CRC for Construction Innovation (2004) *Final report : a software diagnostic tool for evaluating distress mechanisms in bridges exposed to aggressive environments.* CRC for Construction Innovation, Brisbane , Qld. □□

CRC Construction Innovation
BUILDING OUR FUTURE

Final Report
A Software Diagnostic Tool for Evaluating Distress Mechanisms in Bridges Exposed to Aggressive Environments

Research Project No: 2004-018-C-02

The research described in this report was carried out by:

Project Leader	Sujeeva Setunge
Researchers	Tom Molyneaux Rebecca Gravina Srikanth Venkatesan Matthew Humphreys Sugi Alwi
Project Affiliates	Lex Vanderstaay John Fenwick Peter Rotolone Wayne Roberts Wayne Muller Russell Hoskin

Research Program: C
Delivery and Management of Built Assets

Project: 2004-018-C
Sustainable Infrastructure for Aggressive Environments

Leaders in Construction and Property Research

Distribution List

Cooperative Research Centre for Construction Innovation
Authors

Disclaimer

The Client makes use of this Report or any information provided by the Cooperative Research Centre for Construction Innovation in relation to the Consultancy Services at its own risk. Construction Innovation will not be responsible for the results of any actions taken by the Client or third parties on the basis of the information in this Report or other information provided by Construction Innovation nor for any errors or omissions that may be contained in this Report. Construction Innovation expressly disclaims any liability or responsibility to any person in respect of any thing done or omitted to be done by any person in reliance on this Report or any information provided.

Please direct all enquiries to:

Chief Executive Officer
Cooperative Research Centre for Construction Innovation
9th Floor, L Block, QUT, 2 George St
Brisbane Qld 4000
AUSTRALIA
T: 61 7 3138 9291
F: 61 7 3138 9151
E: enquiries@construction-innovation.info
W: www.construction-innovation.info

Content Summary

List of Photos

List of Figures

List of Tables

SYNOPSIS

The main aim of this research project is to develop a diagnostic tool that assists in the interpretation of distress symptoms in bridges exposed to aggressive environments. Distress mechanisms pertinent to Queensland bridge stock have been investigated and the methodology of diagnosing from visual symptoms has been developed. Based on further analysis of about 30 case studies of bridges a database of parameters and issues to be considered in relating the symptoms of distress to their mechanisms has been developed using a mind-map analysis technique “Freemind”. This has led to the systematic documentation of a rule based matrix that includes three levels of confidence (High, Medium and Low). Based on this documentation a software tool (BridgeDIST) has been developed with a “knowledge base” and an inference engine. Imprecise information has been evaluated using a fuzzy-logic approach.

The developed software is simple in application with an open-ended architecture; this helps the experts to create their own new rule-bases as and when sufficient expertise has been gained. Furthermore, the software can potentially be linked to the bridge management systems and future deterioration of bridge stock could be predicted.

A hardcopy costing module has been developed to accompany the software tool which evaluates the cost of repair methods for a given scenario. It is envisaged that the work will be continued with the support of the industry partners to include the costing module to the software tool.

1 OVERVIEW

1.1 Introduction

Durability issues of reinforced concrete construction cost 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 symptoms of degradation of concrete structures, estimate residual capacity and recommend cost effective solutions. This report is a documentation of the research undertaken in connection with this project.

The primary focus of this research is centred on the case studies provided by Queensland Department of Main Roads (QDMR) and Brisbane City Council (BCC). These organisations are endowed with the responsibility of managing a huge volume of bridge infrastructure in the state of Queensland, Australia. The main issue to be addressed in managing these structures is the deterioration of bridge stock leading to a reduction in service life. Other issues such as political backlash, public inconvenience, approach land acquisitions are crucial but are not within the scope of this project. It is to be noted that deterioration is accentuated by aggressive environments such as salt water, acidic or sodic soils. Carse, 2005, has noted that the road authorities need to invest their first dollars in understanding their local concretes and optimising the durability performance of structures and then look at potential remedial strategies. The following section provides further background to the project.

1.2 Background

There are about 2850 bridges including major culverts with an estimated replacement value of about $3 million in Queensland, Australia (Fenwick and Rotolone,2003). These are exposed to a variety of loading and environmental 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 the global context are approximately US $500 billion per year, an international research collaboration has been established for the project. Dr. Steve Millard of Liverpool University, UK has participated in this project providing the UK perspective.

The most common distress mechanisms affecting bridge stock in Queensland are as follows:

(i) Chloride induced corrosion
(ii) Alkali-Silica-Reaction (ASR)
(iii) Delayed Ettringite formation

(iv) Plastic shrinkage
(v) Plastic settlement
(vi) Defective concrete
(vii) Basic corrosion
(viii) Carbonation
(ix) Construction related
(x) Accidental damage

Distress mechanisms such as de-icing salts are uncommon in Queensland and are therefore not considered. Similarly, carbonation is a more serious problem in the state of Victoria than in Queensland. Therefore, the focus is more on the first 7 mechanisms above (i to vii). For readers who are unfamiliar with the descriptions of the above mechanisms the Bridge Inspection Manual (BIM) of QDMR would serve as an informative reference. 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 1 as published in Nezamian, et.al, (2004). The framework is self explanatory.

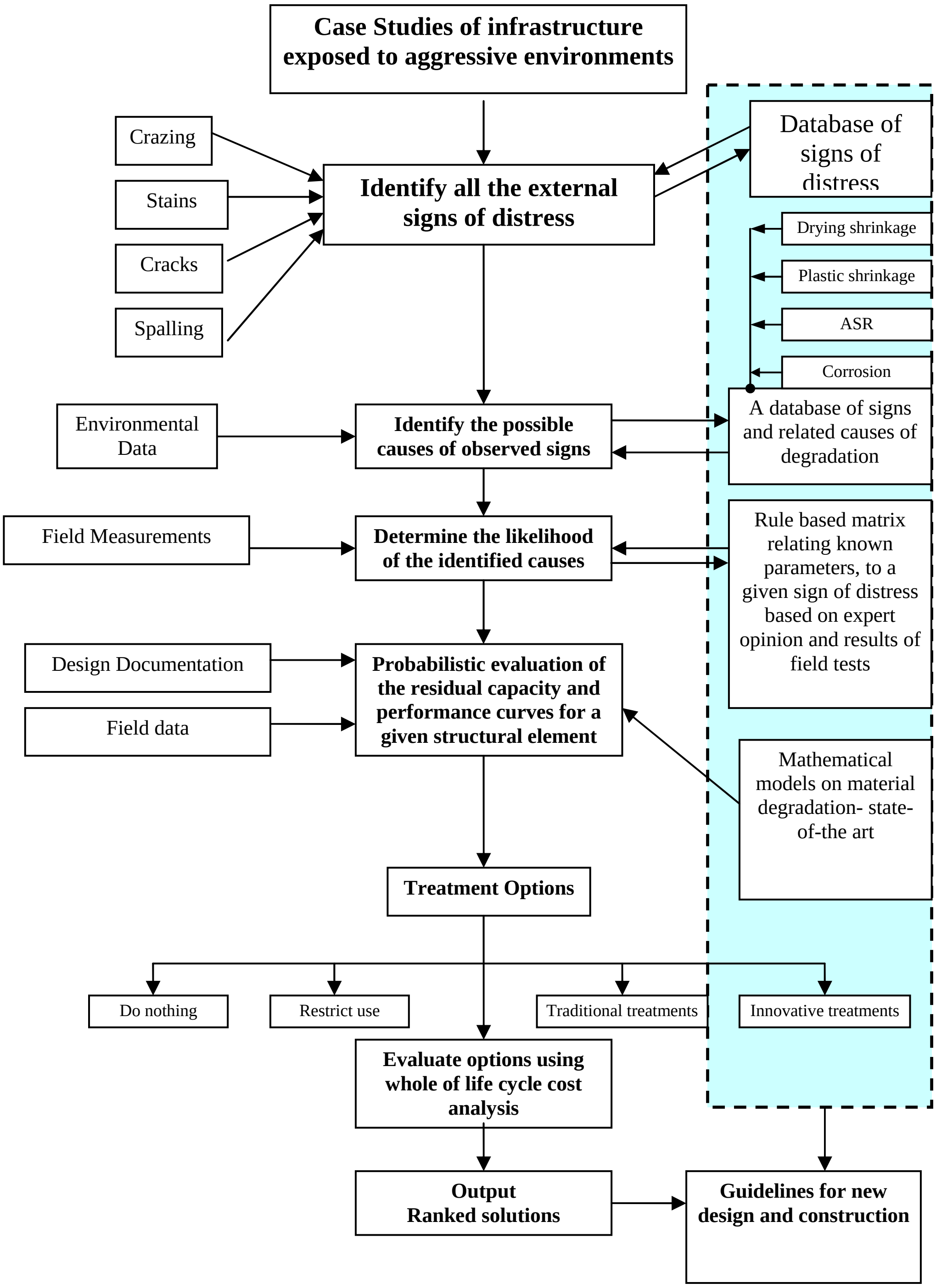


Figure 1. Decision support framework (Nezamian, et.al., 2004)

The above framework clearly revolves around four major tasks (objectives):

- Case studies of bridges exposed to aggressive environments.
- Relating distress mechanisms with symptoms of degradation (Rule based matrix).
- Evaluation of Residual Service capacity.
- 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. A review of literature undertaken to establish the current body of knowledge revealed that typical rule-based matrices have been adopted in other fields; however, the authors could not find an approach comparable to the one described in this report to have been undertaken elsewhere. About 30 case study bridges with the dominant mechanisms that were analysed are presented in the table below:

Table 1.Dominant distress mechanisms in case study bridges

Dominant distress mechanism	**Number of bridges analysed**
Chloride induced corrosion	6
Carbonation	3
Alkali-Silica-Reaction	7
Delayed Ettringite	2
Plastic shrinkage	3
Plastic settlement	3
Defective concrete	3
Basic corrosion	4
Construction related	3
Accidental damage	2

Details of two case study bridges selected from the above table are presented in the next section.

3 ANALYSIS OF `QDMR' CASE STUDY BRIDGES

For privacy reasons the names and locations of the case study bridges have been excluded. Consequently, the bridges have been numbered as Bridge 1, Bridge 2 and so on. Detailed analysis results of these two case study bridges have been published in Venkatesan, et.al., (2006).

3.1 Bridge 1

3.1.1 Bridge details

Bridge 1 is a seven-span structure consisting of 15 m long prestressed concrete (PSC) deck units supported by reinforced cast-in-situ piers and driven PSC piles. Each pier consists of a head stock supported by two cylindrical columns, which in turn is supported by a pile cap. The headstocks, columns and pile caps are all cast in-situ concrete. Below each pier pile cap are ten 450 mm driven pre-cast concrete piles. The outermost piles are raked outward (i.e. lateral to span at a gradient of 1:5. The remainder of the piles are raked longitudinally in alternating directions at a gradient of 1:5. Photo 1 shows a view of this bridge.

Photo 1. General view of Bridge 1

The location of the bridge is vital to tourism, and to the community. This bridge was constructed in approximately 1978 and thus is less than 30 years old. It has to be noted that the pile caps are located within the tidal zone. Construction drawings of this bridge are available. Reinforcement details of a typical pier pile cap are available in the report. Therefore design details could be extracted if necessary.

3.1.2 Observed Distress

In 1999, problems with the deck seating were observed. In the year 2000, cracks in the range of 2 to 3 mm were observed on headstocks at approximately top reinforcement level.

3.1.2.1 *Distress in Pile caps*

In 2001, severe cracking was noted within the top 300 mm of each pile cap during a boat inspection. Cracks were noted on the top faces, extending down to approximately mid-depth of each pile cap. Tapping with a hammer revealed that much of the cover concrete in these areas had delaminated. In 2002, a diving inspection was undertaken. It was observed that all piles had vertical cracks on almost every face of the pile. The cracks were reported as ranging from hairline to 4 mm wide. Photo 2 presents a typical case showing the extent of cracking observed on the pile caps and Photo 3 presents the distress observed in piles under water.

(i). Cracking near tops and soffits of the sides of a pilecap.

(ii). Cracking observed on top of the pilecaps.

(iii). Cracking observed on the ends and corners.

(iv). Cracking observed on the pilecap sides.

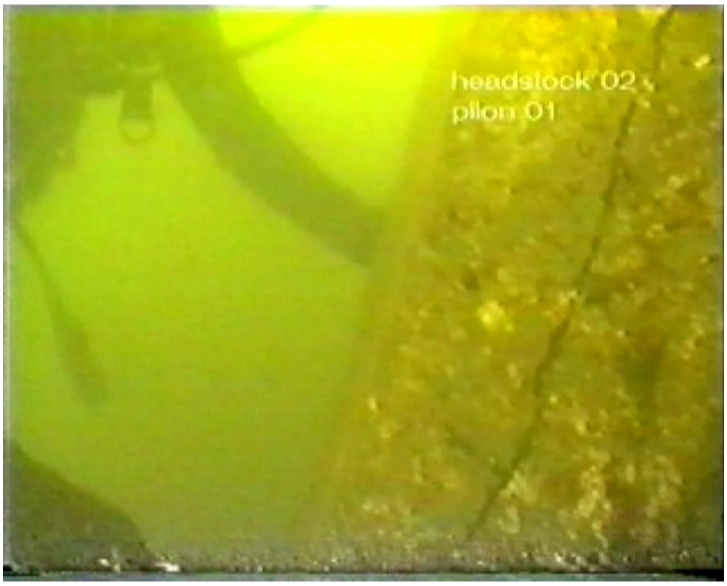
Photo 2. Distress observed in pile caps

It was noted on the video footage that in various locations cracking had developed to a stage where blows with a hammer produced hollow or drummy sounds associated with the delamination of the concrete.

