# Sustainable Infrastructure for Aggressive Environments

## Report 2004-018-C-01

The research described in this report was carried out by

Project Leader Dr. Sujeeva Setunge

Team members Dr. Tom Molyneaux (RMIT)

Mr. Srikanth Venkatesan (RMIT)

Mr. John Fenwick (QDMR)

Mr. Wayne Muller (QDMR)

Mr. Russell Hoskin (BCC)

Research Program C:

Delivery and Management of Built Assets

Project 2004-018-C

Sustainable Infrastructure for aggressive environments

# Content Summary

# List of Tables

# List of Figures

# SYNOPSIS

This report presents a brief summary on the current status of the CRC CI research project entitled “Sustainable infrastructure for aggressive environments”.

The main aim of this research project is to develop a diagnostic tool that assists in the interpretation of distress symptoms experienced by bridges in aggressive environments including an estimation of residual service life based on probabilistic approaches. For this purpose a methodology of research and objectives has been proposed. This has been followed by an investigation of real time case study bridges in the state of Queensland. Early benefits of this research in capturing the knowledge base have been outlined in this report. An evaluation of existing knowledge based expert systems from literature has been presented. Proposals of sophisticated levels of condition assessment and modelling residual life have been presented.

The report concludes with the benefits of this research and identifies future research requirements.

# 1 OVERVIEW

## 1.1 Introduction

Durability issues of reinforced concrete construction costs millions of dollars in repair or demolition. Identification of the causes of degradation and a prediction of service life based on experience, judgement and local knowledge has limitations in addressing all the associated issues. The objective of this CRC CI research project is to develop a tool that will assist in the interpretation of the systems, degradation of concrete structures, estimate residual service life and recommend cost effective solutions. This report presents the current status of the research project undertaken in this context.

The primary focus of this research is centred on the case studies provided by Organisations like Queensland Department of Main Roads (QDMR) and Brisbane city council. These organisations are endowed with the responsibility of managing a huge volume of bridge stock in the state of Queensland, Australia. A range of distress mechanisms have been identified as the potential cause(s) of distress mechanisms. Carse, 2005, has noted that the road authorities need to invest their first dollars in understanding their local concretes and optimising durability performance and then look at potential remedial strategies. The next section provides a brief background to the project.

## 1.2 Background

There are about 2850 bridges including major culverts with an estimated replacement value of about $3 million (Fenwick and Rotolone,2003). These are exposed to variety of exposure conditions and loading conditions. Given the importance of these bridges in relation to the transport network and the expected increase in loading conditions the Queensland Department of Main Roads (QDMR) has already recognised the need for new and effective bridge management practices. It has been stated by QDMR that there are currently no corporate procedures for managing these assets. The first step towards developing these management procedures is to develop an understanding of the causative mechanisms of deterioration and estimate the life cycle costs based on established procedures.

Given the fact that infrastructure investments in global context are around US $500 billion per year, international research collaboration is being envisaged in this project. Dr. Steve Millard of Liverpool University, UK has agreed to participate in this project to provide the UK perspective.

The next section of the report presents a brief summary of the research objectives, methodology and strategies.

# 2 RESEARCH METHODOLOGY

*The proposed research methodology has been presented in Figure 2-1. [Nezamian, et.al, (2004)]. The framework is self explanatory.*

