Vulnerability of road bridge infrastructure under extreme flood events

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Abstract

Road network and critical road structures such as bridges, culverts and floodways have a vital role before, during and after extreme events to reduce the vulnerability of the community being served. Understanding the resilience of existing structures to known natural hazards empowers the road authorities in risk mitigation and emergency management. Major resources available to researchers to address the complex problem are the recent case studies of extreme events where failures of infrastructure and resultant impact on community have been captured by some road authorities. For example, 2010-2011 floods in Queensland in Australia had a huge impact particularly on central and southern Queensland resulting in the state owned properties such as 9170 km road network, 4748 km rail network, 89 severely damaged bridges and culverts, 411 schools and 138 national parks.

The paper presents a detailed analysis of the case study of 2013 floods in Lockyer valley region in Australia to identify the critical failure mechanisms of road bridge structures exposed to flood events. In the region, 43 out 46 bridges were damaged due to the 2013 flood. Major failure mechanisms of bridge structures have been identified as scouring of abutments and piers, damage to bridge decks due to urban debris impact and severe damages to bridge approach ramps. A framework comprising of a combination of the concept of fault tree method and damage index is proposed for vulnerability modelling of bridges for an extreme event.

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Introduction

The recent flood events in Queensland, Australia had an adverse effect on the country's social and economic growth. Queensland state controlled road network included 33,337 km of roads and 6,500 bridges and culverts [1]. 2011-2012 flood in Queensland produced record flood levels in southwest Queensland and above average rainfall over the rest of the state [2]. Frequency of flood events in Queensland, during the past decade appears to have increased. In 2009 March flood in North West Queensland covered 62% of the state with water costing $234 million damage to infrastructure [3]. 2010-2011 floods in Queensland had a huge impact particularly on central and southern Queensland resulting in the state owned properties such as 9,170 road network, 4,748 rail network, 89 severely damaged bridges and culverts, 411 schools and 138 national parks [4]. Approximately 18,000 residential and commercial properties were significantly affected in Brisbane and Ipswich [5] during this time. More than $42 million support was provided to individual, families and households while more than $121 million in grants have been provided to small businesses, primary producers and not-for-profit organizations. Furthermore, more than $12 million in concessional loans to small businesses and primary producers have been provided [4]. The Australian and Queensland governments have committed $6.8 billion to rebuilding the state.

Pritchard [2] identifies that urban debris, such as cars, and the insufficient bridge span to through the debris are main cause for damaging bridges in the aftermath of 2011/2012 flood in Queensland. Using 2013 flood event in Lockyer Valley, Lokuge and Setunge [6] concluded that it is necessary to investigate the failure patterns and the construction practices adopted during the initial construction and rehabilitation stages in the lifetime of bridges. These findings raised a question that what are the failure mechanisms and contributing factors which require consideration in designing of bridges to be resilient to extreme flood events.

Methodology

Delivering resilience requires a cyclic practice of identification, assessment, addressing and reviewing [7]. This research paper aims at the identification stage of this cycle which is shown in Figure 1. At the identification stage, a case study should be selected to analyse the parameters that are affecting the functionality of the infrastructure and to find the impact of the element of failure towards the overall performance of the infrastructure. Although resilience and vulnerability are widely accepted terms to measure the performance of a structure, the authors have investigated the use of damage index instead. Blong [8] used a damage index to evaluate the performance of buildings and it 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:

$$\text{Damage index} = \frac{\text{Cost for repair}}{\text{Cost of replacement}}$$

Estimates of downtime and repair/replace costs are important factors for loss modelling of the extreme events [9]. The same authors reported that these costs can be estimated based on the inspection reports and estimates, costs of work completed and bid estimates. It is reported that the normalized repair cost (repair cost/deck area) increased by a factor of 25 when moving from slight to moderate damage, and a factor of 8.5 when moving from moderate to extensive damage.