Based on the video and file records, the most severe cracking and delamination was noted around the ends, corners and near the top of the sides of pile caps. It appears that cracking in certain other areas had also approached a similar severity. Corrosion products were noted to be emanating from a number of cracks within the tidal zone.

3.1.2.2 ***Distress in Piles***

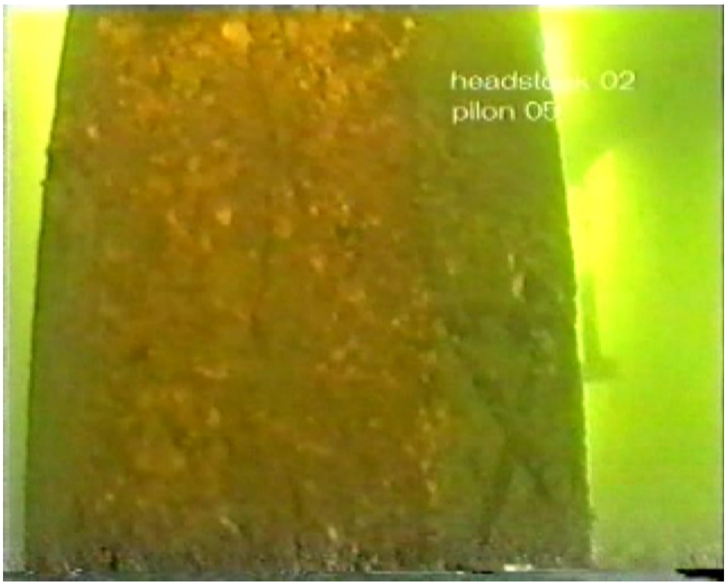
Deterioration observed in Piles is shown in Photo 3.



(i). Underwater cracks in piles

(ii). ASR observed in piles

(iii). Underwater cracks in piles…contd..



(vi). Underwater cracks in piles…contd..

Photo 3. Distress observed in piles

3.1.3 Hypothesis

The delaminations observed in the cover concrete were observed to be the effect of expansive corrosion of the reinforcement. Part of this hypothesis could be considered to be heuristic knowledge and partly based on scientific evidence.

The sizes of cracks and the extent of delamination observed varied from location-to-location and pier-to-pier. Essentially the deterioration mechanism had affected the majority of pier pile caps. It was believed that the variations in the severity and extent of the defects were due to changes in the degree of compaction, differences between concrete batches & variability in the depth of cover. Thus the construction related issues have been considered as possible contributing factors to distress, although it is difficult to quantify their influence.

The type of cracking observed in the pile caps especially within the tidal zone has been attributed to chloride-induced corrosion. This has been further confirmed based on the possibility of double diffusion of chlorides from two adjacent faces of the pile caps. Constant wetting and drying of the surfaces in the tidal zone could produce a greater build up of chlorides and when followed by increased oxygen supply, would accelerate the rate of corrosion.

The type of cracks observed in the piles underwater, their appearance and the age of the bridge, were indicative of Alkali-Silica-Reaction (ASR). On further investigation, the coarse aggregates used in the construction of this bridge were obtained from quarry sources that were found to be sensitive to ASR.

Based on the distress symptoms and signs, various levels of hypothesis were postulated in the report, initially based on the visual symptoms. This was followed by a program of laboratory tests.

3.1.4 Tests undertaken

In 2001, approximately ten concrete core samples were extracted for laboratory testing. Chloride profiles, petrographic analysis, strength tests, density tests and carbonation tests were undertaken on these samples. The tests were necessary to examine the cause of severe cracking. 14 additional cores had been extracted specifically from the damaged areas of concrete. Photographs of the core samples are presented in Photo 4. The severity of the cracking in the core samples is apparent in this photo.

Core 1, East f.
Core 2, West f.
Core 3, East f.
Core 4, Top.
Core 5, East f.
Core 6, Top.
Core 7, Top.
Core 8, West f.
Core 9, East f.
Core 10, West f.
Core 11, West f.
Core 12, West f.
Core 13, East f.
Core 14, West f.

Photo 4. Photographs of concrete cores (April 2001).

3.1.5 Diagnosis

The potential for ASR to have occurred for both the pile cap and the samples, based on the petrography, was judged to be mild. Prominent calcium hydroxide in the cement paste was identified, which is consistent with the practice at the time of construction.

The carbonation test results proved that the depth of carbonation was much less than the actual cover. Therefore, carbonation was considered as an unlikely cause. However, several of the cores tested from the 14 samples extracted, showed average carbonation depths of 66 mm. This is very close to the depth of the concrete cover (70 mm). These particular results were considered anomalous to the earlier results, since the majority of the samples demonstrated otherwise.

The grade of concrete was estimated at around 20 MPa based on test results and the age of the structure.

Plots of chloride content versus depth are presented in Figure 2. It is clear that the chloride content is roughly double that of the theoretical threshold necessary for chloride-induced corrosion to occur. For comparison purposes, the chloride content of sea water (approx 20 kg/m^3) is also shown in the figure.

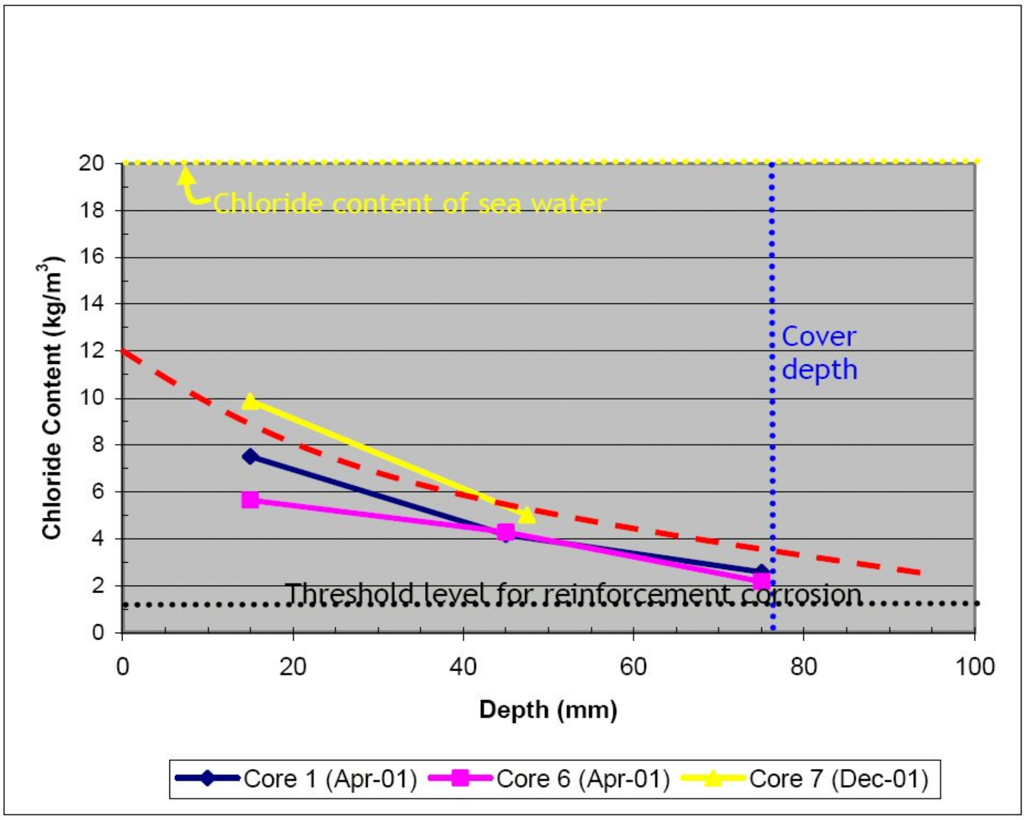


Figure 2. Profile of chloride ingress in concrete cores

3.1.6 Prediction of the dominant mechanism causing distress

- ❖ Summary of deterioration mechanisms

*3.1.6.1 **Pile caps***

The cracking and spalling defects seen in the video of the visual inspections, observations of cracking in the photographs of extracted cores and the chloride testing results are consistent with the diagnosis of chloride-induced corrosion of the reinforcement steel. This was anticipated in light of the structure's aggressive tidal environment, its age and the low grade of concrete used in the pile caps. The extent of cracking and delamination noted in the video of the pile cap inspection indicates that the mechanism is widespread affecting all pier pile caps.

The effects of ASR in the pile caps are believed to be relatively minor, based on the findings of the petrographic report. Carbonation of the cover concrete is not believed to have been a significant cause of the observed problems, despite the one large anomalous reading recorded.

The long-term prognosis for the pile caps, if no action is taken, is accelerating corrosion of the internal reinforcing steel leading to further cracking and spalling, facilitated by easier access to chlorides. Eventually, significant loss of cross section of the steel and failure of the pile caps would be likely to occur.

*3.1.6.2 **Piles***

From the orientation and size of cracks, the type of piles and the age of the structure it is concluded that the observed defects are due to ASR within the concrete.

The cracks are unlikely to have been caused primarily by chloride or carbonation induced corrosion of internal prestressing strands because the cracks caused by the ASR provide easy ingress for water, oxygen and chlorides. The current condition of the internal prestressing within the piles is not known. Spalling of the pile cover concrete was not noted during the diving inspection, indicating that corrosion of the strand has not yet reached that stage.

The long-term prediction if left `as-is' is the continuing cracking due to ASR leading to chloride-induced corrosion of the prestressing strands, spalling of the cover concrete and eventually, failure of the strands.

*3.1.6.3 **Prediction summary***

- Summarising the above discussion, it is clear that (specifically to Bridge 1):
    - Chloride induced corrosion is the dominant mechanism in the pile caps
    - The environment, age and low grade of concrete are significant factors influencing the deterioration
    - ASR and carbonation were not dominant mechanisms in the pile caps
    - ASR is the dominant mechanism in the piles
    - The cracks due to internal prestress of the piles and ASR are potential causes for the Chloride ingress within the piles
    - Concrete cover, construction practices are also noted as significant factors influencing the deterioration.

3.1.7 Proposed Remedial actions

Three remedial actions have been proposed for Bridge 1. They are:

1. Monitor the structure and replace when required (Leave `as-is')
2. Concrete repair and Cathodic protection (CP) of the pile caps
3. Underpin piles and pile caps

Photos (and artist's impressions of option 3 are provided below)

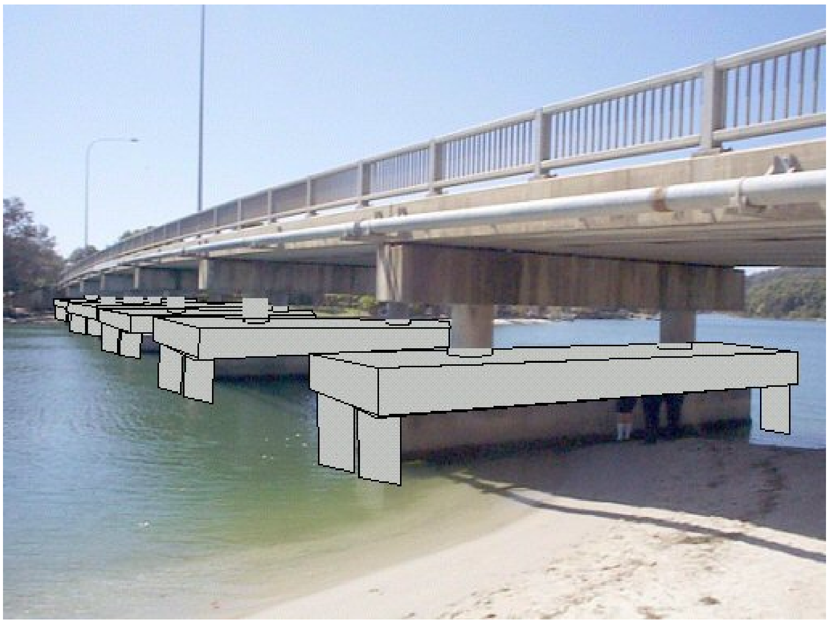


Photo 5. Underpinning Option-1

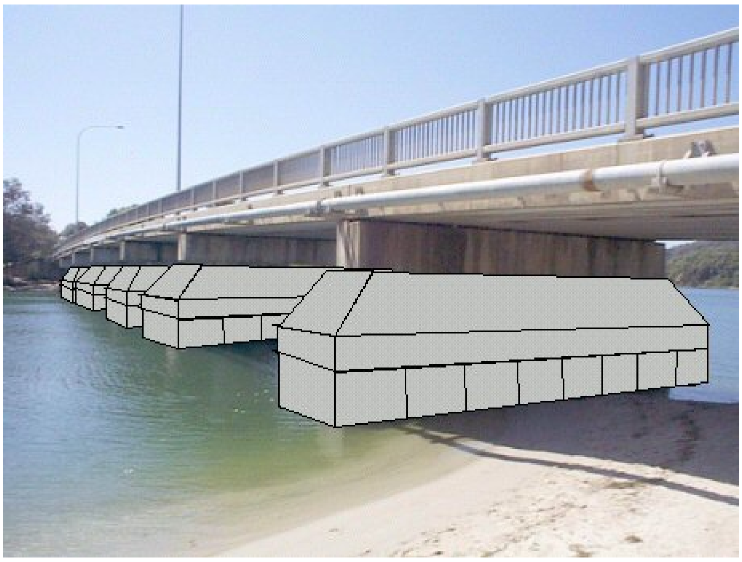


Photo 6. Underpinning Option-2

Importantly, the predicted costs for the above options were not significantly different. However, there are other significant factors to be considered in the execution of these options. These include:

- Quality of workmanship
- Degree of initial defects
- Type and extent of curing

The above factors can be grouped under "best construction practice" although it is difficult to set the guidelines for best practice at this stage. However, these factors can be largely controlled by adopting option 2 and therefore option 2, cathodic protection, has been chosen as the best remedial option for this bridge. Further details are provided below.

