# Will you still need me… when I'm sixty-four? A story of ageing bridges

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**ABSTRACT**

Major rehabilitation projects for severely deteriorated reinforced concrete structures can easily run into the millions of dollars, and therefore maintaining a suite of operational infrastructure becomes increasingly difficult when contending with limited budgets. Unfortunately, the deterioration of reinforced concrete is not visibly evident until very late in the deterioration cycle, and by then significant works are typically required.

The authors will present three case studies which explore the ability of modern investigation techniques to diagnose the current condition and expected life of a bridge.

In each case, a different remedial strategy was selected, always aimed at either preventing/delaying future deterioration or at treating the active deterioration. The case studies consider bridges ranging from 20-100 years old, constructed using various methods, exposed to different environmental conditions (non-saline river to full marine) and subject to different load requirements (pedestrian to highway traffic).

The projects illustrate the benefits of early investigation of the concrete structures which enable the prediction of the cause and onset timeframe for future deterioration. Once this information is available, the selection and implementation of suitable preventative maintenance works (such as coatings) can significantly delay more costly repairs. However, even in the cases where corrosion has initiated, mid-stage intervention using targeted corrosion control techniques show the ability to provide long term life without the cost and disruption of a full-scale rehabilitation.

A brief overview of available preventative maintenance and rehabilitation techniques, when to use them and their relative cost is also presented.

## 1 INTRODUCTION

Early detection of deteriorating reinforced concrete is practically impossible with visual inspections. By the time concrete deterioration becomes visually apparent the degradation process is already very advanced in its cycle, with reinforced corrosion initiation first occurring some 10-15 years prior. This can be detrimental to the forward planning of bridge maintenance programs as the rehabilitation of advanced-stage degradation can easily run into the millions of dollars.

Three case studies of bridge remediation at different stages of their life cycle will be used to demonstrate the effects of early, mid, and late identification of concrete degradation on the time and monetary cost of rehabilitation. The presented bridges are constructed of reinforced concrete, , exposed to different environmental conditions (non-saline river to full marine) and subject to different load requirements (pedestrian to highway traffic).

The paper describes the difficulties of early detection of concrete degradation, and why visual inspections fail to identify concrete deterioration until its later stages. This is followed by a brief overview of testing methods which can be used for early detection of concrete degradation. Finally, three case studies are presented illustration the differences between early, mid, and late detection of concrete degradation to assist management of bridges. These case studies include an overview of preventative maintenance and rehabilitation techniques.

# 2 REINFORCED CONCRETE DETERIORATION

## 2.1 Concrete Deterioration and Investigation Timing

### 2.1.1 Concrete Matrix Environment and Deterioration Mechanisms

The naturally high pH of freshly cured, fully compacted, high cement content concrete provides a passive environment which protects steel reinforcement from corrosion. As the concrete ages, carbon dioxide and chloride from the natural environment enter the concrete, removing the passivity and allowing corrosion to initiate.

- When atmospheric carbon dioxide dissolves in concrete pore water it forms carbonic acid, a weak acid which neutralises the concrete pH. Over time, this process (known as carbonation) moves deeper into the concrete matrix eventually resulting in a loss of alkalinity to the concrete surrounding the reinforcement, which allows the initiation of corrosion at these locations.
- When chloride ions diffuse through the concrete matrix to the reinforcement at what is known as critical concentrations, they attack the passive film on the reinforcement surface cause a localised loss of passivity and corrosion initiation [ref1].

Once corrosion initiation occurs due to these processes, the rate of reinforcement corrosion is controlled by other environmental factors including (but not limited to) temperature and moisture levels.

The corrosion of concrete reinforcement bars is an electrochemical reaction in which the steel bars oxidise. The products of this reaction (rusts, such as iron oxide) take up a greater volume than steel, effectively causing the bars to expand, creating internal stress within the concrete matrix. Once the expansion creates sufficient internal stress to fracture the concrete, the degradation becomes apparent as the concrete begins to crack, delaminate, and spall.

