UNIVERSITY OF SOURTHERN QUEENSLAND

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ANALYSIS OF BRIDGE FAILURE DUE TO CYCLONE MARCIA IN CENTRAL QUEENSLAND USING FAULT TREE METHOD

A dissertation submitted by

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ABSTRACT

Over the past few years Queensland has suffered from a number of severe tropical cyclones, the most recent one being Marcia, that took place on 20th of February 2015. Damage bill of Marcia exceeded $50 million which included cost of repairing a number of damaged bridges. Failure of road infrastructure isolates communities from accessing essential services and commodities. This necessitated an urgent need to develop a systematic method of assessing the failure of the bridge component to improve the resilience of future bridges and provide base knowledge for developing emergency maintenance response. There are several methods available to investigate the bridge failure. Fault tree analysis (FTA) was selected considering its positive attributes over other methods. FTA was used to estimate the probabilities of failure of main components (Super Structure and Sub Structure) and elements of timber and concrete bridges. Secondary data (Level 1 and level 2 bridge inspection reports from the department of transport and main roads) before and after the cyclone Marcia were used in conjunction with expert consultations to construct fault trees for both timber and concrete bridges. Results indicated potential failure mechanisms and the degree of susceptibility of main components of timber and concrete bridges to cyclonic events. However, the extent of the data was not adequate to draw firm conclusions and further studies (i.e. probabilistic models) are recommended to strengthen the understanding of the complete dynamics of the bridge failure under cyclonic event.

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CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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29 /10/2015

Date

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GLOSSARY

FTA	Fault Tree Analysis
FTD	Fault Tree Diagram
TMR	Department Of Transport and Main Roads
USQ	University Of Southern Queensland
BIM	Bridge inspection Manual

CHAPTER1

INTRODUCTION

1.1 Introduction

Over the past century, severe tropical cyclones have been reported to cause devastating impacts on properties, livestock, forests, buildings and infrastructure and caused major disruption to livelihoods of the communities that have been exposed to the event. In certain occasions it has taken lives, caused injuries and illnesses by restraining access to clean water and food.

Natural disasters also cause significant impacts on road infrastructure and Bridges, making affected areas isolated from ground assistance. Queensland state controlled road network consists of 33,337 km of roads and 6,500 bridges and culverts (Kuhlicke 2010) which experienced the impacts of numerous disaster events over the past few decades.

In 2011, Cyclone Yasi (category 5) caused significant damages to buildings and road infrastructure and timber bridges in North Queensland which accounted for 5% of the total damage cost. Damages to bridges can isolate communities for weeks in a natural disaster event. Resilience of critical road infrastructure such as bridges, culverts and flood-ways is vital in evacuation support activities for disaster response and recovery.

Cyclone Marcia was expected to reach category 5, however when it reached the landslide, it has reduced to category 2/3 and when it reached Rockhampton it has further reduced to category 1 (James Cook University Cyclone Testing Station 2015). Despite lowering its intensity, the damage bill of cyclone Marcia approached to $53.4 million after a weeks' time and at least 1000 homes suffered structural damage in the disaster and 385 properties have been deemed uninhabitable (Brisbane Times 2015).

Devastating impacts of past cyclones have imposed tighter regulations on building codes and technological advancements and warning systems associated with cyclones, including the use of satellite imagery and meteorological modelling have shown marked improvements in recent years.

Bridges in Australia have been designed to various standards as they were built in different periods. Bridges constructed in Australia after 2004 generally complies with AS5001:2004, which is mainly written for rural constructions (Pitchard 2013). Pitchard (2013) suggested that AS5001:2004 should be amended to include potential loads that may be applied in natural disasters such as floating objects and bridge design should consider the context and connectivity and post disaster functionality. Ataei et al. (2010) suggested that probabilistic models of structural vulnerability are required to predict any damages to bridge infrastructure under cyclonic event.

In Australia a few studies have been done to assess the resilience of buildings and road infrastructure under natural disaster events (Lebbe et al., 2014; Lokuge and Setunge, 2014). Information on the probabilistic response of road infrastructure during cyclones appears to be sparse in scientific literature.

This study endeavours to understand the response of road infrastructure to tropical cyclone Marcia and comprehend their potential response to any tropical cyclones with high magnitude that might occur in the future.

1.2 The Problem

This project is anticipated to provide broad understanding on the nature of any damages to the road infrastructure caused by tropical cyclones. This includes the probability of different mechanisms of failure i.e. attributes of the cyclone and elements of the substructure and superstructure of the bridge. This broad understanding will provide a guideline for road engineers to improve the climatic resilience of the existing and future road infrastructure.

1.3 Objectives

- To investigate the damages directly and indirectly caused by the cyclone Marcia on road infrastructure with special reference to bridges
- To determine indicative probable mechanisms of bridge failure under cyclone Marcia using fault tree analysis (FTA)

1.4 Thesis out line

The Thesis consists of six chapters. In chapter 1 the background and motivation of this research with the objectives is presented. In Chapter 2; literature review of bridge failure due to cyclones is discussed. It explains the anatomy of the tropical cyclones, the impact of cyclone on bridges and how bridges are damaged in a cyclone event.

It also contains the methods of analysis of bridge resilience. Last section of this chapter describes the Fault Tree Analysis method.

Chapter 3 provides the methodology which was used to construct the Fault Tree Diagram (FTD) which was used to investigate the probabilities of bridge failure. It also illustrates the basic fault tree diagram which was constructed to determine the failure mechanism of a bridge. FTD was also expanded to find the bridge failure due to cyclone Marcia using basic events related to a cyclone. It also describes the method used to determine the probabilities of bridge component failure using basic events connected by logic gates.

Chapter 4 explains the analytical methods used in assigning probabilities for bridge components and elements. It explains the methods of assigning probabilities for component and element failure and for basic events relevant to cyclone Marcia, using level 1 and level 2 bridge inspection reports obtained from department of transport and main roads.

Chapter 5 discusses the results and outcomes of the study. It provides a comparative account on possible responses of two main components of a bridge and variations in the response of concrete and timber bridges to a cyclonic event.

Finally, summary and limitations are in discussed in chapter 6. The outcome of this study provides a basic understanding of the probability of a timber and concrete bridge failure due to a cyclone.

CHAPTER 2

LITERATURE REVIEW

2.1 Tropical cyclones

Tropical cyclones generally develop as non-frontal low-pressure systems on warm waters in the tropics which have organized convection. They can become intensified to generate sustained gale force winds of at least 63km/h (Fig 2.1). If the sustained wind achieves hurricane force of at least 118km/h, the system is defined as a severe tropical cyclone. The same phenomenon is known as hurricanes or typhoons in other parts of the world. Based on the intensity, tropical cyclones are generally grouped into categories ranging from 1 (weakest) to 5 (strongest), depending on the maximum mean wind speed as shown in Table 2.1

If a cyclone has maximum wind gusts of ≥164 km/hr with very destructive winds, it is described as a severe tropical cyclone (BOM, 2012). Over the years severe tropical cyclones have been reported to destroy properties, livestock, forests, buildings and infrastructure and caused major disruption to livelihoods of the communities that have been exposed to the event. In certain occasions it has taken lives, caused injuries and illnesses by restraining access to clean water and food.

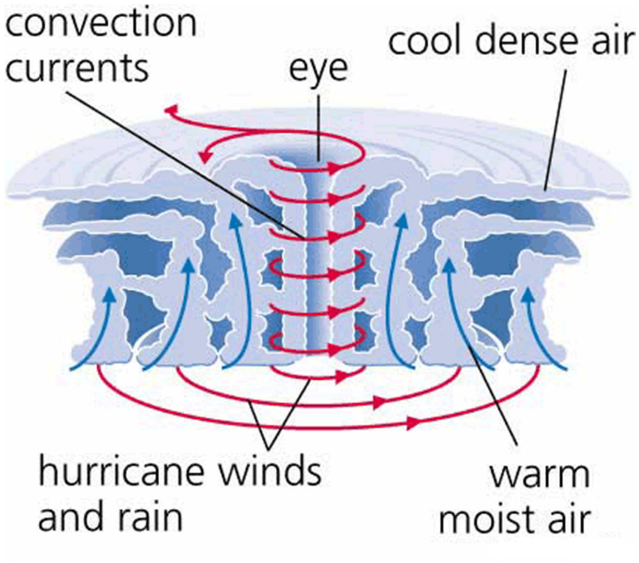


Figure 2-1: Anatomy of a Cyclone (Bureau of Meteorology 2015)

James (2010) described the importance of the use of standard to investigate the factors that influence critical wind speeds in different locations. The amended version of (Australian Standard AS 4055-2006 provides useful guide on wind speed regions of Australia.

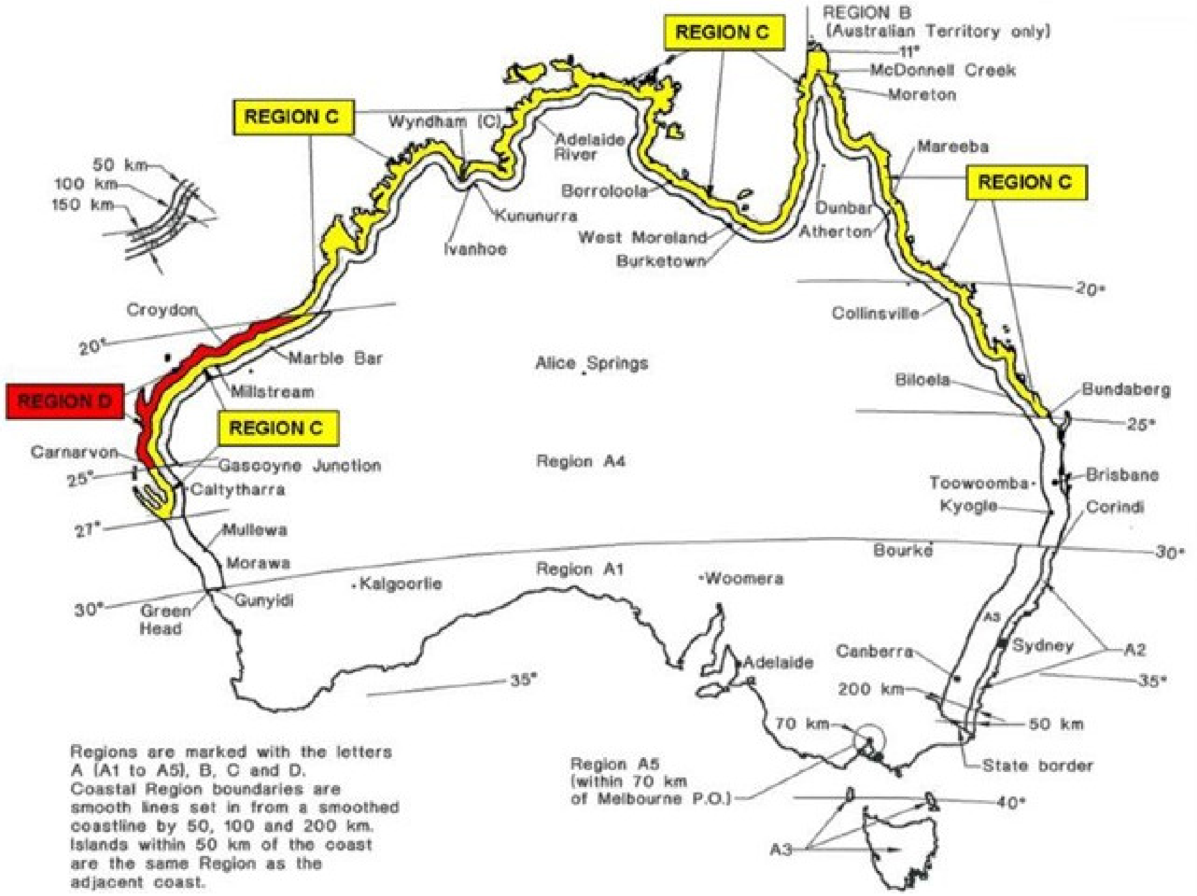


Figure 2- 1: Wind speed regions in Australia, according to the Australian Standard AS4055-2006 (Australian Standards, 2012)

Table 2-1: A description of the Category system used in Australia for Tropical Cyclones (BOM, 2012)

Category	Maximum Mean Wind (km/h)	Typical Strongest Gust (km/h)	Central Pressure (hPa)	Typical Effects
1	63 - 88	< 125	> 985	Negligible house damage. Damage to some crops, trees and caravans. Craft may drag moorings
2	89 - 117	125 - 164	985 - 970	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure. Small craft may break moorings. (e.g. Ului)
3	118 - 159	165 - 224	970 - 955	Some roof and structural damage. Some caravans destroyed. Power failures likely. (e.g. *Winifred*)
4	160 - 199	225 - 279	955 - 930	Significant roofing loss and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris. Widespread power failures. (e.g. *Tracy*, *Olivia*)
5	> 200	> 279	< 930	Extremely dangerous with widespread destruction. (e.g. *Vance*)

Devastating impacts of past cyclones have imposed tighter regulations on building codes and technological advancements and warning systems associated with cyclones, including the use of satellite imagery and meteorological modelling have shown marked improvements in recent years.

Potential risk of building failure in a cyclone can be crudely determined by comparing the building structure with the Australian Standard AS/NZS 1170.2 (2002), which is identified as the benchmark standard. It provides guidelines for structures that could be potentially affected by strong wind and less than 200 m high.

2.2 Impact of tropical cyclones on bridges

Natural disasters cause devastating impacts on road infrastructure and Bridges, making affected areas isolated from ground assistance. In the United States, annual monetary losses due to tropical cyclones and other natural hazards have been increasing at an exponential pace, now averaging up to $1 billion a week (Mileti, 1999).

The overall damage bill on repairing and replacing bridges damaged during Hurricane Katrina, including emergency repairs, was estimated to be over $1 billion based on damage inspection reports and bid estimates (Padgett 2008).

Bridges in Australia have been designed to various standards as they were built in different periods. Bridges constructed in Australia after 2004 generally complies with AS5001:2004, which is mainly written for rural constructions (Pitchard 2013). Pitchard (2013) suggested that AS5001:2004 should be amended to include potential loads that may be applied in natural disasters such as floating objects and bridge design should consider the context and connectivity and post disaster functionality.

In 2011, Cyclone Yasi (category 5) caused significant damages to timber bridges which accounted for 5% of the total damage cost. Two timber bridges required replacement due to the bridge being lifted and moved sideways by the flood water and adjacent segments of spliced piles were no longer connected together. There were broken timber piles and the approach road was also damaged (Pitchard 2013).

A concrete bridge downstream of the dams on the North Pine River system had to be replaced as it underwent 4 m scouring at the river piers due to overtopping of the bridge. Subsequent load testing of the bridge showed that there was significant decline in the pile capacity of the bridge (Pitchard 2013). A steel girder bridge on the Mitchell River required replacement due to scour of the piers. Scouring of numerous abutments spill-through embankments was observed. Relieving slabs at bridge abutments were rendered un-functional and hence had to be replaced (Pitchard 2013).

Cyclone Marcia was expected to reach category 5 but when it reached the landslide, it has reduced to category 2/3 and when it reached Rockhampton it has further reduced to category 1 (James Cook University Cyclone Testing Station 2015).

Figure 2-2: Cyclone Marcia Damaged Bridge in Monto

Figure 2-3: Cyclone Marcia Damaged Bridge in Gladstone Biloela Rd

Figure 2-4: Cyclone Marcia Damaged Bridge in Mount Morgan

Damage bill of cyclone Marcia reached $53.4 million after a weeks' time and at least 1000 homes suffered structural damage in the disaster and 385 properties have been deemed uninhabitable (Brisbane Times 2015). Cyclone Marcia has destroyed numerous properties in Yeppoon and road infrastructure including bridges in Monto (Fig 2.3), Gladstone Biloela Road (Fig 2.4) and in Mt Morgan (Fig 2.5) (Brisbane Times 2015).

2.3 How Bridges Are Damaged in a Cyclonic Event

In a cyclonic event, bridges are mostly damaged by the storm surge that arises from the severe weather event. In most occasions bridges have failed due to unseating or drifting of superstructures which depend on connection type between decks and bents (Meng and Jin 2007; Padgett et al. 2008; Chen et al. 2009). Padgett et al. (2008) studied bridge damage mechanisms using observations of 44 damaged during Hurricane Katrina. Their study revealed that major bridge damages during hurricane events are caused by the increased uplifting loads and impacts from debris and objects near the bridge, induced by the storm surges, and partially by high winds, scour, and malfunction of electrical and mechanical equipment due to water inundation. In a hurricane or cyclone, bridges are mainly damaged by (1) impact (2) catastrophic winds scouring, (3) Damages due to surge induced loadings (4) Scouring (Padgett et al. 2008).

a) Impact damage

Impact damage is quite common bridges associated with large water ways. Impact damage is generally caused by floating objects i.e. debris, boats any items that gets transported due to flooding resulted from the intensive rainfall caused by cyclones. Post disaster inspections found that in most occasions, impact damage demonstrated itself in the form of span misalignment and fascia girder, fender, and pile damage (Padgett et al. 2008).

A

B

Figure 2-6, 2-6: Damage due to impact (Padgett et al. 2008).

b) Damages caused by catastrophic winds

Suspension bridges are mostly vulnerable for wind damage. Long cable-stayed and suspension bridges must withstand the drag forces induced by strong winds. In addition, such bridges are prone to aeroelastic effects, which include torsion divergence (or lateral buckling), vortex-induced oscillation, flutter, galloping, and buffeting in the presence of self-excited forces (Simiu and Scanlan 1986). Due to the aeroelastic and aerodynamic effects from high winds on long-span bridges, strong dynamic vibrations will be expected. Excessive vibrations will cause the service and safety problems of bridges (Conti etal. 1996; Gu et al. 2001). In Australia there are very few suspension bridges. During Cyclone Marcia 2015, a timber bridge at Mt Morgan was found to be damaged by strong winds (Fig 2.5).

c) Damages due to surge induced loadings

Bridges with spans of the same or lower elevation than peak surge levels experience severe structural failure during hurricane events level (Irish and Cañizares, 2009). Under a storm surge the surface waves strike the superstructure and overcome the capacity of the anchorages (Douglass et al. 2006; Chen et al. 2009) and subsequent waves pushes the superstructures off of the supporting substructure. Robertson et al. (2007) described that hurricane damaged bridges experience reduced dead weight due to air trapped below the deck, which complements the hydro-dynamic uplift forces overcame the capacity of the anchorages.

d) Scouring

Figure2-7: Damage caused by scouring (Padgett et al. 2008)

Another failure mode was due primarily to scour. Observations revealed that this damage type may or may not accompany the other damage modes inherent to storm-surge loads.