3.1.7.1 *Option 1: Leave `as-is'*

Whilst the option of leave `as-is' avoids many difficulties of repairing the existing bridge it still has a range of additional costs and challenges associated with it. The option of building a new bridge along existing alignment has to address the following issues:

- Disruption to residents, tourists and other travelling public, traffic diversions during demolition and new construction.
- Noise, disruption, environmental impact and cost of demolishing the old bridge.
- Noise and disruption associated with new bridge construction.
- Costs of geotechnical investigations, hydraulic analysis and detailed design of the new structure
- Risk of cost overruns during construction – e.g., additional piling, contract variations.
- Costs associated with ongoing inspections and assessments of the structure to determine the replacement time of the structure.

The option of building a new bridge adjacent to the existing alignment might overcome some of the above listed issues, however additional issues arise. They are:

- Resumptions would probably be required due to the lack of available undeveloped land for approach road works.
- Cost of approach roadwork construction.
- Risk of cost overruns during construction – e.g. due to access restrictions due to proximity of old bridge.

Thus it is clear that the option of leave `as-is’ is neither useful nor strategic. Therefore, option 2 cathodic protection has been investigated for Bridge 1.

3.1.7.2 Option 2: Cathodic protection & repair of pilecaps; Encasement of piles

Option 2 proposes the application of a cathodic protection system and concrete repair of the pile caps and encasement of the piles with reinforced concrete jackets. The investigation phase concluded that the cracking in the pile caps was due to expansive corrosion of the reinforcing steel, accelerated by the tidal environment. Option 2 addresses the corrosion mechanism by proposing the installation of an impressed current Cathodic (CP) system and undertaking concrete repairs of the pile caps. With the mechanism causing steel corrosion controlled by the CP system, the new repairs would ensure a sound condition of the pile caps. (Refer Photo 7).

Photo 7. Example of a Cathodic Protection installation. [Left: Anodes are grouted into strips cut into the concrete surface. *Centre:* All loose and delaminated concrete removed prior to reinstating with suitable cementitious material. *Right:* Appearance of a column after grouting the anodes]

For the piles, ASR was noted as the dominant cause of deterioration. The CP system could not be considered for the following reasons.

1. Impressed current CP systems may potentially lead to hydrogen embrittlement of the strands, which would reduce the load carrying capacity.

As strands are typically stressed to 80% of ultimate capacity during pile manufacture any reduction in capacity may lead to strand failure.

2. It would not control cracking due to ASR.

For the above reasons, encasing the piles was proposed. Two alternatives were considered. However, the first option has been considered here for project reasons. A typical photograph of this type of encasement is presented in Photo 8.

Photo 8. Typical appearance of Concrete encasements in bridges [Encasements constructed within 1 m of the headstock. The tops of the hollow spun piles wrapped with a carbon fiber system]

Issues and challenges associated with option 2 include hydraulics, use of steel and significant interaction between departments.

The above sections summarise the issues associated with one of the case study bridges. Clearly, the approach adopted for investigating this type of case study bridge provides useful insight into the issues governing the residual life estimate of bridge infrastructure. The numbers and significance of each of the issues need further investigation in developing a rule based matrix. In this connection additional case study bridges were reviewed and have been published in *Venkatesan, et.al (2005)*.

4 EXAMPLES OF EXISTING RULE BASED MATRICES AND EXPERT SYSTEMS

4.1 Expert systems for general concrete structures

This section of the report presents several of the rule based matrices and expert systems that might be relevant to the context of this research. 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 the structure covering corrosion and ASR is presented in Table 2.

Table 2. 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 longitudnl	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

Adopting the above table of information as a basis for evaluating our case study bridges, two significant differences can be noted. Firstly, the above table does not include tidal zone as a parameter for crack locations and the onset time of cracks is approximately 2 to 5 years. ASR can occur within the first 10 years of service life. It is to be noted that the case study bridge analysed in the previous section is about 30 years old. Therefore direct application of the expert systems of the above type is bound to have limitations. Chan, P.P.F., (1996) reports that the above table was adopted to diagnose the deterioration of a reinforced concrete bridges in Hong Kong which exhibited problems such as cracking, spalling, reinforcement corrosion and accidental damage. “Physical damage” and “Chemical attack” were concluded as the likely causes of deteriorations using the above table and the subsequently developed expert system. It can be noted that this is just one level of diagnosis. There are other similar tables proposed in the literature such as those by Bungey and Millard, (1996) and Dhir, R.K., (1993).

Chao, C. and Cheng, F. (1998) has presented a “Fuzzy pattern recognition model” for diagnosing cracks in RC structures. The methodology uses a cause-effect diagram to analyse the reasons for cracking. A significant criticism of this methodology is that the relationship between the causative variables cannot be accounted in developing a diagnostic tool. Given that the bridge deterioration is a complex phenomenon, the authors believe that the interaction between influential variables must be considered in the development of a rule-based matrix. However, a significant advantage of this approach is that the influential variables can be grouped and identified as the principle elements causing distress.

4.2 Experts systems on transition probability models

DeStefano, P.D. and Grivas, D.A. (1998) have presented a method for estimating the transition probability in bridge deterioration models. The methodology applies "life data" analysis techniques employed in reliability studies of engineering systems and incorporates the inherent censorship of the utilized bridge data. It involves a two-phase process: one concerned with the condition of a set of similar bridge components composing a system and the other concerned with the condition of a specific component within the system. The information required for modelling purposes is derived from historical data typically available in bridge inventory and inspection systems. A limitation of this methodology is that the approach does not capture the structure of the deterioration process. Furthermore, QDMR is currently undertaking the electronic conversion of the inspection reports of their bridge stock. Therefore the methodology described by DeStefano, P.D. and Grivas, D.A. (1998) could not be applied in this research.

4.3 Expert systems on prioritising sewer inspections

Hahn et.al, 2002, has presented an expert system known as SCRAPS for prioritizing the inspection of sewers. Although the current research is on bridges, the methodology employed in developing the expert system SCARPS has been presented herein.

SCRAPS has two primary components: (1) an inference engine; and (2) a knowledge base. An inference engine defines the mathematical algorithm by which a decision is reached. The knowledge base is the body of information that presents the topic of interest. SCRAPS is implemented in an expert system shell using a Bayesian belief network. This is a probabilistic model that conditionally relates two or more independent variables. Relationships among variables in a Bayesian belief network are described graphically and probabilistically. The graphical representation consists of a series of nodes and arcs. The relationship among the connected variables is further described by conditional probabilities associated with the state of the parent variables and the child variable. All variables have a discrete set of values or states that they can assume. The relationship between a set of parent variables and their child is described by the state of the parents and the conditional probabilities that relates the state of parents to the state of their child. The calculations performed in a Bayesian network interface engine propagate the uncertainty, inherent in conditional probabilities, throughout the network. A vector which represents a set of nodes influencing a specific node with possible states is described a confidence interval formula and the values are evaluated.

The above methodology in principle might be suitable to be applied in this research if the conditional probabilities of the different states can be established. Also the relationship matrix between the influential variables is not as complex as has been described in the above methodology. Furthermore, the intention herein is to develop a software tool and not a complete expert system. Owing to the limited data available for each of the distress mechanism, this methodology could not be adopted in the present time.

It is clear from the above review that methodologies available in the literature are not directly applicable to this research; however some of the principles and ideas can be included in developing the proposed "Rule base matrix". This is explained in the next section.

5 DEVELOPMENT OF THE SOFTWARE DIAGNOSTIC TOOL

5.1 Development of the knowledge base

Each of the case study bridges were analysed using a mind map technique. That is the type of element, construction, pattern of cracking together with observed defects were analysed. The figure below presents a typical mind map for a case study bridge.

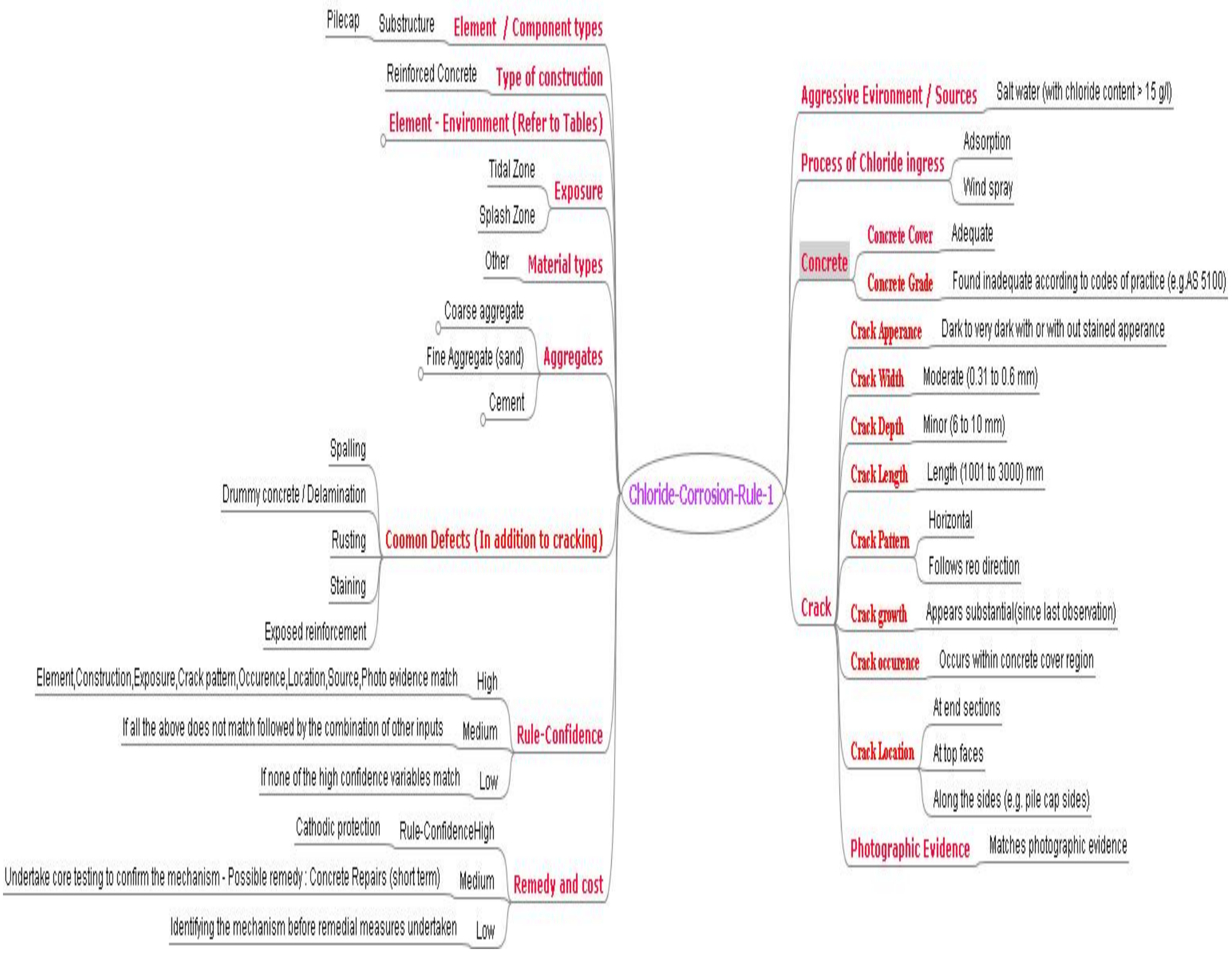


Figure 3.Mind map analysis of a typical case study bridge

Further analysis of the scientific evidence of relating these symptoms to the corresponding mechanisms was undertaken. For example prestressed elements affected by ASR, displayed cracking along the line of least resistance of the member. This is due to the fact that the expansion due to ASR could initiate the formation of gels leading to the cracking of the aggregates or the cement paste, in which case, the elements that are prestressed already would only crack along the line of least resistance. This may be at the point where the concrete cover might be less (Photo 9). The octagonal pile shown here, has the least concrete cover at mid-face and hence the cracking has occurred along the line of least resistance. Further evidence of this rule can be found on prestressed concrete decks and kerbs, where a single line longitudinal cracking would occur with typical map cracking at the ends. The reason for this map cracking could be that the ends are unrestrained and hence the expansion and the cracking would try to follow the reinforcement pattern, whereas due to the restraint a typical “map cracking pattern” could be observed. The validity of these discussions is well supported by Photo 10. For chloride induced corrosion, the cracking occurred only within the concrete cover and was clearly accompanied by stains, delamination and spalling. This is due to the fact that the ingress and build up of the chlorides would de-passivate the protective film of the reinforcement in the concrete. Once the reinforcement is exposed, corrosion is initiated and the cover delaminates and spalls off. Thus the rule that chloride induced corrosion affects the concrete cover is valid (photo 2). Based on the detailed analysis a complete mind map involving all the dominant mechanisms was developed for the software tool. The components identified from the mind map are presented herein as tables.