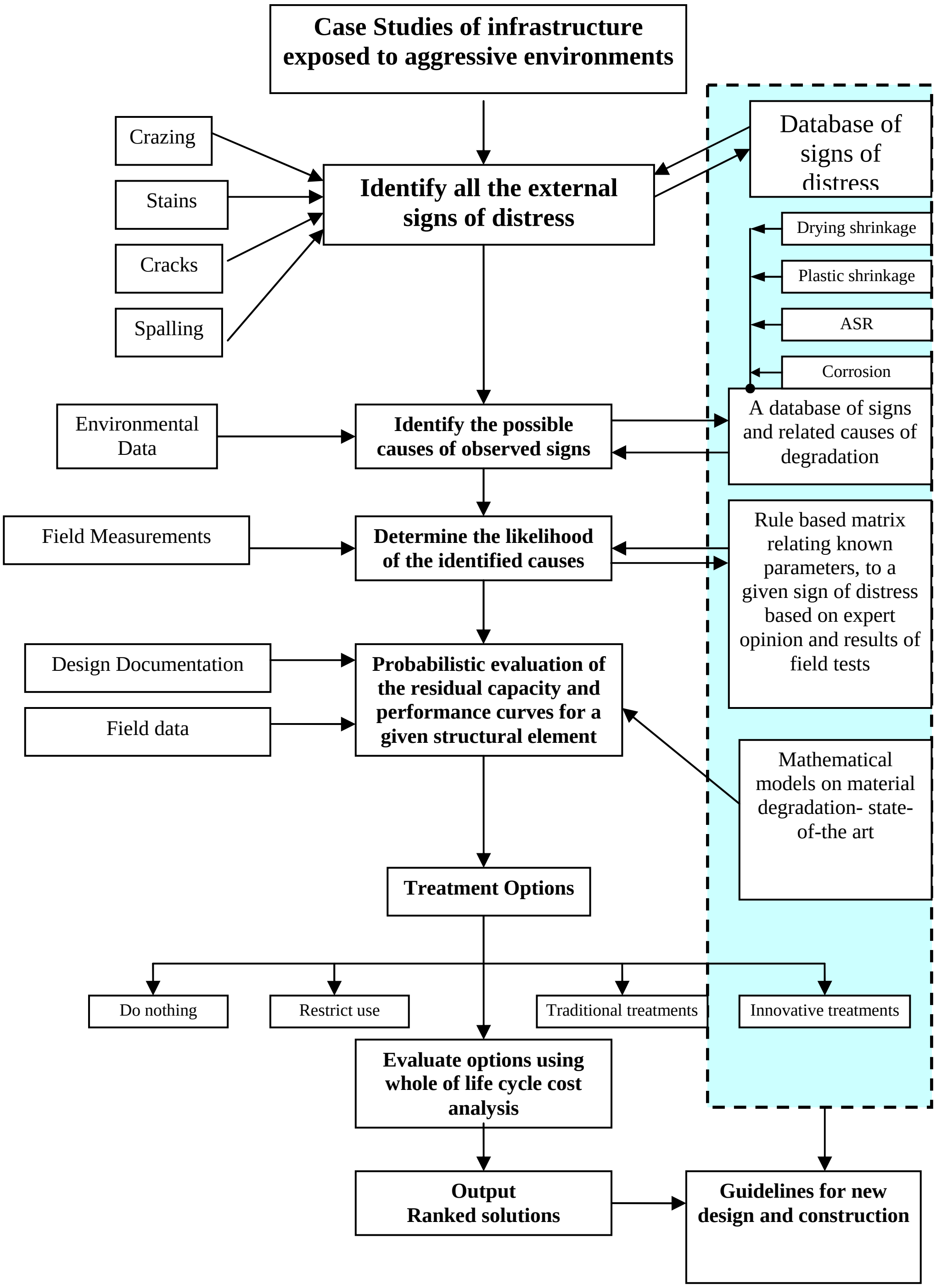


*Figure 2-1: Decision support framework (Nezamian, et.al., 2004)*

*The above framework clearly revolves around four major tasks:*
*Case studies of bridges exposed to aggressive environments*
*Relating distress mechanisms with symptoms of degradation (Rule based matrix)*
*Evaluation of Residual Service Life*
*Life cycle cost analysis for different options*

*It can be noted that the foremost task in the above framework is the development of a rule-based matrix. Initially a literature review has been undertaken to establish the current body of knowledge (Refer to the list of references). Documents such as QDMR – BIM 's provide detailed descriptions and can be referred in this connection.*