The scour damage that was readily visible to inspectors included scour and erosion of the abutment, slope failure, and undermining of the approach (Figure2.7)

Scour results in foundation failure, which is caused by water flow eroding the foundations. When the foundation depth is shallow enough that the abutment or pier can move vertically, failure can occur (LeBeau and Wadia-Fascetti 2007). The major cause of bearing failure is extreme lateral forces that knock the superstructure off the bearings (LeBeau and Wadia-Fascetti 2007).

e) Damage in bridge connection

Lehrman et al. (2012) tested three bridge connection types a) headed stud, b) clip bolt, c) through bolt (varying in elasticity and stiffness) against (1) vertical pseudostatic cyclic loading, (2) horizontal pseudostatic cyclic loading, (3) combined horizontal and vertical pseudostatic cyclic loading, and (4) combined horizontal and vertical dynamic loading on the basis of wave force histories from simulated hurricane wave loads on a 1:5 scale bridge model. According to those authors vertical forces alone represent the impacts on off-shore bridges.

Lehrman et al. (2012) concluded that headed stud (HS) anchorage is the most robust of the three anchorages tested. It showed higher load capacity and had minimal ancillary damage to the prestressed concrete girders at the point of failure. Failure of the HS anchorage was influenced by the performance of the steel studs, which allows high level of predictability and anchorage can be detailed to limit forces that could act on the substructure.

The CB and TB anchorages exhibited concrete cracking and strand slip prior to failure which may impact long-term performance of the bridge after survival of the hurricane event. None of the three anchorages were able to withstand the simulated vertical loadings generated by 3.6 m wave as prescribed by AASHTO guide specifications (Lehrman et al. 2012).

They also concluded that bridges that have CB, TB and HS connections have to be retrofitted with higher anchorage into the stem and end diaphragms.

2.4 Methods of studying the resilience of buildings and road Infrastructure

2.4.1. Vulnerability Index

Risk of a natural hazard is depending on the intensity of the hazard and the vulnerability of the community and infrastructure.

Risk = Hazard Intensity x Vulnerability (Holland 1993).

According to Varnes (1984), vulnerability refers to the potential degree of damage that can be expected based on the characteristics of an 'element at risk' with reference to a certain hazard.

Even at present, this understanding of vulnerability has been complemented by encompassing 'the conditions determined by physical, social, economic, and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (Hufschmidt 2011).

Vulnerability research has recently encompassed the challenge of integrating three different aspects, (1) components such as exposure, sensitivity or adaptive capacity, (2) different methods used in different disciplines, (3) target dimension of vulnerability (Fuchs et al. 2011). Vulnerability index (VI) refers to numerical values representing the quality of the structural and non-structural parameters which are considered to influence in the response of the building to a natural hazard (Belheouane and M. Bensaibi 2013).

Vulnarability Index VI= $\sum_{i=1}^{n} K$

Where n=number of items in a building structure, K = correlation coefficient of building response (Tesfamariam and Saatcioglu 2010).

Pompe and Haluska (2011) described following components as factors influencing hurricane vulnerability index (HVI): (1) the level of exposure, (2) physical susceptibility to the hurricane, and (3) the hurricane's frequency and intensity. They used the following formula:

HVI = (E)*(S)*(H)

Where E and S are the exposure and susceptibility to the hurricane, and H is likelihood of the hazard. Pompe and Haluska (2011) used a multiplicative model (Saaty 1980) since risk is a product of exposure, susceptibility, and hazard. The three elements are calculated with the following equations:

E = wE1R E1 + wE2R E2 + wE3R E3

S = wS1R S1 + wS2R S2 + wS3R S3

H = wH1R H1

Where R E1, R E2, and R E3 are population, housing units, and housing value; R S1, R S2, and RS3 are building code effectiveness, average building age, and vulnerability to sea-level rise; R H1 is hurricane probability; and w is the appropriate weight for each indicator (Pompe and Haluska 2011)

2.4.2 Damage index

Blong (2003) used damage index to evaluate the performance of buildings which relies on the construction cost per square metre and a replacement cost ratio which is approximately equal to the costs relative to the cost of replacing a median-sized family home. In this research damage index for the infrastructure is defined as:

Damage index = Cost for repair/Cost of replacement

2.5 Methods of studying bridge

2.5.1 Probabilistic models

Studying the interactions between waves and bridge decks is important to understand the damages to bridges caused by storm surge. Fluid structure interaction is a complex phenomenon, due to air entrainment, turbulence and wave diffraction (Ataei et al. 2010).

Ataei et al. (2010) suggested that probabilistic models of vulnerability are required to predict any damages to bridge infrastructure under hurricane event. According to them the first step in developing the probabilistic model involves studying of dynamic responses of the bridges to hurricane induced loadings (Ataei et al. 2010). Kaplan et al. (1995) proposed a mathematical model for predicting the forces on cylinders and plates of offshore bridges based on Morrison's equation which considered drag and inertial terms. Morrison's equation applies to structures that have large clearance between the deck and the water level.

Ataei et al. (2013) proposed following equation for the damage index for the bridges by using Longuet-Higgins (1983) joint probability wave function:

$$P\,[Damage|IM] = \begin{cases} P\,[D>C|IM = s] & \text{Single valued IM} \\ P\,[D>C|IM_1 = s_{1,\ldots\ldots,} IM_n = s_n] & \text{Single valued IM} \end{cases}$$

[Equation 7: Damage Index Equation]

Where D =structural demand, C = structural capacity, and IM =s= realization of the measure of hazard intensity for a single-valued IM and where IM_1 = s1 to $IM_n = s_n$ are the measures of intensity for a vector-valued IM.

2.5.2. Risk Analysis and Fault Tree Analysis (FTA)

Current risk analysis methods and tools used in bridge maintenance can be grouped into three categories: field inspections, computer simulations, and real-time monitoring by using on-site sensors. The visual field inspections look for signs and symptoms of deterioration that could form into a failure. Real-time monitoring sensors, such as structural health monitoring (SHM) sensors, detect symptoms by a number of sensors on the bridge that can be connected to a computer network.

Computerized models and simulations predict failure by using historical data and trends. Pontis (Futkowski and Arenella 1998; Cambridge Systematics, Inc. 2004) and artificial neural network (ANN) (Huang 2010) are two examples for computerised risk assessment models. In addition to historical data and trends, computerized knowledge based systems use expert opinions and results from other methods (e.g., field inspections).Despite the numerous practical advantages; risk assessment methods still have several limitations. Fault Tree Analysis (FTA) could be used to resolve majority of these issues.

2.5.2.1. Advantages of FTA method

Fault Tree Analysis could be used to address the limitations of risk assessment methods on following ways (Davis-McDaniel 2013):

- Computerized mechanistic-based simulations and knowledge-based models require large amount of technical data. In FTA, if the exact information is not known, an educated guess or probable range can be used as input for the probability of basic events.

- Structural health monitoring, computerized mechanistic-based simulation, and in certain occasions visual inspection do not consider the chain of events that lead to bridge failure. The FTA models are developed using the chain of events; therefore, all the events that lead to failure can be identified through the analysis.
- Majority of the visual inspections, computerized simulations, and computerized knowledge-based systems only evaluate the condition of individual bridge components instead of assessing the both individual components and their interrelationships.
- Fault-tree analysis can also be used to assess the condition of individual components and the cause-and-effect relationships between different levels of events.
- Only few computerized simulations are known to use or produce a visual model of the bridge system. On the contrary, FTA produces a fault-tree model, which illustrates the individual bridge components with the chain of events leading to their failure of the bridge, and the relationships between the various causal events and the individual bridge components.

In addition to these advantages, FTA has the benefit of being fast and easy to use. Although FTA appears to have multiple advantages, it also comes with some limitations. FTA uses significant amount of background knowledge required on the bridge to construct the fault-tree. FTA also finds it difficult to compute probabilities for each event in the quantitative analysis due to the lack of research material or large amounts of data that require analysis. Visual inspections can be used to extract a majority of the data required for FTA; hence, FTA is best used in combination with visual inspections (Davis-McDaniel 2013).

2.5.2.2 Fault Tree Analysis Method

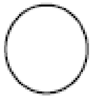
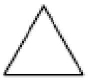
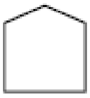
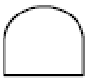
Whilst the damage index offers the level of damage to the structure, it doesn't allow identification of the probability of bridge collapse at a given intensity of an extreme event. Fault tree method can be used to establish this relationship (FHWA 2011). It is also used as a prognostic tool in the design stage of a bridge which trouble shoots all possible events that could cause bridge to collapse (LeBaeu et al. 2007).

Fault tree analysis (FTA) is a technique adopted to determine the root cause and the probability of failure of a structure due to an undesired event (Ericson, 2005). It can be used for risk assessment based on the likelihood and consequence ratings of various events of fault tree

(Williams et al., 2001). FTA is also a systematic analysis and often used in evaluating large complex dynamic systems to identify and prevent potential problems.

FTA uses a graphical model based on logic gates and fault events to model the interrelations involved in causing the undesired event.

Table 2-2: Fault tree gates and events (Zhu 2008)

Symbol	Name	Usage
	Rectangle	Event at the top and intermediate positions of the tree
	Circle	Basic event at lowest positions of the tree
	Triangle	Transfer
	House	Input Event
	AND Gate	Output event occurs if all input events occur simultaneously
	OR Gate	Output event occurs if any one of the input events occurs
	Voting Gate	M of N combinations of inputs causes output to occur.

A logic gate may have one or more input events but only one output event. AND gate means the output event occur if all input events occur simultaneously while the output event of OR gate occurs if any one of the input events occurs. In this analysis, two fault tree diagrams were developed for pre stressed concrete bridges and the timber bridges.

To develop the fault tree diagrams, damages in each element of the bridges were identified. In this analysis, four symbols were used i.e. event, sub event, AND gate, and OR gate.

One of the advantages of fault tree is its ability to unveil logical interrelationships of the bridge system through graphical depiction and Boolean algebra. The bridge can be modelled in its entirety, including element interactions, redundancy, deterioration mechanisms such as corrosion and fatigue, and environmental factors (LeBaeu et al. 2007).

Fault tree method has both qualitative and quantitative analysis. Qualitative analysis derives a graphical Boolean depiction of the factors (events) which could lead to bridge failure (top event). Each event is connected to an upper-level event by an OR, AND, EXCLUSIVE OR, INHIBIT, and PRIORITY AND gates (Davis-McDaniel 2013). The events that constitute fault tree are classified as intermediate, basic, undeveloped, conditional, or house events (Fig 2-8).

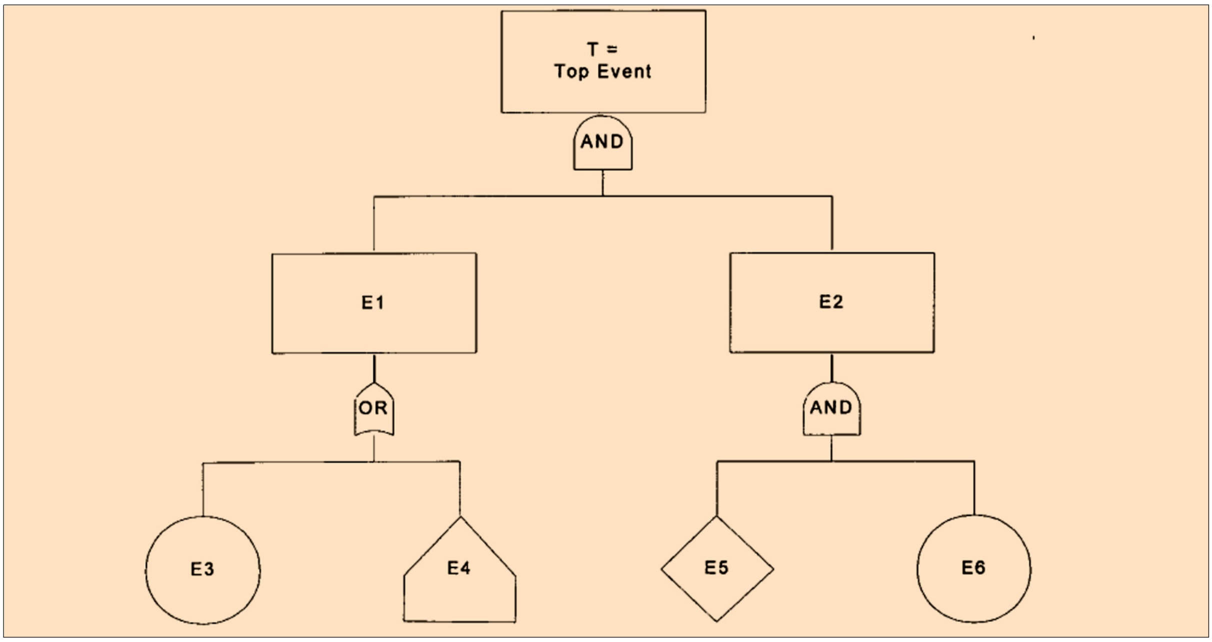


Figure 2-8: A Simple Fault Tree (Setunge et al. 2010).

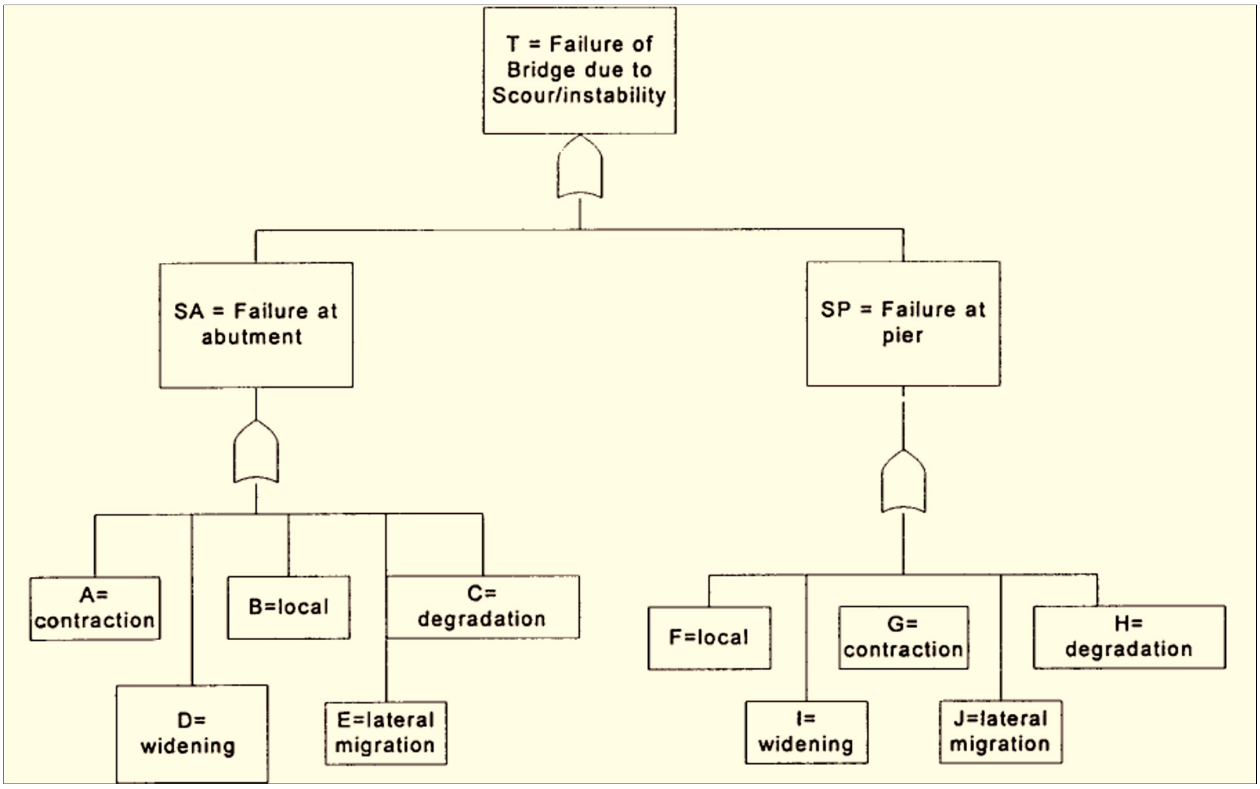


Figure 2-9: Main Fault Tree Diagram for Scour and Channel Instability at Bridges (Setunge et al. 2010)

2.5.3 Voting gate

Voting gate means once M of N combinations of inputs occur, the output event Occurs, (Ericson, 2005). It is a combination of $V_n m$ AND gates with M inputs and OR gate with $V_n m$ inputs.

$$P_f = 1\text{-}(1 - P_C^M)^\wedge C_N^M$$

Where P_f is the system probability of failure, Pc is the component probability of failure, M is the number of failure of components and N is the total number of parallel components. The intensity of failure changes with M.N is easy to determine but M is a crucial factor for the accuracy of the calculation.

The voting gate model can provide a connection of the quantitative results of component probability of failure due to initiation of a distress mechanism and the previous fault tree model

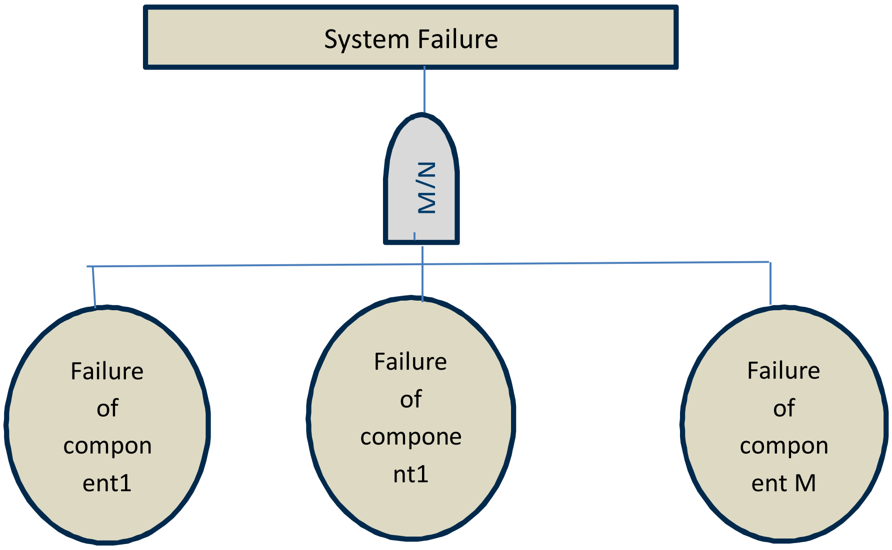


Figure 2.10.Voting gate diagram

CHAPTER 3
METHODOLOGY

3.1Summary of the Methodology

This chapter describes the methodology used to analyse the damaged bridges due to cyclone Marcia. A case study was carried out to identify all potential attributes of bridges that contributed or could contribute to failure such as bridge approaches, bridge surface, waterway, bridge substructure, bridge superstructure etc.

Data used in this exercise was obtained from Department of Transport and Main Roads based on level 1 and level 2 pre-cyclone and post cyclone bridge inspections. Level 1 inspection indicates the damaged components and the morphology of the damage. The level 2 inspection provides more details of the damage including its severity.

The failure criteria was used to calculate the failure of two different types of bridges, Concrete and timber bridges. Inspection data were grouped based on the type of bridges as timber or concrete and evaluated for type of damage, age, standard used to design these bridges and separate databases were developed for each bridge type.