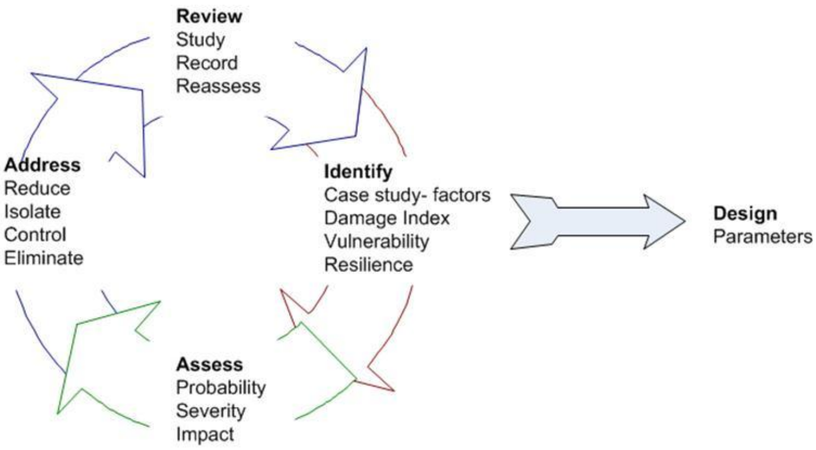

Figure 1: Delivering resilience

Evaluating or re-evaluating resilience can be related to the aftermath of an event, a near miss, or event affecting a similar infrastructure elsewhere. There are many ways that a bridge could be damaged in an extreme flood event. If the structure is completely inundated during the flood, the damage to the property depends on the length of time it was submerged as well as the elements collected around or passing the structure. Even after the flood water recedes, extra care should be taken to inspect the supports of the bridges. Approaches of a bridge could be damaged due to debris impact, settlement or depressions. Debris against substructure and superstructure, bank erosion and damage to scour protection will damage the waterways. Movement of abutments, wing walls, piers, rotation of piers and missing, damaged dislodged or movement of seating of the bearings are the major reasons for substructure failure. Superstructure could be damaged due to the debris on deck, rotation of deck, dipping of deck over piers or damage of girders. Due to any of these reasons, the members of a bridge could be damaged and bridge may not be completely functional. Table **1** shows the main failure criteria reported in the literature for a concrete girder bridge [10].

Table 1 Failure criteria for bridges in a flood event [10]

Element		Failure criteria	Influence on failure
Superstructure	Beam or girder	Unseating (loss of span)	Collapse
	Deck	Damage due to debris and built up of mud, undermining	Local damage, may be collapse
	Approaches	Missing, damaged or obscured signs and delineation, guardrails Blocked inlets/outlets Missing, damaged, settlement or depression of road surface	Doesn’t lead to failure Some restrictions Local damage, may lead to collapse, may restrict use
	Surface	Missing, damaged, scuppers blocked	Restrict use
Substructure	Pier or column	Movement, rotation and scour Moment damage, shear damage, moment and shear damage, inadequate ductility capacity	Local damage, may be collapse
	Abutment	Wingwall, back wall damage, inclination of abutment, damage to shear keys	Local damage, may be collapse
	Bearing	Missing, damaged or dislodged and poorly sealed	Local damage, may be collapse
	Footing	Pile, footing damage	Local damage, may be collapse
Other	Footpath	Damaged	Local damage, restrict use
	Barriers/handrails	Damaged, missing fixing, loose post bases	Local damage, restrict use
	Expansion joints	loose or damaged, missing or damaged seal, obstructions in gap	Local damage, restrict use

In developing a vulnerability model for bridges, understanding of the contributing factors which will lead to closure of a bridge and the associated roadway is an essential measure to be established. Whilst the damage index will offer the level of damage to the structure, it doesn’t allow identification of the probability of bridge closure at a given intensity of an extreme event. Fault tree method [11] can be used to establish this relationship.