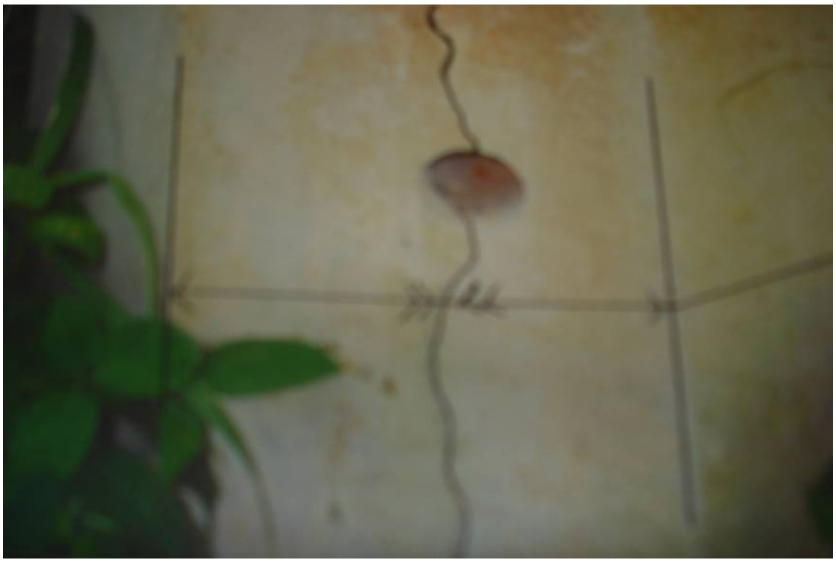


Photo 9. Typical ASR cracking in a prestressed pile

Photo 10a. Typical ASR cracking in bridge kerbs (a) Longitudinal cracking

Photo 10b. Typical ASR cracking in bridge kerbs (b) Longitudinal cracking plus map cracking at ends

Photo 10. Typical ASR cracking in bridge kerbs, beams

5.1.1 List of Elements and components

Note: This document is prepared based on the component / element schedule provided in the Bridge Inspection Forms of QDMR.

Table 3. Database of components and elements

Category: Deck Surface
Number: 1 – 9 (5 to 9 reserved)

NO	COMPONENT
1	Fill
	Wearing Surface on Deck
2	Bridge Railing
	Bridge Barriers
3	Bridge Kerbs
4	Footways

Category: Deck Joints
Number: 10 – 19

NO	COMPONENT
10	Pourable Joint Seal
11	Compression Joint Seal
12	Assembly Joint Seal
13	Open Expansion Joint

14	Sliding Joint
15	Fixed Movement Joints
	Small Movement Joints

Category: Super Structure
Number: 20 – 39

NO	COMPONENT
20	Deck Slab
	Culvert Base Slab
	Joints
21	Closed Web
	Box Girders
22	Open Girders
23	Through Truss
24	Deck Truss
25	Arches
26	Cables
	Hangers
27	Corbels
28	Cross Beams
	Floor Beams
29	Deck Planks
30	Steel Decking
31	Diaphragms
	Bracing (Cross Girders)
32	Load bearing Diaphragms
33	Spiking Plank

Category: Bearings
Number: 40 – 49

NO	COMPONENT
40	Fixed Bearings
41	Sliding Bearings
42	Elastomeric Bearings
	Pot Bearings
43	Rockers
	Rollers
44	Mortar Pads
	Bearing Pedestals
45	Restraint Angles
	Restraint Blocks

Category: Substructure

Number: 50 – 69

NO	COMPONENT
50	Abutment
51	Wing wall
	Retaining Wall
52	Abutment Sheeting
	Abutment Infill Panels
53	Batter Protection
54	Head Stocks
55	Pier Headstocks (Integral)
56	Columns
	Piles
57	Pile Bracing
	Pile Wales
58	Pier Walls
59	Footing
	Pilecap
	Sill Log

Category: Miscellaneous
Number: 70 – 79

NO	COMPONENT
70	Bridge Approaches
71	Waterway
72	Approach Guardrail

Category: Culverts
Number: 80 – 89

NO	COMPONENT
80	Pipe Culverts
81	Box Culverts
82	Modular Culverts
83	Arch Culverts
84	Head Walls
	Wing Walls

Note: Reserve numbers included in all categories

5.1.2 Types of Construction

Table 4. Database of construction types

NO	Construction
1	Reinforced Concrete
2	Prestressed Concrete
3	Driven
4	Hollow Spun
5	Other

5.1.3 Types of Material

Note: This document is prepared based on the component / element schedule provided in the Bridge Inspection Forms of QDMR.

Table 5. Database of material types

NO	MATERIAL
1	Steel (S)
2	Precast Concrete (P)
3	Cast-in-situ
4	Timber (T)
5	Other (O)

5.1.4 Type of aggressive environment

Table 6 .Database of types of aggressive environment

No	Definition
1	Salt water containing chlorides (> 15 g/l)
2	Water containing sulfate ions (> 1 g/l)
3	Water with pH > 7.5
4	Aggressive soils
5	Humid / Temperate / Dry environments
6	Aggressive pollutants
7	Aggressive soils (rich in nitrates)
8	Salt deposits (e.g. due to water evaporation)
9	Salt water retention (e.g. hollow spun piles cast with saline water mix)
10	Added during construction (e.g. Calcium Chloride added as accelerator)
11	Running or Standing water (e.g. in culverts)
12	Abrasion / Scouring / Water current effects

5.1.5 List of common defects

Table 7 .Database of common defects other than cracking

No	Pattern Definition
1	Spalling
2	Delamination or Drummy concrete
3	Rusting
4	Staining
5	Honey combing
6	Segregation
7	Pop outs
8	Blistering
9	Crazing
10	Loss of reinforcement
11	Exposed reinforcement
12	Discolourisation
13	Disintegrated components
14	Form streaking
15	Scabbing
16	Efflorescence
17	Soft spots
18	Surface mottling
19	Gel exudations
20	Encrustation
21	Formation of stalactites

5.1.6 Cracking

5.1.6.1 Crack width

Table 8 .Database of crack widths

No	Pattern Definition
1	Hairline (0 to 0.1 mm)
2	Minor (0.1 mm to 0.3 mm)
3	Moderate (0.3 mm to 0.6 mm)
4	Severe (0.6 mm to 3 mm)
5	Very Severe (above 3 mm)

5.1.6.2 Crack pattern

Table 9 .Database of crack patterns

No	Pattern Definition
1	Longitudinal
2	Vertical
3	Horizontal
4	Diagonal
5	Map Cracking
6	Follows reo direction

7	Random or Unspecified -1,2,3…

5.1.6.3 Crack location

Table 10 .Database of crack locations

No	Pattern Definition
1	At midsections
2	At ends (along the width of an element)
3	At ends (along the length of an element)
4	At corners of elements
5	Within the Cover region of concrete
6	Along the reinforcement lines
7	At top surfaces
8	At soffits (bottom faces)
9	Surficial only
10	Along the member sides (e.g. pile cap sides)

5.1.6.4 Crack appearance

Table 11 .Database of crack appearances

No	Pattern Definition
1	Clean
2	Slightly Dark or evidence of stained appearance
3	Dark or very dark with or without stained appearance

5.1.6.5 Crack depth

Table 12 .Database of crack depths

No	Pattern Definition
1	Hairline (0 to 5 mm)
2	Minor (6 mm to 10 mm)
3	Moderate (11 mm to 20 mm)
4	Severe (21 to 50 mm)
5	Very Severe (>51 mm)

5.1.6.6 Crack length

Table 13 .Database of crack lengths

No	Pattern Definition

1	Length <500 mm
2	Length 501 to 1000 mm
3	Length 1001 to 3000
4	Length > 3000
5	Runs along the Member length
6	Runs along the Member Width
7	Runs above and or below ground

5.1.6.7 ***Crack growth***

Table 14 .Database of crack growths

No	Definition
1	Appears Substantial
2	No growth since last observation
3	Not known
4	No evidence of growth
5	Roughly double in a five year period

5.1.6.8 ***Crack occurrence***

Table 15 .Database of crack occurrence

No	Pattern Definition
1	Pre-Existing
2	Caused during construction
3	Immediately after placement and curing
4	Caused by other known mechanisms
5	Not known
6	

5.1.7 Environmental data

Note: QDMR has divided Queensland into15 MRD districts. In order for the software tool to be generic, the user must be able to enter separate values of Environmental data such as Temperature, Humidity and Average annual Rainfall. Similar table is required district wise.

Table 16 .Climatic conditions in Queensland

Location	Mean 3 p.m Temperature °C	Mean 3 p.m Humidity %	Annual Mean Rainfall (mm)
Cairns	27.5	60	2036

Charleville	27	29	505
Cloncurry	31.5	25	472
Cunnamala	27.1	30	367
Goondiwindi	25.7	37	614
Marybrough	25.2	56	1187
Quilpie	28.2	27	333
Roma	26.9	33	597
Stanthorpe	20.3	48	763
Toowoomba	21.3	52	964
Townsville	27.3	57	1195
Warwick	23	44	716

5.1.8 Design data

5.1.8.1 *Concrete Cover*

Table 17 Database on adequacy of concrete cover

No	Definition
1	Inadequate according to Construction Drawing
2	Inadequate due to (wrong) Design
3	Inadequate in accordance with Codes of practice (e.g. AS 5100)
4	Improper size of aggregate (e.g. River gravel / oblong aggregates)
5	Varied cover - Due to construction defects
6	Other
7	Adequate
8	Table to check the adequacy of the concrete cover

5.1.8.2 *Concrete Grade*

Table 18 Database on adequacy of concrete grade

No	Definition
1	Inadequate due to (wrong) Design
2	Inadequate in accordance with Codes of practice (e.g. AS 5100)
3	Poor grading due to inaccurate water cement ratio
4	Poor Grade due to inappropriate aggregates
5	Poor Grade due to non-uniform compaction
6	Poor Grade due to non-uniform curing
7	Poor Grade due to other reasons
8	Adequate or Good Grade
9	Table to check the adequacy of the Concrete Grade

5.1.9 Construction data

5.1.9.1 *coarse aggregate*

Note: Following chemical elements, (opaline or glassy) present in coarse aggregate might influence the ASR mechanism.

Table 19 Database of coarse aggregates sensitive to ASR

NO	Element
1	Tuff
2	Andesite
3	Trachyte
4	Quartz
5	Feldspar
6	Granite
7	Chert
8	Sand stone
9	Slate
10	Greenstone
11	Ferniginous rock
12	Quartzite
13	Meta-greywacke

5.1.9.2 *Fine aggregate (Sand)*

Note: Following chemical elements present in Fine aggregate (Sand) might influence the ASR mechanism.

Table 20. Database of fine aggregates sensitive to ASR

NO	Element
1	Quartz
2	Feldspar
3	Granite
4	Quartzite
5	Chert

5.1.9.3 *Cement*

Table 21. Database of cement types sensitive to ASR

NO	Element
1	Less fly ash content
2	More sulphur content

5.1.10 Exposure classification

Table 22. Database of element exposures

No	Pattern Definition
1	Below low water level (submerged)
2	In tidal zone (also wetting and drying zone)
3	In Splash Zone
4	In Splash - Spray zone (also wetting and drying zone)
5	In splash-tidal zone
6	Above Splash zone
7	Well above splash zone (nearly top deck)
8	Benign Environment

5.1.11 Process of Chloride ingress

Table 23. Database of chloride ingress processes

NO	MATERIAL
1	Diffusion
2	Capillary absorption
3	Permeation
4	Adsorption
5	Spray and permeation

The above tables clearly represent the number of variables that were adopted in the development of the software diagnostic tool. It can be noted that number of rule bases may rise following user inputs and that the software must be clearly capable of identifying the rule-base that matches best. The approach employed in developing the software inference engine is presented in the next section.

5.2 Modelling approach

About 40 case study bridges affected by various distress mechanisms such as Alkali-Silica-Reaction (ASR), Chloride Induced Corrosion, Delayed Ettringite formation, Plastic Shrinkage, Plastic settlement and Basic corrosion were analysed. A mind-map technique was adopted to identify the principal variables that influence the distress mechanisms that are listed below:

- Type of element (e.g. Pier, Pile cap, Deck)
- Type of construction (e.g. Pre-stressed, Reinforced Concrete, Hollow spun)
- Material type (e.g. Cast-in-situ, Pre-cast)
- Environmental conditions (e.g. Salt water, Inland, Coastal)
- Climate (Mean annual Temperature, Rainfall, Humidity)
- Position of the element (e.g. Above water level, Submerged, Tidal Zone)
- Grade of Concrete (e.g. 20 Mpa, 40 Mpa)
- Clear Cover to reinforcement (expressed in mm, e.g. 50 mm, 75 mm)
- Type of Coarse Aggregate (e.g. Aggregates with opaline quartz influence ASR)

- Type of Fine Aggregate (e.g. Quarry sources having ASR sensitive chemicals)
- Type of Cement (e.g. Cements without fly ash contents can influence ASR)
- Crack characteristics (such as width, pattern, appearance and growth are indicators of the distress mechanisms)
- Other defects (such as Spalling, Staining, Macro-cell formations are indicators of the severity and extent of the mechanism)

Experts would normally use the information available on the above variables to arrive at conclusions and possibly recommend lab tests to confirm their assessment. It can be noted that there are sub variables for each of the main variables i.e., there are about 60 different types of elements, at least 5 different types of construction, different material types and so on. Schematically this can be represented using the cause-and-effect diagram concept (Chao and Cheng, 1998). The procedure adopted herein has to be different since the distress mechanism is a complex phenomenon and is dependent on the relationship between the variables and their sub-variables.