Other methods of reinforced concrete deterioration, including degradation of the concrete matrix itself, do occur, however are outside of the scope of this paper.

### 2.1.2 Corrosion Life Cycle

Concrete deterioration due to reinforcement corrosion is typically a long process, with little-to-no clear visual evidence until its later stages. This is because the corrosion does not result from deterioration of the concrete matrix itself, but instead causes it.

The first visible signs of deterioration (cracking) typically first occur after 10-15 years after corrosion initiation, with more severe deterioration (delamination and spalling) occurring after another 10-15 years. Depending on the structure, this could mean that once the occurrence of reinforcement corrosion is realised, corrosion initiation will have occurred in widespread areas of the structure.

### 2.1.3 Corrosion Intervention

Regardless of the severity of degradation, once corrosion of the reinforcement has initiated, passivity cannot be reinstated without either complete removal and replacement of all affected areas (i.e. full depth concrete patch repair) or the use of an electrochemical intervention.

If active corrosion is caught early enough it is possible to apply local electrochemical rehabilitation solutions in order to reduce rehabilitation cost. The ideal case is identifying the pending initiation of corrosion before it has begun and preventing it from occurring through preventative maintenance such as protective coatings which are significantly cheaper than later intervention methods.

## 2.2 Investigation Techniques

### 2.2.1 Visual and Tapping Investigation

Non-destructive testing of concrete elements can be performed onsite to evaluate a structure. While suitable for identifying structural defects such as cracking, when assessing deterioration visual investigations are only able to identify advanced corrosion evident from cracks, delamination, and spalls. Hammer or tap testing (which involves hitting the concrete and listening for a change in pitch similar to a drum) is able to identify delamination of the concrete from the reinforcement which results from the corrosion process. These techniques are both rapid and can be performed quickly onsite but can only detect advanced stages of corrosion. Early detection of pending, or recently initiated, reinforcement corrosion requires the use of specialised techniques.

### 2.2.2 Electrochemical Measurements

As corrosion is an electrochemical reaction, site electrochemical measurements can be undertaken to assist in identification and assessment of reinforcement corrosion. These measurement techniques provide condition information very localised to the test location and provide information relevant to whether corrosion is occurring, rather than assessing the likelihood of future deterioration.

#### *2.2.2.1 Half-Cell Potential Measurements*

Half-cell potential testing, if performed correctly, is an effective and efficient way of completing a preliminary assessment on a reinforced concrete structure. It is particularly useful as a fast method of scanning large areas of a structure to quantify the amount of reinforcement corrosion present within a structure, which in turn can lead to a more accurate accounting of budgets and costs for remediation.

Half-cell potential measurements utilise electrochemical principles to measure the electrochemical potential of the reinforcement within its environment, with more negative potentials indicating active corrosion is more likely. Although there are published guidance on typical criteria for interpretation of results, the appropriate criteria for a given element varies significantly depending on the environmental conditions, properties of the concrete and the deterioration mechanism affecting the reinforcement.

However, as there is no consensus for an absolute set of criteria which apply for all reinforced concrete structures, it is important that half-cell potential measurements alone are not relied on for assessment of condition. A detailed knowledge of factors which affect the half-cell potential measurements are required to successfully interpret data, as well as contextual information for the measured results, such as exposure conditions, weather conditions, concrete materials etc. [ref2].

#### *2.2.2.2 Corrosion Rate Measurements*

Commercially available equipment enables the in-situ measurement of corrosion rate using various electrochemical techniques such as linear polarisation resistance (LPR) and connectionless electrical pulse response a (CEPRA). These measurements provide an indication of the rate of corrosion at a particular location and are therefore most useful in assessing the severity of current deterioration rather than scanning large areas of a structure to identify risk.