*In order to capture the knowledge base available in the inspection reports of QDMR, a model towards developing the rule-based matrix, has been presented in Figure 2-2.*

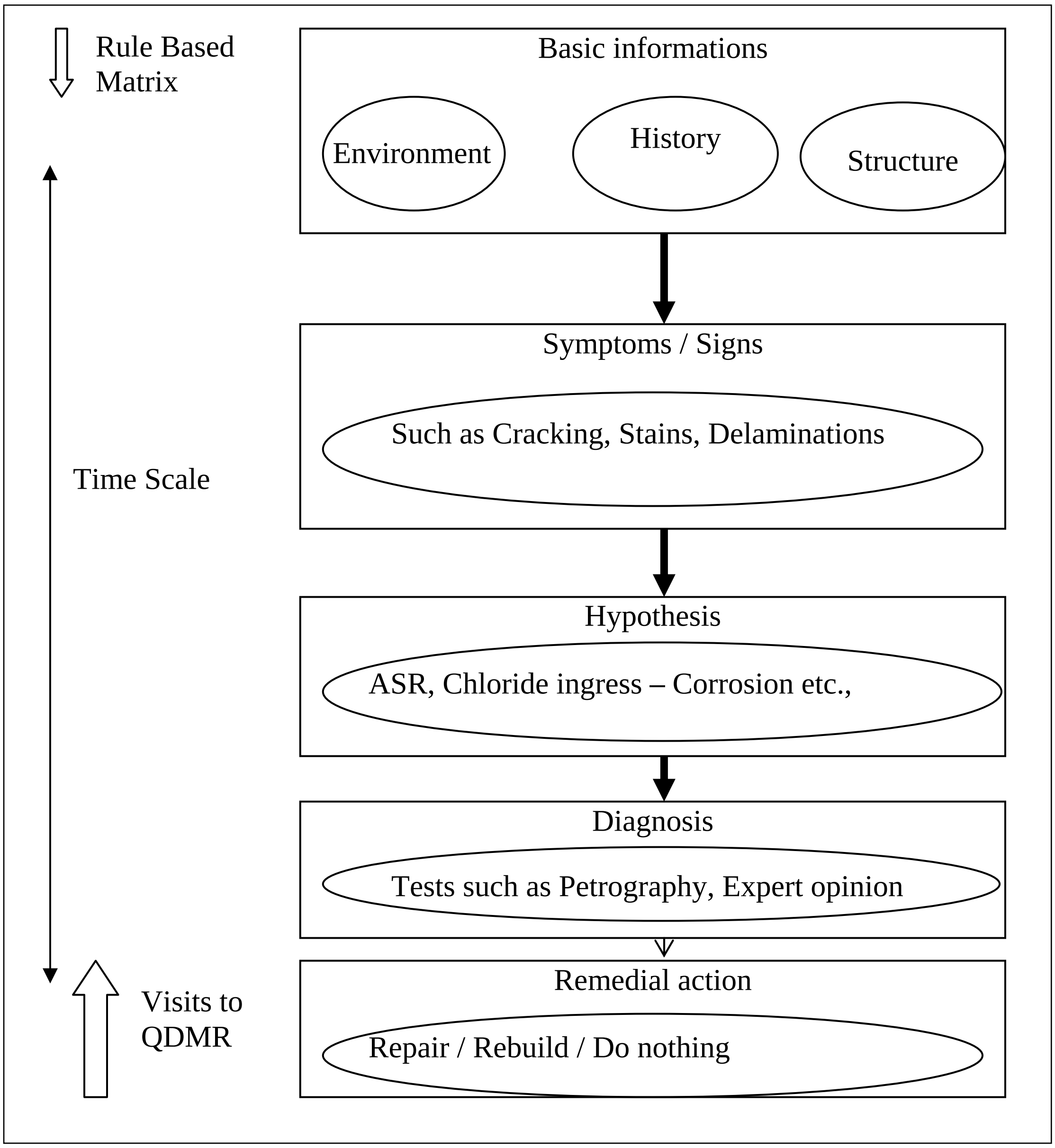


*Figure 2-2. A knowledge based model for QDMR inspection reports*

# 3 ANALYSIS OF `QDMR' CASE STUDY BRIDGES

By adopting the above model, about ten case study bridges has been reviewed. A summary of the results of this investigation has been presented in the following sections of the report.

