

## **Long Life Chloride Affected Concrete Structures – Some Corrosion Mechanistic Considerations**

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### **ABSTRACT**

Reinforced concrete structures in marine and saline environments can be very durable and may not necessarily suffer significant chloride-induced corrosion of steel reinforcement even when well beyond their design lives. Several condition surveys of reinforced concrete marine structures and coastal bridges up to 100+ years of age have identified chloride levels at reinforcement depth of up to 0.6% by weight concrete (~4% by weight cement) but with no significant reinforcement corrosion propagation occurring (or duly diagnosed as occurring). The reasons for this are contemplated via deliberations on corrosion mechanistic considerations including exploration as to why “active corrosion/pit propagation” does not necessarily progress despite what should be sufficient chloride at the reinforcement surface to result in propagation. It is surmised that several mechanisms may explain this effect including cement chloride binding and adsorption, the presence of a sound portlandite rich layer around reinforcement and the “active corrosion model” and “metastable pitting and pit growth mechanistic considerations”. An understanding of these mechanisms and models results in long-life durable structures in chloride environments with minimal maintenance expenditure (including not having to waste monies on electrochemical treatment technologies) as well as improved assurance of chloride durability in the design of new structures.

**Key words:** chloride-induced corrosion; metastable pitting; chloride binding and adsorption; steel-concrete interface condition; ‘do nothing’; patch repair; low maintenance; chloride durability.

## INTRODUCTION

Reinforced concrete structures in marine and saline environs can be very durable and do not suffer significant chloride-induced corrosion of steel reinforcement (and prestressing) even when well beyond their design lives. Some structures suffer premature chloride induced reinforcement corrosion within their design lives. There are also those reinforced concrete structures where owners/stakeholders are led to believe that chloride induced reinforcement (and prestressing) corrosion is occurring or will soon occur based on limited or non-representative information such that monies are spent on unnecessary expensive protection, such as on electrochemical treatment technologies.

Condition surveys utilizing closely spaced electrode potential measurements, polarization resistance measurements and other techniques can be used to determine the condition of the reinforcement or prestressing strands, including pitting corrosion.

Findings from several condition surveys of chloride affected reinforced concrete structures are summarized and discussed. Studies include reinforced and prestressed concrete marine structures and coastal reinforced concrete bridges up to 100+ years of age in various States/Territories of Australia that have needed no maintenance or only local conventional concrete patch repair despite chloride levels at reinforcement depth of up to 0.6% (by weight concrete) and prestressing depth of up to 0.2% (by weight of concrete).

Deliberations on cement/binder chemistry considerations, corrosion mechanistic considerations and chloride threshold/critical chloride content considerations are presented and exploration of why “active corrosion/pit propagation” does not necessarily progress despite what should be sufficient chloride at the reinforcement (and prestressing) surface to effect such. The “active corrosion model” and “metastable pitting and pit growth mechanistic considerations” are also deliberated upon.

## STRUCTURE CONDITION SURVEY FINDINGS

### 100+ Year Marine Structure

Limited investigation was undertaken on a reinforced concrete marine berth structure constructed circa 1908, located on the east coast of Australia. Superficially the structure appeared visually in sound condition (Figure 1) with no major signs of reinforcement corrosion induced deterioration such as rust staining, cracking, delamination or spalling. Sampling and chloride content determinations identified very high chloride ion concentrations at the depth of reinforcement of ~0.39% by weight of concrete (~2.73% by weight cement).<sup>1</sup>