The relationship between the collected data and the failure of the specific bridge of interest were analysed using fault tree method (Fig 2-8) (Setunge et al. 2010). Fault tree was constructed using data on element failure reported in level 1 and level 2 inspections in conjunction with the advice from experts in bridge engineering.

This chapter has three sections

A) Secondary Data collection and Pre Analysis
B) Development of Fault tree
C) An example of probability Calculation using the fault tree diagrams

3.2. Data collection

Pre-disaster and post-disaster inspection data for damaged bridge were obtained from department of transport and main roads Rockhampton. Bridges inspection system (BIS) has been developed at TMR (Transport and Main Road) to keep all the records of the bridges nationwide. Level 1 and level 2 inspection reports were used to analysed the data.

- Level 1 - Routine Maintenance Inspections
- Level 2 - Bridge Condition Inspections

3.1.1 Level 1 reports-Routine Maintenance inspection

Purpose of the level 1 inspection report is to check the general serviceability of the structure, particular for the safety of the road users and identifying the emergency problems (Bridge Inspection Manual, 2004)

Scope

The scope of a Routine Maintenance Inspection includes:

- Inspection of approaches, waterway, deck/footway, substructure, superstructure and attached services to assess and report any significant visible signs of distress or unusual behaviour,
- Inspecting the active scours or deck joint movements.
- Check of miscellaneous inventory items, including the type, extent and thickness of the bridge surfacing as well as details of existing services.
- Recommendation of a Bridge Condition Inspection if warranted by observed distress or unusual behaviour of the structure.
- Identify maintenance work requirements and record on the Structure Maintenance Schedule form

Level 1 inspection was carried out immediately for all the damaged bridges after the cyclone Marcia. An example of a Level1 inspection report was attached in Appendix B.

3.1.2 Level 2 - Bridge Condition Inspections

Purpose of the level 2 inspection report is to assess and rate the condition of a structure (as a basis for assessing the effectiveness of past maintenance treatments, identifying current maintenance needs, modelling and forecasting future changes in condition and estimating future budget requirements).

Scope

The scope of the Bridge Condition Inspection includes:

- Compiling, verifying and updating inspection inventory element items as appropriate.
- Visual inspection of the principal bridge components (including measurement of crack widths, and an assessment of condition using a standard condition rating system as defined in the inspection procedures.
- Visual inspection to identify any suspected asbestos containing material.
- The inspection of timber bridges will be supplemented by a drilling investigation, and also include the identification and reporting of under sized timber members.
- Reporting the condition of the principal bridge components and determining an aggregate rating of the structure as a whole.
- Identifying and programming preventative maintenance requirements and recording on the Structure Maintenance Schedule form (M1). If access equipment is required to conduct the
- Inspection, then routine / preventative maintenance may also be completed in conjunction with the inspection.
- Requesting a detailed bridge inspection by a bridge engineer if warranted by apparent rapid changes in structural condition and/or apparent deterioration to condition state 4.
- Underwater inspections of those elements in permanent standing water at the specified frequency.
- Recommending requirements for the next inspection and nominating components for closer monitoring as appropriate.
- Recommending supplementary testing as appropriate.

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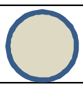
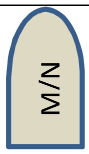
An example of level 2 report was attached in Appendix C

Level 1 Inspection data were available for 41 pre stressed concrete bridges, and 18 Timber bridges. Level 2 inspection reports were available for 6 concrete bridges and 8 timber bridges. Data were analysed separately for level 1 and level 2 inspection reports before and after the cyclone Marcia. An excel sheet was used to analyse the nature of damage for each element of the bridges individually (Excel sheets were attached in Appendix D Appendix E).

3.2 Development of Fault Tree

Bridges can deteriorate before the end of service life, if the design does not give the structure resilience to the environment to which it is exposed. However, deterioration of a structure does not necessarily imply structural collapse but could lead to loss of structural serviceability, such as poor durability and poor appearance with cracking, spalling, etc. Evaluation of the risk of failure of serviceability is important in decision making in relation to identifying different rehabilitation options for managing aging bridges.

Table 3-1: Different symbols used in fault tree construction

Symbols	Name	Usage
	Circle	Basic event
	Triangle	Transfer
	AND Gate	Output event occurs if all input events occur simultaneously
	OR Gate	Output event occurs if any one of the input events occurs
	Voting gate	M of N combination of inputs causes output to occur

Components/elements of all the bridges can be grouped under two headings

- Super structure
- Substructure

The main components of the Super structure and the Sub structure are shown below:

Table 3-2: Components of a typical bridge structure

	Bridge Component	Description
Super Structure	Deck	A bridge deck or road bed is the roadway, or the pedestrian walkway, surface of a bridge, and is one structural element of the superstructure of a bridge. The deck may be constructed of concrete, steel, open grating, or wood. Sometimes the deck is covered with asphalt concrete or other pavement. The concrete deck may be an integral part of the bridge structure (T-beam or double tee structure) or it may be supported with I-beams or steel girders. The main function of deck is to distribute Superstructure loads transversely along the bridge cross section.
	Girder	A girder bridge, in general, is a bridge that utilizes girders as the means of supporting the deck. Girders distribute loads longitudinally and resist flexure and shear.
Sub Structure	Pier	Piers are structures which support the superstructure at intermediate Substructure points between the end supports (abutments). Single-span bridges have abutments at each end that support the weight of the bridge and serve as retaining walls to resist lateral movement of the earthen fill of the bridge approach. Multi-span bridges require piers to

		support the ends of spans between these abutments.
	Bearing	Bearings are mechanical systems which transmit the vertical and horizontal loads of the superstructure to the substructure, and accommodate movements between the superstructure and the substructure
	Abutment	Abutments are earth-retaining structures which support the superstructure and overpass roadway at the beginning and end of a bridge. abutments at each end which provide vertical and lateral support for the bridge, as well as acting as retaining walls to resist lateral movement of the earthen fill of the bridge approach

Generally, the problems associated with concrete structures can be grouped into following aspects (Rendell et al., 2002):

a) Initial design errors: either structural or in the assessment of environmental exposure.
b) Built-in problems: the concrete itself can have built-in problems. A good example of this is alkali-silica reaction (ASR).
c) Construction defects: poor workmanship and site practice can create points of weakness in concrete that may cause acceleration in the long-term deterioration of the structure. A common defect of this type is poor curing of the concrete.
d) Environmental deterioration: a structure has to satisfy the requirement of resistance against the external environment. Problems may occur in the form of physical agents such as abrasion, and biological or chemical attack such as sulphate attack from ground water.

Considering above basic events, and using the analysis of bridge inspection data, and referring to the models used by Zhu (2008) Johnson (1999) and Davis-McDaniel,etal (2013)the following fault tree diagrams were developed for concrete bridges and timber bridges.

Fault tree diagram for concrete bridges

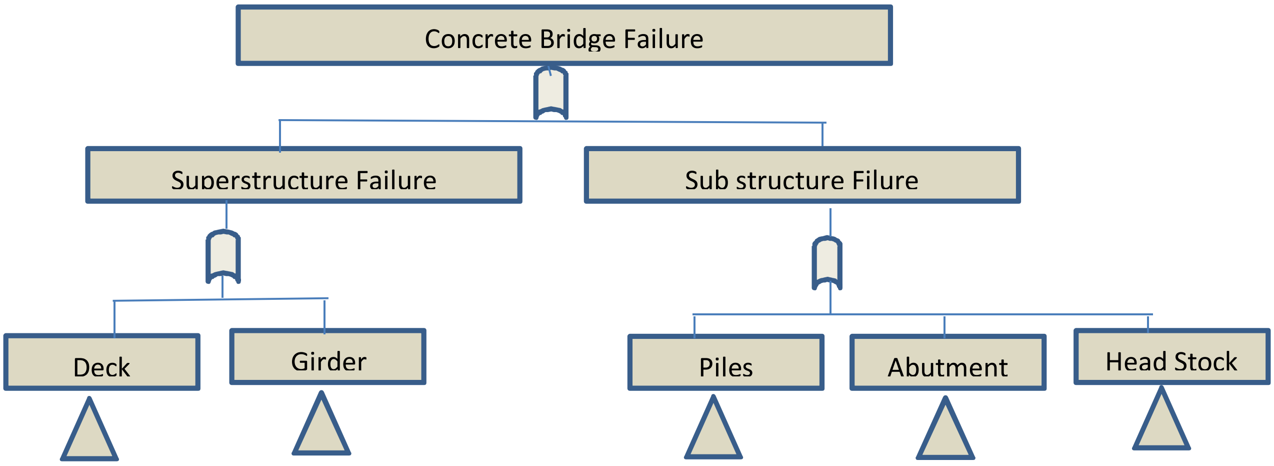


Figure 3.1: The main Fault tree diagram for concrete bridge

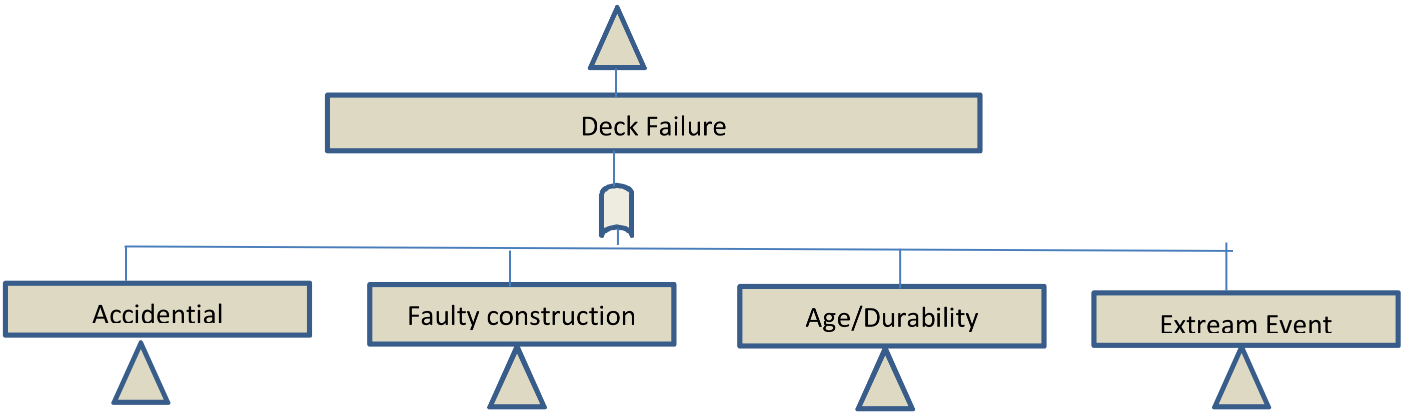


Figure 3.2: Main Sub tree Branch for the deck failure

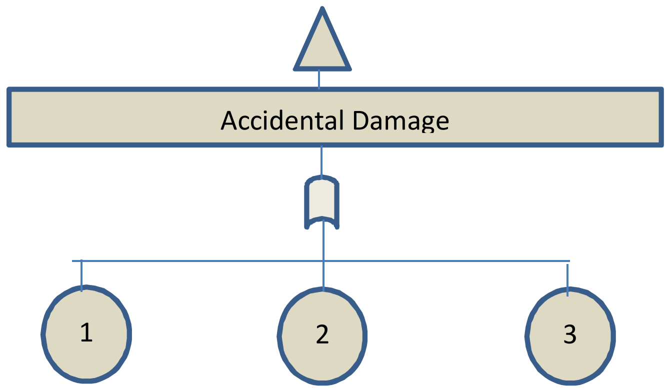


Figure 3.3: Main sub tree branch for accidental damage

1-Train accident

2-Marine accident

3-Road accident

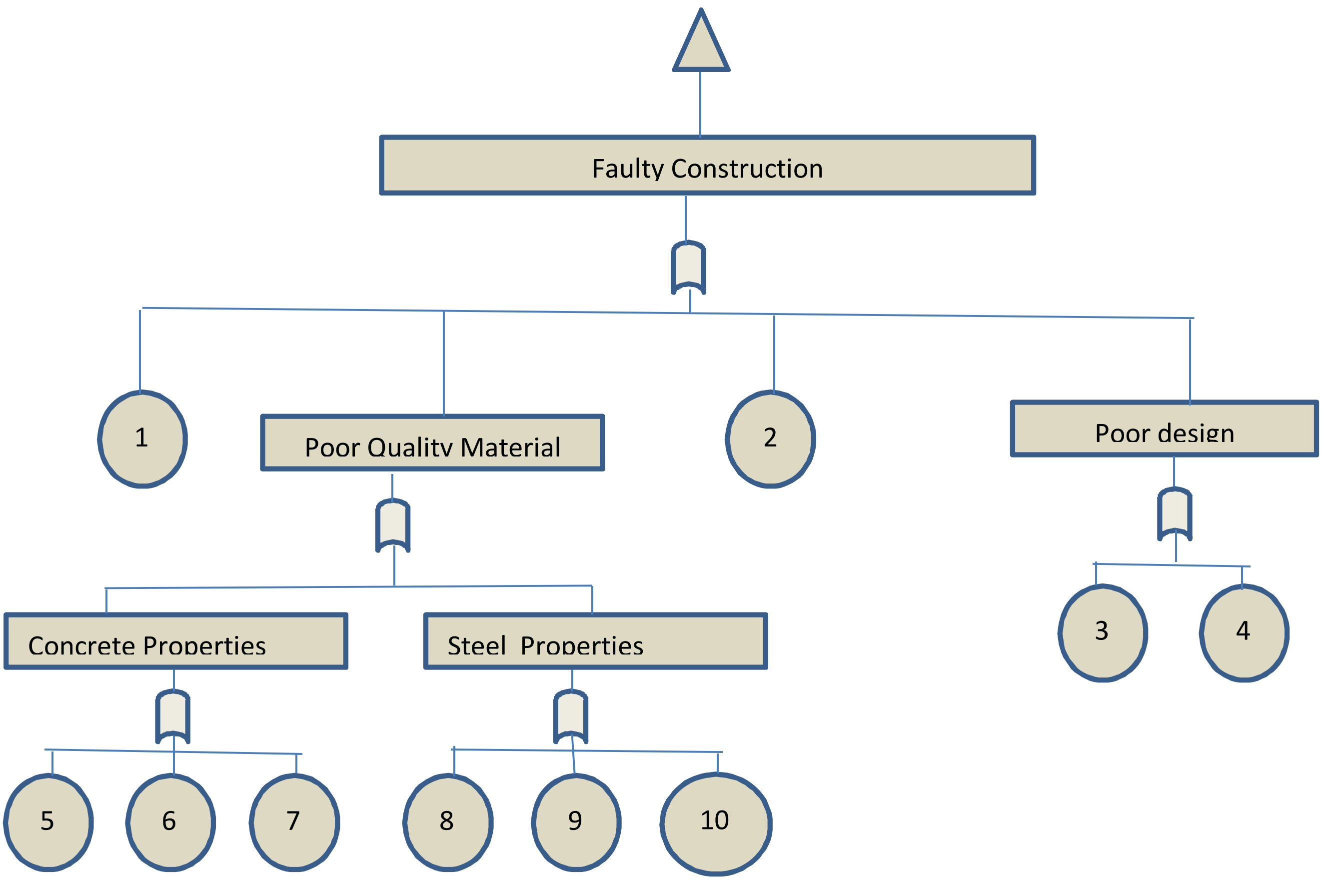


Figure 3.4: Main sub tree branch for faulty construction

1-Wrong Alignments

2-Scour

3-Poor detailing

4-Wrong load estimation

5-Inadequate Curing

6-Improper construction

7-Wrong Strength

8-Wrong size

9-Poor detailing

10-Wrong type

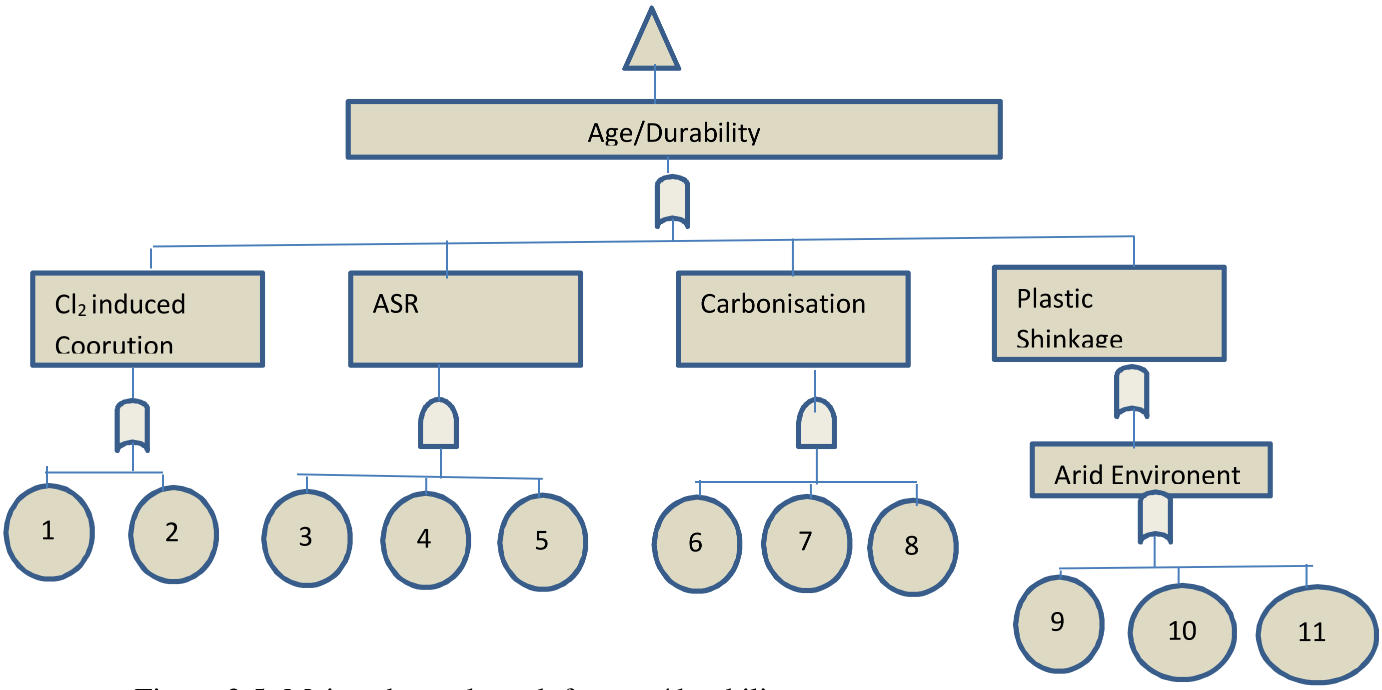


Figure 3.5: Main sub tree branch for age /durability

1-Chloride exposure

2-Access to Reinforcement

3-Reactive Aggregates

4-Poor material

5-Excessive Moisture

11-Improper Curing

6-High CO_2

7-High Reactive Humidity

8-Permeable Concrete

9-High Wind Speed

10-Low reactive humidity

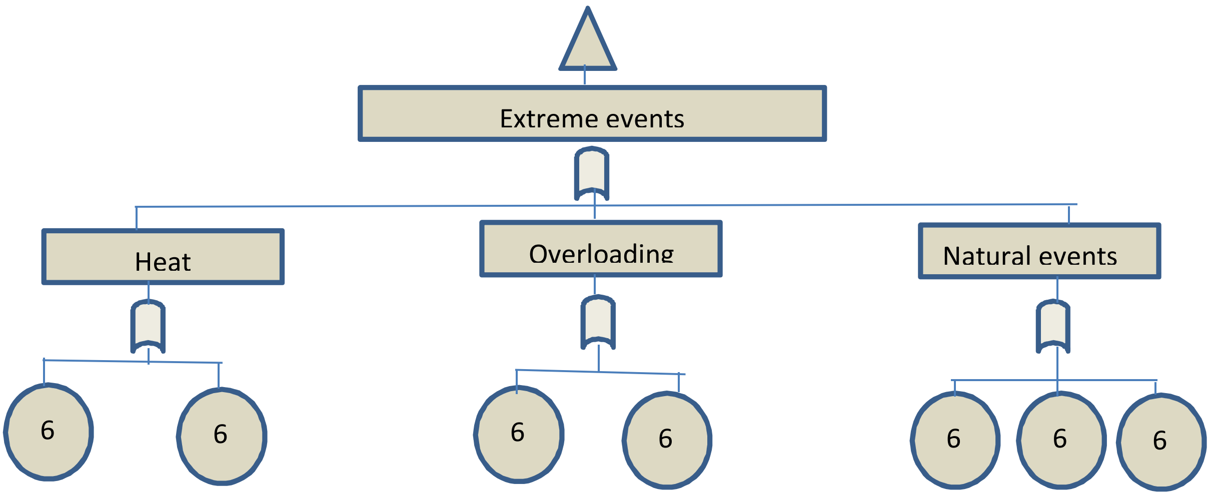


Figure 3.6 Main sub tree branch for extreme events

1-Heat (Temperature of the environment)

2-Fire

3-High Traffic loads

4-Over Weigh Traffic

5-Cyclone

6-Flood

7-Earth Quake

The basic fault Tree diagram for the Deck, Girder, Abutment, Column and Head stock was similar. But the assigned probabilities for the basic events under each bridge component were different. For an example when considering the fault tree diagram for an extreme event, the probability of natural events result from flood, cyclone and earthquake varies along the deck, Girder, abutment, head stock and piles.