## 3.1 Munna Point Bridge, Noosa Shire Council

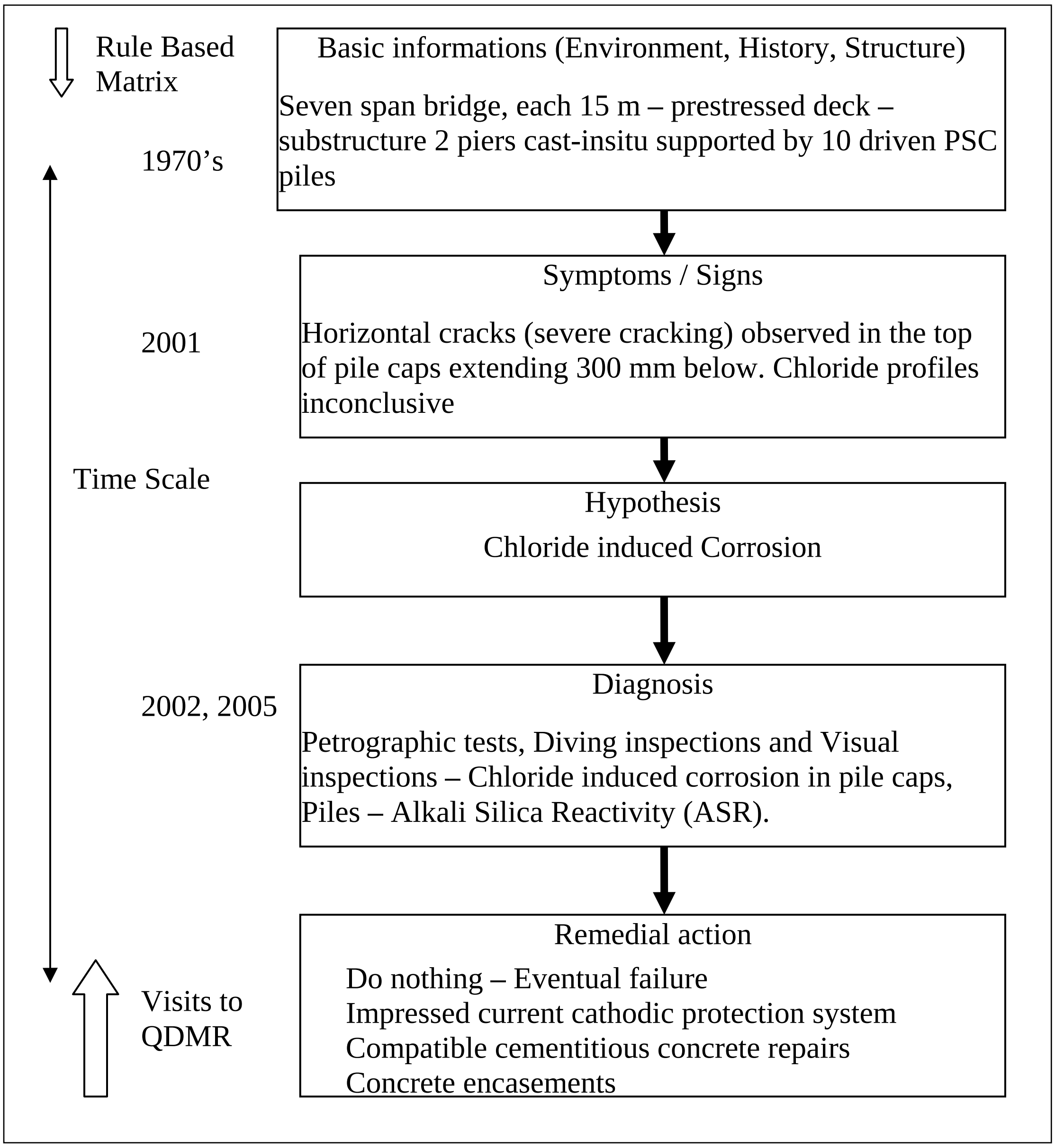


*Figure 3-1. Knowledge base model for Munna Point bridge based on QDMR inspection reports*

The intention of the above figure is to demonstrate the applicability of the model developed in Figure 2-2. However, the reports do contain more informations than described in Figure 3-1. Therefore, additional informations available from the reports have been documented in the form of dot points. It has been noted that this is an example and many other bridges have been reviewed thus far. The following Table 3-1 summarises the distress mechanisms observed in case study bridges and the corresponding symptoms.

## 3.2 Summary of additional case study bridges

*Table 3-1. Summary of distress mechanisms observed in case study bridges*

| Case study bridge | Observed distress mechanisms / causes | Defects / symptoms | Remedial options | Additional comments |
|---|---|---|---|---|
| Tallebudgera | Chloride ingress - Corrosion, Potential ASR | Cracking, | Pile encasement | Cathodic protection not recommended considering the cracked nature of hollow spun piles |
| Munna point | Chloride ingress – corrosion & ASR | Horizontal cracking in pile caps, delamination in vertical faces of pile caps, rusting. Pitting observed | Impressed cathodic protection, cementitious coating | Cracks evident in tidal zone |
| Vines Creek | Structurally adequate | Observed cracking not related to durability issues (Flexural) | Carbon fibre wrapping to piers and encasement to piles | Level 2 inspection according to BIS |
| Sandy Creek | Chloride ingress - Corrosion | Vertical cracking in the tidal zone, cracking at the corners of piers. No spalling observed | Encasement of piers for short term options and Cathodic protection for long term option | Crack widths not increasing with time are the results of flexural cracks |

From the above table and in going through other observations it is possible to gain further understanding of the distress mechanisms and defects. For example, the cracks observed in the tidal zone in a salt water environment decreasing with height and in the corners could be attributed to the chloride induced corrosion. This form of documentation is considered to be the early benefits of this research. This is further explained with two case study bridges namely the Dawson River Bridge and the Nerang River Bridge. Interestingly, in the Dawson River Bridge, the distress mechanism was hypothesised as ASR – however, petrographic analysis of the reports provided evidence of Delayed Ettringite formation as and additional cause of the distress mechanism. A typical format or a logic chart for ascertaining the possible distress mechanism has been presented in Figure 3-2.