### 2.2.3 Assessment of Deterioration Mechanisms

Testing of the concrete matrix itself provides information about the progress of the deterioration mechanisms identified in Section 2.1.1. These mechanisms do not cause initiation of reinforcement corrosion until they reach the steel surface. By assessing their progress early in a structure's life, a model can be built which allows prediction of time until corrosion initiation.

#### *2.2.3.1 Carbonation Testing*

Carbonation testing is undertaken by measuring the pH of the concrete at various depths. In practice, this testing involves making a hole in the concrete structure (or retrieving a core) and spraying a pH indicator on the freshly exposed surface which can show the approximately depth to which carbonation has occurred. This allows the depth of carbonation ingress to be assessed on-site.

#### *2.2.3.2 Chloride Concentration Testing*

Chloride concentration testing is undertaken by retrieving concrete samples (typically dust or concrete cores) and testing in a laboratory. This data is then used to assess if chlorides have reached the critical corrosion initiation threshold at the depth of steel reinforcement. There is no way to conduct this testing on site.

#### *2.2.3.3 Modelling*

When structure condition data (such as chloride concentrations or carbonation depth, depth of reinforcement and age of structure), predictive modelling can be undertaken to estimate the likely date of reinforcement corrosion initiation from these deterioration mechanisms. Using this process, small amounts of data collected early in the life of a structure (i.e. its first 15 years) can be used to determine when a bridge should undergo a large-scale condition investigation. Similarly, screening of a large number of assets can identify which structures require more detailed investigation, in the same way a Level 1 or Level 2 bridge inspection can identify which bridge requires additional structural or loading assessment.

### 2.2.4 Other Techniques

A range of other techniques can be used to either assess the occurrence of corrosion (e.g. visual examination of the reinforcement at local breakouts) or assess the likelihood or potential rate of corrosion (e.g. concrete resistivity).

# 3 CASE STUDIES IN INVESTIGATION AND REMEDIATION

## 3.1 Early Intervention for a Tidal Marine Exposed Road Bridge

An 18-year-old reinforced concrete bridge in south eastern Australia was investigated as part of a high-level condition assessment (which inspected three bridges in two days on site). The bridge is located in tidal marine exposure, across a river mouth approximately half a kilometre from the coast.

The bridge traverses its 160 m length in 12 spans, with 10 piers and two abutments. At each pier the bridge is supported by a precast headstock beam and five prestressed piles. Between each of the piers and abutments the deck is supported by five prestressed beams, see Figure 1 and Figure 2.

**Figure 1 – Road Bridge overall structure**

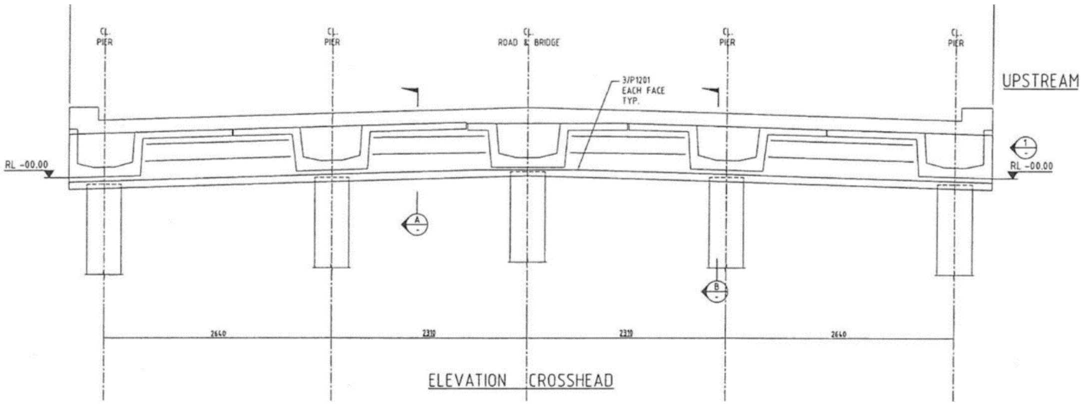


**Figure 2 – Bridge cross-section**

### 3.1.1 Visual Condition and Investigation Findings

At the time of investigation, the bridge appeared to be good condition, with only minor local areas of visible degradation to the piles and prestressed beams. Minor local spalling of the pre-stressed beams was identified only where there was low reinforcement cover. Pile cracks did not appear to be the result of active corrosion and could be mended by an epoxy adhesive repair paste.