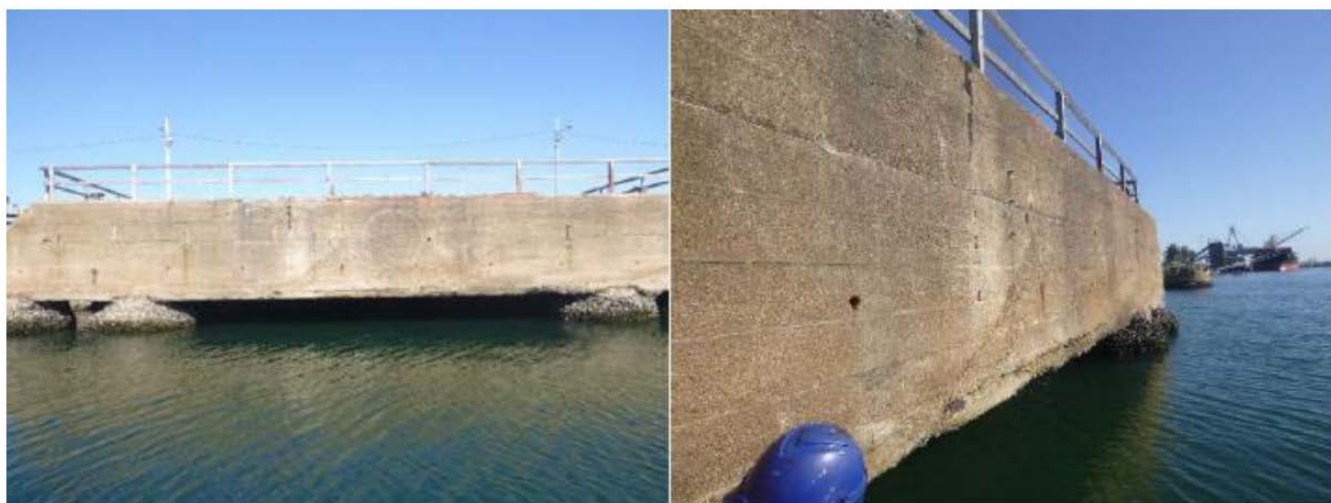


**Figure 1: 100+ berth structure (now fishing jetty).**

The age of the structure, and its high chloride content, suggest that it should be showing signs of considerable deterioration, particularly reinforcement corrosion.<sup>1</sup> Further investigations, as part of undergraduate or post-graduate engineering student research projects, are proposed in the future to diagnose reinforcement corrosion state and concrete composition.

### 65+ Year Coastal Road Bridge

This reinforced concrete bridge was constructed in 1954 and is located on the coast in north west Tasmania, Australia. The bridge is 61m (200ft) in length, made up of five spans, with the outer two spans cantilevered from the piers. The superstructure is a rectangular concrete girder/reinforced concrete road deck construction featuring five longitudinal girders. The girders are supported on four bridge piers within the river. The outer two are reinforced concrete blade type piers on a spread footing. The inner two piers are two part reinforced concrete caissons keyed into the bedrock. Reinforced concrete curtain and return walls are located at the bridge ends to retain the road formation and fill. The general arrangement of the bridge is shown in Figure 2.

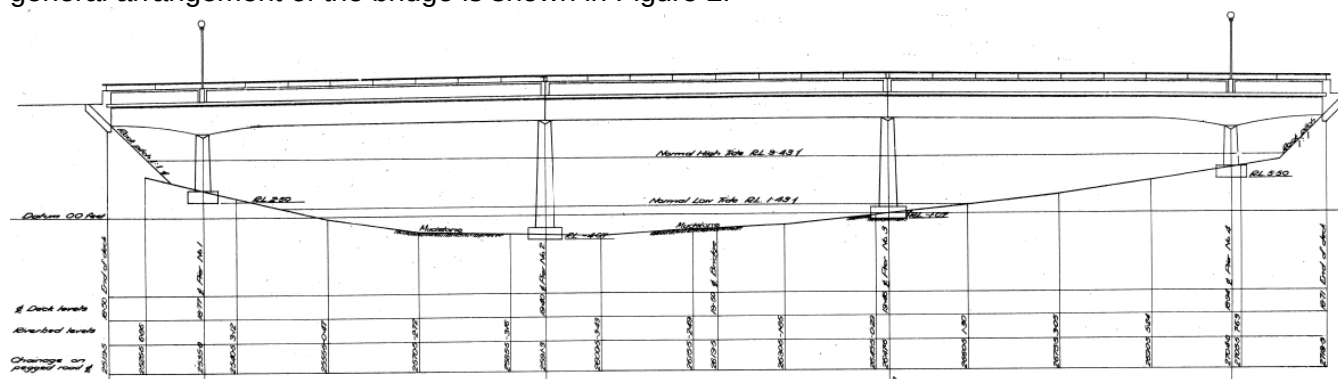


**Figure 2: General arrangement of 65+ coastal road bridge.**

A limited condition survey of the bridge substructure elements was undertaken and the diagnostic testing results from such are summarized at Table 1.