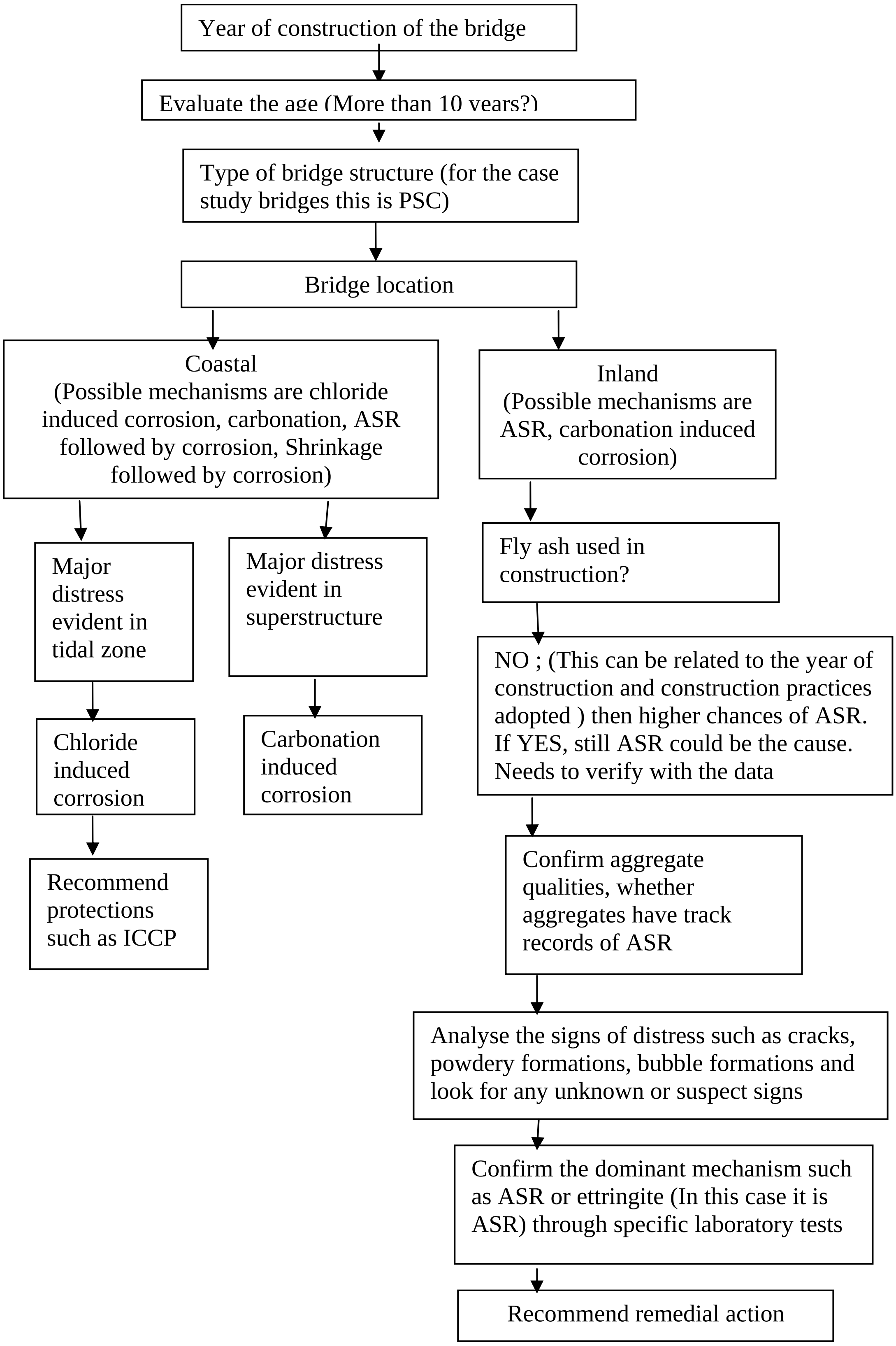


*Figure 3-2. Typical format or logic for ascertaining the distress mechanisms based on case study bridges*

Despite the limitation of the above format lacking generic application, it is at least possible to hypothesise the distress mechanism with a certain degree of confidence. It has to be noted however that further case studies and careful assessment of the information would be required in developing a rigorous rule based matrix to cover a range of distress mechanisms.

# 4 EXAMPLES OF EXISTING RULE BASED MATRICES

This section of the report presents some of the rule based matrices from the literature. Chan, P.P.F (1996) developed an expert system for diagnosing durability problems in concrete structures. A typical table on crack information and location of structure covering corrosion and ASR has been presented in Table 4-1.