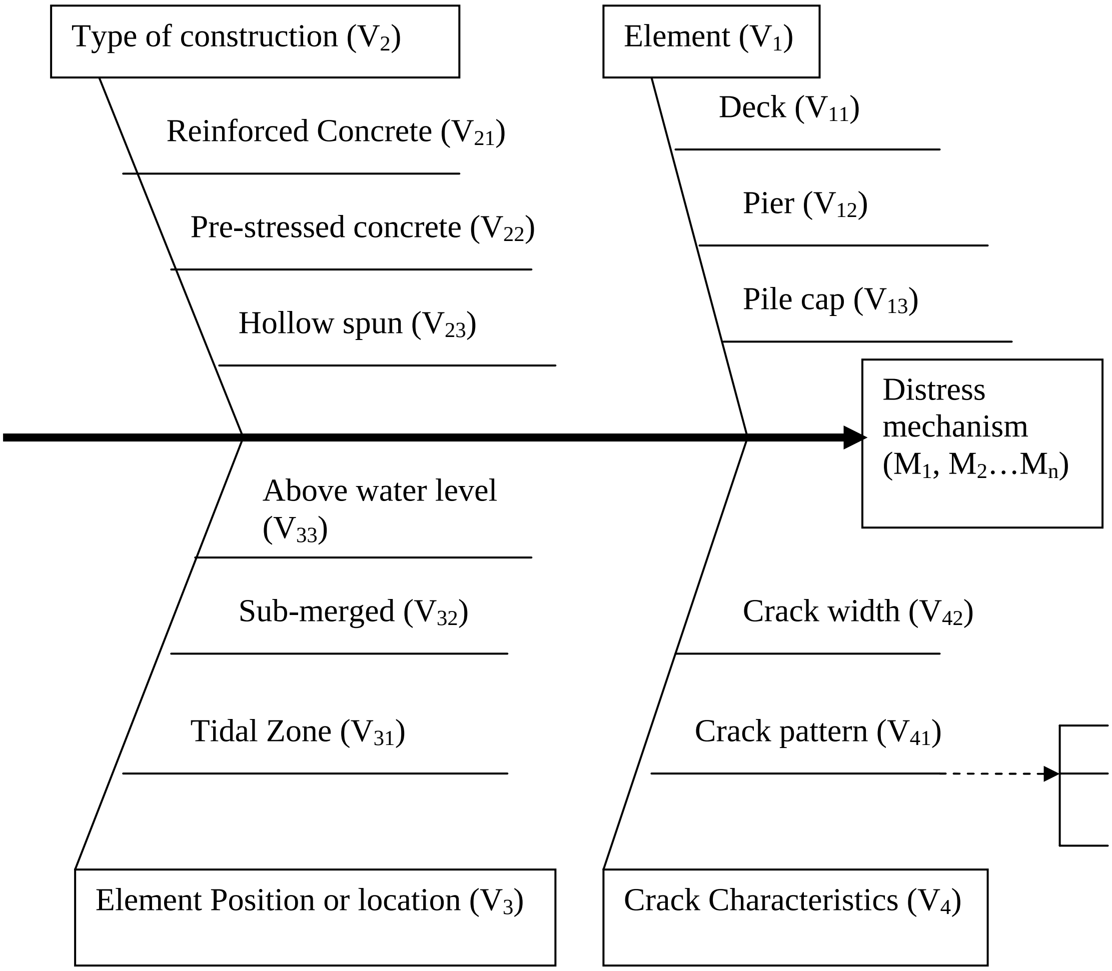


Figure 4. Schematic cause-and-effect diagram for distress mechanisms in bridges

In the above figure, not all the variables and sub-variables have been highlighted. A sub-tree for the crack pattern has been indicated which includes patterns such as vertical cracking, map cracking, horizontal cracking etc., Based on Figure- 4, we state that a fuzzy rule having multiple antecedents is represented as a combination of (V_{1i} ^ V_{2i} ^ ….V_{ni}) $\longrightarrow$ M_n, τ_γ (1)

Where V is the variable, M is the mechanism and τ_γ is the degree of confidence with γ = 0, 0.5 and 1 to denote Low, Medium and High confidence levels. In the case of the variables `V' having additional levels such as the ones described for "Crack Pattern" an additional subscript is added. For convenience (of using in the software), these variables can be identified by using unique codes (e.g Reinforced Concrete Construction can be coded as "RCC" or just "RC"). It is to be noted that the user may not have information for all the variables defining a rule base. For example, the user may have no information on the Grade of Concrete and Clear Cover. Sometimes this informations is strictly required to evaluate the mechanism in the case of Chloride induced corrosion but may not be required in the evaluation in the case of ASR. Therefore we define an additional variable α_j such that α_j = 0, 0.5 and 1 indicating that it is compulsorily required in the evaluation (1); not compulsory in the evaluation (0) or qualitative which is neither compulsory nor non-compulsory. In cases where the information is non-compulsory but qualitative, these values provide additional information towards the truth-qualified fuzzy rule. In other words this increases the degree of confidence. It must be noted that the rule bases have to used as an "either-or" type of evaluation for several of the variables. For example, poor Concrete Grade and Inadequate concrete cover are susceptible to Chloride ingress. Some combinations of these variables can be: Good or High strength Concrete Grade and Low Cover or Poor Concrete Grade and adequate cover; in these situations, the decision has to be based on the combined evaluation of Grade of Concrete and Clear Cover. As in most cases, a typical rule might apply to a number of material types used in the construction. Thus, the software can be programmed to accept any one of the variables out of a group. That is a variable might take up fuzzy prepositions within that hierarchical rule. All these can be included in the program.

From the foregone discussion (and expanding Equation 1), a typical rule base can take the form shown below:

V_{1i} (Element; α_j=1) ^ V_{2i} (Construction; α_j=1)^ V_{3i} (Material type; α_j=0) ^ V_{41i} (Crack pattern; α_j=1) ^ V_{51i} (Crack appearance; α_j=0)^…. M_1 (ASR),τ_μ(High Confidence) (2)

Assigning a code for each of the variable in the software, will result in
PILE(1) ^ PSC(1) ^ CIS (0) ^(CRA_PAT=VER+LLR) ^(CRA_APR=DARK) = ASR (HIGH) (3)

Here, the Element is a Pile (noted as PILE) of Pre-stressed construction (PSC) of Cast-in-situ material (CIS) with a vertical crack (VER) along the line of least resistance (LLR) with a possible dark appearance (DARK) - (Photo 9). Again only a few variables have been considered for ease of explanation. Complete rule bases of this form have been input into the software.

5.2.1 Reasoning engine

Fuzzy sets and linguistic variables are used within the engin to quantify concepts used in natural language, which can then be manipulated. A linguistic variable must have a valid syntax and semantics, which can then be specified by fuzzy sets or rules. A syntactic rule defines the well-formed expressions in T(L), where the term T(L) is a set of linguistic variable and L is the set of values it may take. For example, T(Age) = {Very_young, Young, Middle_Age, Old, Very_Old}, where each of these values may itself be a linguistic variable that can take on values that are fuzzy sets. The membership function could be defined as the S function $\mu_{old}(x) = S(x ; 60,70,80)$.

Herein, the quality of information provided by the user between the variable V_i and the matching q_k, is defined as a set A = {No_match, Very_Low_match, Low_match, Medium_match, High_match, Very_High_match}. Then, the fuzzy set is defined as A(x), x = {0, 0.1, 0.2 .. 1} and the membership function is defined as $\mu_A(x) = S(x ; 0,0.5,1)$, x X X, where X is the quality space. Thus the membership functions of the element set A can be chosen from the following equations or as shown in Figure 5.

$\mu_{No\_match}(x) = S(x ; 0,0.5,1) = 0$, where x = 0 (5)
$\mu_{Very\_Low\_match}(x) = S(x ; 0,0.5,1)=0.1$, where x = 0.2 (6)
$\mu_{Low\_match}(x) = S(x ; 0,0.5,1)=0.25$, where x = 0.35 (7)
$\mu_{Medium\_match}(x) = S(x ; 0,0.5,1)=0.5$, where x = 0.5 (8)
$\mu_{High\_match}(x) = S(x ; 0,0.5,1)=0.75$, where x = 0.65 (9)
$\mu_{Very\_High\_match}(x) = S(x ; 0,0.5,1)=0.9$, where x = 0.8 (10)

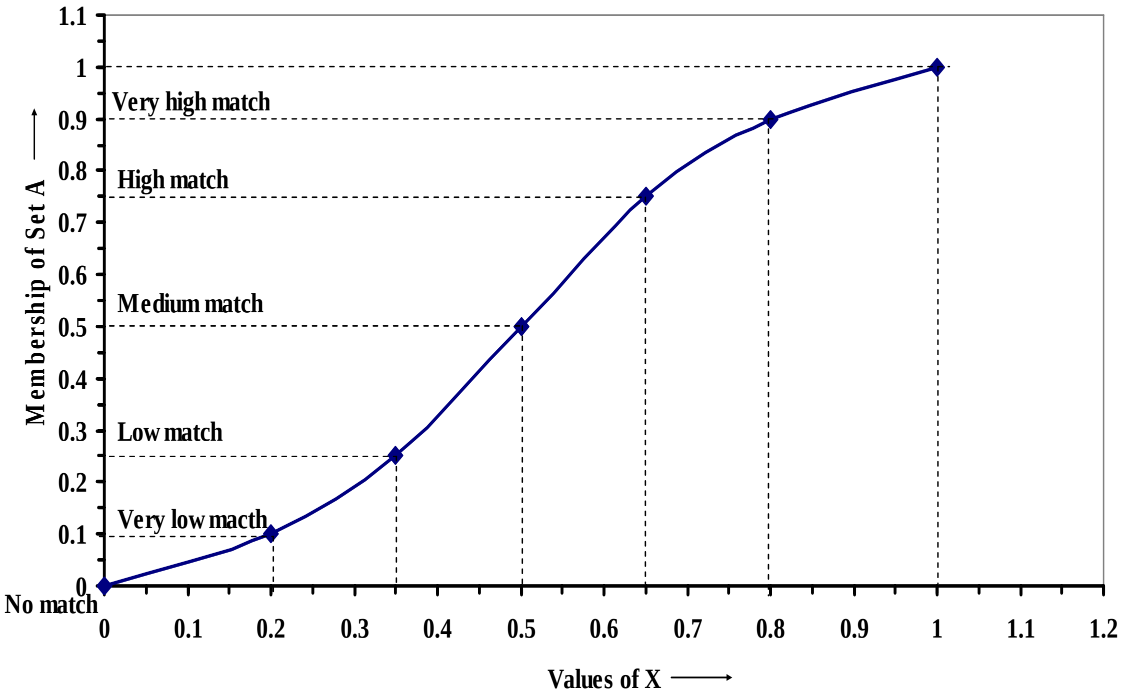


Figure 5. Membership functions of linguistic variable – Set A

A similar set B can be defined in the confirmation space such that x X Y with the following equations or as shown in Figure 6.

$\mu_{Very\_Low}(x) = S(x ; 0,0.5,1)=0.1$, where x = 0.2 (11)
$\mu_{Low}(x) = S(x ; 0,0.5,1)=0.25$, where x = 0.35 (12)
$\mu_{Medium}(x) = S(x ; 0,0.5,1)=0.5$, where x = 0.5 (13)
$\mu_{High}(x) = S(x ; 0,0.5,1)=0.75$, where x = 0.65 (14)
$\mu_{Very\_High}(x) = S(x ; 0,0.5,1)=0.9$, where x = 0.8 (15)