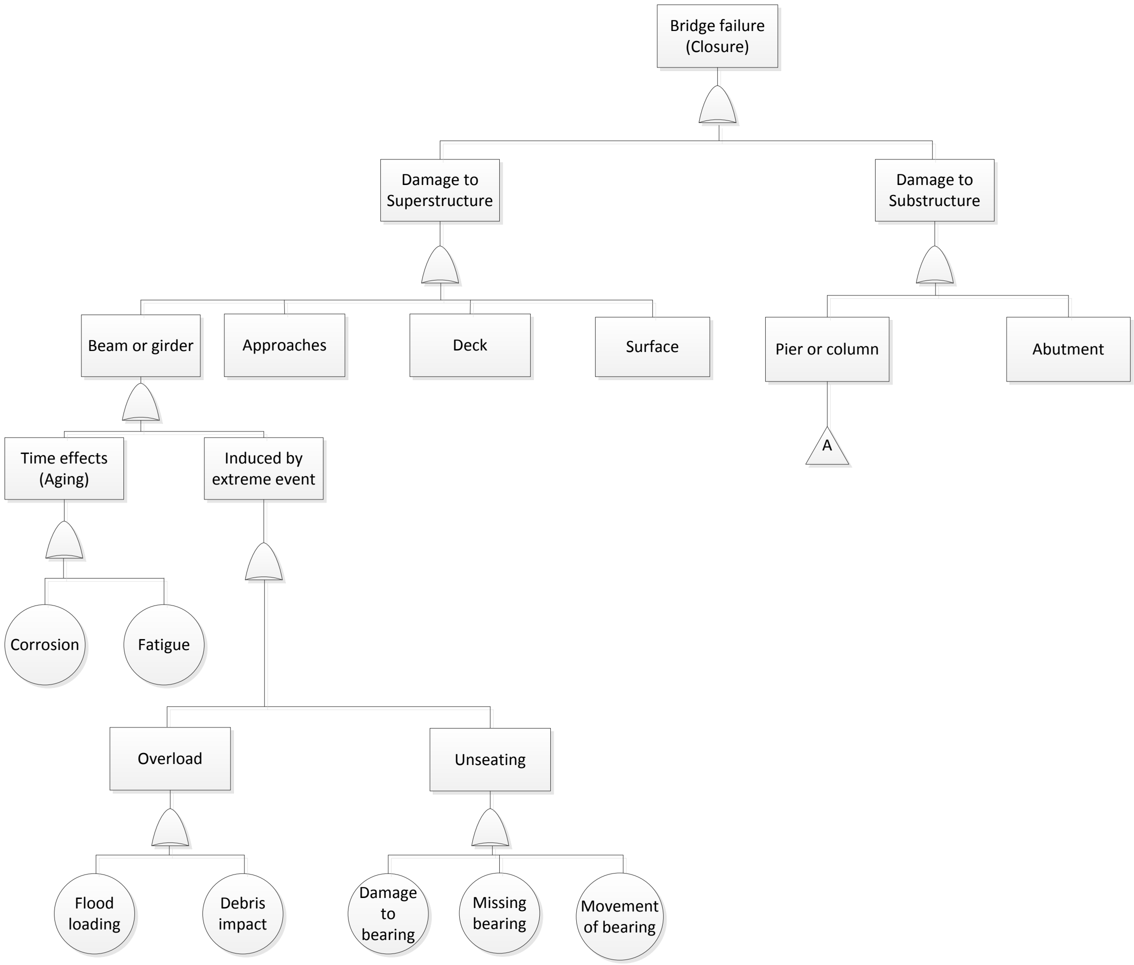

Figure 2: Concrete bridge fault tree

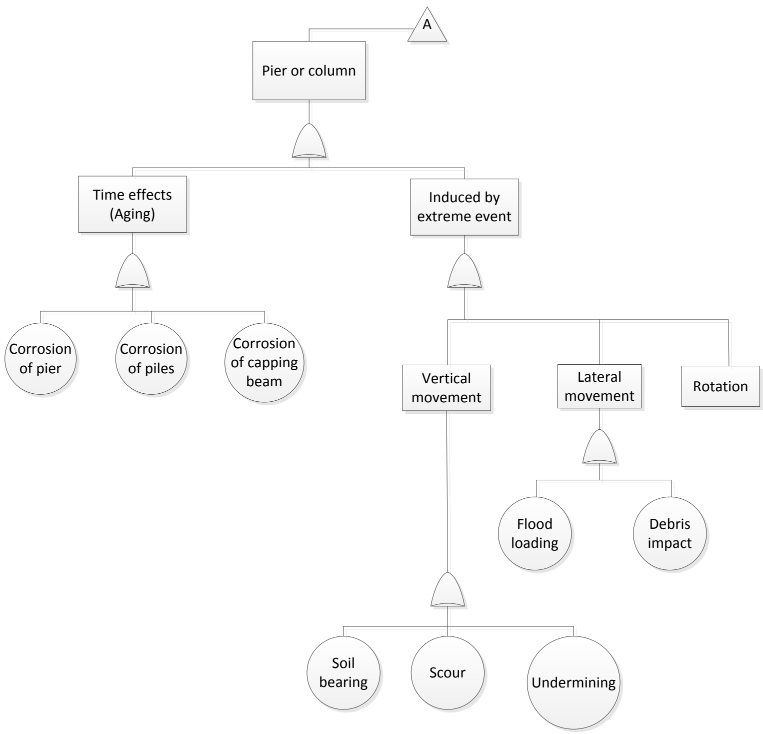

Figure 3: Sub-tree for pier/column

FHWA [11] used a fault tree diagram to establish the potential failure mechanisms and their interactions in a complex system such as a bridge. This method is proposed as a qualitative method to be used by bridge designers to improve designs and prevent failure [11]. However, if the probability of occurrence of contributing factors can be established, fault tree can be used to establish the probability of occurrence of the top event [12]. A possible fault tree diagram developed based on the information in Table 1 is shown in Figure 2. Due to the limitations of the length of this paper, only two branches have been expanded. Figure 3 shows the sub-tree for pier/column.

Case study

Lockyer Valley Region of Queensland has been selected as a case study. 2011/2012 floods had severely affected road and bridge infrastructure in the region which enormously impacted on the community in the Lockyer Valley region. This case study aims at identifying all possible attributes of bridges contributing to failure such as bridge approaches, bridge surface, waterway, bridge substructure, bridge superstructure etc. It further analyses the failure criteria/ mode of failure of bridges and identifies the relationship of the component failure of a bridge to the overall failure of the infrastructure system. Lockyer Valley Regional Council (LVRC) has compiled a comprehensive bridge inspection reports for about 46 bridges in the region before they open the bridges for traffic after the flood has receded. The study on this report indicated that the damage to bridge structures are complex and requires a detailed knowledge of underlying design principles, current classification of roads/bridges as well as construction methods adopted during different periods of design and construction. Critical observation of this bridge inspection data that included the photos of the affected bridges revealed that the failure of the bridges was primarily due to the impacts on the attributes of bridge such as