Fault Tree diagram for timber bridges

The basic structure of the fault tree diagram for the timber bridges is similar to concrete bridges. The only difference occurs in faulty construction subtree and age/durability sub tree.

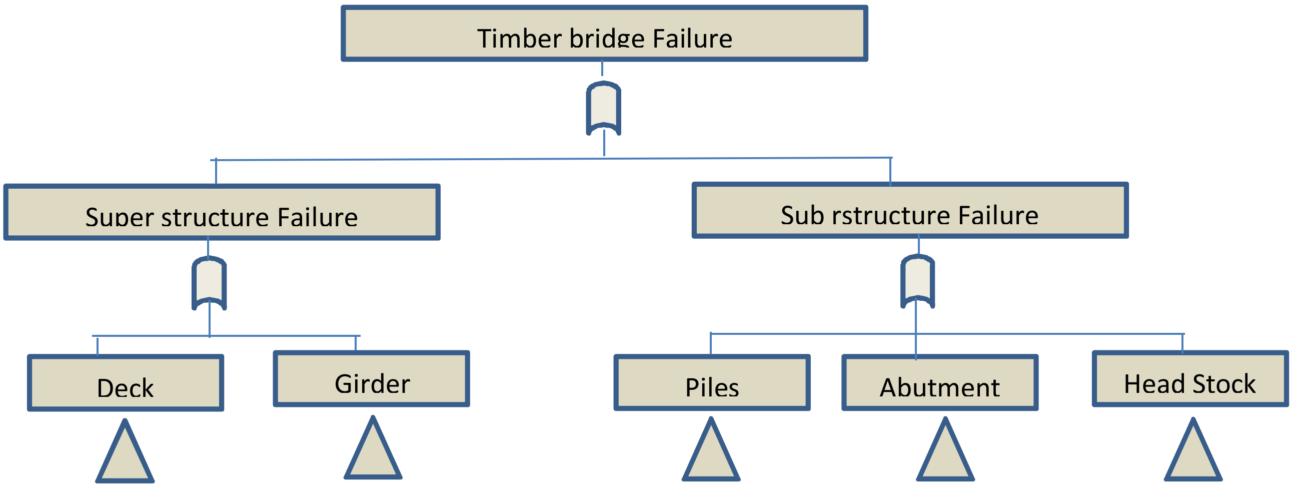


Figure 3.7: Fault tree diagram for timber bridges

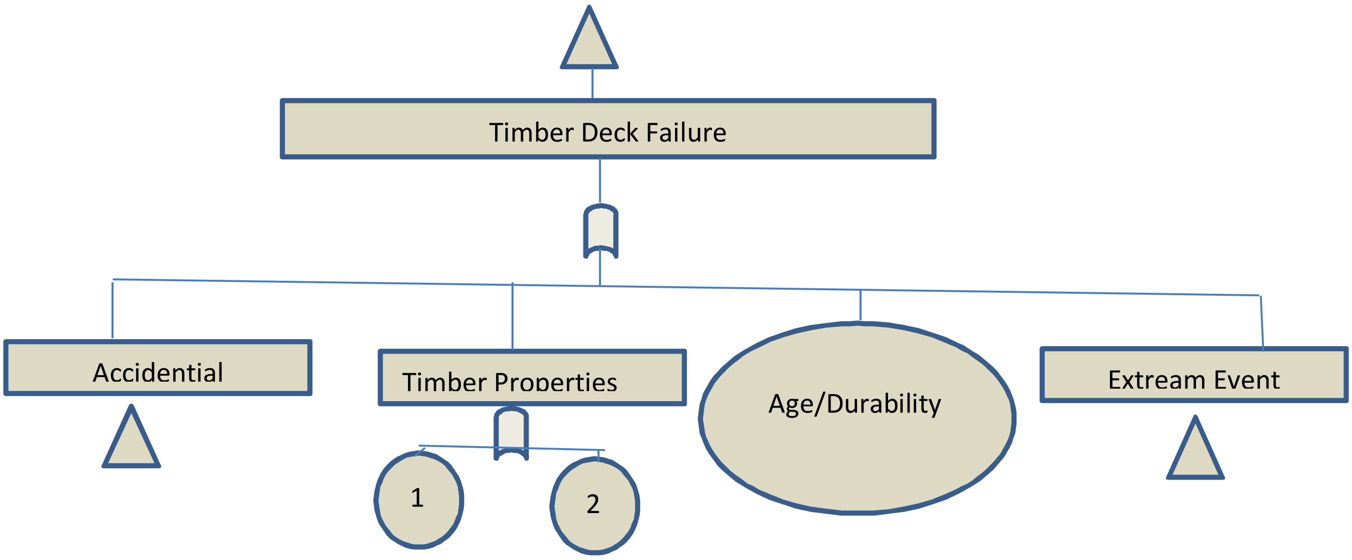


Figure 3.8: Sub Tree Diagram for the timber deck Failure

1 –Termite Attack

2-Excessive moisture

The accidental subtree branch and the extreme event sub tree branch is the same as for concrete bridges. The only difference is that the concrete properties have been replaced by timber properties. In the timber bridge fault tree diagram, age/durability represent as a basic evet. This is because in timber bridges ASR, carbonisation, Cl_2 corrosion and plastic shrinkage don't occur.

Fault tree Diagram for the concrete and timber bridge failure due to cyclone Marcia

In this study concrete and timber bridge failure due to cyclone Marcia was only considered. Therefore the Fault Tree Diagram due to the cyclone Marcia was further developed to analyse the data.

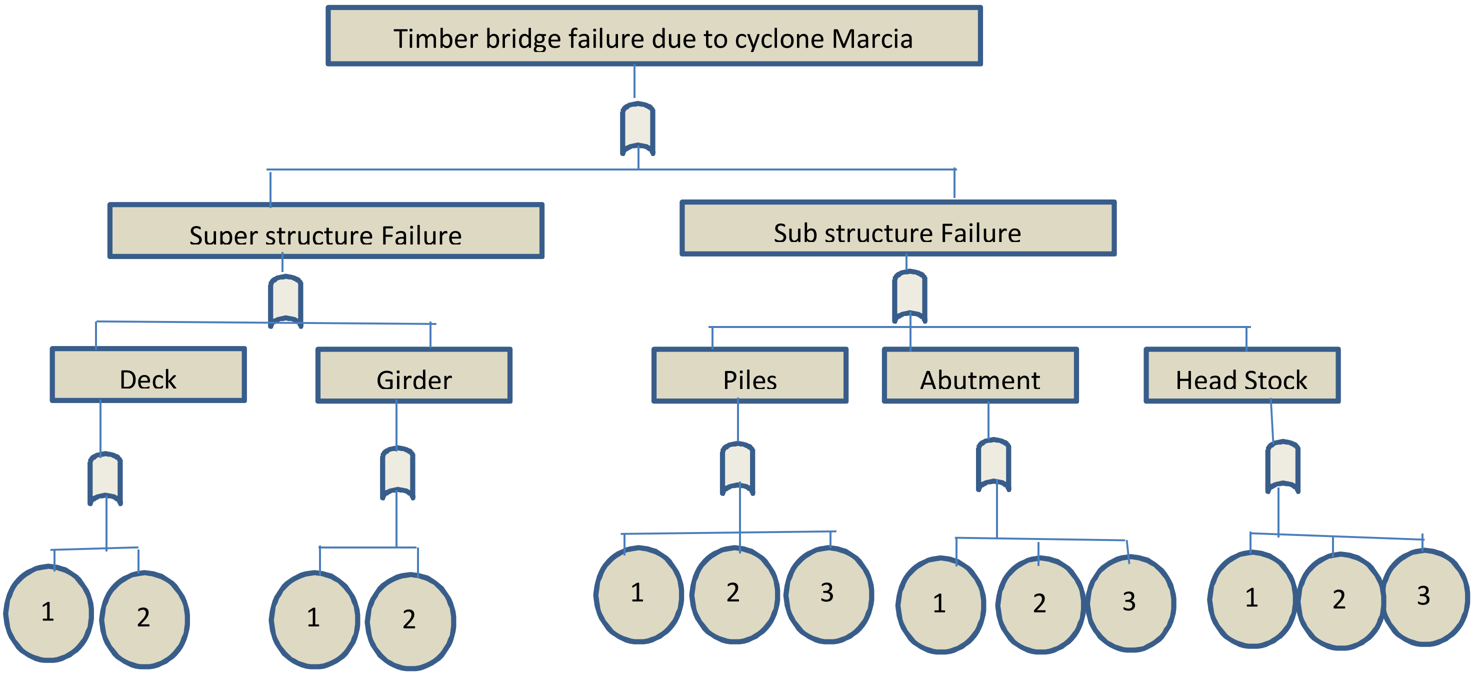


Figure 3.9: Fault tree diagram for timber bridges due to a cyclone

1-Debris/Impact

2-Surge induced loadings

3-Scour

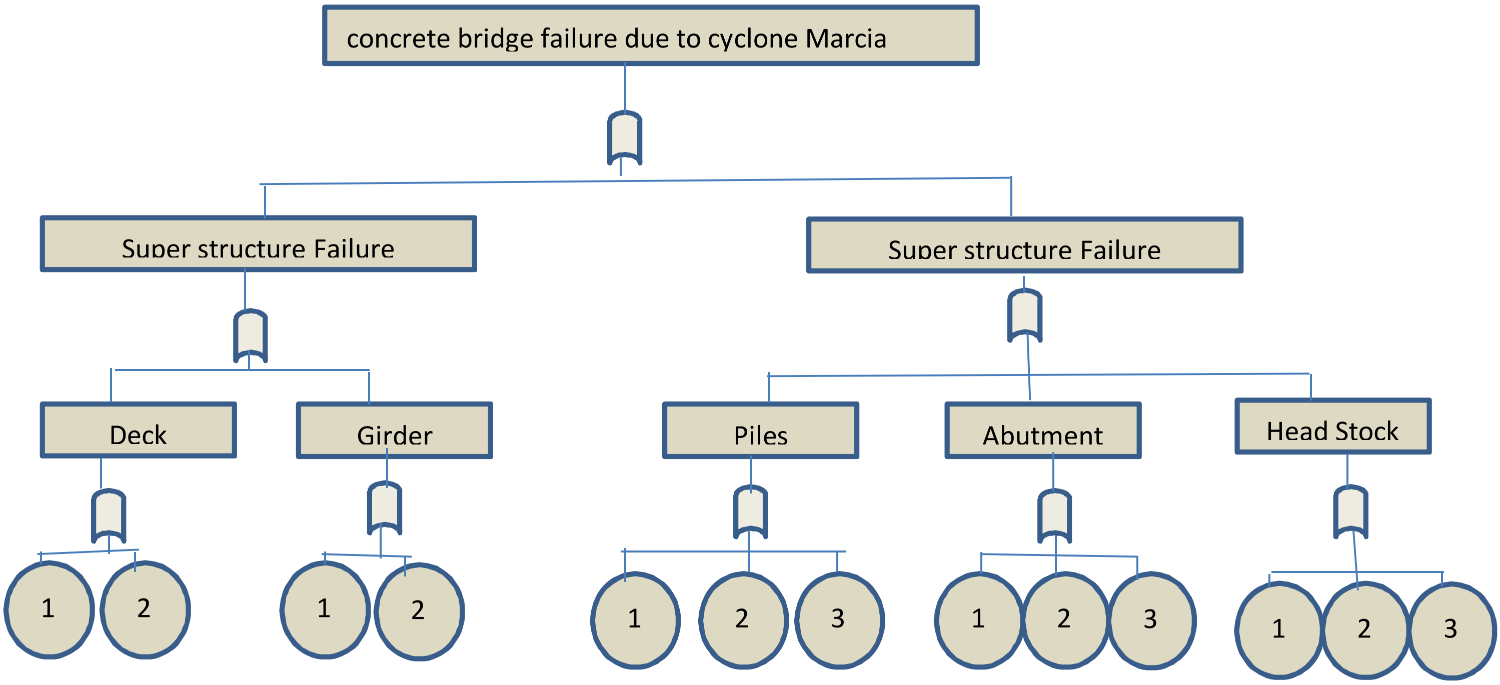


Figure 3.10: Fault tree diagram for concrete bridges due to a cyclone

1-Debris/Impact

2-Surge induced loadings

3-Scour

A bridge could fail due to a cyclone because of the impact damage blocked debris, surge induced forces and scour. The main purpose of this study is to find the basic event probabilities for super structure and substructure failure. To estimate and assigns probabilities for basic events, level 1and level 2 bridge inspection reports from Department of Transport and Main Roads (DTMR) were used. The Probability calculation is shown in the analysis section.

3.3 Probability of failure of each element

The fault tree model can be converted into a mathematical model to compute the failure, probabilities and system importance measures (Ericson, 2005, Mahar and Wilbur, 1990). The main logic gates used to combine the events are:

- AND gate
- OR gate

Equation for AND gate is

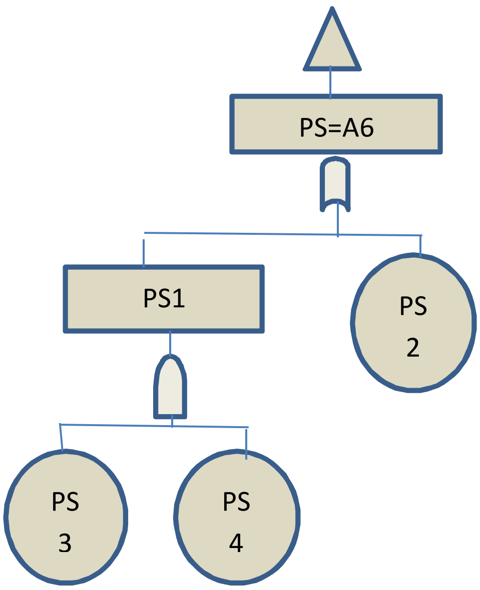
$$P = \prod_{i=1}^{n} Pi$$

Equation for OR gate is

$$P = 1 - \prod_{i=1}^{n} (1 - Pi)$$

<u>Example of calculation of the probability of top event</u>

If the basic event probabilities are known (Basic events-Events happens at the very end of the Fault tree diagram and represent as a circle) Using the above two equation for OR gate, AND gate the probability of the top event can be calculated



The probability of Occurrence of top event can be calculated as follows

P(PS1) =P(PS3).P(PS4) (AND gate)

P(PS) =1-[1-P(PS1)].[1-P(PS2)] (OR gate)

For this example let's take the probability of basic events as 0.01 and 0.001

PS3 =0.01

PS4 =0.001

Then the probability of PS1 is calculated as follows.

PS1 =P (PS3).P (PS4)

=0.01*0.001

=0.00001

Then the probability of the top event,

PS =1-[1-P (PS1)]. [1-P (PS2)]

=1-[1-(0.01)]. [1-(0.001]

=0.0109

CHAPTER 4

MODEL DEVELOPMENT

4.1 Condition rating of the level 2 inspection reports

The condition rating system reflects the performance, integrity and durability of the structure and its principal components. The assessment of the nature and extent of defects shall be detailed in the procedures as appropriate to each component type. The overall structure condition rating is based on the condition of its principal load bearing components. The condition ratings have been developed to represent the easily discernible stages of deterioration. (Bridge inspection manual, 2004)

4.1.1 Assigned Probabilities for the condition states

Qualitative ratings were extracted from the TMR Bridge Inspection manual and assigned probabilities were selected in consultation with the experts and resource personal with substantial knowledge and experience in the field of road infrastructure (Expertise- Director of the infrastructure management and delivery section in Rockhampton, TMR, Two Structural engineers from TMR, two senior civil engineers from TMR, Rockhampton and Toowoomba, head of the department of civil engineering at CQ university, and Two senior lecturer in USQ)

The majority (99%) of the experts consulted have agreed with the following approach in assigning probabilities;

a) Change of condition state 1 to condition 2 is negligible.

b) Change of condition 2 to 3 is a concern but it doesn't need immediate action.

c) Change of condition 3 to 4 needs immediate action.

d) Condition 5 was allocated as the worst case scenario and normally before any element reaches condition 5; TMR immediately repairs that particular component/element or repair the whole bridge. Based on these general agreement assigned probabilities were chosen as below.