**Table 1: Diagnostic testing results summary – 65+ year coastal road bridge.**

| Test Site                                                    | Depth (mm) | Chloride Content<br>(% by wt of concrete) | Depth of Carbonation (mm) | Covermeter<br>Min-Max<br>(Avg) (mm) |               | Electrode Potentials<br>(mV vs Ag/AgCl/0.5M KCl) | Resistivity<br>( $\Omega$ .cm) | Breakout Observations        |
|--------------------------------------------------------------|------------|-------------------------------------------|---------------------------|-------------------------------------|---------------|--------------------------------------------------|--------------------------------|------------------------------|
|                                                              |            |                                           |                           | Loc.                                | Cover         |                                                  |                                |                              |
| Test Area 1<br>West Abutment<br>Atmospheric Zone             | 0-10       | 0.04                                      | 22                        | Horizontal                          | 21-66<br>(28) | -100mV to -400mV.<br>Gradients are 50mV or less. | 133,000                        | As placed corrosion on bars. |
|                                                              | 10-25      | 0.02                                      |                           |                                     |               |                                                  |                                |                              |
|                                                              | 25-50      | 0.01                                      |                           | Vertical                            | 13-27<br>(16) |                                                  |                                |                              |
|                                                              | 50-75      | <0.01                                     |                           |                                     |               |                                                  |                                |                              |
| Test Area 2<br>Western Pier Column<br>Footings<br>Tidal Zone | 0-10       | 0.28                                      | Negligible                |                                     |               | -400 to -500mV.<br>Gradients are 50mV or less.   | 9,000                          | No breakout.                 |
|                                                              | 10-25      | 0.40                                      |                           |                                     |               |                                                  |                                |                              |
|                                                              | 25-50      | 0.38                                      |                           |                                     |               |                                                  |                                |                              |
|                                                              | 50-75      | 0.31                                      |                           |                                     |               |                                                  |                                |                              |
| Test Area 3<br>Western Pier Column<br>Tidal Zone             | 0-10       | 0.39-0.58                                 | Negligible                | Horizontal                          | 50-66<br>(60) | -300mV to -500mV.<br>Gradients are 50mV or less. | 14,000                         | As placed corrosion on bars. |
|                                                              | 10-25      | 0.41-0.56                                 |                           |                                     |               |                                                  |                                |                              |
|                                                              | 25-50      | 0.40-0.41                                 |                           | Vertical                            | 57-73<br>(67) |                                                  |                                |                              |
|                                                              | 50-75      | 0.37-0.41                                 |                           |                                     |               |                                                  |                                |                              |
| Test Area 4<br>Western Pier Column<br>Splash Zone            | 0-10       | 0.24-0.27                                 | 18                        | Horizontal                          | 64-69<br>(67) | -200mV to -400mV.<br>Gradients are 50mV or less. | 47,500                         | As placed corrosion on bars. |
|                                                              | 10-25      | 0.20-0.26                                 |                           |                                     |               |                                                  |                                |                              |
|                                                              | 25-50      | 0.17-0.21                                 |                           | Vertical                            | 61-68<br>(65) |                                                  |                                |                              |
|                                                              | 50-75      | 0.10-0.13                                 |                           |                                     |               |                                                  |                                |                              |
| Test Area 5<br>Western Pier Column<br>Atmospheric Zone       | 0-10       | 0.07-0.10                                 | 26                        | Horizontal                          | 56-66<br>(62) | -100mV to -300mV.<br>Gradients are 50mV or less. | 177,000                        | As placed corrosion on bars. |
|                                                              | 10-25      | 0.04-0.06                                 |                           |                                     |               |                                                  |                                |                              |
|                                                              | 25-50      | 0.02-0.04                                 |                           | Vertical                            | 62-63<br>(63) |                                                  |                                |                              |
|                                                              | 50-75      | <0.01-0.02                                |                           |                                     |               |                                                  |                                |                              |

The diagnostic testing results from within the tidal and splash zone pier locations indicate the following:

- Chloride levels at mean reinforcement depth (60-67mm) of ~0.1-0.4% by weight of concrete (~0.7-2.8% by weight of cement).
- Gradients of electrode (half-cell) potentials, together with breakouts to expose reinforcement, did not indicate that pier reinforcement was corroding.

In terms of the absolute values of the electrode (half-cell) potentials, if interpretation were undertaken in accordance with the criteria proposed in ASTM C876<sup>2</sup> then incorrectly the assessment would be that pier reinforcement is corroding.

As should always be remembered, ASTM C876 criteria should not be used to interpret electrode potential values but rather the gradients together with breakouts that enable visual inspection of reinforcement condition.

#### 40+ Year Old Marine Structure 1

The reinforced concrete marine structure in this instance was constructed in 1977 and is a berth wharf within a Port on the east coast of Australia. The wharf structure generally consists of the components indicated in the aerial photograph provided at Figure 3. Dolphin 1, Dolphin 2 and Dolphin 3, most particularly substructure reinforced concrete encased steel beams and reinforced concrete deck, were the focus of an investigation by Green et al<sup>3</sup>.



**Figure 3: Aerial photograph of 40+ wharf structure, east coast of Australia.**

The Dolphins of the wharf generally consist of the components described in Table 2<sup>3</sup>.

**Table 2: Components summary of Dolphins of 40+ wharf structure, east coast of Australia.**

| Item                | General Attributes                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | General Photo                                                                         |
|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| Dolphins 1, 2 and 3 | <ul style="list-style-type: none"> <li>Steel piles supporting reinforced concrete encased steel beams and reinforced concrete deck structure.</li> <li>Rubber fender located on the seaward side with steel fixings into the concrete beams.</li> <li>Two rear bollards and a single front bollard centrally located behind the fender. Rear bollards are tied to a ground anchor system comprising of steel HP2 piles and prestressing bar.</li> <li>Constructed circa 1977.</li> </ul> |  |

The condition survey of dolphin reinforced concrete elements included:- visual inspection, delamination testing, covermeter measurements, electrode (half-cell) potentials (with concrete breakouts), concrete electrical resistivity measurements and concrete sampling (drillings and breakouts); at differing exposure areas of beams and slab soffit of each Dolphin.<sup>3</sup>

The field and laboratory test results are summarised at Table 3 for the Dolphin wharf concrete elements investigated by Green et al.<sup>3</sup>