bridge approaches, abutments, wing walls and misalignment of piers. The report also revealed that some of the bridges were inundated as long as 96 hours and the fill under the relieving slab had undermined. The impact load of the huge rocks, ship containers, vehicles and the other unexpected debris that were carried along the flood water with high velocity was the primary cause of damage to bridge abutments, wing walls and piers. Each report further included about the damages to services by inspecting the damage to brackets or conduits. Finally it gives recommendations such as bridge ok to open or bridge requires work prior to opening or further assessment required. LVRC completed such inspection reports for 46 bridges in the Lockyer Valley region.

Failure mechanisms of bridges

In a performance based design it is important to investigate the consequences of individual member behaviour on the performance of the structural system [13]. Information captured from the case study shown in Table 2, clearly indicates the factors contributing to bridge closure in the Lockyer valley case study. Some bridges have failed to provide the designed function due to the of loss of bridge approach while some other bridges have failed due to scouring at the bridge pier or bridge abutment/wing wall etc. **Error! Reference source not found.** summarizes the details of failure of some selected bridges in the region including the extent of the damage to the bridge and the possible design standard used.

Fault tree analysis

Using the fault tree diagram shown in Figures 2 and 3, contribution of failure of bridge components to closure of a bridge can be identified. The damage index can then be used to determine the period of closure. A bridge with small vertical clearance between the underside of the bridge and the waterway could be damaged due to the debris flow, impact load from boulders and storm surge in a flood. These will add additional lateral loads on the piers and girders. Scour damage which may accompany the other modes of failure, include scour and erosion of the abutment, piers, slope failure and undermining of the approaches.

