes grouted into slots cut in the atmospheric zone surfaces
- Discrete anodes (manufactured from ribbon mesh) grouted into holes drilled into the splash and upper tidal zones
- MMO water anodes in submerged and buried zones

Design considerations included:

- Achieving uniform current distribution from the anode layout in each zone
- The requirement to ensure that the maximum driving voltage is not exceeded
- The possibility of current dumping and localised over-protection in the tidal zone
- Redundancy and spare capacity in all connections and reference electrodes
- Ease of installation

A detailed system design was carried out, with various differences between the two bridges arising from the differing environmental and structural factors at each, as noted in the following sections 2.3 and 2.4.

The final design layout is indicated in the drawings in the Appendix to this paper.

2.3 Environmental factors

Water Levels

The primary environmental factor which influenced the design of the Cathodic Protection was the water level and how it could be expected to fluctuate.

At Brooks Creek, the water flowed into Lake Illawarra, which is relatively stable in level. Flood levels were forecast on the basis of historical records, but in normal conditions the zones could be defined with some confidence.

At Fairy Creek, the level of the lagoon downstream of the bridge was controlled entirely by the ebb and flow of sand on the sand bar at the beach outlet. Generally the sand bar was high enough to dam the lagoon up to near, and sometimes above, the headstock levels. On occasions the actions of wind and tide would cut a deeper channel in the sand bar, and the water level at the bridge would drop significantly as a result. Based on records of prior floods, however, the predicted flood levels were up to one metre above the roadway.

These factors influenced both the zoning of each structure and the choice of anode types. At Brooks Creek, the stable and relatively low water level allowed for well-defined zones:

Atmospheric = Headstock beams full height (760mm)
Splash = 1000mm below headstock soffits
Tidal = 400mm
Submerged & Buried = 6500mm

These dimensions permitted the use of optimum anode configurations of

- ribbon mesh anodes in the headstocks, grouted into slots cut in the sides and soffit of the beams;
- five discrete anodes in the splash and upper tidal zone of each pile, grouted into holes drilled horizontally into each pile at spacings calculated from the amount of steel;
- MMO water anodes for the submerged and buried elements.

At Fairy Creek, the water level was generally too close to the headstocks, and too dependent on the vagaries of the sand bar, to permit four zones to be identified. The design was therefore based on the following zones:

Atmospheric = Headstock beams full height (760mm)
Splash and Tidal = 600mm below headstock soffits
Submerged & Buried = 7500mm

This led to a significant departure from the atmospheric zone design used on the other bridge, as it was determined that there was insufficient clearance to install anodes on the headstock soffits. The congestion of stirrups in the beans made discrete anodes inappropriate for the soffit reinforcing, so additional ribbon mesh anodes were specified to be grouted into slots cut at the bottom corners of each beam. Furthermore, there was only space for two discrete anodes to be grouted in each pile above low water.

The submerged and buried anode design concept remained the same for both bridges.

Siltation and Scour

At Fairy Creek Bridge, it was observed that the south abutment was silted up but the north abutment was scoured out by the water flow. About 600mm of rock fill was exposed below the abutment. These factors meant that the soffit of the south abutment could be protected by the buried/submerged anodes, but the exposed heights of piles on the north side required the same ribbon anode protection as on the pier piles. This was only possible on the three accessible sides of each pile.

Protective RC Jackets at top of Piles

At both bridges, there is a protective reinforced concrete jacket extending 1.5m below the headstock on the upstream piles at each pier. These jackets were all specified to be protected by horizontal ribbon anodes, as there was too much congestion of steel to permit discrete anodes to be installed. At Brooks Creek, the predictability of the water levels allowed the five anodes to be separated into two zones, so that current flows in the splash zone could be controlled in detail, and none was in the tidal zone.

At Fairy Creek, there was only room for two anodes but they were treated similarly.

2.4 Structural aspects

There were a number of structural aspects which affected the Cathodic Protection design, and some of them were different at the two sites.

Precast Piles

The precast piles at both bridges were the same size, and a pile offcut was found at the Brooks Creek site, so this was cut open to confirm that it was reinforced without any prestressing. The reinforcement consisted of four vertical corner bars within a cage of stirrups; this suited protection by discrete anodes grouted into holes drilled horizontally into each pile at spacings calculated from the amount of steel.

At Fairy Creek, however, it was found on opening up the cover concrete that the piles were prestressed with 12 strands contained within a spiral stirrup, with a reinforcing cage in the top section of each pile (presumably to resist extra stresses during pile driving). This congestion of steel made it impractical to use discrete anodes as designed for Brooks Creek, and it was decided to use two horizontal ribbon anodes fixed in slots in the cover concrete.

Because there was insufficient cover to the stirrups, and because of the probability of immersion, the ribbon anodes were provided with a minimum of 30mm of cover by building up the grout thickness beyond the original concrete surface, and two coats of a cement-based waterproofing compound were applied to the surface of the grout.