Based on site and laboratory testing, chloride ingress was found to be the deterioration mechanism affecting these elements of the bridge. Chloride ingress in across the structure had reached critical levels at approximately 25-28 mm deep, with design cover to conventional reinforcement in some elements only 30 mm, and 40 mm to the pre-stressed strands. As-constructed cover in some areas was lower than designed.

The measured chloride levels, low cover and risks associated with pre-stressed reinforcement meant that allowing reinforcement corrosion was a significant economic and safety risk for the structure. A more detailed investigation was subsequently performed to provide additional information and risk assessment across the structure.

### 3.1.2 Recommended Solution

To minimise life cycle maintenance costs, a preventative maintenance strategy was recommended. This strategy included application of a protective coating to all surfaces of prestressed beams, headstock beams and the piles from mid-tide level and above and local patch repairs (incorporating galvanic anodes) into existing concrete deterioration. The selected protective coating was a silane, which repels water ingress, preventing additional chloride ions from migrating into the concrete matrix. This strategy was intended to prevent/delay the need for larger scale concrete repair and electrochemical treatments in the future. Protection of the prestressed beams before corrosion initiation was considered critical, as remediation of active corrosion in prestressed elements is both difficult and costly.

Applying the silane coating was considered time-critical to minimise the risk of further chloride ingress, and it was recommended these works were undertaken within 6 months. Silane impregnation coatings can be expected to last from 3-7 years in the splash zone, and up to 20 years in the atmospheric zone. This makes the implication of a regular monitoring and maintenance program essential for this remediation system. The pile elements in the splash zone are expected to require inspection and coating reapplication at approximately 5-year intervals.

The proposed remediation strategy (including maintenance) was expected to provide a delay to chloride induced reinforcement of at least 40 years. The initial costs of the work were ~$120k, which is substantially cheaper then the requirements for a later stage electrochemical CP remediation program which were estimated to be required within 5 years and cost in the order of $1.5-2.5 million, (depending on how much concrete repair was required).

## 3.2 Mid-Stage Intervention for a Tidal Marine Exposed Pedestrian Bridge

A 22-year-old reinforced concrete footbridge on the west coast of New Zealand's South Island was investigated (by others) in response to the existence of rust-stained cracks on the eastern ends of the arches and the transverse tie strut at the same bank, deterioration suspected to arise from reinforcement corrosion.

The footbridge is a 63 m single-span arch bridge, across a sheltered tidal river approximately 200 m from its mouth. The bridge is predominantly constructed from precast reinforced concrete elements with two reinforced concrete arches are tied together with six cross-tie beams and supported at their base by reinforced concrete pile caps, see Figure 3.

**Figure 3 – Pedestrian footbridge overall structure at low tide**

### 3.2.1 Visual Condition and Investigation Findings

When inspected, the bridge was showing little-to-no visual evidence of concrete degradation. However, a detailed investigation identified that localised active reinforcement corrosion was occurring in the tidal and splash zone elements of the bridge, e.g. the arch footings, pile caps, and bottom two cross-tie beams (see Figure 4). This degradation was attributed to chloride-induced reinforcement corrosion by the investigative engineer. Other elements of the bridge were not considered to be subject to a short- or medium-term corrosion risk.