Table 4-1: Qualitative rating for the condition levels of a bridge

Condition levels	Qualitative Rating	Assigned Probability
1	Good	7%
2	Fair	12%
3	Poor	25%
4	Very poor	50%
5	Worst	65%

Table 4-2: Change Of probabilities according to the change of condition state

Change of condition state of a bridge component	Change of probability
Condition state 1-condition state 2	0.05 (12%-5%)
Condition state 1-condition state 3	0.18 (25%-7%)
Condition state 1-condition state 4	0.43 (50%-7%)
Condition state 2-condition state 3	0.13 (25%-12%)
Condition state 2-condition state 4	0.38 (50%-12%)
Condition state 3-condition state 4	0.25 (50%-25%)

4.1.2 Reasons for allocating the assigned probability for each condition levels

As shown in the above table the change of probability from condition 1 to 2 was given as 5%.This is because according to the TMR procedures the change of condition from 1 to 2 is negligible. Change of condition state 2 – 3 is a concern; hence the probability difference between condition levels 2 to 3 was taken as 13% (25% -12%). If the condition state changes from 3 to 4, it is a main concern and immediately need to repair the component. Therefore the change of possibility from condition state 3 to 4 is chosen as 25% (50%-25%)

4.2 Example for Probability calculations: Roubdstone Timber Bridge (structure ID 718)

4.2.1 Calculations for girder failure of span 1

Table 4-3: Change of condition state for girders in span1

No of Girders	Span1 conditions state before the cyclone				Span 2 conditions state after the cyclone				Probability of failure of girders in span1
7	1	2	3	4	1	2	3	4	
		5	2					7	0.343

<u>Probability calculation for the girders of span1</u>

<u>a)</u>

Condition state before the cyclone Marcia = 2 (12%)

Condition state after the cyclone Marcia = 4 (50%)

The probability difference between condition levels = (0.5-0.12)

=0.38

Number of girders changed from condition 2 to condition 4 = 5

Therefore the probability of failure of girders in span 1 = 0.38*5

=1.9 (result 1)

b)

Condition state before the cyclone Marcia = 3 (25%)

Condition state after the cyclone Marcia = 4 (50%)

The probability difference between condition levels = (0.5-0.25)

=0.25

Number of girders changed from condition 3 to condition 4 = 2

Therefore the probability of failure of girders in span 1 =0.25*2

=0.5 (Result 2)

Therefore the probability of all girder failure for span 1 =1.9 + 0.5 (result 1+result 2)
=2.4

Total number of girders changed the existing condition =7

The probability of a girder failure =2.4/7

=0.343

4.2.2 Calculations for girder failure of span 2

Table 4.4: Change of condition state for girders in span2

No of Girders	Span2 conditions state before the cyclone				Span 2 conditions state after the cyclone				Probability of failure of girders in span1
7	1	2	3	4	1	2	3	4	
		5	1	1				7	0.3583

a)

Condition state before the cyclone Marcia =2 (12%)

Condition state after the cyclone Marcia =4 (50%)

The probability difference between condition levels = (0.5-0.12)

= 0.38

Number of girders changed from condition 2 to condition 4 = 5

Therefore the probability of failure of girders in span 2 =0.38*5

=1.9 (result 1)

b)

Condition state before the cyclone = 3 (25%)

Condition state after the cyclone = 4 (50%)

The probability difference between condition levels = (0.5-0.25)

=0.25

Number of girders changed from condition 3 to condition 4 = 1

Therefore the probability of failure of girders in span 2 =0.25*1

=0.25 (Result 2)

Therefore the probability of all girder failure for span 2 (result 1+result 2) =1.9+0.25(result

=2.15

Total number of girders changed it existing condition =6

The probability of a girder failure of span 2 = (2.15)/6

=0.3583

Same method can be applied for span 3 and span 4.The result are as below.

The probability of a girder failure of span 3 =0.3428

The probability of a girder failure of span 4 =0.331

4.2.3 Calculation of the probability of girder failure using span1, span2, span3, span4 results

The probability of a girder failure of span 3 due to cyclone Marcia =0.343

The probability of a girder failure of span 4 due to cyclone Marcia =0.3583

The probability of a girder failure of span 3 due to cyclone Marcia =0.3428

The probability of a girder failure of span 4 due to cyclone Marcia =0.331

Total = (0.343+0.3583+0.3428+0.331)

=1.3746

Total number of span =4

Total number of girder =7

$$P_{GS} = \frac{Probability\ of\ girder\ failure\ for\ all\ spans}{Number\ of\ girders * Number\ of\ span}$$

=1.3746/ (7*4)

=0.049

Where P_{GS} -Probability of girder failure for all span

4.2.4 Probability of a girder failure for all bridges

Using the same method probability of a girder failure for eight timber bridges were calculated. The results are shown below.

Table 4-5: Results from the excel sheet for the girder failure

Bridge	Probability of a girder failure for all bridges
1	0
2	0
3	0
4	0.01
5	0.032
6	**0.049 (calculation for this bridge shown above)**
7	0
8	0.01
Total	0.101 (0+0+0+0.01+0.032+0.049+0+0.01)

In the above table, the probability of failure for four bridges stated as 0.This because the condition state of girders haven't changed before and after the cyclone Marcia for all the span in those bridges.

$$P_G = \frac{Probability\ of\ girder\ failure\ for\ all\ bridges}{Number\ of\ bridges}$$

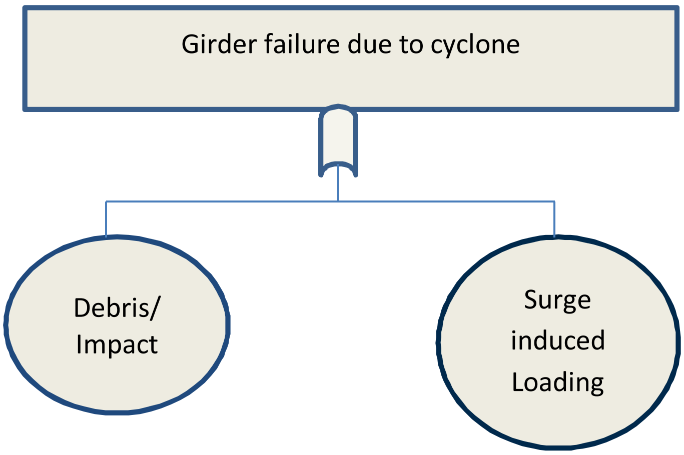
$= (0.101)/8$

$= 0.013$

Where P_G -Probability of a girder failure for timber bridges

Using the same method the probability of failure of the deck, piles, abutments, and headstock were calculated.

4.3 Method of calculating the basic events for the FTD



The probability of the girder failure was calculated as 0.013.In the fault tree diagram the girder failure was divided into two basic events, debris/impact damage and surge induced loadings. To find the basic event probabilities, top to bottom method was used.

To assign the weight for the basic event, the same expert consultation method mentioned in the previous section was used. The level 1 inspection report was also used to assign the weight for debris and impact damage.

<u>Level 1 inspection report</u>

41 concrete bridges and 18 timber bridges were analysed before and after the cyclone Marcia using the level 1 inspection reports. According to the data results as follows

<u>Timber bridges</u>

Total number of bridges considered	-18
Number of Impact damage	- 6
Number of debris damaged	-3
Scour (Bed, spill through, bedside)	-9

<u>Concrete bridges</u>

Total number of bridges considered	-41
Number of Impact damage	- 8
Number of debris damaged	-3

Scour (Bed, spill through, bedside) -25

Using above results and consulting expertise (Section 4.3) the weight of a girder failure due to debris/ impact and surge induced forces were assigned as below. In a cyclonic event, bridges are mostly damaged by the storm surge that arises from the severe weather event. In most occasions bridges have failed due to unseating or drifting of superstructures which depend on connection type between decks and bents (Meng and Jin 2007; Padgett et al. 2008; Chen et al. 2009).

Girder failure due debris/impact =25%

Girder failure due to surge induced forces =75%

Probability calculation for the basic events

In the above fault tree diagram (Figure 1) the probability of the girder failure due to a cyclone was connected by two basic events; debris/impact and surge induced loadings. OR gate was used to connect the secondary branches. Using the equation for the OR gate probability of the basic two events can be calculated as follows.

Probability of a girder failure = P_D

Probability of a girder failure due to debris/impact = P_d

Probability of a girder failure due to surge induced loadings = P_i

P_D =1.3% (Calculated probability from level 2 inspection report)

P_d =25% (assigned probabilities using level 1inspection reports and expertise knowledge)

P_i =75% (assigned probabilities using level 1inspection reports and expertise knowledge)

P $=1- [(1- P_d)\times(1-P_i)]$ [Equation 8:Equation for the OR gate]

0.013 $=1-[(1-0.25\ P_d)(1-0.75P_d)]$ (P_i can be replaced as $0.75\ P_d$)

0.013 $=1-[1-0.75P_d-0.25P_d+0.1875\ (P_d)^2]$

$0.1875 (P_d)^2 - P_d + 0.013 = 0$

By solving this equation:

Calculated P_d is = 0.0143

$0.25\ P_d = 0.75\ P_i$

$P_d = (0.75\ P_i)/0.25$

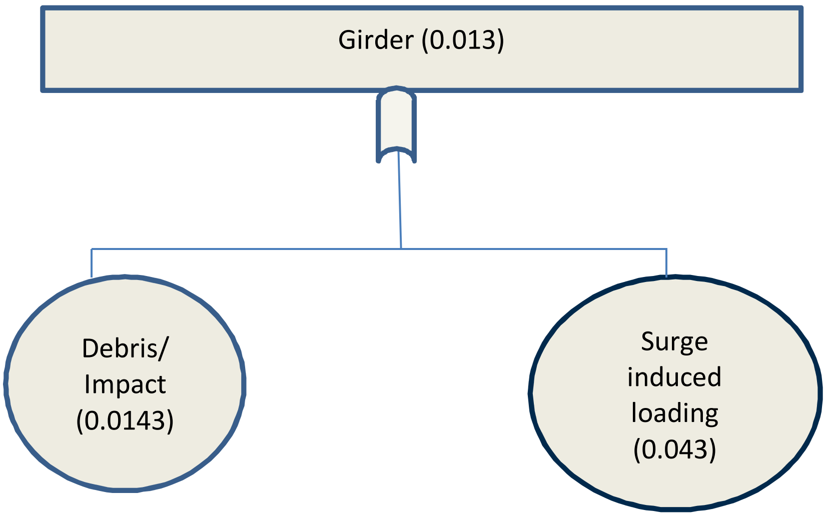
$= 3\ P_i$

Therefore P_i is $= 0.0143 \times 3$

$= 0.043$

Probability of a girder failure of a timber bridge due to debris/impact =0.0143

Probability of a girder failure of a timber bridge due to surge induced loadings = 0.043



Using the same method the probability of basic events for each bridge components can be calculated.

Table 4-6: Basic events used to calculate the main element failure of a bridge

	Bridge component	Basic events
Super structure	Girder	Debris/Impact, surge
	Deck	Debris/impact, surge
Sub structure	Piles	Debris/impact, surge, scour
	Columns	Debris/impact, surge, scour
	Abutments	Debris/impact, surge, scour

As shown in the table 4-6, impact/debris and damages caused by surge induced loadings were only considered as basic events for the girders and deck failure. But for substructure components, debris/impact, surge induced loadings and scour were selected as basic events.

When selecting the probabilities of basic events for substructure, results from the level 1 inspection reports (Mentioned above refer to page 43) and expert knowledge was used.

Assigned probabilities for piles are shown below:

Pile failure due debris/impact =25%

Pile failure due to surge induced loadings =45%

Pile failure due to scour =35%

All the basic event for the components of the substructure failure are connected using an OR gate. Therefore probabilities of the basic events were calculated using the same equation and same method described in earlier section (The method used to calculate the probabilities of basic events of the girder). Same method was applied to calculate the probabilities for the concrete bridges.

T-tests

Unbalanced paired t-tests were used to compare the mean probability values of selected elements of timber and concrete bridges.

CHAPTER 5

RESULTS & DISCUSSION

5.1. General Observations

Post cyclone inspection data (level 1 inspection) for 59 bridges (41 were concrete bridges, 18 timber bridges), were tabulated for analysis.

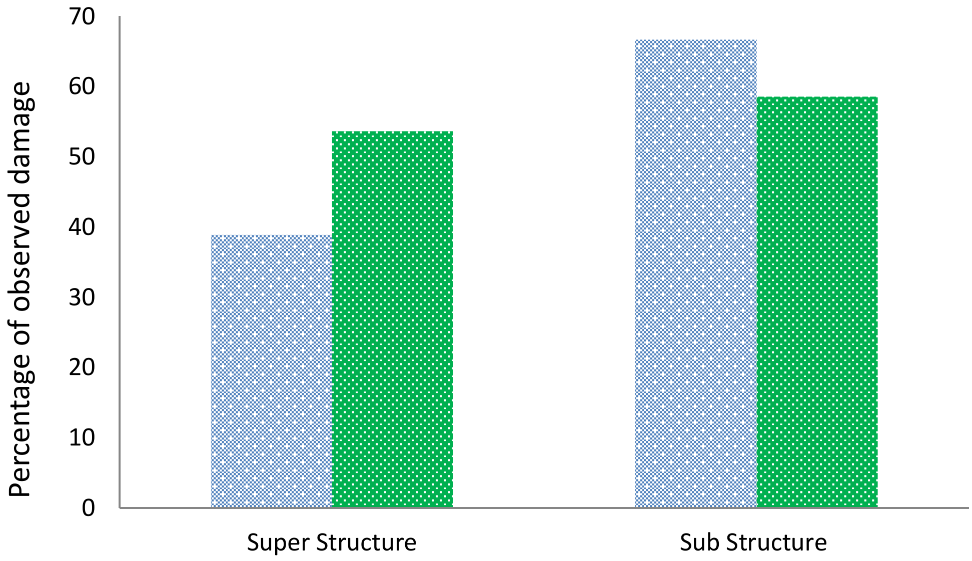


Figure 5-1: Comparison of super structure and substructure failure between concrete and timber bridges

Preliminary observations showed that there are no significant difference between potential cyclones induced damage on superstructure and substructure on both timber and concrete bridges. Potential cyclone related impact on substructure was most prevalent in timber bridges (˜66 %) (Fig 5-1).

However, pre-cyclone level two inspection data indicated that majority (62%) of the timber bridges were in exhausted state (condition 3). After the cyclone the condition of 82% of the timber bridges reached critical state which required immediate attention.

5.2 Results from Fault Tree Analysis (FTA)

Level 1 inspection data for 41 concrete bridges and 18 timber bridges and level 2 inspection data for 8 timber bridges and 6 concrete bridges were used in the FTA analysis. Below table shows the calculated probabilities for the concrete and timber bridge failures due to cyclone Marcia.

Fault tree analysis for the selected concrete and timber bridges using cyclonic events suggested that in general timber bridges are more susceptible for forces of natural disasters (P timber =0.17, P concrete =0.14).

Probability values for basic events selected to construct fault tree for concrete bridges are closely in line with the reported probability values in the study conducted by Mc Daniel et al .(2013)

5.2.1 Failure of timber bridges under cyclone events

Fault tree analysis for timber bridges indicated that substructure is more susceptible for cyclone induced damage than super structure (Table). Failure of substructure was found to have mostly influenced by damages to headstock.

Table 5-1: Probability of main element failure for timber bridges

Probability of component failure of a timber bridges				
Super structure 0.06898		Substructure 0.1121		
Deck	Girder	Piles	Abutments	Head stock
0.057	0.0127	0.0297	0.01423	0.0718

Results suggested that superstructure failure in timber bridges under cyclonic even is mainly due to deck failure which is likely to have caused by surge induced loadings (Table 5-1, Table 5.2)

Table 5-2: Probability of basic events of the super structure for timber bridges

Super structure failure of timber bridges (basic event probabilities)			
Deck		Girder	
Debris/Impact	Surge Induced Loading	Debris/Impact	Surge Induced Loading
0.01439	0.04319	0.00319	0.00956

A number of authors have also reported and discussed similar observations where super structure failure was found to be influenced by damage or displacement of the deck (Douglass et al. 2006; Chen et al. 2009). Douglass et al. 2006 suggested that surface waves generated by storm surge, can overcome the anchorage and subsequent waves dislocate them causing bridge to collapse.

Fault tree analysis for timber bridges indicated the substructure failure is mostly influenced by surge forces followed by weakness caused by scouring (Table 5-3).

Table 5-3: Probability of basic events of the sub structure for timber bridges

Sub structure failure of a timber bridge (basic event probabilities)								
Piles			Abutment			Head stock		
Surge	Scour	Impact	Surge	Scour	Impact	Surge	Scour	Impact
0.013426	0.010442	0.00596	0.0062	0.00483	0.00276	0.032832	0.025536	0.01459

Surge induced loading seems to have caused the majority of the substructure elements failures. The intensity of the damage may have been compounded due to the age of these timber bridges in question as anchorage and joints may have weakened over the years. Some of the bridges that have been included in this study are as old as 35 years.

5.2.2 Failure of concrete bridges under cyclonic events

Table 5-4: Probability of main element failure for concrete bridges

Probability of component failure of concrete bridges				
Super structure 0.00958		Substructure 0.13934		
Deck	Girder	Piles	Abutments	Head stock
0.0036	0.006	0.0035	0.1327	0.004167

According to the FTA (Table 5-4), probability of substructure failure in concrete bridges at the presence of cyclonic forces is slightly greater than that of superstructure failure. Results did not indicate marked difference in the susceptibility of super structure and substructure of concrete bridges. Unlike timber bridges, failure of superstructure in concrete bridges has found to be mainly caused by girder damage. Similar to timber bridges, surge induced loadings have caused super structure element failure (Table 5-5)

Table 5-5: Probability of main element failure for concrete bridges

Super structure failure for concrete bridges (basic event probabilities)			
Deck		Girder	
Debris/Impact	Surge Induced Loading	Debris/Impact	Surge Induced Loading
0.00065	0.00195	0.001502	0.004505

Results (Table 5-6) suggested that surge induced loading closely followed by structural weakness caused by souring are responsible for substructure element failure. In contrast to timber bridges, abatement failure has shown significant impact on substructure failure (Table 5-6)

Table 5-6: Probability of basic events of the sub structure for concrete bridges

Sub-structure failure for concrete bridges(basic event probabilities)								
Piles			Abutment			Head stock		
Surge	Scour	Impact	Surge	Scour	Impact	Surge	Scour	Impact
0.001466	0.00114	0.000652	0.06197	0.0482	0.02754	0.001869	0.00145	0.00083

Probabilities of failure for both timber bridges and concrete bridges as a direct or indirect impact from cyclone were calculated by using the probabilities in the table.

- The probability of a timber bridge failure due to a cyclone =0.17
- The probability of a concrete bridge failure due to a cyclone =0.14

Probability of timber bridge failure due to cyclonic events is higher than that for concrete bridges. The main reasons for this may be due to age of the timber bridges. All the timber bridges studied for these case studies were built more than 35 years ago. The timber code during those days was different to the current standard. Components of timber bridges are vulnerable to decay if exposed to moisture.