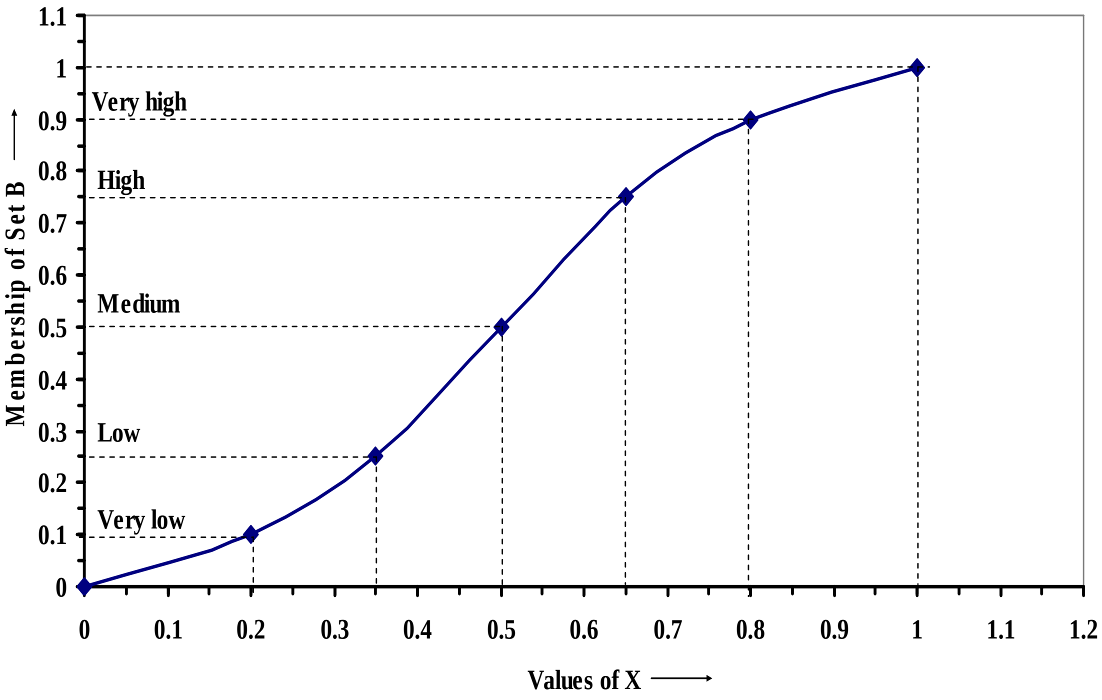


Figure 6. Membership functions of linguistic variable – Set B

Initially the software checks for the presence of the "Element" variable (i.e., a Pile, Pile cap, Columns etc.,). It is compulsory to pick an element; otherwise the software doesn't proceed to the next screen. Once the user chooses an element and enters the information available, then all rule-bases related to that element are taken up for assessment. Then, a fuzzy vector $F_{(i)}$ i = 1,2,3,4.. is generated based on the comparison of the user input with different rule-bases and the memberships identified from Equations 5 to 10. Then each of the fuzzy vector is compared with the subsequent vector such that if $F_{(i)} < F_{(i+1)}$ then the vector $F_{(i+1)}$ is selected. This procedure is repeated until all the vectors are compared and the vector that has the maximum positive rating is selected as the closest possible match. Note that a weighting vector herein is not required since the comparison is based on the user's input which serves as the datum. (However, it will be useful to assign importance vectors for each of the Variable `V_i' in the developed rule-base, which is currently under consideration by the authors). If the situation so arises that the difference between any two vectors is zero (which is unusual), then both of them are taken for further assessment with the remaining vectors. In these situations the user is provided with three matching solutions with a degree of confidence attached to each assessment. The process herein is to screen the database and identify the best possible match. Once best match(es) are identified in the order, the confidence of the assessment or prediction is determined using the equation: Confidence $\gamma = (F_{ij} / \Sigma F_{ij}) * \mu_B(x)$. Incase two or three mechanisms with close confidence limits seem to fit the inputs, then the matching mechanisms based on the percentage of their input match is listed to the user with the advise that further precise information is required or re-run the software in order to evaluate the dominant distress mechanism.

5.2.2 Software development

The software has been developed as an open-ended tool with flexibility as the main theme. There are two main sections: One is the creation/edition of existing rule-bases and the other is the prediction part. In creating new-rules, the users can develop their own pick-lists, e.g. different types of crack pattern: Vertical cracking (in piles / piers), longitudinal cracking (in beams, headstocks), Map cracking etc., with additional information like the crack pattern following the reinforcement neatly defined with field photos. User's can pick the descriptions that best match. This gives the user sufficient confidence to define inputs and the user considers the photos as visual evidence of the textual description. Similarly, users can develop their own pick-lists for element types, construction types and material types either by adding to existing database or by disabling the existing ones. For new users, they can define any number of new variables and develop a rule-base either in combination with the ones already developed or solely within the new variables. There is also a facility to disable the existing rules. However, the modifications need extreme care, as this requires a careful screening of the variables involved. It is to be noted that the pick-lists help in modularizing a set of variables and or the sub-variables.

In the prediction section, the user is presented with a list of components and elements together with the observed distress (e.g. cracking, spalling, delamination, staining, honey-combing etc.,) Although crack characteristics are of prime importance the presence of symptoms such as staining and spalling are indicators of the growth and severity of the distress mechanisms and symptoms such as honey-combing are the result of poor construction. Further details of crack characteristics and other factors of construction and design related issues (e.g. type of construction, material and adequacy of concrete Grade, concrete cover, aggregate sources or their chemical composition), environment, climatic condition, test results (if available) are all obtained from the user. The software then performs the comparison-analysis with the existing rule-base and provides the best match. Adequacy of information (regardless of the quality of the information) is also provided to the user as a general guide.

5.2.3 Trial run of the software tool

Only one example of the application has been demonstrated below. This is a bridge from the case study area with imprecise and incomplete information. Industry partners in this research have trialed the tool using case study bridges that did not form a part of the software development. Thus, the robustness of the tool has been demonstrated.

Example 1:

Several of the Pre-stressed cast-in-situ concrete piles in a bridge in Queensland were observed to have a vertical cracking roughly about the mid-section of the octagonal pile. The cracks were observed above and below water level. The materials especially the coarse aggregate used in construction were obtained from quarry sources that were historically considered as sensitive to ASR. However, this information was unclear to the user. The bridge is constructed across a river known to be influenced by salt water and the climatic condition is humid. The user is allowed to pick a photograph that best matches the description of the crack pattern and the crack location.

The user's input into the software system is classified as shown in the table below (Table 24) together with the actual sample rule-bases that match the element type. Note that order of the variables shown here is consistent with that developed in the software and the software would have compared all the rule bases existing in the database.

Variable (Vi)	Title	Description	Degree of confirmation
V_1	Element	Pile / Pier	Very High
V_2	Construction	Pre-stressed	Very High
V_3	Material	Cast-in-situ	Very High
V_4	Environment	Salt water	Very High
V_5	Climate	Humid	High
V_6	Element Zone (position)	Above and Or below water	Very High
V_{71}	Crack pattern	Vertical, running above and below water	Very High
V_{72}	Crack Location	Sections where concrete cover is less (e.g Mid-face of polygonal piles)	Very High
V_{10}	Coarse aggregate	ASR sensitive elements present (e.g.Chert, Paline quartz)	High
V_{11}	Fine aggregate	ASR sensitive elements present	Low (this input is assumed to have been provided by the user)
V_{13}	Other accompanying distress	None	High
V14	Construction practice	Quality of construction, type of material, contractor, construction practices at the time of construction	Medium (this input is assumed to have been provided by the user)

Table 24. Typical user input to the software

For the element that is Pile, 3 different rule-bases pertinent to ASR, Chloride induced corrosion and construction have been selected from the database for comparison. The three rule-bases are listed in a tabular form for ease of comparison. (C – denotes compulsory, NC – denotes Non-compulsory, Q – denotes qualitative)

Table 25. Rule base-1: ASR

Variable (Vi)	**Title**	**Description**
V_1	Element (C)	Pile / Pier
V_2	Construction (C)	Pre-stressed
V_3	Material (NC)	Cast-in-situ
V_4	Environment (NC)	Salt water
V_5	Climate (Q)	Humid – High Humid
V_6	Element Zone (position) (C)	Above and Or below water
V_{71}	Crack pattern (C)	Vertical, running above and below water
V_{72}	Crack Location (C)	Sections where concrete cover is less (e.g Mid-face of polygonal piles)
V_{73}	Crack Width (NC)	Hairline to Moderate
V_{74}	Crack appearance (NC)	Slightly dark / dark / very dark
V_{75}	Crack Growth (NC)	Substantial (about 1.5 to 2 times since first observation ; period of inspection : approx 2 years)
V_8	Concrete Grade (Q)	Adequate
V_9	Concrete Cover (Q)	Adequate
V_{10}	Coarse aggregate (Q)	ASR sensitive elements present (e.g.Chert, Paline quartz)
V_{11}	Fine aggregate (Q)	ASR sensitive elements present
V_{12}	Type of Cement (Q)	Unblended cement
V_{13}	Other accompanying distress (Q)	None
V_{14}	Construction practice	Medium to Good

	(Q)	

Table 26. Rule base-2: Chloride Induced Corrosion

Variable (Vi)	**Title**	**Description**
V_1	Element (C)	Pile / Pier
V_2	Construction (C)	Reinforced concrete
V_3	Material (NC)	Cast-in-situ
V_4	Environment (C)	Salt water
V_5	Climate (NC)	Humid – High Humid
V_6	Element Zone (position) (C)	Submerged / tidal zone
V_{71}	Crack pattern (C)	Initially horizontal
V_{72}	Crack Location (C)	Along the length
V_{73}	Crack Width (NC)	Hairline to Moderate
V_{74}	Crack appearance (NC)	Slightly dark / dark / very dark
V_{75}	Crack Growth (NC)	Substantial (about 1.5 to 2 times since first observation ; period of inspection : approx 2 years)
V_8	Concrete Grade (C)	Mostly Inadequate
V_9	Concrete Cover (C)	Highly Inadequate
V_{10}	Coarse aggregate (NC)	Medium to Good quality
V_{11}	Fine aggregate (NC)	Medium to Good quality
V_{12}	Type of Cement (NC)	Medium to Good quality
V_{13}	Other accompanying distress (Q)	Usually accompanied by spalling, delaminations
V_{14}	Construction practice (Q)	Poor to Medium

Table 27. Rule base-3: Construction_Related

Variable (Vi)	**Title**	**Description**
V_1	Element (C)	Pile
V_2	Construction (C)	Hollow spun
V_3	Material (NC)	Cast-in-situ
V_4	Environment (Q)	Inland
V_5	Climate (Q)	Temperate
V_6	Element Zone (position) (Q)	Away from water influence
V_{71}	Crack pattern (C)	Horizontal / circumferential
V_{72}	Crack Location (C)	Along the length
V_{73}	Crack Width (NC)	Minor
V_{74}	Crack appearance (C)	Clean to Slightly dark
V_{75}	Crack Growth (C)	Not Substantial
V_8	Concrete Grade (Q)	Adequate / Inadequate
V_9	Concrete Cover (Q)	Adequate / Inadequate
V_{10}	Coarse aggregate (NC)	Medium to Good quality
V_{11}	Fine aggregate (NC)	Medium to Good quality
V_{12}	Type of Cement (NC)	Medium to Good quality
V_{13}	Other accompanying distress (C)	None
V_{14}	Construction practice (C)	Poor to Medium

Comparing the user input with the 3 rule bases in accordance with the membership equations 5 to 10 results in the following values:

Table 28. Comparison of user input with Rule base-1

Variable (Vi)	**Status of the variable**	**Matching with user input**	**Membership value – Set A**
V_1	(C)	Y	0.9
V_2	(C)	Y	0.9

V_3	(NC)	Y	0.5
V_4	(NC)	Y	0.5
V_5	(Q)	Y	0.75
V_6	(C)	Y	0.9
V_{71}	(C)	Y	0.9
V_{72}	(C)	Y	0.9
V_{73}	(NC)	N	0
V_{74}	(NC)	N	0
V_{75}	(NC)	N	0
V_8	(Q)	N	-0.25
V_9	(Q)	N	-0.25
V_{10}	(Q)	Y	0.75
V_{11}	(Q)	Y	0.75
V_{12}	(Q)	N	-0.25
V_{13}	(Q)	Y	0.75
V_{14}	(Q)	Y	0.75

Note: The negative sign is used herein as a weighting factor.

Table 29. Comparison of user input with Rule base-2

Variable (Vi)	**Status of the variable**	**Matching with user input**	**Membership value – Set A**
V_1	(C)	Y	0.9
V_2	(C)	Y	0.9
V_3	(NC)	Y	0.5
V_4	(C)	Y	0.5
V_5	(NC)	Y	0.75
V_6	(C)	N	-0.1
V_{71}	(C)	N	-0.1
V_{72}	(C)	N	-0.1
V_{73}	(NC)	N	0
V_{74}	(NC)	N	0

V_{75}	(NC)	N	0
V_8	(C)	N	-0.25
V_9	(C)	N	-0.25
V_{10}	(NC)	N	0.0
V_{11}	(NC)	N	0.0
V_{12}	(NC)	N	0.0
V_{13}	(Q)	N	-0.25
V_{14}	(Q)	Y	0.75

Table 30. Comparison of user input with Rule base-3

Variable (Vi)	**Status of the variable**	**Matching with user input**	**Membership value – Set A**
V_1	(C)	Y	0.9
V_2	(C)	N	-0.1
V_3	(NC)	Y	0.5
V_4	(Q)	N	-0.25
V_5	(Q)	N	-0.25
V_6	(Q)	N	-0.25
V_{71}	(C)	N	-0.1
V_{72}	(C)	Y	0.9
V_{73}	(NC)	N	0
V_{74}	(C)	N	-0.1
V_{75}	(C)	N	-0.1
V_8	(Q)	P	0.5
V_9	(Q)	P	0.5
V_{10}	(NC)	N	0.0
V_{11}	(NC)	N	0.0
V_{12}	(NC)	N	0.0
V_{13}	(C)	Y	0.9
V_{14}	(C)	Y	0.9

From the above tables, three fuzzy vectors are available for comparison as shown:

$$\begin{array}{lcccccccccccccccccc}
 & V_1 & V_2 & V_3 & V_4 & V_5 & V_6 & V_{71} & V_{72} & V_{73} & V_{74} & V_{75} & V_8 & V_9 & V_{10} & V_{11} & V_{12} & V_{13} & V_{14} \\
F_1=[& .9 & .9 & .5 & .5 & .75 & .9 & .9 & .9 & 0 & 0 & 0 & -.25 & -.25 & .75 & .1 & -.25 & .75 & .75] \\
F_2=[& .9 & .9 & .5 & .5 & .75 & -.1 & -.1 & .1 & 0 & 0 & 0 & -.25 & -.25 & 0 & 0 & 0 & -.25 & .75] \\
F_3=[& .9 & -.1 & .5 & -.25 & -.25 & -.25 & -.1 & .9 & 0 & -.1 & -.1 & .5 & .5 & 0 & 0 & 0 & .9 & .9
\end{array}$$

It is clear from the above matrix that Σ F_1-F_2 > 0 & Σ F_1-F_3 > 0. Thus the fuzzy vector that corresponds to Rule base 1 is selected as the best possible matching mechanism. (The authors have deliberately tried scenarios in which the vector comparisons were close to zero or two such sets resulting in close values. In these cases, the software listed three best possible matches.)