**Figure 4 – Close up of deteriorating concrete elements at high tide: arch footings, submerged cross-tie beam, and submerged pile caps.**

### 3.2.2 Recommended Solution

As the desired outcome for the bridge was to ensure a further 50-year service life, the investigative engineer recommended the use of an electrochemical protection system (in this case a hybrid cathodic protection was recommended) to protect the at risk and currently corroding elements of the bridge. Infracorr’s role was limited to designing the hybrid CP system as part of a design and construct contract to remediate the bridge. With the exception of the tidal and splash zone elements, no deterioration was identified in the other bridge elements. Had an increased risk of deterioration been identified application of a silane or barrier coating, similar to those recommended in case study 1 (refer Section 3.1) would have been recommended.

The bridge protection was achieved by applying targeted hybrid CP to the reinforcement of the arch footings, pile caps, and bottom two cross-tie beams. The system was designed to provide a 50 years life extension for these elements.

This targeted approach was able to economically protect the structure as costs were not incurred providing protection to the deterioration free (and low corrosion risk) buried and atmospherically exposed elements.

The costs for this remediation are estimated to have been between $100k-$200k, substantially cheaper than a full remediation and installation of ICCP would have been.

## 3.3 Late Stage Intervention of a Historical Road Bridge

Constructed at the turn of the nineteenth century, the Morell Bridge is an iconic Heritage listed structure and the first reinforced concrete bridge in Victoria. The unique earth filled arch bridge was designed and built by Sir John Monash’s company, Monash and Anderson. Its 99 m length crosses the Yarra River adjacent the Botanical Gardens in three (3) equal arch spans and was originally constructed for a total cost of £6,000 [ref3].

### 3.3.1 Visual Condition and Investigation Findings

In 1993, almost 100 years after it was constructed, evidence of concrete spalling and outward movement of the side walls (see Figure 5) instigated a detailed investigation which found the entire lower matt of reinforcement was activity corroding, due to carbonation of the concrete surrounding the reinforcement.

**Figure 5 – Morell Bridge general condition, circa 1993**

### 3.3.2 Recommended Solution

In addition to restoring full structural integrity to the bridge, the historical significance and heritage listing of the bridge required it to be restored to its original late 19th central condition. However, the advanced nature of the deterioration meant that extensive concrete and reinforcement repairs would be required to almost all exposed concrete surfaces. This presented a logical challenge as the bridge was required to remain open to river, vehicular and foot traffic for the duration of the works.

Owing to the bridge's unique earth filled construction, a soil anode impressed current corrosion prevention (ICCP) system was installed below the footpath, passing protective current through the soil and 0.5 m thick concrete to protect the reinforcement. Reference electrodes were used to monitor the system performance/reinforcement protection and to ensure stray currents were not adversely affecting surrounding services, e.g. water mains, cable ducts, etc.

This novel solution (ICCP soil anodes) significantly reduced the repair quantities as partial-depth concrete repairs could be used in lieu of more costly full-depth repairs. As a result, only the spalled and delaminated concrete of the arch soffits was required to be required, with replacement of extensivity corroded reinforcement. If the soil anode system was not possible, an "in concrete" CP system would have been required, where titanium anodes (either as discrete rods or in the form of a ribbon/mesh) would have had to be installed within the cover concrete to pass protection to the reinforcement, a much more expensive proposition.

While the use of an ICCP current system was able to economically remediate the bridge, it added complexity as the system required testing and balancing, and its effects on surround structures had to be considered. The cost of late-stage intervention was also significant, with the remediation cost being approximately one-third of the original construction price when adjusted for inflation. With modern safety and construction practices, this cost is expected to be even higher today.

**Figure 6 – Fully restored Morell Bridge overall structure, circa 2017**

# 4 DISCUSSION

## 4.1 Current Bridge Inspection Practices

The case studies demonstrate how early stage intervention, in the form of preventative maintenance, can be a key to avoiding expensive, complex and disruptive remediation works. The challenge for asset owners arises because early stage corrosion is not visually apparent.