*Table 4-1. Crack formation and location on structures (Chan, P.P.F., 1996)*

| Type of cracking | Crack Pattern | Most common location | | Cause of problem | | Remedy | Time of appearance |
|---|---|---|---|---|---|---|---|
| | | Crack formation | Structural element | Primary cause | Secondary cause | | |
| Corrosion of reo | Vertical | Natural | Columns and beams | Inadequate cover | Poor quality of concrete | Eliminate causes | More than two years |
| Corrosion of reo | Horizontal | Calcium chloride | Precast concrete | Excess calcium chloride | Poor quality of concrete | Eliminate causes | More than two years |
| ASR | Random | | Damp locations | Reactive aggregates plus high alkali cement | | Eliminate causes | More than five years |

Applying the above table of information as a basis for evaluating our case study bridges, two significant differences can be noted. First, the above table does not include tidal zone as a parameter for crack locations and the onset time of cracks is about 2 to 5 years. However, we find in most cases the case study bridges are about 30 years old. Therefore application of existing expert systems directly to typical case study bridges is bound to have limitations. Chan reports that the above table was adopted to diagnose the deterioration of a reinforced concrete bridge in Hong Kong which exhibited problems like cracking, spalling, reo corrosion and accidental damages. “Physical damage” and “Chemical attack” were concluded as the likely causes of deteriorations. There are other similar tables proposed in the literature such as the ones from Bungey and Millard, (1996) and Dhir, R.K., (1993). Perhaps organisations like QDMR and BCC would require more comprehensive assessment. This requires a detailed evaluation of existing knowledge based systems similar to Chan’s methodology and this is currently being undertaken. In addition, this leads us to the requirement of analysing the existing methods of inspection and management procedures adopted by QDMR and BCC. The following section presents the analyses and possibilities of developing a comprehensive diagnostic tool.

# 5 DEVELOPMENT OF A DIAGNOSTIC TOOL

A review of the discussion thus far highlights that the existing methodologies do not specify any information about the remaining life of the bridge structure in relevance to the existing condition. It can be clearly noted from the inspection reports of QDMR that the repair strategies were dependent on the probable estimation of the remaining service life. Literature presents some of the probabilistic methodologies of assessing residual service life of concrete structures. However, these models recommend a suit of condition assessment procedures which may not be synonymous with the inspection procedures of QDMR. Therefore, an integrated effort of condition assessment, identification of distress mechanism and residual service life is essential. This has the benefits of selecting the appropriate remedial action, minimising cost and prioritising the remedial actions or repair.

Reviewing the BIM of QDMR and other similar documents it is possible to categorise the present levels of condition assessment into three or four levels (QDMR adopts a 3 level approach). These can be summarised as follows:

Level 1 : Routine Maintenance Inspections – Lower tier of assessment

Level 2 : Bridge Condition Inspections – next higher level of assessment (Typically assessing conditions according to an established condition rating system)

Level 3: Detailed structural engineering inspections – Higher level of assessment (Includes physical testing and structural analysis)

Detailed guidance for carrying out these levels is available and reasonably established in practice. However, these levels do not provide any indication of the probable remaining life of the structures in the absence of remedial actions. As noted earlier remedial actions are driven by the remaining life. Further analysis and prioritising the ranking of remedial actions are required for optimising the maintenance cost. Therefore, the following levels are proposed that significantly leads to higher level of sophisticated maintenance.

**Level 4: Probabilistic evaluation of Residual Service life capacity**. This will include the development of performance curves for a given element and scenario. Limit states of performance needs to be established for this purpose.

**Level 5: Prioritising maintenance regimes:** This will be based on the evaluation of different remedial options and ranking. Knowledge gained from these two levels can be integrated for future design and construction.

These levels can be further enhanced to incorporate a global requirement and possibly documented in the BIM's of QDMR.