Having selected fuzzy vector F_1 as the best matching mechanism, the degree of confidence is calculated taking into account the degree of confirmation of the user's input as follows:
Confidence = $(F_{ij} / \Sigma F_{ij}) * \mu_B(x)$ = .11*.9 + .11*.9 + .06*.9 + .06*.9 + .1*.75 + .11*.9 + .11*.9 + .11*.9 +-.03*.9 +-.03*.9 + .1*.75 + .1*.75 = 0.89, approx = 0.9, which indicates a higher degree of confidence.

5.3 Software details

The software is named as "BridgeDIST" that stands for bridge distress mechanisms. It can be obtained via CRC CI network or through industry partners.

5.4 Screen dumps of the software

- The following screen dump is the main screen of the software:

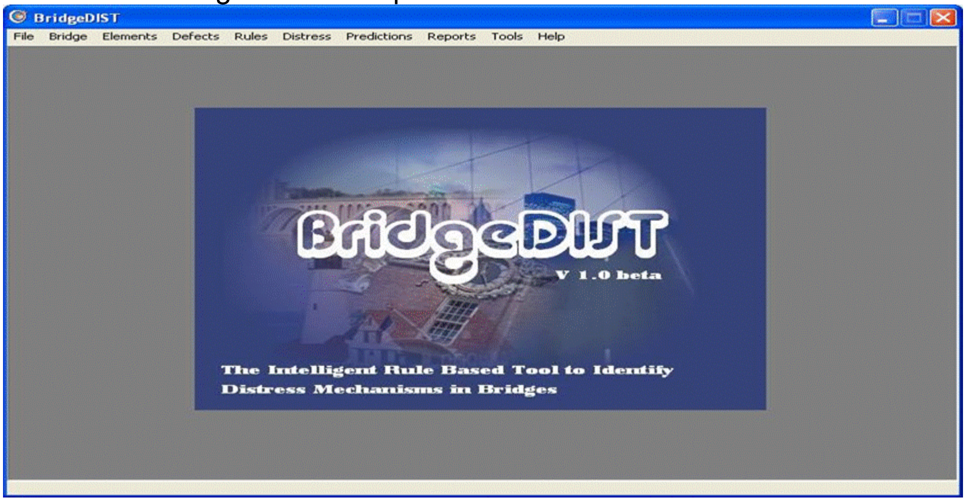
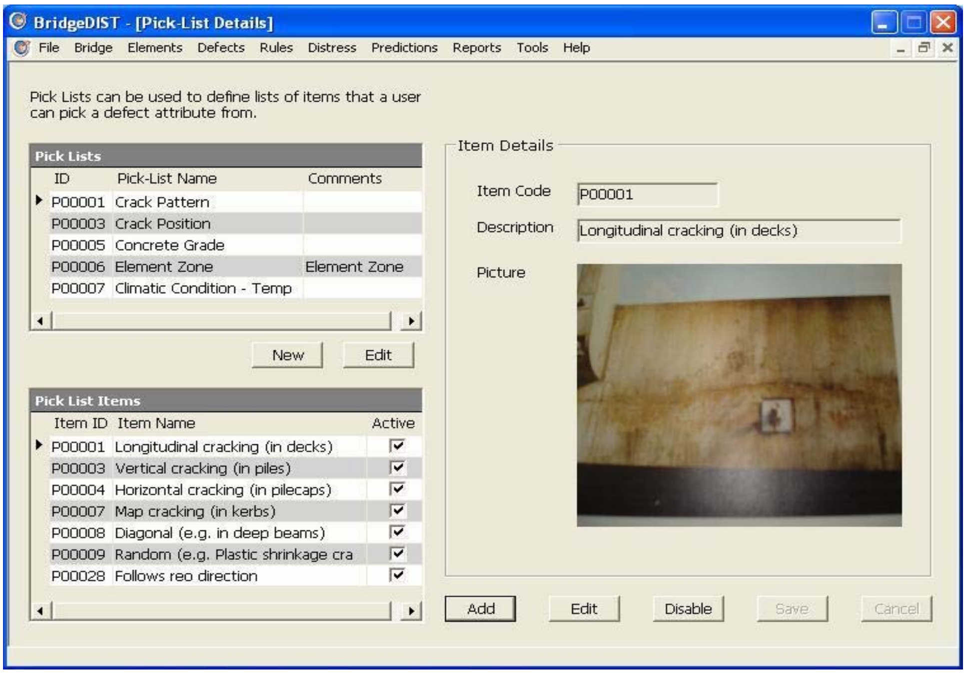


Figure 6. Main screen of software "BridgeDIST"

- The following screen is part of the database (not the user interface). This defines the pick list items available in the software (typically the crack pattern, crack width, concrete grade etc.,)



Pick Lists can be used to define lists of items that a user can pick a defect attribute from.

Pick Lists

ID	Pick-List Name	Comments
P00001	Crack Pattern	
P00003	Crack Position	
P00005	Concrete Grade	
P00006	Element Zone	Element Zone
P00007	Climatic Condition - Temp	

Pick List Items

Item ID	Item Name	Active
P00001	Longitudinal cracking (in decks)	☑
P00003	Vertical cracking (in piles)	☑
P00004	Horizontal cracking (in pilecaps)	☑
P00007	Map cracking (in kerbs)	☑
P00008	Diagonal (e.g. in deep beams)	☑
P00009	Random (e.g. Plastic shrinkage cra	☑
P00028	Follows reo direction	☑

Item Details

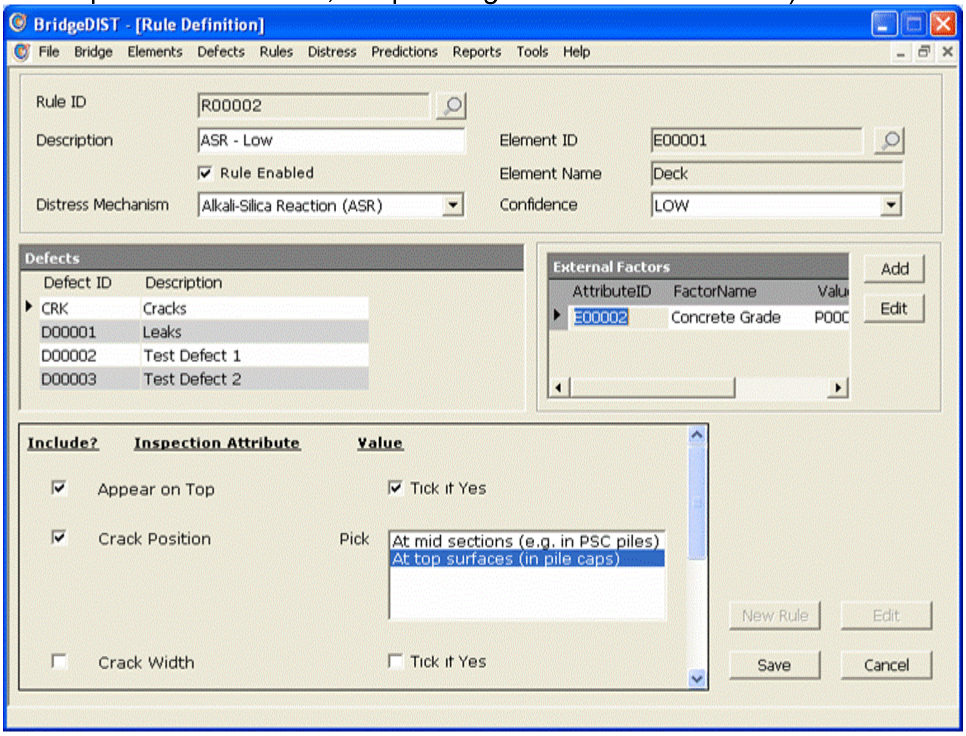
Item Code: P00001

Description: Longitudinal cracking (in decks)

Picture

Figure 7. Database of pick list items

- The following screen is the interface where new rules are defined (part of the expert user interface; not part of general user's interface).



Rule ID: R00002

Description: ASR - Low

☑ Rule Enabled

Distress Mechanism: Alkali-Silica Reaction (ASR)

Element ID: E00001

Element Name: Deck

Confidence: LOW

Defects

Defect ID	Description
CRK	Cracks
D00001	Leaks
D00002	Test Defect 1
D00003	Test Defect 2

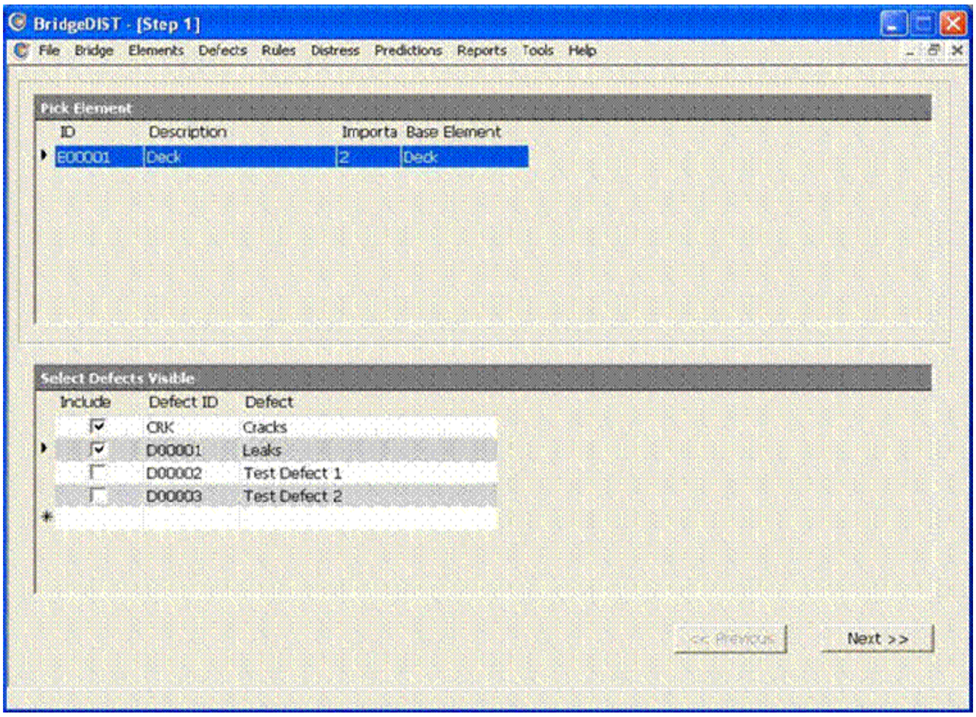
External Factors

AttributeID	FactorName	Valu
E00002	Concrete Grade	P00C

Include?	Inspection Attribute	Value
☑	Appear on Top	☑ Tick if Yes
☑	Crack Position	Pick: At mid sections (e.g. in PSC piles) At top surfaces (in pile caps)
☐	Crack Width	☐ Tick if Yes

Figure 8. Database of rule based matrix

- The following screen is the user interface screen. Typically the user chooses the element and the defects observed in it.



Pick Element

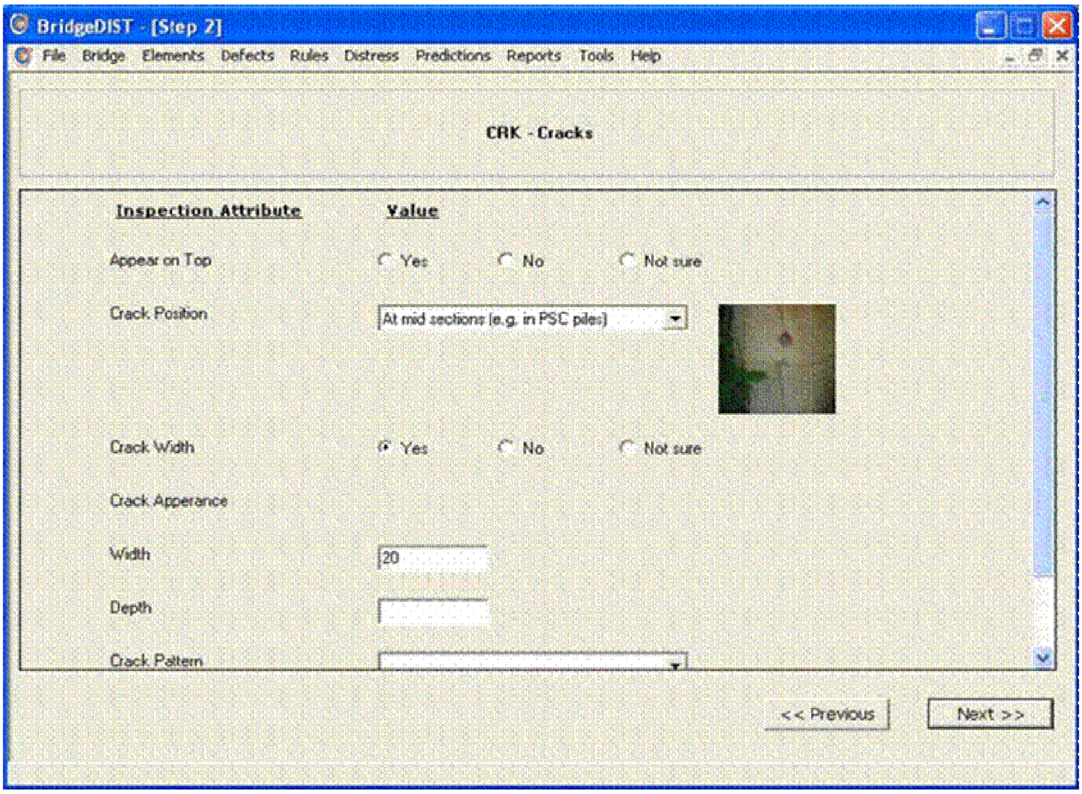
ID	Description	Importa	Base Element
E00001	Deck	2	Deck

Select Defects Visible

Include	Defect ID	Defect
☑	CRK	Cracks
☑	D00001	Leaks
☐	D00002	Test Defect 1
☐	D00003	Test Defect 2

Figure 9.User interface screen 1

- Detailed input of the above screen is entered in the following screen. For example the details of the crack such as the crack pattern, crack width are entered here.