The condition of bridge structures is typically managed via the use of Level 1 and 2 bridge inspections. Level 1 and 2 bridge inspections are visual only inspections which can successfully identify visible deterioration which impacts the general serviceability of the structure (particularly for the safety of road users) and assess and report any significant visible signs of distress or unusual behaviour. Unfortunately, they are limited in scope and can therefore only identify any emerging problems once they are visible. There is an underlying assumption in Level 1 and 2 inspections that the visual condition of a bridge correlates to its performance. This is suitable for identification/assessment of structural defects but not for materials durability related issues. Although a Level 3 bridge inspection could include the type of investigation needed to identify durability risks, such an investigation (and the scope of testing) is typically only triggered when an existing risk is identified.

As a result, in the majority of cases it is not until long after corrosion has initiated, and the clearly evident mid-to-late deterioration stage is visible, that an assessment is undertaken. At this time, due to the costs of any successful works program, the remedial work is often postponed until it is critical. This reactive approach ultimately results in significant financial waste that could be avoided by adopting a screening process, similar to Level 1 and 2 inspections but for durability. The delayed approach can even cause an increase in costs over mid-stage intervention which would otherwise allow targeted remedial designs saving substantial repair costs. The main deterrent for mid-stage intervention is often the additional investigative costs which are required (compared to early or late stage intervention) to ensure that the targeted approach successfully remediates all existing deterioration and treats at risk areas.

Another factor which can affect the success of the Level 1 and 2 inspections identifying requirements for early stage intervention is the experience and knowledge of the inspectors. These inspections are typically undertaken by experts in bridge structures (who naturally inspect for signs of structural distress), rather than infrastructure materials durability experts (who are experienced in identifying and assessing the cause and extent of materials deterioration such as reinforcement corrosion).

## 4.2 Best Practice Durability Approach

The early stage investigation offers an “hold point” in which design assumptions can be validated, and any unanticipated deterioration due to construction mistakes (e.g. low cover) or localised but highly aggressive micro-environments can be identified. This work can establish sufficient information to enable the development of a preventative maintenance plan for the majority of assets. In most cases this preventative maintenance plan will not need to begin for years or even decades, however the key is to know when it needs to be implemented to be effective.

The scope of the early stage investigation need not be large, with simple inspection by a materials durability expert and some preliminary testing (e.g. spot measurements of chloride and carbonation ingress) providing substantial data enabling predictive modelling undertaken in a relatively short period of time. Where concerns are identified, a more thorough assessment/investigation can be undertaken as part of an asset management risk assessment.

Bridges which have undergone recent remediation works should also have similar plans put into place to ensure they do not fall into an advanced stage of degradation in the future.

## 4.3 Preventative Maintenance and Rehabilitation Techniques

Depending on the cause (deterioration mechanism) and extent of deterioration, there are a range of remediation techniques which can be adopted as preventative maintenance or for rehabilitation. Once this information is available, the selection and implementation of suitable preventative maintenance or rehabilitation works can significantly delay more costly repairs.

Regardless of the severity of degradation, once corrosion of the reinforcement has initiated, passivity cannot be reinstated without either complete removal and replacement of all affected areas (i.e. full depth concrete patch repair) or the use of an electrochemical intervention. However, even in the cases where corrosion has initiated, mid-stage intervention using targeted corrosion control techniques show the ability to provide long term life without the cost and disruption of a full-scale rehabilitation.

Table 1 contains a brief overview of available preventative maintenance and rehabilitation techniques, when to use them and their relative cost is also presented.