5.2.3 Comparison of the Responses of Timber and Concrete Bridges under Cyclonic events

Timber and concrete bridges were found to demonstrate significant difference in the susceptibility of their superstructure to cyclonic forces (Figure 5-2). A strong possibility exists for the surge related vertical forces to lift or dislocate the deck of a timber bridge causing super structure to collapse.

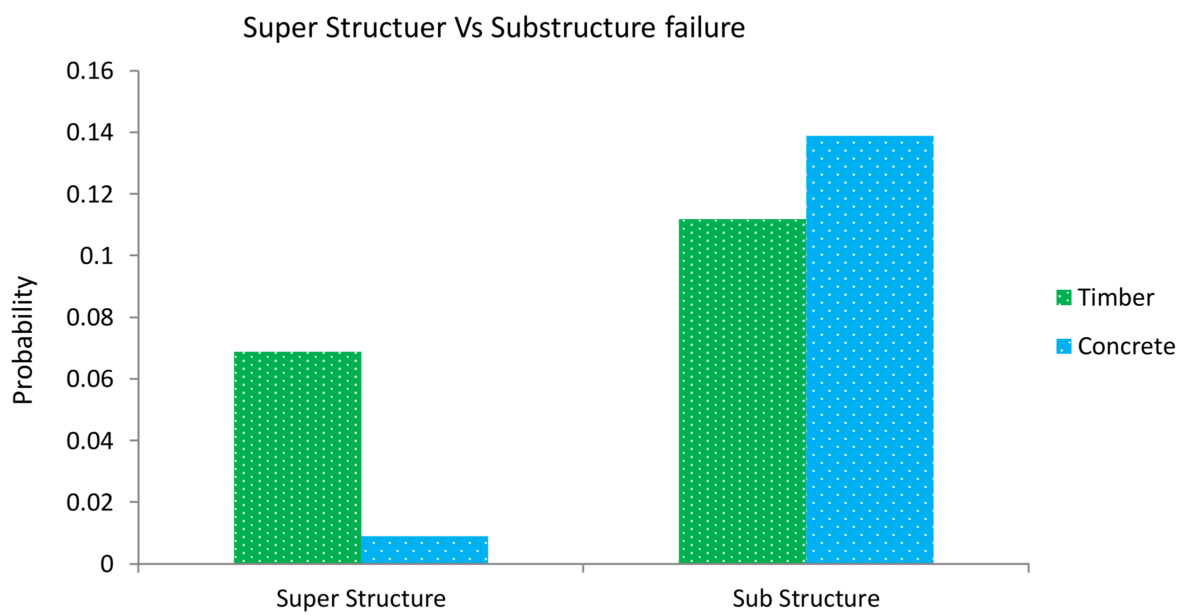


Figure 5-2: Comparison of super structure and substructure failure between concrete and timber bridges

Results indicated that substructure of concrete bridges is more sensitive to surge induced forces compared to that of timber bridges. However, it should be noted that this indication has been exaggerated by the probality of abutement failure in concrete bridges (Figure 5-3). If the probability values of abutements had been taken off, then the overall probability of substructure failure for conctre bridges would have been markedly less than that of timber bridges.

Most conctere bidges do not have a relieving slabs for abutements, and show poor compaction of the appraches. Load distribution in timber bridges are differnet to that of concrete bridges and hence it impats on the piles of concrete bridges (Eberhard el al. 1993). Timber bridges due to its specific construction method have better anchorage in their abutments compared to that of concrete bridges resulting relatively higher resilience under surge induced forces. Due to this reason timber bridges can sustain longer under scouring.

Results (Figure 5-3) indicated that the majority of the elements of timber bridges, have low resilience to cyclonic events compared to that of concrete bridges. However there was a marked variation in the probability of abutment failure in timber and concrete bridges, which impacted over all response of the substructure of concrete bridges.

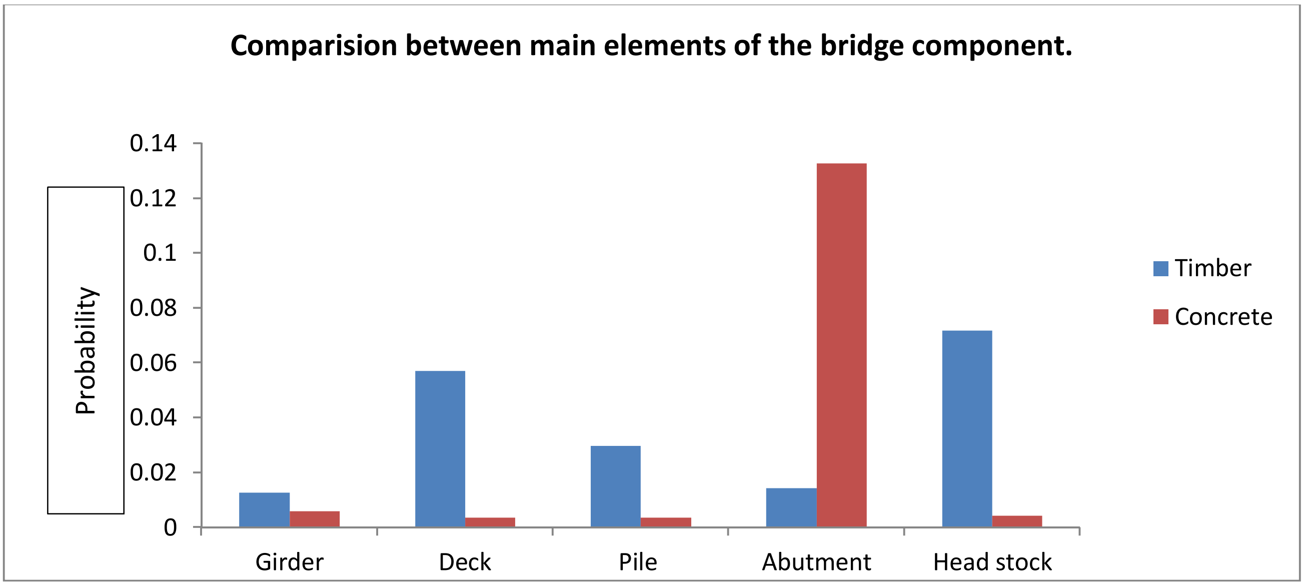


Figure 5-3 Comparison between main elements of the bridge component

Table 5.6: Comparison of mean probabilities of bridge elements in timber and concrete bridges using unbalanced paired t-test.

	Super Structure		Sub Structure		
	Deck	Girder	Pile	Abutment	Head Stock
Timber	0.056a	0.013a	0.0297a	0.007a	0.058a
Concrete	0.0036a	0.006a	0.0035b	0.065a	0.004a
Significance			P=0.03	P=0.05	

Unbalanced paired t-tests were used to compare the mean probability values. n=8 *Means followed by the same letter are not significantly different at the P<0.05 level.

Resulted showed significant variations (P<0.05) in the failure of substructure elements which is consistent with the outcomes of fault tree analysis (FTA) results. Probability of failure for other components were not found to be statistically significant (P>0.05). However, the extent of data was not adequate to draw firm conclusion.

CHAPTER 6

CONCLUTION AND FURTHER RECOMMENDATION

Existing data were not adequate to draw firm conclusions; however the resultant probability values from FTA were consistent with those values for the events in hurricanes that were reported by numerous authors in America. Based on the results following outcomes could be drawn:

- Timber bridges appear to be more susceptible to cyclones compared to concrete bridges mainly due to the attributes of its super structure. However this difference in their resilience was not found to be statistically significant.
- Surge induced forces are the main contributing factors for both super and substructure failure
- Vulnerability of sub-structure (piles and abutments) of concrete bridges under cyclonic events is significantly greater than that of timber bridges due to the characteristics of abutments, method of construction, anchorage and load distribution.

Future recommendation

Using further data for cyclones, FTA can be refined. Also the normal deterioration will have an impact on the effect due to cyclone.

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APPENDIX

Appendix A: Risk assessment

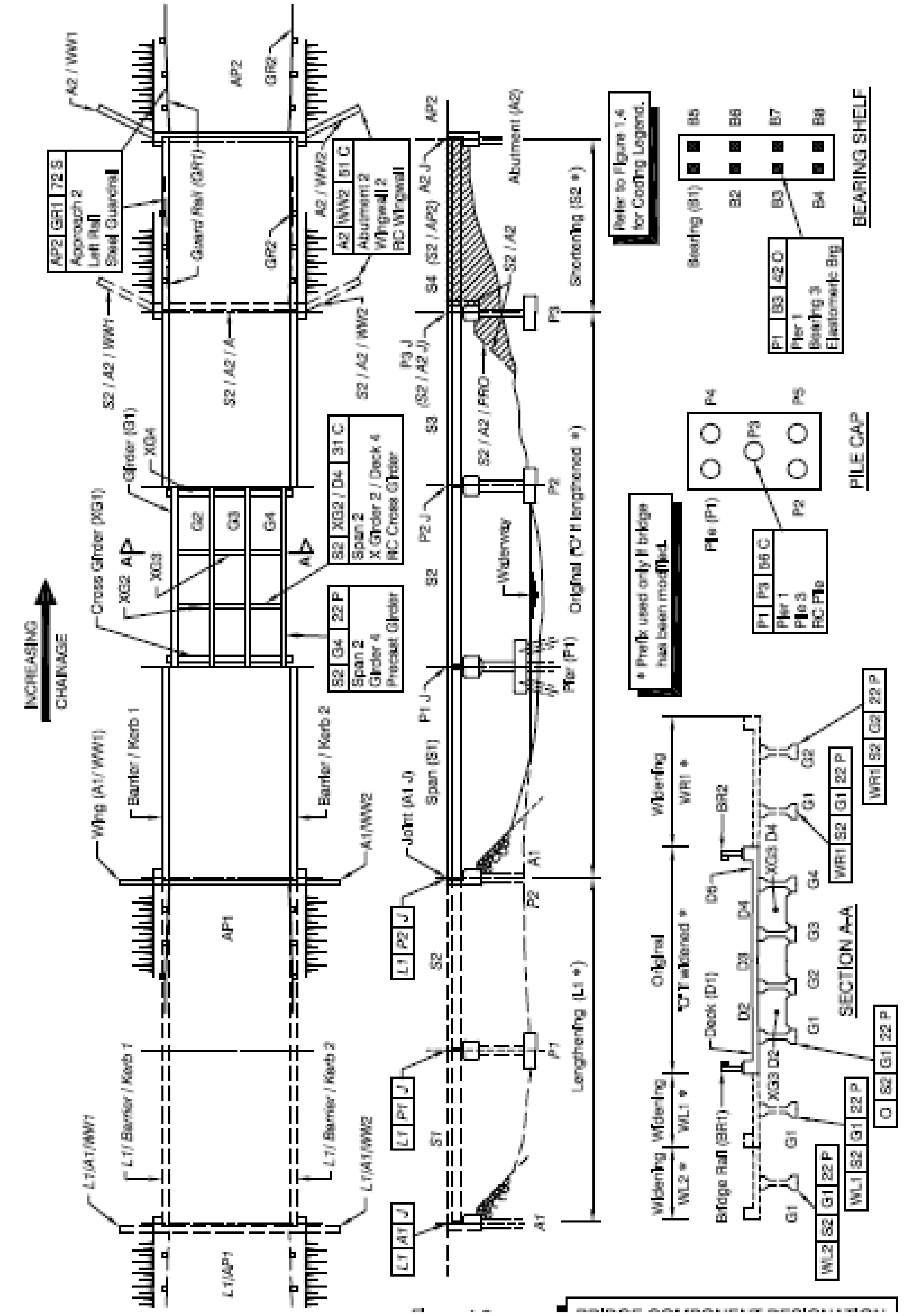
Risk Assessment

Since this study was undertaken using secondary data obtained from DTMR safety risks associated with the study was determined to be negligible.

Resource requirements

- Statistical and analytical software
- Electronic journal resources, secondary data from department of main roads
- Digital camera and image analysis software

Appendix B-Cross section of a bridge



APPENDIX B: Level 1 bridge inspection report

Routine Maintenance Inspection Report	B1/1	Sheet 1 Of 3

Structure ID..............7799..............................
Crossing....................Barron River...............
Structure Type...........Bridge..........................
Construction Type........Girder / Beam.............
Construction Material...Steel............................
Inspector...................Phil Rae........................

Bridge Name...
Road Number........32A...
Road Name ....
Owner...............Department of Main Roads......
District...............Peninsula District......................
Local Authority.....Mareeba Shire Council...........

Level 1 Inspection   Programmed ☑   Exceptional ☐

Date of Inspection.........03-SEP-2002...............
Date of Next Inspection.........03-SEP-2003............
Chainage...12.67....(km) on the ....Cairns..............to...............Mareeba...................Road

Inspection Elements (*Refer to bottom of form)	Problem (tick) Y	Problem (tick) N	Location and Comments (include maintenance activity number)	Rectified Y	Rectified N	Maintenance Required Y	Maintenance Required N	Inspection Required Y	Inspection Required N
Approaches									
1 Signs and Delineation									
▪ Missing, damaged, obscured (includes ID plate)	✓		Clean		✓	✓		✓	
2 Guardrail									
▪ Accident damage	✓		Impact, minor		✓	✓		✓	
▪ Incorrect alignment	✓		Too low		✓	✓		✓	
▪ Connection to bridge		✓			✓		✓		✓
▪ Delineators	✓		Clean and replace		✓	✓		✓	
3 Road Drainage									
▪ Blocked inlets/outlets		✓			✓		✓		✓
▪ Scour of outlets/embankment	✓		Clean high shoulders		✓	✓		✓	
4 Road Surface									
▪ Material defects* - concrete		✓			✓		✓		✓
▪ Material defects* - surfacing		✓			✓		✓		✓
▪ Settlement, depressions		✓			✓		✓		✓
▪ Rough joint transition	✓		Abutment A relieving slab		✓	✓		✓	
Bridge Surface									
5 Bridge Surface									
▪ Material defects*: surfacing		✓			✓		✓		✓
▪ Material defects*: concrete	✓		Shrinkage cracking		✓	✓		✓	
▪ Material defects*: timber		✓			✓		✓		✓
▪ Scuppers	✓		Clean and clear		✓	✓		✓	
6 Footpaths									
▪ Clean	✓		Sweep		✓	✓		✓	
▪ Even		✓			✓		✓		✓
7 Barriers									
▪ Impact Damage		✓			✓		✓		✓
▪ Loose/damaged fixings	✓		Loose bolts on hand rails		✓	✓		✓	
▪ Loose post base	✓		Loose rails		✓	✓		✓	
▪ Material Defects*		✓			✓		✓		✓
▪ Delineators	✓		Replace both sides		✓	✓		✓	
8 Expansion Joints									
▪ Loose/damaged fixings		✓			✓		✓		✓
▪ Damaged/missing seals		✓			✓		✓		✓
▪ Deck/nosing/ballast wall damage		✓			✓		✓		✓
▪ Obstructions in gap	✓		Requires cleaning		✓	✓		✓	

Routine Maintenance Inspection Report

B1/1 | Sheet 2 Of 3

Structure ID…………….7799 ……………………… **Bridge Name** ………………………………………………………

Inspection Date…………03-SEP-2003…………

Inspection Elements	Problem (tick) Y	Problem (tick) N	Location and Comments (include maintenance activity number)	Rectified Y	Rectified N	Maintenance Required Y	Maintenance Required N	Inspection Required Y	Inspection Required N
<u>**Waterway**</u>									
9 General			Clear trees and vegetation.						
▪ Trees or bushes under bridge	✓		Excessive litter. Noxious weeds –		✓	✓		✓	
▪ Debris against structure		✓	Singapre Daisy		✓		✓		✓
▪ Riverbank/Embankment Erosion		✓			✓		✓		✓
▪ Scour holes in bed		✓			✓		✓		✓
▪ Damaged bed protection		✓			✓		✓		✓
<u>**Substructure**</u> <u>**(Including culvert wingwalls)**</u>									
10 Material Defects*									
▪ Piles		✓			✓		✓		✓
▪ Footings		✓			✓		✓		✓
▪ Walls/Stems		✓			✓		✓		✓
▪ Headstocks		✓			✓		✓		✓
11 General									
▪ Forward movement of abutments/wings		✓			✓		✓		✓
▪ Blocked drains/weepholes		✓			✓		✓		✓
▪ Debris on shelf/bearing		✓			✓		✓		✓
▪ Scour/erosion of spillthrough		✓			✓		✓		✓
▪ Dampness/leakage from deck		✓			✓		✓		✓
▪ Substructure protection (over-bridges)		✓			✓		✓		✓
12 Bearings									
▪ Gap closed/decks in contact/damaged		✓			✓		✓		✓
▪ Bearing displaced/damaged		✓			✓		✓		✓
▪ Poorly seated		✓			✓		✓		✓
▪ Corroded/Seized/No lubricant		✓			✓		✓		✓
<u>**Superstructure**</u>									
13 Material defects* in:									
▪ Girders (including fasteners)		✓			✓		✓		✓
▪ Cross Girders		✓			✓		✓		✓
▪ Deck	✓		Minor cracking on kerb, exposed		✓	✓		✓	
▪ Coatings		✓	reo midstream LHS		✓		✓		✓
14 General									
▪ Debris/dirt build-up		✓			✓		✓		✓
▪ Impact damage		✓			✓		✓		✓
▪ Excessive movement/vibration		✓			✓		✓		✓
▪ Dampness		✓			✓		✓		✓
▪ Ventholes		✓			✓		✓		✓

APPENDIX C-Level 2 bridge inspection report

Structure Condition Inspection Report	B2/1	Sheet 1 Of 4

Structure ID..............7799 ....
Crossing....................Barron River...............
Structure Type............Bridge.........................
Construction Type.........Girder/Beam ....
Construction Material....Steel............................
Inspector....................Roy West ....

Bridge Name ....
Road Number......32A..
Road Name..
Owner...............Department of Main Roads ....
District..............Peninsula District.....................
Local Authority.....Mareeba Shire Council.............

Inspection Level 2 ☑ Level 3 ☐ Programmed ☑ Exceptional ☐ Underwater ☐

Date of Inspection.........03-SEP-2001 ....
Date of Next Inspection........03-SEP-2004..............