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Beam Locating Dowels

Each of the precast deck beams was located on the headstocks by vertical dowels, grouted into the headstock and fitting into the gap between each beam as it was positioned. These dowels were electrically isolated from the rest of the reinforcing steel cage.

At Brooks Creek, these dowels were set in the middle of the rebar cage. Establishing electrical continuity between the dowels and the cage would have caused structural issues, and it was decided that they were sufficiently remote from the anodes and the external chlorides that they could remain not bonded into the Cathodic Protection system.

At Fairy Creek, the dowel detail was different in that one side of each headstock had a cast-in railway iron that supported the deck beam on that side, and on the other was a dowel, with less cover than at Brooks Creek. It was therefore decided that both the railway iron, which had little cover, and the dowels would require bonding into the Cathodic Protection system. This decision was facilitated by the fact that the majority of the beam sides needed repair, which exposed many of the dowels and all of the railway irons.

Extent of Damage to Concrete Elements

At Brooks Creek, there was relatively little repair needed, and no structural implications from that which was required.

At Fairy Creek, however, there was extensive damage to the headstocks and piles, and previous repairs consisted of a mixture of epoxy and cementitious products, many of which had failed. Wollongong City carried out a review of the structural implications, and it was determined that the headstocks could be repaired without restrictions. This was facilitated by the shallow nature of the repairs; a traditional patch repair requires removal of all contaminated concrete around the steel, including otherwise sound concrete from behind the bars, whereas repairs prior to Cathodic Protection only need whatever has spalled or become loose to be removed and replaced. This typically means that a Cathodic Protection repair exposes a part only of the outer bars, and the structure is less invasively threatened.

Some piles at Fairy Creek were badly damaged, including loss of reinforcing steel, and structural repairs were required, as well as restrictions on the number of piles that could be repaired at once. This was particularly so in the northern abutment, where extensive movement of the rock fill had occurred behind the headstock and structural cracks were evident. A detail was developed with Wollongong City to stabilise the rock fill with concrete and stitch the cracks with rebars epoxied into the concrete.

New reinforcing bars were welded in place where the existing steel had lost more than a specified amount of cross-section.

Presence of Previous Concrete Repairs

The Brooks Creek Bridge had no previous concrete repairs, while there was evidence of many repairs to the headstocks at Fairy Creek. Closer inspection revealed most of these to be epoxy resin mortar repairs, and most were delaminated, cracked or otherwise failed. All epoxy mortar repairs had to be removed, irrespective of their condition, because their electrical resistivity was too high for the cathodic protection.

Configuration of Reinforcing Steel

It was found during the construction phase that the existing reinforcing bars, particularly the beam stirrups, were often very variable in both position and cover. This required design checks to ensure that the anode distribution was adequate in all locations. The low cover in some places necessitated the repairs on one beam to be built out beyond the original surface in order to ensure sufficient cover.

2.5 Concrete Repair

In all areas where corrosion damage was evident but no Cathodic Protection was to be installed, the performance specification called for repairs to be excavated at least 25mm behind the reinforcing steel, and the repair was to be extended in plan sufficiently to expose steel that was not actively corroding. The steel was to be cleaned of all corrosion products and treated with a primer before backfilling with high-performance cementitious repair mortar.

In all areas to be protected by Cathodic Protection, the repair specification was to remove all loose, drummy or otherwise unsound concrete, clean the exposed reinforcing steel, add supplementary steel where excessive corrosion loss was identified, and reinstate the repair with the same mortar. No primer was permitted on the steel, as this would interfere with the performance of the Cathodic Protection.

The primary method of concrete removal was to be either by jack-hammers (for small repairs) or by hydrodemolition (for large repairs). Hydrodemolition uses water at very high pressures (in the order of 15,000psi) and significant volumes (around 60 litres per minute) to break up the concrete matrix. This is a standard repair procedure which is both efficient and creates a good surface for bond of the repair mortar.

The methods chosen for reinstating the repairs included forming and pouring, and hand patching. Two different products were used for the two methods.

Curing products were chosen that would not interfere with the ability of the Cathodic Protection system to breathe through the concrete surface.

2.6 Protective Silane

The performance specification called for application of a penetrating silane or suitable coating on areas of the substructures exposed to the atmosphere. As this type of product interferes with the ability of the Cathodic Protection anodes to breathe, the application was restricted to the soffit of the precast deck planks and the sides of the bridges.

A thixotropic cream was selected for environmental reasons, as a liquid silane requires flood coating of the concrete and it was important to prevent pollution of the waterway. This consisted of a water dispersed emulsion of iso-octyltriethoxysilane which is formulated to limit the ingress of chlorides and water into the concrete, and is applied as a gel coat.

3. CONSTRUCTION

3.1 Environmental aspects

The main environmental consideration for the work at both bridges was the water level.

At Brooks Creek, the level was stable, predictable and at a suitable depth below the bridge for the access platforms to be suspended above the water. This provided a dry work environment and allowed the use of electric power tools under the bridge.