# 6 CONCLUDING REMARKS

This report has presented the current status of the CRC CI Research Project entitled “Sustainable infrastructure for aggressive environments”. Significant conclusions from this report are:

- Evaluation of distress mechanisms based on the prevalent distress symptoms is essential towards successful maintenance of bridges exposed to aggressive environments.
- Analyses of inspection reports on case study bridges provide useful information in identifying the real cause of distress mechanism(s).
- Existing expert systems of identifying distress mechanisms needs rigorous evaluation to confirm their applicability to real time large bridge stocks
- Need for sophisticated levels of bridge management has been highlighted

This report has covered a reasonable volume of literature. Further work is needed to undertake a state-of-the-art review on distress mechanisms and evaluation of knowledge based expert systems. Thus the future research needs are;

- Undertake a state-of-the-art review on distress mechanisms affecting bridges exposed to aggressive environments
- Review and evaluation of knowledge based systems specifically on bridges
- Further review of case study bridges
- Development of a rule-based matrix connecting symptoms and distress mechanisms
- Development of the diagnostic tool covering sophisticated levels of condition assessment of bridges

# 7 REFERENCES AND BIBLIOGRAPHY

Australian Infrastructure Report Card, (2005).
**http://www.ieaust.org.au/policy/publications.html**

Bungey, J.H., and Millard, S.G., (1996). “Testing of concrete in Structures” Blackie Academic & Professional, an imprint of Chapman & Hall, Glasgow G64 2NZ

Bridge Inspection Manual, (2000), Registration number 80.640, Issued by the Queensland Department of Main Roads, Transport Technology Division.

Carrier, R.E., and Cady, P.D., (1975). “Factors affecting the durability of concrete bridge decks”, SP-47-7, American Concrete Institute, 1975.

Chan, P.P.F., (1996). “An expert system for diagnosis of problems in reinforced concrete structures”, Masters degree thesis, RMIT University, 1996.

De Brito, J., Branco, F.A., Ibanez, M., (1993). “A knowledge based oncrete bridge inspection system”, Concrete International, Vol.16, pp. 59-63, United States.

Dhir, R.K., (1993). “Mechanisms of deterioration I: Carbonation, chlorides and reinforcement corrosion”, in standing committee on concrete technology, Seminar on concrete for durable construction, Civil engineering Department, Hong Kong Government, 1993, pp 19-28.

Dhir, R.K., (1993). “Mechanisms of deterioration I: Carbonation, chlorides and reinforcement corrosion”, in standing committee on concrete technology, Seminar on concrete for durable construction, Civil engineering Department, Hong Kong Government, 1993, pp 35-43.

Fenwick, J. M., and Rotolone, P., (2003). “Risk Management to Ensure Long Term Performance in Civil Infrastructure” *21st Biennial Conference of the concrete institute of Australia*, Brisbane, Australia, pp. 647-656.

Gannon, E.J., and Cady, P.D., (1992). “Condition evaluation of concrete bridges relative to reinforcement corrosion, Volume-1, State of the art of existing methods”, Report number SHRP-S/FR-92-103, National Research Council, Washington DC, 1996.

Nezamian, A., Setunge, S., and Molyneaux, T., (2005). “A framework for predicting the residual load carrying capacity of concrete structures exposed to aggressive environments”, Proceedings of the 3rd International conference on construction materials: Performance, Innovations and structural implications, Aug, 2005.

Teng, T.P., (2004). “Critical literature review on High performance corrosion reinforcements in concrete bridge applications”, Final Report, FHWA-RD-04-093, 2004.

# 8 AUTHORS BIOGRAPHY

**Dr Sujeeva Setunge,**

***Education*:** PhD, Monash University, Australia (1993), B.Sc. Eng.(Hons) Sri Lanka (1985)

***Professional Experience*:** 1 year in Civil Engineering Construction and 15 years in Academia.

***Research Interests:*** Infrastructure asset management, creep and shrinkage of concrete, innovative construction materials and composites, high strength and high performance concrete

**Dr Tom Molyneaux,**

***Education*:**

***Professional Experience*:**

***Research Interests*:**

**Mr Srikanth Venkatesan,**

***Education*:** (PhD), University of Melbourne, Australia,

***Professional Experience*:** Six years of experience in consulting engineering companies.

***Research Interests*:** Residual Service Life of structures, Infrastructure asset management and Earthquake Engineering.