Chainage...12.67...(km) on the ....Cairns...............to............Mareeba.................Road

Component Location: Modification	Group	Component	Standard Number	Exposure Class	Quantity	Unit	Quantity Per Condition State: 1	2	3	4	Maintenance Req'd	Comments (▪ Location of item/condition ▪ Description of defects by location type, magnitude, extent ▪ References of sketches and photos (Roll / Exposure Nos))
O	AP1	AP	70O	2	1	Each	1					
O	AP1	GR	72S	2	2	Each			2			Single bolt connection to bridge only. Photo 4_07
O	AP1	PRO	53O	2	180	m²	177		3			Side 1 – slight scour at relieving slab. Photo 4_04
O	A1	J1	14S	2	8.5	Lin m			8.5			Loose plate, rattles, leaks water onto headstock. Photos 4_02, 4_08
O	S1	BR	2S	2	86	Lin m		86				All posts and rail bolts are loose. Refer to comments.
O	S1	K	3C	2	73	Lin m		73				Hairline shrinkage cracks to soffits. Photo 1_01
O	S1	WS	1C	2	310	m²		310				Slightly wavy surface, craze cracked, missing stone. Photo 4_09
O	A1	J2	15O	2	8.5	Lin m	8.5					
O	P1	J1	15O	2	8.5	Lin m	8.5					First joint in deck after P1
O	P1	J2	11O	2	8.5	Lin m		8.5				Choked with gravel. Photo 4_10
O	P1	J3	14S	3	8.5	Lin m			8.5			Choked with dirt and grass. Leaks onto bearings. Photo 4_11
O	P1	J4	15O	2	8.5	Lin m	8.5					Last joint in deck before P2
O	S2	BR	2S	2	91.2	Lin m		91.2				All post and rail bolts are loose. Refer to comments.
O	S2	K	3C	2	91.2	Lin m		91.2				Minor shrinkage cracks below on deck soffits.
O	S2	WS	1C	2	388	m²		388				Craze cracked and wavy
O	P2	J1	15O	2	8.5	Lin m	8.5					First joint in slab after P2
O	P2	J2	15O	2	8.5	Lin m	8.5					Last joint in slab before P3
O	S3	BR	2S	2	91.2	Lin m		91.2				All post and rail bolts are loose. Refer to comments.

Overall Ratings	1	2	3	4	5	Comments
Original Structure (O)			✓			Poor condition due to rusting bearings/bolts. At all spans, all bridge rail bolts are loose and the rails rattle. All bolts are lock nutted and set to be loose. The bolt holes are in the post to rail connectors are slotted. This seems to cater for the amount of movement and bounce under heavy traffic
Modification ( )						
Modification ( )						
Modification ( )						

Structure Condition Inspection Report

B2/2 Sheet 3 Of 4

Structure ID………7799 ……………………………… Bridge Name ……………………………………………………

Inspection Date……03-SEP-2001…… Inspection Level 2 ☑ Level 3 ☐ Underwater ☐

Component Location							Quantity Per Condition State					Comments
Modification	Group	Component	Standard Number	Exposure Class	Quantity	Unit	1	2	3	4	Maintenance Req'd	▪ Location of item/condition ▪ Description of defects by location type, magnitude, extent ▪ References of sketches and photos (Roll / Exposure Nos)
O	S1	XG	31S	2	4	Each	4					
O	P1	B	43S	2	4	Each			4			
B1 – hold down bolt on outside rusting badly. Photos 3_18, 3_20. B1 – Bearing through bolt head very badly rusted. Photos 3_19–20. B2 is fixed hinge bearing in Span 2. G1 rocker hold down bolt almost rusted away. Girder and bearing blistering badly. Photos 1_09, 1_11, 3_09-10. Expansion hinge bearings in span 2 rusty hold down bolts and rockers. Photos 1_12-13												
O	P1	H	54C	2	1	Each	1					
O	P1	C	56C	2	1	Each	1					
O	P1	F	59C	2	1	Each	X	X	X	X		Buried
O	S1	W	71O	2	1	Each	1					Scrubby
O	S2	G	22S	2	4	Each			4			
Rust coming through paint on bottom flanges. Photo 1_22. Ends of girders and top flange rusting at mid-span joint. Photos 1_18, 1_21. Travelling stage rails are rusting. Photos 1_15, 3_12.												
O	S2	D	20C	2	442	m^2	441		1			D1 soffit spalled at finger joint plate. Photo 3_11. Shrinkage cracks D1-D5 soffits.
O	S2	XG	31S	2	8	Each	8					
O	P2	B	43S	2	4	Each	3		1			Bearing No. 1 hold down bolt rusting badly. Photo 3_08
O	P2	H	54C	2	1	Each	1					
O	P2	C	56C	2	1	Each	1					
O	P2	F	59C	2	1	Each	X	X	X	X		Underwater
O	S2	W	71O	2	1	Each	1					
O	S3	G	22S	2	4	Each			4			G1-G4 rust coming through paint on lower flanges.
O	S3	D	20C	2	442	m^2	442					Numerous shrinkage cracks to soffits D1-D5
O	S3	XG	31S	2	6	Each	5		1			XG1 rusting over Pier 2.
O	P3	B	43S	2	4	Each			4			All 4 bearings, pedestals, bolts rusting. Photos 2_01-02.
O	P3	H	54C	2	1	Each	1					
O	P3	C	56C	2	1	Each	1					
O	P3	F	59C	2	1	Each	X	X	X	X		Underwater. Photos 2_08-09
O	S3	W	71O	2	1	Each	1					
O	S4	G	22S	2	4	Each		4				Rust spots coming through paint on all lower flanges. G4 rusting on ribs inner side at P3. Photo 2_15
O	S4	D	20C	2	442	m^2	441		1			D5 – small spall to soffit. Photo 2_11.
O	S4	XG	31S	2	6	Each	5		1			XG1 is rusting over P3.
O	P4	B	43S	2	4	Each			4			
B1-B4 rusting at base plates and bolts. Photos 2_04-06. B1 badly rusted nut on anchor bolt No. 1. Photo 3_05 (O/P4). B2/G2 expansion hinge, girder to bearing bolt head rusting badly. Photo 3_06. B2/G1 Rocker bolt rusted away. Photo 3_03. Bearing through bolt and anchor bolt rusting badly. Photos 2_16. 3_04. B3/G1, Fixed hinge, Bearing through bolt nut rusting away. Photo 3_01. B3/G1 Bearing ledge rusting. Photo 3_02. Photo 2_21 is outer face. Rusty gussets. Photo 2_20 is under side of G3 bearing ledge.												
O	P4	H	54C	2	1	Each	1					

APPENDIX D: Primary data analysis using level 1 inspection reports

			Road drainage			
			Blocked inlets/outlet	scour of outlet,embankment	matarial defects surfacings	Settlements/Depressions
Structural ID	Name	Material				
628	Six mile creek	Pre stressed Concrete	N	N	N	N
632	Bobs Creek	Pre Stressed concrete	N	N	N	N
635	Hut Creek	Concrete	N	Y-AP1/PRO 1m3 scour side1,!m3 scour side 2,A2/PR	N	N
636	Larcom creek	Pre Streesed concrete	N	Y-AP1/PRO 20M3 embankment scour	N	N
637	Raglan Creek	Pre Streesed concrete	N	Y-AP1/PRO 1m3 scour side1,!m3 scour side 2,A2/PR	Y-AP1/AP pushing typical	Y-AP1/AP 40M2 depression typical
641	Station Creek	Pre Streesed concrete	N	Y-AP2/PRO scour undermined inlet relive	N	Y-AP2/AP 30M settlemnt of relieve AP2/A
650	Ramsay Creek	Pre stressed Concrete	N	N	N	N
658	Princhester Creek	Pre Streesed concrete	N	N	N	N
662	Pine Mountain Creek	Pre stressed Concrete	N	N	N	N
664	Seven Mile Creek	Pre stressed Concrete	N	N	N	N
667	Unnamed Creek	Pre stressed Concrete	N	N	N	N
668	Deep Creek	Pre stresses Concrete	N	Y-AP1/side 2 hole in batter	N	N
669	Tooloombah Creek	Pre stresses Concrete	N	N	N	N
673	Gracemere Creek	Pre stressed Concrete	N	N	N	N
674	Middle Creek	Pre stressed Concrete	N	N	N	N
675	Neerkol creek NO1	Pre stressed Concrete	Y	Y-sever erotion	Y-road collapsed	Y-road collapsed
677	Neerkol Creek(No 2)	Pre stressed Concrete	N	Y	N	N
680	Sebastopol Creek	Pre stressed Concrete	N	N	N	N
682	Gogango Creek	Pre stressed Concrete	N	N	N	N
683	Sandy creek	Pre stressed Concrete	N	N	N	N
684	Googango Creek(NO 2	Pre stressed Concrete	N	N	N	N
690	Woolian Creek	Pre stressed Concrete	N	Y	Y	Y
692	Four Mile Creek	Pre stressed Concrete	N	N	N	N
699	Grevillia Creek	Pre stressed Concrete	N	N	N	N
703	Kroombit Creek	Pre stressed Concrete	N	Y-scoured AP2 side2	N	N
704	Dee River	Pre stressed Concrete	N	N	N	N
707	Collard Creek(No 4)	Pre stressed Concrete	N	N	N	Y-AP2/AP releiving slab settled 40MM
730	Don River	Pre stressed Concrete	N	Y-5M AP2 side1 scour to batter	N	N
754	Oaky Creek	Pre stressed Concrete	N	Y-AP1 18M scour	N	N
756	Headlow Creek	Pre stressed Concrete	N	Y-AP1/PRO 5M3 scour	N	N
757	Limestone Creek	Pre stressed Concrete	Y-AP2/PRO blocked b	N	N	N
760	Washpool Creek	Pre stressed Concrete	N	N	N	N
805	Nankin creek	Pre stressed Concrete	N	Y-embankment scour behind A1/WW1	N	N
806	Coorooman creek	Pre stressed Concrete	N	N	N	N
814	Moores Creek	Concrete	N	N	N	N
9011	Dgranite Creek	Pre stressed Concrete	N	Y-around A1-PRO side2	N	N
13350	Palm Tree Creek	Pre stressed Concrete	N	N	N	N
25380	Poison Creek	Concrete	N	N	N	N
25897	Portensia Creek(Part (	Pre stressed Concrete	N	N	N	N
34318	South Kariboe Creek	Pre stressed Concrete	N	Y-AP2 PRO scour	N	N
35784	Kianga Creek	Pre stressed Concrete	N	Y	N/A	N
			2	16	3	5
			0.048780488	0.390243902	0.073170732	0.12195122

	Bridge surface	Barriers		water way		
Rough joint transittoins	material defects-surfacing	Impact damage	Damaged missing seals	trees under bridge	Debris against structure	River bank/embankment e
N	N	N	Y-A2 joint exposed	Y-debris at AP1 GR1,tree at AP1	Y-dbris at AP1 GR1,tree at GR2	N
N	N	N	N/A	N	N	N
N	Y-S2/WS pushing,cracks	N	N/A	N	N	Y-S3/W 200M3 embankmer
N	N	N	N	N	N	N
Y-AP1/AP 30MM transition typica	N	N	N	N	N	N
N	N	N	N/A	N	N	N
N	N	N	N/A	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N/A	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	Y-S1/WS pushing	N	N/A	N	N	N
N	N	N	N/A	N	N	N
Y-Road collapsed	Y	Y	Y	Y	Y	Y
N	N	N	N	N	Y	N
N	N	N	N/A	N	N	N
N	N	Y-S5/BR2,S2/BR2	N	N	Y	N
N	N	N	N	N	Y-p3/c2	N
N	N	N	N	N	N	Y-embankment erotion at s
Y	N	N	N/A	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N/A	N	Y-GR and BR	N
N	N	N	N	N	N	Y-Span 2 exposingh P2 colu
Y-AP1/AP 40MM transition	N	N	Y-P2/J damaged seal	N	N	N
N	N	N	N/A	N	N	N
N	N	N	N/A	Y-S2/W	N	N
N	N	N	N/A	N	N	N
N	N	N	N	N	N	N
N	N	N	N/A	N	Y-timber against P2/P1	N
N	N	N	N	N	Y-debris against side1	Y-span 1 side1 embankmen
N	N	N	N/A	N	Y	N
N	N	N	N	N	Y-minor debris	N
N	N	N	N	N	N	N
N	N	N	N	N	Y-P1/P4 debris on side 2	N
N	N	N/A	N/A	N	N	N
N	N	N	N	N	N	N
N	N	N	N/A	N	Y-debris against all GR	N
N	Y	N	Y	Y	N	Y
4	4	2	2	4	12	6
0.097560976	0.097560976	0.048780488	0.048780488	0.097560976	0.292682927	0.146341463

	sub structure					
	Material defects			General		
Scour holes in bed	piles/columns/braces/	Walls/stems	Head stocks	Forward movements of abuments/	Debirs on shelf/bearir	scour/erotion of spill through
N	N	N/A	N	N	N	N
N	N	N	Y-P1-H cracking in bottom face	N	N	N
N	N	N	Y-P1/H 2M2 shallface	N	N	N
Y-S1/W 400M3 scour	N	N	N	N	N	Y-A1/PRO settled/cracked,A2/
N	N	Y-A1/A barrier wall broken	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N	Y-movement and cracking A1/WW1	N	Y-Embankment erotion water
Y-localised scour at P2/P3	N	N	N	N	N	N
Y-in water way mainly span 2	N	N	N	N	N	N
Y-ABS/A1-large scour	N/A	N	N	Y-Cracking and settlement A1,A/ABS	N/A	N
N	N	N	N	N	N	Y-settlement both ABS PRO
N	N	N	N	N	N	N
N	N	N	N	N	N	Y-A2/side1 spill throughheavy
N	N	N	N	N	N	N
N	N	N	N	Y-settlement A1/ABS	N	N
Y	Y-severly damaged	Y	Y	Y	Y	Y
N	Y-cracked	N	Y	N	N	N
N	N	N	N	Y-settlement of ABS	N	N
N	Y	N	Y	Y	N	Y
Y-localised scour P3/Column 1	N	N	N	N	N	Y-Spill through erotion at A2
Y-scour around P1.scour at bas	N	N/A	N	N	N	N
N	N	N	N	Y	N	Y
N	N	N	N	N	N	Y-both voiding
Y-scour infront of A1 PRO	N	N	N	N	N	Y-A1 Pro severly damaged.A2
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	N	N	N	N
N	N	N	Y-P2/H diagonal stress cracks	N	N	N
Y-S1/W 160M3 bed scour,S3/W	N	Y-A2/ABS bases exposed by b	N	N	N	N
Y-S1/W 160M3 bedscour,S3 50	N	Y-ABS footing voided by beds	N	N	N	N
N	N	N/A	N	N	N/A	N
Y-Span1	N	N	N	N	N	N
Y-Scour in S1/W near sill throu	N	N	N	Y-spalling at base of A1/PRO side1	N	N
Y-scouring under pier2	N	N	N	N	N	N
N	N	N	N	Y-minor settlement A2/PRO	N	Y-A1 spill through
N	N	Y	N	Y	N	N
N	N/A	N	N/A	N	N/A	N/A
N	N	N/A	N	N	N	N
N	N	N/A	N	N	N	N
Y	N	N	N	N	N	N
14	3	5	6	10	1	11
0.341463415	0.073170732	0.12195122	0.146341463	0.243902439	0.024390244	0.268292683

	super structure			
	Material defects		General	
Dampeness/leakage from deck	Girders	deck	Debris/dirt build up	impact damage
N	N	N	N	N
Y-P1/H evidence of leaking typica	Y-S1-D ASR cracking	Y-S1/K1 ASR crackin	N	N
N	N	N	N	N
N	N	N	N	N
N	N	N	N	N
N	N/A	N	N	N
N	N/A	N	Y-At A1	N
N	N	N	N	N
N	N	N	N	N
N	N/A	N	N	N
N	Y	N	N	N
N	N	N	N	N
N	N	N	N	N
N	N/A	Y-S4/D1 ASR crackin	N	N
N	N/A	N	N	N
Y	Y	Y	Y	Y
N	N	Y	N	N
N	N	N	N	N
N	N	N	N	N
N	N	N	N	N
N	N	N	N	N
Y	Y	Y	N	N
N	N	N	Y-both water way spa	N
N	N	N	N	N
N	N	N	N	N
N	N	N	N	N
N	N	N	N	N
N	N	N	Y-GR.ABUT A2	N
N	N	N	N	N
N	N	Y-S2/D1 small spall (	N	N
N	N	Y-S3/D/ASR cracks u	N	N
N	N	N	N	N
N	N	N	N	N
N	Y	N	N	N
N	N/A	N	N	N
N	N	N	N	N
N	N	N	N	N
N/A	N/A	N	Y-Dirt and Rock built (	N
N	N	N	N	N
N	N/A	N	N	N
N	N	N	N	N
3	5	7	5	1
0.073170732	0.12195122	0.170731707	0.12195122	0.024390244

				Road drainage	Road surface	
			Blocked inlets/outlet	scour of outlet,embankment	matarial defects surfacings	Settlements/Depressions
679	Valentine Creek	Timber	N	N	N	N
695	Banana Creek	Timber	N	N	Y	Y
701	North Kariboe Creek	Timber	Y-All drains blocked	N	N	N
702	Poor Mans Gully	Timber	N	N	N	Y-AP2 settled 50mm
716	Banana Creek	Timber	N	N	N	Y-minor depressioj at AP2
718	Roundstone Creek	Timber	Y-AP1/PRO MATERIAL	Y-AP2/PRO 1M3 SCOUR SIDE 1	Y-AP1/AP PUSHING/CRACK	Y-AP2/AP 9M2 DEPRESSION SIDE 1
724	Alma Creek	Timber	N	N	Y-AP2-AP debris and silt	N
725	Dee River	Timber	N	Y-AP2/PRO rivebank errosion	Y-AP1/AP silt built up	N
743	Nine Mile Creek	Timber	N	Y-AP1/PRO1/21M3 scour,AP/PRO 1m3 scour	N	Y-AP2/AP 30M2 depression
749	Maxwellton Creek	Timber	N	Y-AP1/PRO SCOURED AT A1 SIDE1 TYPICAL #4 AP1/P	Y-15M2 BROKEN AWAY	N
752	Doutful Creek	Timber	Y-AP1/PRO blocked b	Y-AP1/PRO scour side2,AP2/PRO scour 2M3	N	N
767	Marble Creek	Timber	N	Y-GR,near WS	Y-AP1 side 2 bitument mo	N
768	Delcalgil Creek	Timber	N	Y-0.5M scour side1	Y-AP2 has silt built up,AP2	N
769	Ridler Creek	Timber	Y-AP2 pro blocked	N	N	N
770	Boyne River (No1)	Timber	Y-AP1/PRO side 1-0.5	Y-side2	N	N
771	Boyne River (NO 2)	Timber	Y-5M silted side 2.5m	Y-AP1+AP2 5M scour on side	Y-4M missing span 1,50MM	N
774	Limestone Creek	Timber	N	N	Y-holes in AP2,wearing sur	N
791	Stringy Bark Creek	Timber	N	N	N	N
			6	0.5	9	5
			0.333333333		0.5	0.277777778