**Table 1: Overview of preventative maintenance and rehabilitation techniques**

| Technique Overview | When to Use | Relative Cost |
|---|---|---|
| <u>Coatings</u><br><br>Protective coatings can be used to protect a concrete element from its environment, preventing ingress of aggressive environmental species which cause deterioration. Coatings cannot stop the deterioration process once reinforcement corrosion initiates, however can provide some benefit by slowing the rate of corrosion by limiting available oxygen and moisture at the reinforcement. | Preventative Maintenance – Prior to initiation of reinforcement corrosion | Low. The highest costs are often associated with providing safe access for application. |
| <u>Concrete Repair</u><br><br>Patch repair of reinforced concrete is an effective way of repairing deteriorating concrete. However, to be effective, all contaminated concrete must be completely removed, a process which is expensive once deterioration is widespread. | After deterioration has commenced, but preferably when deterioration is localised | Medium. However relative cost is very high when repeated repairs are required over the life of a structure. |
| <u>Electrochemical Treatment</u><br><br>Various types of electrochemical treatment can provide maintenance and rehabilitation options. Cathodic Protection (CP) options include galvanic CP (typically not suitable for high chloride environments), impressed current CP (applied full scale with large outlay in terms of control equipment) and hybrid CP (which can readily be applied to small, localised areas).<br><br>Other electrochemical treatments including chloride extraction and realkilisation are sometimes used in specific cases. | After corrosion has initiated (mid or late stage).<br><br>Different CP options would be selected depending on the structure and asset owner requirements as well as the extent of deterioration. | Medium to High<br><br>When designed correctly, a CP system can minimise ongoing maintenance of a structure, preventing the need for ongoing repair works. Initial costs for a full CP system can be high, while local, targeted application of galvanic or hybrid systems can be undertaken economically. |
| <u>Other Structural Repair</u><br><br>Other forms of structural repair, including pile encasement, member replacement (recasting), and structural augmentation can be used to reinstate structural capacity once deterioration has significantly advanced. | Late stage deterioration, once structural capacity has or will be compromised due to deterioration. | High<br><br>In addition, these forms of repair can require closure of the structure during the works. |

## 5 CONCLUSION

Early stage intervention, in the form of preventative maintenance, can be a key to avoiding expensive, complex and disruptive remediation works. The challenge for asset owners arises because early stage corrosion is not visually apparent, and the current approach of Level 1 and 2 bridge inspections does not capture the information required to adopt best practice.

The industry could benefit from the adoption of routine preliminary condition assessments, undertaken by personnel experienced in infrastructure materials deterioration and intended to identify the:

- potential deterioration mechanisms placing the structure at risk;

- appropriate timing for a larger scale investigation; and/or
- appropriate timing for the implementation of preventative maintenance.

Such a program would involve undertaken testing for chloride concentration and carbonation depth to establish diffusion rates and subsequently allow predictive modelling of future deterioration, enabling programming of the required preventative maintenance works.

Prioritising expenditure on preventative maintenance as well as mid-stage intervention, instead of delaying until significant deterioration is affecting the serviceability or capacity of the bridge would result in a decrease in life cycle costs for such assets, ultimately improving the economic and social outcomes for all stakeholders.

## 6 REFERENCES


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## 8 AUTHOR BIOGRAPHIES

**Dean Ferguson,** General Manager of Infracorr Consulting, still spends as much time as possible getting his hands dirty in sewers or under bridges! He has a decade of experience undertaking condition assessments of structures, includes detailed destructive and non-destructive testing of various construction materials such as concrete, stainless steel, FRP and protective coatings. Dean is a Director of the Australasian Corrosion Association (ACA) and is the immediate past-President of the ACA Victorian Branch, where he has been a branch committee member since 2010.

**Ian Godson,** Director and Principal Consultant of Infracorr Consulting, has 35 years’ experience in all aspects of remedial engineering including condition assessment, remedial design and cathodic protection design and installation. Ian’s experience with cathodic protection of reinforced concrete structures traces back to 1987 when following training in Italy he introduced the technology to Australia. A regular presenter at technical conferences around the world, Ian’s commitment to being at the forefront of remediation technology is a strong driver in his ongoing success.

**Scott Gleason,** Materials Engineer at Infracorr Consulting, has a doctorate in materials engineering specialising in physical metallurgy, and recently joined Infracorr to apply these skills to corrosion prevention. He has worked in both in labs and in the field giving him a wide range of theoretical and practical experience in materials production and degradation.