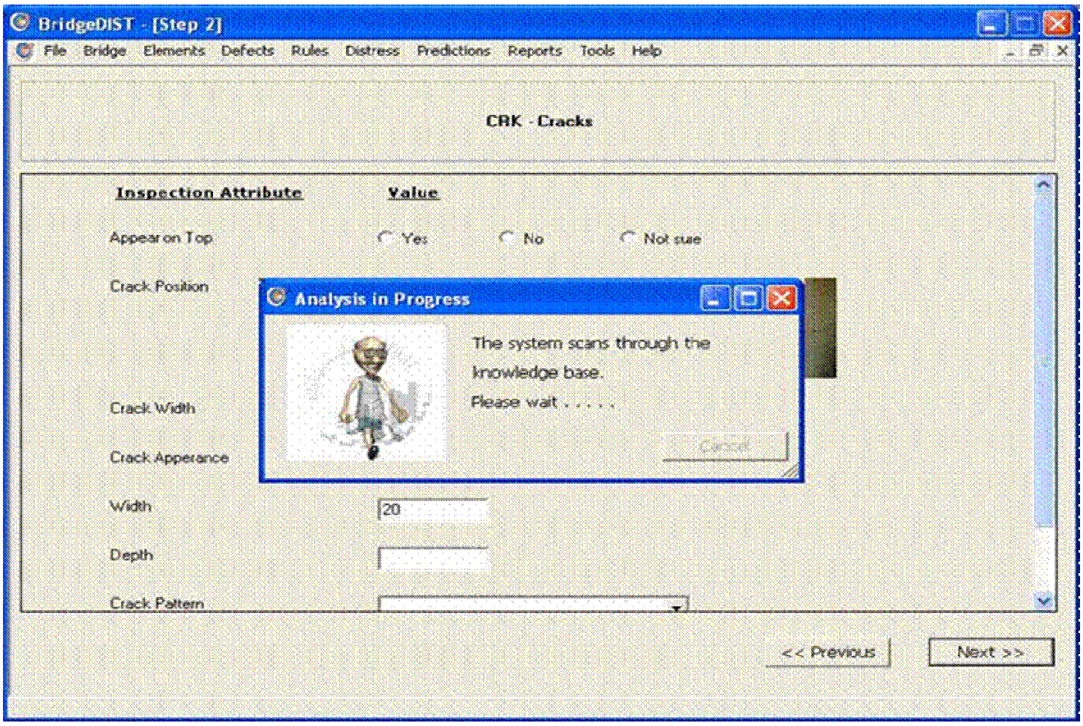


CRK - Cracks

Inspection Attribute	Value
Appear on Top	○ Yes ○ No ○ Not sure
Crack Position	At mid sections (e.g. in PSC piles)
Crack Width	● Yes ○ No ○ Not sure
Crack Apperance	
Width	20
Depth	
Crack Pattern	

Figure 10.User interface screen 2

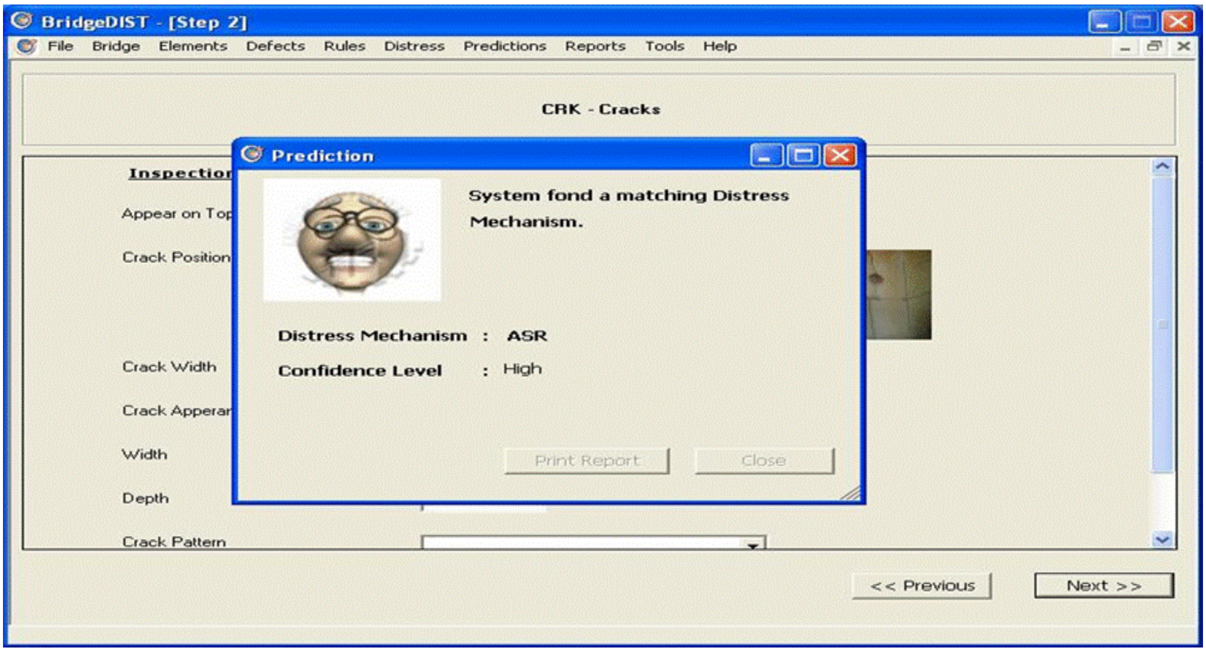
- The following screens show the results of the analysis. The tool presents a degree of confidence for the predictions based on the number and quality of the information. In the case of a conflict between two possible mechanisms, the user is advised to undertake concrete core tests or other petrographic tests to resolve the issue.



The system scans through the knowledge base.
Please wait . . . . .

Width: 20

Figure 11 (a).Analysis



System fond a matching Distress Mechanism.

Distress Mechanism : ASR
Confidence Level : High

Figure 11 (b) Results

Figure 11.Software analysis and results (a) Analysis and (b) results

6 Sample of the rule based matrix

An example of the typical rule based matrix developed in this research is presented in the table below (in three parts and to be read in conjunction). The complete rule base is embedded in the software.

Table 31. Typical rule based matrix for evaluating distress mechanisms in bridges

(Part – 1)

Element	**Construction**	**Material**	**Environment**	**Climatic condition**	**Element position**	**Concrete Grade**	**Concrete Cover**
Pile /Pier	Prestressed	Cast-in situ	Salt water	High humidity	Below water + tidal zone	Adequate	Inadequate
Bridge Kerb	Prestressed	Precast	Salt water	Not known	Near Road surface	Adequate	Adequate
Deck surface	Prestressed	Precast	Salt water	Not known	Near Road surface	Adequate	Adequate
Pile /Pier	Driven	Precast	Salt water	Not known	Sub-merged	Adequate	Inadequate
Pilecap	RCC	Cast-in-situ	Salt water	Not known	Tidal zone	Inadeq (M20)	Adequate
Deck surface	RCC	Precast	Coastal	Wind and sea breeze	Near road surface	Adequate	Adequate
Pile	Hollow spun	Cast-in-situ	Inland	Not known	Away from water	Not known	Not known
Deck / add ons	RCC	Cast-in-situ	Benign environment	Not known	Away from water	Not known	Not known

(Part - 2)

Coarse Agg	**Fine Agg**	**Cement**	**Crack**					
			Width	**Location**	**Pattern**	**Appearance**	**Occurrence**	**Growth**
Quarry sources known to have ASR sensitivity	Details not known	Un blended cement used	Hairline to moderate	At mid section of the pile where concrete cover is less	Vertical, running above and below water level	Slightly dark	Probably caused by a dominant distress mechanism	Appears substantia since last inspectio
Quarry sources known to have ASR sensitivity	Not known	Not known	Hairline to moderate	At mid depth, line of least resistance	Longi + map cracking at un restrained ends	Slightly dark	Probably caused by a dominant distress mechanism	Not known
Not	Not	Not	Severe	At mid	Longi	Slightly	Initial	Not

known	known	known		spans of soffits		dark	occurrence plus mechanism influence	known
Not known	Not known	Not known	Mod	Along the length	Initially horiz'al	Dark to very dark	During driving plus mechanism influence	Not known
Not known	Not known	Not known	Severe	At corners of elements, within the cover region	Vertical	Dark	Probably caused by a dominant distress mechanism	Appears substantia
Good	Good	Good	Severe	Soffits, Bridge with skewed orientation	Longi	Dark to very dark	Not known	Appears substantia
Good	Good	Good	Minor	Along the length of the member	Horiz plus longi plus circum ferential	Slightly dark	Pre-existing	No growth
Good	Good	Good	< Severe	Surficial	Random	Sub standard	Pre-existing, no influence of a mechanism	No growth

(Part - 3)

Other defects	**Mechanism**
Cracks only	ASR (High)
Cracks only	ASR (High)
Leaks	ASR (High)
Drum my concre	Chloride Induced Corrosion (High)
Spall stains	Chloride Induced Corrosion (High)
Spall, macro cells, drum my	Chloride Induced Corrosion (High)
None	Construction Related
Most defects found	Plastic shrinkage

7 CONCLUDING REMARKS

This report has presented comprehensive documentation of the development of the knowledge base and the inference engine encompassing a rule-based matrix approach for the development of a diagnostic tool “BridgeDIST”. The software has the capability to determine distress mechanisms affecting bridges exposed to aggressive environment based on the visual signs and symptoms of degradation. The developed software is open ended and further development of the rule base can be undertaken or input by expert users. This report is part of the CRC CI Research funded research project entitled “Sustainable infrastructure for aggressive environments”. Significant conclusions from this report are:

- The expert system encompassing a rule-based matrix approach is capable of determining the distress mechanisms in bridges exposed to aggressive environments.

- The developed software has the potential to be incorporated as an expert system linked to the bridge inspection database so that future deterioration of bridge stock can be predicted. Thus the software facilitates the management of bridge infrastructure.

- The application developed herein can be further extended to include whole of life cycle costs or can be applied to a network of bridges that can serve as a basis for prioritising maintenance.

8 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.

Carse, A., (2005) “The design of durable concrete structures for aggressive environments”. *Proceedings of the 22nd BiennialConference, Melbourne, 2005.*

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

Chao, C. and Cheng, F. (1998). “Fuzzy pattern recognition model for dignosing cracks in RC structures”, Journal of Computing in Civil Engineering, Vol.12, No.2, April, 1998.

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.

DeStefano, P.D. and Grivas, D.A. (1998). “Method for estimating transition probability in bridge deterioration models”, Journal of Infrastructure Systems, Vol.4, No.2, June 1998.

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.

Hahn, M.A., Palmer, R.N., Merrill, M.S., and Lukas, A.B. (2002). “Expert systems for prioritising the inspection of sewers: Knwoledge base formulation and Evaluation”, Journal of Water Resources Planning and Management, Vol.128, No.2, March 1, 2002.

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.

Venkatesan, S., Setunge, S., Molyneaux, T., and Fenwick, J., (2006). “Evaluation fo distress mechanisms in bridges subjected to aggressive environments”, in the proceedings of the 2nd CRC conference on “Clients driving innovation: Moving ideas into practice”, Gold Coast, Australia, 12-14th, March 2006.

Venkatesan, S., Setunge, S., Molyneaux, T., Gravina, R.J., and Fenwick, J., (2007). “An expert system for evaluating the distress mechanisms in bridges subjected to aggressive environments”, Journal of Concrete Institute of Australia, (submitted for publication).

9 AUTHORS BIOGRAPHY

Dr. Srikanth Venkatesan,

Education: PhD, University of Melbourne, Australia.

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

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

A/Prof. Sujeeva Setunge,

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

Professional Experience: 15 years in academia and 1 year in the industry.

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: B Sc, PhD.

Professional Experience: 15 years in academia and 3 years in the industry

Research Interests: Concrete Durability, Corrosion in concrete, Static and Dynamic response of masonry structures, Reactive powder concrete, cricket bats and Non-destructive testing of Concrete.

Dr Rebecca Gravina

Education: PhD, BEng (Civil)(Hons).

Professional Experience: 8 years in academia and 2 years in the industry

Research Interests: Non-linear analysis of reinforced and prestressed concrete structures, ductility and bond mechanics of composite concrete structural elements. Rehabilitations of concrete structures using Fibre Reinforced Polymers. Creep and shrinkage of concrete

Cooperative Research Centre
for Construction Innovation
9th Floor, L Block
QUT Gardens Point
2 George Street
BRISBANE QLD 4001
AUSTRALIA

Tel: +61 7 3138 9291

Fax: +61 7 3138 9151

Email:
enquiries@construction-innovation.info

Web:
www.construction-innovation.info

Established and supported
under the Australian
Government's Cooperative
Research Centres Program