			Expansion joints		water way	
Rough joint transittoins	material defects-surfacing	Impact damage	Damaged missing seals	trees under bridge	Debris against structure	River bank/embankment e
N	N	N	N/A	N	Y	N
Y	Y-All typical degraded	N/A	N/A	N/A	N	N/A
N	N	N	N	N	N	N
Y-AP2 settled 60MM	N	N	N	N	N	N
N	N	N	N/A	N	N	N
Y-AP2/AP 50MM TRANSITION	Y-S1/WS CRACKING/PEELIN	N/A	N/A	N	N	N
N	N	N/A	N/A	N	Y-S1/W	N
N	Y	Y-S2-BR1	N/A	N	Y-S5-W	N
Y-AP2/AP 40MM transition	N	N/A	N/A	N	N	N
N	N/A	N/A	N/A	N	Y-S4/W FALLEN TREE/DEBRIS	N
N	Y-S1/WS extensive crackin	N/A	N/A	N	Y-S1/W	N
N	N	N/A	N/A	N	Y	N
N	Y-pavement cracked	N/A	N/A	N	Y-large logs	N
N	N	N/A	N/A	N	Y	N
N	N	N/A	N/A	N	Y-Large debris AP2 GR and span	N
N	N	N	N/A	N	Y-up to 5m side1,Large log BR 2	N
N	N	N	N	N	Y-AGAINST A2	N
N	N	N/A	N/A	N	Y-S1/W DEBRIS	N
4	5	1	0	0	12	0
0.222222222	0.277777778	0.055555556			0.666666667	0

Scour holes in bed	piles/columns/braces/\	Walls/stems	Head stocks	Forward movements of abuments/v	Debirs on shelf/bearin	scour/erotion of spill through	Dampeness/leakage from deck	Girders	deck	Debris/dirt build up	impact damag
Y-scouring around P1 and P2	N	N	N	N	N	N	N	N	N	N	N
N/A	Y-cracked/rotten splice	N/A	Y-P1/*H2 rotating at pile seat*	N	N	Y-both a1/A2	Y-All typical	Y-S1/G2vwell degraded	Y-breaking,minor ro	N/A	N/A
N	N	N	N	N	N	N	N	N	N	N	N
Y-MS PROPS scoured side 1	N	N	N	N	N	N	N	N	N	N	N
N	N	N	N	N	N	Y-A2	N	N/A	N/A	N	N
N	N	Y-A1/ABS DROPPED 100MM/	Y-P1/H1 PITTING	N	N	N	N	PUSHING/CRUSHING,P1/COR 1	N	N	N
N	N	N	N	N	N	Y-A1-ABS not supported	N	N	N	N	N
N	N	N	N	N	N	N	N	N	N	Y-AP1-AP	N
N	N	Y-A1/ABS dropped 200MM/A.	Y-A2/H2 15MM gap from A2/P4	Y-A2/WW2 220MM FORWARD AT TO	N	Y-A2/A 300MM X 400MM FULL \	Y	N/A	N/A	N	N
N	N	N	N	N	Y	N	N	N	N	N	N
N	Y-A2/WW1 pile loose a	Y-A2/WW1 top plsnk displace	N	N	Y-A1/H debris	Y-A2/A scour voids,1.5M3 scou	N	N	N	N	N
N	N	N/A	N	N	N	Y-on bearing shelf	N	N	N	N	N
N	N/A	N	N/A	N	N	N	N	N/A	N/A	N	N
N	N	N/A	N	N	N	N	N	N	N	N	N
N	N	N/A	N	N	N	N	N	N	N	N/A	N/A
N	N	N	N	N	N	N	N	N	N	N	N
Y-MINOR SCOUR AT BASE A1/A	N	N	N	N	N	N	N	N	N	N	N
N	Y	N	N	N	N	N	N	Y	N	N	N
3	3	3	3	1	2	6	2	3	1	1	
0.166666667	0.166666667	0.166666667	0.166666667	0.055555556	0.111111111	0.333333333	0.111111111	0.166666667	0.055555556	0.055555556	

APPENDIX E:Primary data analysis using level 2 inspection reports

Struture ID	Name	Material	Original Struture(B)				Original Struture(A)				obabili	No of Girder	Span1(Before)				Span1 (After)				Change of probability
			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
743	Nine Mile Creek	Timber			X					X	0.25	5	4	1			4	1			0
752	Doutful Creek	Timber			X					X	0.25	5		5				5			0
768	Delcalgil Creek	Timber			X				X		0	4		4				4			0
769	Ridler Creek	Timber			X					X	0.25	4		3		1		4			0
770	Boyne River No 1	Timber				X				X	0	4		4					4		0.13
718	Roubdstone Creel	Timber				X				X	0	7		5	2					7	0.342857143
771	Boyne River No 2	Timber				X				X	0	4		2	2			2	2		0
695	Banan Creek	Timber			X					X	0.25	5	3	1	1			4	1		0.05
											0.125										

Span 2(Before)				Span 2(After)				Proability	Span3 (B)				Span3(A)				Probability	Span4(B)				Span 4(A)				Probability
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4	
	5				5			0									N/A									N/A
	5				5			0		5				5			0		5				5			0
	4				4			0		4				4			0									N/A
	2	2			2	1	1	0.25		2	2			4			0		1	2	1		3		1	0
	3	1			3	1		0		3	1			3		1	0.25		4				1	3		0.13
	5	1	1				7	0.358333333		5	2					7	0.342857143	1	3	3					7	0.331428571
	1	2	1		1	2	1	0		1	3			2	2		0		1	3			1	3		0
3	2				5			0.05	5					5			0.05									N/A

Span 5(B)				Span 5(A)					Probability	Span 6(B)				Span 6(A)					Probability	Probability of girder fauilure
1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			
									N/A										N/A	0
									N/A										N/A	0
									N/A										N/A	0
	3	1			3	1			0		4				4				0	0.010416667
									N/A										N/A	0.031875
									N/A										N/A	0.049364286
									N/A										N/A	0
									N/A										N/A	0.01
																				0.012706994

S1(B M2)				S1(A)				Probability	S2(B)				S2(A)				Probability	S3(B)				S3(A)				Probability
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4	
	59				59			0		57				57			0									N/A
	69				69			0		60				60			0		63				63			0
	39		5		34		10	0.38		39		5		34		10	0.38		40		5		35		10	0.38
	14.4				14.4			0		23.6				23.6			0		25.4				25.4			0
	37.4				37.4			0		30.4				30.4			0		32.6				32.6			0
	54	17			54	17		0		71				61	10		0.13		63				53	10		0.13
	33				33			0		29.6				29.6			0		30.4				30.4			0
71					71			0.05		62				62			0	70					70			0.05

No of piles	A1(B)				A1(A)				Probability	No of pile	P1(B)				P1(A)				Probability	No of piles	P2(B)				P2(A)				Probability
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
4	3	1			2	2			0.05	4	3	1			1	2		1	0.16										N/A
7	4	1	2			4	3		0.066	4	2	2			2		1	1	0.255	4		3	1			3	1		0
3	ot visible				not visible				NV	3		2	1			2	1		0	3		3				3			0
3		3				2		1	0.38	3		3				2		1	0.38	3		2	1			2	1		0
3		2	1			2		1	0.25	3			2	1		2		1	0	3		3				3			0
7	3	2	1	1		5	1	1	0.05	5	5					3	2		0.102	5	4	1				5			0.05
3			3					3	0.25	3		1	2			2		1	0.25	3				3				3	0
6	1		5			6			0	4	1	2	1			1	3		0.1033333	4	1	1	1	1			1	3	0.27

S4(B)				S4(A)				Probability	S5B)				S5(A)				Probability	S6(B)			S6(A)					Probability og deck failure
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	4	1	2	3	4		
								N/A									N/A								N/A	0
	70				70			0									N/A								N/A	0
								N/A									N/A								N/A	0.38
24.5					24.5			0.05	24.6					24.6			0.05	25.5				25.5			0.05	0.027028986
	31.2				31.2			0									N/A								N/A	0
	71				61	10		0.13									N/A								N/A	0.014130435
	30.8				30.8			0									N/A								N/A	0
								N/A									N/A								N/A	0.034729064
																										0.056986061

No of pil	P3(B)				P3(A)				Probability	No ofpile	P4(B)				P4(A)				Probability	No of pil	P5(B)				P5 (A)				Probability	No of piles	A2(B)				A2(A)				Probability	robability of pile failur
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
									N/A										N/A										N/A	9	2	2	2	3	2	2	2	3	0	0.012352941
4	3	1				3		1	0.1325										N/A										N/A	8	1	5		2		5		3	0.215	0.024759259
									N/A										N/A										N/A	3	ot visible				not visible				0	0
3		2	1			1		2	0.315	3	1	2				2		1	0.215	3		3				2		1	0.38	3	1	2				1	1	1	0.186666667	0.088412857
3		2	1				1	2	0.253333333										N/A										N/A	3			1	2			1	2	0	0.033553333
5		4	1			4	1		0										N/A										N/A	7	1	3	3			5	1	1	0.15	0.012137931
3			2	1			1	2	0.25										N/A										N/A	4		2	1	1		2	1	1	0	0.046875
									N/A										N/A										N/A	8	6	2				8			0.05	0.019227273
																																								0.029664824

Abutment (Approh1 B)				Abutment (Aprroah 1(A))				robabilit	utment 2 (Approh2				Abutment 2 (Approh2 B)				Probability		No of sheeti	Abutment Sheeting(A1-B)				Abutment Sheeting (A2-A)				Probability	lo of sheetin	Abutment Sheeting (A2-B)				Abutment Sheeting(A2-A)					Probability of abutment sheeting failu
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4				1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
								N/A									N/A	0	14			13	1			13	1	0	58		52	6			52	6		0	0
								N/A									N/A	0	15		15				15			0	14		14				14			0	0
	1				1			0		1				1			0	0	3.6		3.6				3.6			0	3.6		3.6				3.6			0	0
								N/A									N/A	0	5		5				5			0	16		16				14	2		0.016	0.012380952
								N/A									N/A	0	5		5					5		0.13	4		4				4			0	0
								N/A									N/A	0	18		18				18			0	20		20				20			0	0
								N/A									N/A	0	12.6		12.6				12.6			0	18		18					18		0.13	0.076470588
								N/A									N/A	0	26		26				26			0	26	6	19	1			26			0.05	0.025
																		0																					0.014231443

No of head st	A1 (B)				A1(A)				No of head s		Head stock (Pile 1 B)				Head stock (Pile 1 A)				
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
2		2				2			0	2	2					2			0.05
2	2					2			0.05	2		2					1	1	0.255
0									N/A	1			1					1	0.25
2	1	1				1		1	0.215	2	1	1				2			0.05
2		2				2			0	2		1	1			1		1	0.25
2	2					2			0.05	2				2		1		1	0
2		1		1			1	1	0.13	2		1	1				1	1	0.19
2	1	1				2			0.05	2	1	1				2			0.05

Noof head st	Head stock (Pile 2 B)				Head stock (Pile 2 A)					No of h	Head stock (Pile 3 B)				Head stock (Pile 3 A)				No c
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
									N/A										N/A
2	2					1	1		0.15	2	1	1				1	1		0.09
1		1				1			0										N/A
2			2				2		0	2		1	1				1	1	0.19
2				2				2	0	2		2				1		1	0.38
4	4					3	1		0.0825	4	4					4			0.05
2			2					2	0.25	3		1		2		1		2	0
2		2				2			0	2	1	1				2			0.05

of head s	Hesad stock (pile 4 B)				Hesad stock (pile 4 A)					No Of HS	Head stock (pile 5 B)				Head stock (pile 5 B)			
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4
									N/A									
									N/A									
									N/A									
2	1		1			2			0.05	2		1	1			1	1	
									N/A									
									N/A									
									N/A									
									N/A									

	No of HS	Head Stock (A2 B)				Head Stock (A2 A)					Probability of head stock fa
		1	2	3	4	1	2	3	4		
N/A	2	2				2				0	0.008333333
N/A	2	2					1	1		0.115	0.066
N/A										N/A	0.125
0	2	1	1				2			0.05	0.04625
N/A	2				2			1	1	0.25	0.088
N/A	4		3		1		3		1	0	0.0578125
N/A	2				2			1	1	0	0.051818182
N/A	2	1	1				2			0.05	0.025
											0.058526752

No of Corb	Pile 1 corbles (B)				Pile 1 corbels(A)					No of (	Pile 2 corbels (B)				Pile 2 Corbels (A)					No of cc	Pile 3 corbels (B)				Pile 3 corbels (A)				N
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
5		5				5			0										N/A										N/A
5		4	1			4		1	0.25	5		5				5			0	5		5				4	1		0.13
4		4				4			0	4		4				4			0										N/A
4		4				1	3		0.13	4		4					4		0.13	4		4					4		0.13
4			2	2				4	0.25	4		3		1		2	1	1	0.13	4		3		1			3	1	0.13
7	1	3	1	2				7	0.364	7	1	1	3	2				7	0.312	7		2	4	1				7	0.29333
4		4				3	1		0.13	4		4				4			0	4		4				4			0
5	2	3				5			0.05	5	1	4				4	1		0.09										N/A

lo of corbe	Pile 4 coels (B)								No	of corb	Pile 5 coels (B)				Pile 5 cobels (A)					Probability of corbels failure
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
									N/A										N/A	0
									N/A										N/A	0.025333333
									N/A										N/A	0
4	2	1	1			3		1	0.1167	4		2	2			1	3		0.13	0.0316875
									N/A										N/A	0.0425
									N/A										N/A	0.046142857
									N/A										N/A	0.010833333
									N/A										N/A	0.014
																				0.021312128

	Struture ID	Name	Material	Original Struture(B)				Original Struture(A)				obabili	No of Girde	Span1(Before)				Span1 (After)				hange of probability
				1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
1	708	Collard Creek NO	Pre streesed cocrete			X					X	0.25	8	4	4			4	4			0
2	650	Ramsay Creek	Pre streesed cocrete		X				X			0	N/A									N/A
3	674	Middle Creek	Pre streesed cocrete		X					X		0.13	N/A									N/A
4	680	Seastopol Creek c	Pre streesed cocrete		X					X		0.13	N/A									N/A
5	707	Collard Creek No4	Pre streesed cocrete				X			X		0	8	4	4				8			0.05
6	756	Hedlow Creek	Pre streesed cocrete		X				X			0	N/A									N/A
												0.085										

Span 2(Before)				Span 2(After)				Proability	Span3 (B)				Span3(A)				Probability	Span4(B)				Span 4(A)				Probability
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4	
4	4			1	4	3		0.09	4	4			2	6			0.05									N/A
								N/A									N/A									N/A
								N/A									N/A									N/A
								N/A									N/A									N/A
4	4				8			0.05	3	4	1			8			0.05									N/A
								N/A									N/A									N/A

Span 5(B)				Span 5(A)					Probability	Span 6(B)				Span 6(A)					Probability	Probability of girder failure
1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			
									N/A										N/A	0.005833333
									N/A										N/A	N/A
									N/A										N/A	N/A
									N/A										N/A	N/A
									N/A										N/A	0.00625
									N/A										N/A	N/A
																				0.006041667

S1(B M2)				S1(A)				Probability	S2(B)				S2(A)				Probability	S3(B)				S3(A)				Probability
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4	
	160				160			0		160				160			0		160				160			0
16				14	2			0.00625	16				14	2			0.00625	16				16				0
15	1			15		1		0.008666667	16				16				0	16				16				0
19				19				0	18				18				0	19				19				0
	176				176			0		175	1			176			0		175.5	0.5			176			0
14	1		1	14	2			0.027142857	15	1			13	2	1		0.01533333	15			1	14	1	1		0.00333333

S4(B)				S4(A)				Probability	S5B)				S5(A)				Probability	S6(B)			S6(A)					Probabilty Of Deck failure
1	2	3	4	1	2	3	4		1	2	3	4	1	2	3	4		1	2	4	1	2	3	4		
								N/A									N/A								N/A	0
								N/A									N/A								N/A	0.004166667
								N/A									N/A								N/A	0.002083333
19				19				0									N/A								N/A	0
								N/A									N/A								N/A	0
								N/A									N/A								N/A	0.015269841
																										0.00358664

No of piles	A1(B)				A1(A)				Probability	No of pile	P1(B)				P1(A)				Probability	No of piles	P2(B)				P2(A)				Probability	No of pil
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
									N/A										N/A	2	ot visible								0	
5	ot visible								NV	4	4				3	1			0.05	4	4				4				0	
5	ot visible				not visile				NV										N/A										N/A	
6	6				2	4			0.05	6	6				6				0	6	6				5		1		0.25	6
									N/A	2	buried				buried				0	2	buried				buried				0	
5	ot visible				not visible				NV	5	5				5				0	5	5				5				0	

P3(B)				P3(A)				Probability	No ofpile	P4(B)				P4(A)				Probability	No of pil	P5(B)				P5 (A)				Probability	No of piles	A2(B)				A2(A)				Probability	robability of pile failur
1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
								N/A										N/A										N/A										N/A	0
								N/A										N/A										N/A	5		5				5			0	0.002777778
								N/A										N/A										N/A										N/A	0
6				5		1		0.25										N/A										N/A	6	6				6				0	0.018333333
								N/A										N/A					0					N/A										N/A	0
								N/A										N/A					0					N/A	5	ot visible				not visible				NV	0
																																							0.003518519

Abutment (Approh1 B)				Abutment (Aprroah 1(A))					utment 2 (Approh2				Abutment 2 (Approh2 B)				Probability		No of sheeti	Abutment Sheeting(A1-B)				Abutment Sheeting (A2-A)				Probability	lo of sheetin	Abutment Sheeting (A2-B)				Abutment Sheeting(A2-A)				Probability Of abutment sheeting	
1	2	3	4	1	2	3	4	robabilit	1	2	3	4	1	2	3	4				1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
	1				1			0			1				1		0	0	10		10				10			0										N/A	0
1				1				0	1				1				0	0	12		12				12			0										N/A	0
1				1				0	1					1			0.05	0.025	14	13		1				14		0.23214286										N/A	0.232142857
	2*			2*				0	2*				1		1		0.25	0.063	18	16.5			1.5	16.5			1.5	0	8	7			1	7		1		0	0
		1				1		0			1			1			0	0	10				10				10	0	15		14	1					15	0.371	0.2228
1				1				0	1					1			0.05	0.025	16	15		1				16		0.234375	10			10				2	8	0.2	0.221153846
																		0.019																					0.112682784

No of head s		Head stock (Pile 1 B)				Head stock (Pile 1 A)				Noof head st		Head stock (Pile 2 B)				Head stock (Pile 2 A)					No of h	Head stock (Pile 3 B)				Head stock (Pile 3 A)				No o
		1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4	
N/A	1		1				1			0	1	1				1				0										N/A
N/A	1	1				1				0	1	1				1				0										N/A
N/A	1	1				1				0	1	1					1			0.05										N/A
N/A	2	2				2				0	2	2				2				0	2	2				2				0
N/A	1		1				1			0	1		1				1			0										N/A
N/A	1	1				1				0	1	1				1				0										N/A

of head s	Hesad stock (pile 4 B)				Hesad stock (pile 4 A)					No Of HS	Head stock (pile 5 B)				Head stock (pile 5 B)					No of HS	Head Stock (A2 B)				Head Stock (A2 A)				Probability of head stock fa	
	1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4			1	2	3	4	1	2	3	4		
									N/A										N/A										N/A	0
									N/A										N/A										N/A	0
									N/A										N/A										N/A	0.025
									N/A										N/A										N/A	0
									N/A										N/A										N/A	0
									N/A										N/A										N/A	0
																														0.004166667