At Fairy Creek, the water was always near the soffit of the beams and arrangements were made with Council to ensure the seaward outlet of the downstream lagoon was kept open during the work. This made the water level predictable but still high and the technicians were obliged to wear waders at all times. Compressed air was required to power all equipment under the bridge, including breakers, concrete saws and drills. It was also necessary to have various environmental precautions such as a screen and boom to catch any spillages, and additional safety precautions such as life rings.

The water level at Fairy Creek also prevented any Cathodic Protection work to be done to the soffit.

The predicted flood water levels at both bridges dictated the positioning of the control and monitoring boxes. Both were fixed to the wing walls end posts, but the flood level at Fairy Creek required the cabinet to be set well off the ground.

3.2 Structural aspects

Continuity of Reinforcing Steel

It is essential to be confident that all the reinforcing to be protected by a Cathodic Protection system is electrically continuous, as stray current corrosion may affect any bars that are not bonded into the system. For this reason, the steel exposed in all repair patches is tested for continuity, and any bars that are found to be discontinuous are connected by welding small bars between them. Where there are no repairs, the element must have holes broken in the surface to expose two remote bars for testing.

The normal situation in reinforced concrete is that there are sufficient points of contact between the bars in a cage for all bars to be continuous. In the case of these two bridges, however, initial testing indicated that the stirrups in the beams in both were not reliably continuous. At Brooks Creek, it was decided to cut a slot along the faces of each beam to expose all the stirrups in order to weld a 6mm continuity bar to the bars for the length of the beam. It was necessary to do this on both faces because the stirrups are in pairs, overlapping in the middle of the beam, and not all were continuous from one side of the beam to the other.

The piles were found to be continuous both internally and from pile to pile via the main longitudinal bars.

At Fairy Creek the extensive repairs made testing simpler but confirmed the lack of continuity more emphatically. It was also found that the piles were not only discontinuous with each other; the individual strands were also discontinuous in each pile. As noted in 2.4, the precast dowels required bonding in, and this was achieved in most cases after they were exposed during the extensive repairs.

A programme was developed for cutting continuity chases in each element to ensure all discontinuities were removed from this structure.

Extent of Concrete Repair Work

Although Brooks Creek Bridge was in relatively good condition, extensive concrete repair was needed in the beams at Fairy Creek Bridge. This necessitated checks by Council to ensure that the beams would not be overstressed during the work.

In places the exposed reinforcing steel was corroded to the extent that additional bars were required. These were welded alongside the original steel.

Two piles at the south abutment at Fairy Creek were extensively damaged by corrosion of the prestressing, and a detail was provided by Council for reinstating the structural capacity of these piles by epoxy grouting additional bars into the concrete. In addition, cracks were identified in the south abutment beam and these were repaired by stitching epoxy-grouted bars across the cracks.

The small amount of repair work at Brooks Creek indicated that the defective concrete was most economically broken out by jackhammers. At Fairy Creek, however, the extensive repairs led to the selection of hydrodemolition as the preferred method, on the grounds of its higher productivity and excellent surface preparation. This method is also more suited to the semi-immersed conditions, as the hydrodemolition operator wears a full dry suit.

Loss of Rockfill behind South Abutment at Fairy Creek

The scour noted in 2.3 above had a structural aspect as well as a Cathodic Protection aspect. It was decided to reinstate the scoured material by rebuilding the rock fill, and then pumping mass concrete behind the abutment. This precaution was made both timely and justified by the opening of a sink hole in the footpath at one end of the abutment.

3.3 Installation and Commissioning

Brooks Creek Bridge

The concrete repair and Cathodic Protection installation work at Brooks Creek was started at the end of March 2009. The Cathodic Protection system was energised on 29 June 2009 and it has been monitored regularly since. All zones have been found to be operating satisfactorily and full protection has been achieved.

Fairy Creek Bridge

The work at Fairy Creek began at the end of June 2009 and the Cathodic Protection system was energised on 17 December 2009. Regular monitoring since then has shown that all zones are operating satisfactorily, with full protection being achieved.

4. CONCLUSIONS

The Paper describes two bridges, of very similar design and age, which were in very different condition when rehabilitated.

Relatively minor environmental and structural differences between the two had a major impact on the methodologies of the rehabilitation at each site.

Differences in the costs of the work at the two sites were exacerbated by apparent differences in the quality of construction at the more exposed site.

In the author's opinion, there are some conclusions that can be drawn from this, and other similar, experiences:

- The Design and Construct contract format was effective for these projects, and its value is evident when conditions change from those expected, as the process of changing design details and construction methods can be integrated, costed and optimised relatively quickly.
- Irrespective of the amount of investigation work that goes into it, the extent of concrete repair work can easily be under-estimated.
- Continuity of reinforcing steel cannot be assumed and must be thoroughly verified in all elements of a structure that is to receive cathodic protection.
- Cathodic protection is a long-term rehabilitation strategy that is sufficiently flexible to cope with significant changes in installation requirements.

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