Table 2: Details of damaged bridges

Bridge Name	Road Type	Possible Codes used for Design	Mode of failure	Affected component	OK to open	Requires work before opening	Further assessment required
Peters Bridge	Rural Access		Both run on slabs have been undermined; Abutment headstock not connected to piles; Headstock not centrally located on piles; Some cracking and spalling of piles	Both run on slabs/ scouring or undermined, pile, abutment headstock not connected to piles		1	1
Daveys Bridge	Rural Collector		Significant scour behind the western abutment; Substantial crack in the downstream western wing wall; Downstream western guardrail had been damaged due to build-up of debris	Abutment wing wall/scoured and cracked		1	1
Belford Bridge	Urban Arterial	NAASRA	Scour and slumping of the southern upstream rock spill; Relieving slab and approach road kerb has been undermined; Substantial crack appeared in the downstream western wing wall	Abutment and wing wall/Scour or undermining	1		1
Liftin Bridge		NAASRA				1	1
Logan Bridge	Rural Arterial	AS 5100	Whole section of one approach has been damaged, Significant scour of the eastern abutment, Headstock has been undermined, Cracks noted in the surfacing behind the eastern abutment	Bridge Approach and Abutment/Scouring			1
Frankie Steinhardt's Bridge	Rural Access	AS 5100	Significant scour of approach embankments on opposite corners of the bridge, The approach embankment is unstable and tension cracks have been formed in the pavement.	Both approach embankments/ scouring		1	1
Hoger Bridge	Rural Access	AS 5100	scour of approaches, tension crack	approaches	1		1
Colquhoun Bridge	Rural Access	AS 5100			1		
Sheep Station Bridge	Urban Collector		Western upstream spill through has been undermined, Abutment wing wall has dropped and rotated with a large crack opened, Wing wall not connected to the headstock	Abutment wing walls/scouring or undermining	1		
Mahon Bridge	Rural Collector	AS 5100		approach embankments	1		1
Kapernicks Bridge	Rural Arterial	NAASRA			1		
Duncan Bridge	Rural Arterial		Small scour hole has formed on the downstream eastern abutment, Road shoulder at the end of bridge has been lost	Bridge approach and abutments/scouring	1		
Murphy Bridge	Rural Collector	NAASRA	Significant build-up of debris on the deck, Northern approach had scoured with road surface and pavement removed.	Bridge approach/scouring		1	
Cran Bridge	Rural Arterial	NAASRA			1		
The Willows Bridge	Rural Collector	AS 5100	Both approaches sustained substantial damage, Bridge guardrails ripped off Upstream edge of the bridge broken	Both bridge approach/scouring		1	
The Dairy Bridge	Rural Arterial	AS 5100	Loss of rip rap spill through protection with some minor undercutting of abutment headstocks	Abutments/ scouring or undermining	1		

Vulnerability modelling

Vulnerability of a bridge to an extreme event is a function of probability of failure of bridge components at a given extreme event and the period or cost of recovery. The fault tree proposed can be used to estimate the probability of failure and also the period and or cost of recovery by aggregating cost of repair of individual elements and considering the probability of failure of components.

Evaluation of probability of failure of bridge components

Fault tree developed here assumes that a bridge is designed and constructed as per the relevant design guidelines for normal design loads as well as for the loads experienced in extreme events. It further assumes that regular inspections and maintenance are performed over the service life of the bridge. As the road network grew over the years, different bridge design standards were used at different times of the development of the road network. Therefore the current road network in Australia consists of bridges that were designed using different bridge standards. Different bridge design standards use different bridge load capacities and geometric configurations. The range of age and strength in Australia's bridge infrastructure network reflects the longer service life and increase in mass and number of heavy vehicles. Over the years, bridges have been designed to various standards as they were built in different periods. The road infrastructure grew as the country developed and the population spread out.

In order to evaluate the failure probability of an individual component there are two possible ways forward:

- A rough estimate can be made considering the case studies of failure. For example, for a given structural configuration and a given intensity of flood, if 36 out of 72 bridge piers have failed due to scour, probability of failure of piers due to scour can be crudely estimated as 50%.
- A detailed analysis of design loads and the loads applied on the structure can be used to calculate a time dependent reliability analysis considering deterioration, which can be used to evaluate the failure probability of a bridge component.
- Expert judgement can be used to identify the failure probability as high, medium or low, which can be converted to a numerical representation.

Conclusions

This research paper proposes a framework for assessment of probability of bridge closure after an extreme event which is combination of damage index and fault tree method. A case study from Lockyer Valley Regional Council has been used to demonstrate a typical fault tree for flood events. The analysis of the case study also led to following observations:

- Major failure criteria for bridges are damage to deck and the bridge approach, pier / abutment scouring, significant built up of mud and debris on the structure and approaches, cracks in the abutment wing walls and misalignment of abutment headstock connection to piles.
- A top-down direction fault tree diagram was developed to establish the failure path for a particular bridge that will be subjected to an extreme flood event.
- The bridges in this case study were designed using National Association of Australian State Road Authorities (NAASRA) guidelines, 92 Austroads and AS5100: Bridge design code has been identified depending on the construction period. Fault tree diagrams assume that the bridges are designed for the normal and extreme load combinations and will be inspected and maintained regularly. It is important to revisit

these design standards and to find a correlation between the adopted design methods and the real time loads that the bridges have experienced, which will allow determination of a probability of failure of a bridge component.

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