Failure mechanisms of bridge infrastructure in an extreme flood event

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ABSTRACT

The recent flood events in Queensland, Australia had an adverse effect on the country's social and economic growth. It is reported in the recent literature that due to climate change, frequency of flood events has increased as well as they have become more intense. This research paper focuses on the damage caused by the recent floods in Queensland, on the bridge infrastructure. Bridges affected by 2013 flood in Lockyer Valley region in Western Queensland were selected as a case study. For the damaged bridges, data such as level of damage, material used in these bridges, type of bridge (girder/precast/in-situ), age of the bridge, elevation of the bridge from the mean sea level, annual average daily traffic, class of the bridge, heavy vehicles and inspection data before and after the flood were collected and analysed. This case study aims at identifying all the attributes of bridges contributing to failure such as bridge approaches, bridge surface, waterway, bridge substructure, bridge superstructure etc. It further analyses the failure mechanisms of different types of bridges (Concrete, In situ, pre cast etc.) and identifies the relationship of the component failure of a bridge to the overall failure of the infrastructure system. Major failure mechanisms were identified as 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. It is interesting to observe that there is an inverse relationship between the age of the bridge and the damage level. The reasons for this could be due to different construction practices adopted in the past or they had been rehabilitated after previous disaster event. In order to analyse and confirm these reasons, possible bridge design codes used for the bridge in question have been identified.

KEYWORDS: disaster resilience, failure, bridge infrastructure, flood events

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1.0 INTRODUCTION

A series of extreme weather events occurred in Queensland between April 2010 and January 2013. It experienced heavy rain during the three month summer season in 2010/2011 with Category 5 Cyclone Yasi in northern region that had wind gusts up to 285 km/h, and caused 5 m tidal surge. As a consequence of extensive flooding and cyclonic conditions during these periods, the road network suffered damages of more than $7 billion (Pritchard, 2013). Bridge infrastructure plays a pivotal role in post disaster recovery such as evacuation and search and rescue operations because bridges are critical transportation infrastructures without which the access to the affected areas would be hindered. Many researchers identified the importance of resilient road infrastructure in and after a disaster event (Arumala, 2012; Oh et al., 2010; Reed et al., 2011). Bridge collapse has tremendous consequences in every nation’s transportation system. Reed et al. (2011) included the power delivery, transportation systems and water supply as lifelines of a civil infrastructure system and emphasized the resilience of physical aspects as well as the community in which they are located. Oh et al. (2010) identified four strategies (identifying critical infrastructure, identifying vulnerable infrastructure or vulnerable parts, severity or level of impact and mitigation plans to reduce this impact to the community or industry) in developing a mitigation plan for extreme events.

The recent flood events in Queensland, Australia had an adverse effect on the country’s social and economic growth. Frequency of flood events in Queensland, during the past decade appears to have increased. In March 2009, flood in North West Queensland covered 62% of the state with water consisting $234 million damage to infrastructure (Increasing Queensland's resilience to inland flooding in a changing climate, 2010). 2010-2011 floods in Queensland had a huge impact particularly on central and southern Queensland resulting in the state owned properties such as 9170 road network, 4748 rail network, 89 severely damaged bridges and culverts, 411 schools and 138 national parks (Rebuilding a stronger, more resilient Queensland, 2012). Approximately 18000 residential and commercial properties were significantly affected in Brisbane and Ipswich areas (Queensland floods: The economic impact Special Report, 2011) during this time. More than $42 million was paid for individuals, families and households while more than $121million in grants has been paid to small businesses, primary producers and non-profit organizations and more than $12 million in concessional loans to small businesses and primary produces (Rebuilding a stronger, more resilient Queensland, 2012). The Australian government has committed $6.8 billion rebuilding the state. The damage to the road network alone has been estimated to more than $ 7 billion (Pritchard, 2013).

In simple terms, a flood is defined as water which we don’t want (Middelmann et al., 2014). Heavy rain fall, storm surge, tsunami and dam failure can cause flooding (ARMCANZ, 2000). Following factors are considered as triggering factors for a given flood including:

- Rainfall intensity, duration and its temporal variation
- Total amount of rainfall
- Spatial variation, i.e. the geographic spread and concentration of rain fall
- Precursor catchment and weather condition
- Topography/ground cover
- The capacity of steam network to carry the run off and
- Tidal influence.

Flash flooding occurs when intense rainfall falls over a small catchment in just six or less than six hours. The risk of such flash flooding is high when it occurs in urban or rural area where drainage is poor. When high intensity rainfall falls over a large proportion of a catchment, by contrast, we call it as widespread flooding. Flood depth in urban areas tends to rise fast because of the large proportion of impermeable catchment area covered by building and transport infrastructure in cities. Flood depth in Australia is measured as the difference between the flood water level elevation and the local ground elevation relative to the Australian Height Datum (AHD).

Many researchers discussed about the interdependencies among infrastructure and the effect of them on the functioning of the industries (McDaniels et al., 2007; Rinaldi et al., 2001) while others (Oh et al., 2010) provided decision support tools to help developing disaster mitigation strategies based on the relationships between communities, industries and associated economic, social and technical impacts. (Rinaldi et al., 2001) developed a conceptual framework which includes a range of factors such as infrastructure characteristics, state of operations, types of interdependencies, environment, coupling and response behaviour and type of failure. (McDaniels et al., 2007) characterised infrastructure failure interdependencies in terms of the sectors affected and the consequences for the society.

2.0 RESEARCH METHODOLOGY

Many factors, such as flood velocity, type of debris, contributing to damage of different components of a bridge and failure mechanisms may not be the same. Pritchard (2013) identifies that urban debris, such as cars, and the insufficient bridge span to through those debris are main cause for damaging bridges aftermath of 2011/2012 flood in Queensland. Using 2013 flood event in Lockyer Valley (Lokuge and Setunge, 2013) 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 to be included in designing of bridges to be resilient to extreme flood events. Ultimate objectives of the current research project is to find the correlations between contributing factors, failure modes and design standards so that it will be possible to establish a criteria for managing existing bridges. However this research mainly focusses on finding the failure mechanisms of bridges when subjected to an extreme flood event using the 2013 flood event in Lockyer Valley. After 2011/2012 flood, the Lockyer Valley region was only accessed by air for post disaster operations.

2.0 CASE STUDY

Lockyer Valley Region of Queensland has been selected as one of the case studies. 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 different types of bridges (Concrete, Timber, In situ, pre cast etc.) and identifies the relationship of the component failure of a bridge to the overall failure of the infrastructure system. Therefore, the data will be grouped based on the type of bridge such as timber, steel, concrete and will be evaluated for type of damage, age, standard used to design these bridges and separate databases will be developed for each type.

Lockyer Valley Regional Council in Queensland has compiled a comprehensive bridge inspection reports for about 47 bridges in the region before they are 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, relieving slabs, 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. This report aims at identifying necessary parameters/data such as flood depth, flood velocity, flood intensity, return period of a given flood etc.

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 poorly 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.

Bridge No. 2 abutment headstock damaged

Bridge No. 16 completely washed away

Damaged due to debris

Damaged relieving slab

Figure 1: Damaged bridges

3.1 Inspection data for Damaged Bridges

A bridge inspection template has been prepared by Sinclair Knight Merz (SKM), the private organization engaged by LVRC to undertake inspections of bridges after the January 2013 flood event. These inspections were undertaken in accordance with the Queensland Transport Main Roads Level 1 bridge inspection. They used a template to record the assessment for each inspected bridge and the template included the following information for each inspection element of the bridge.

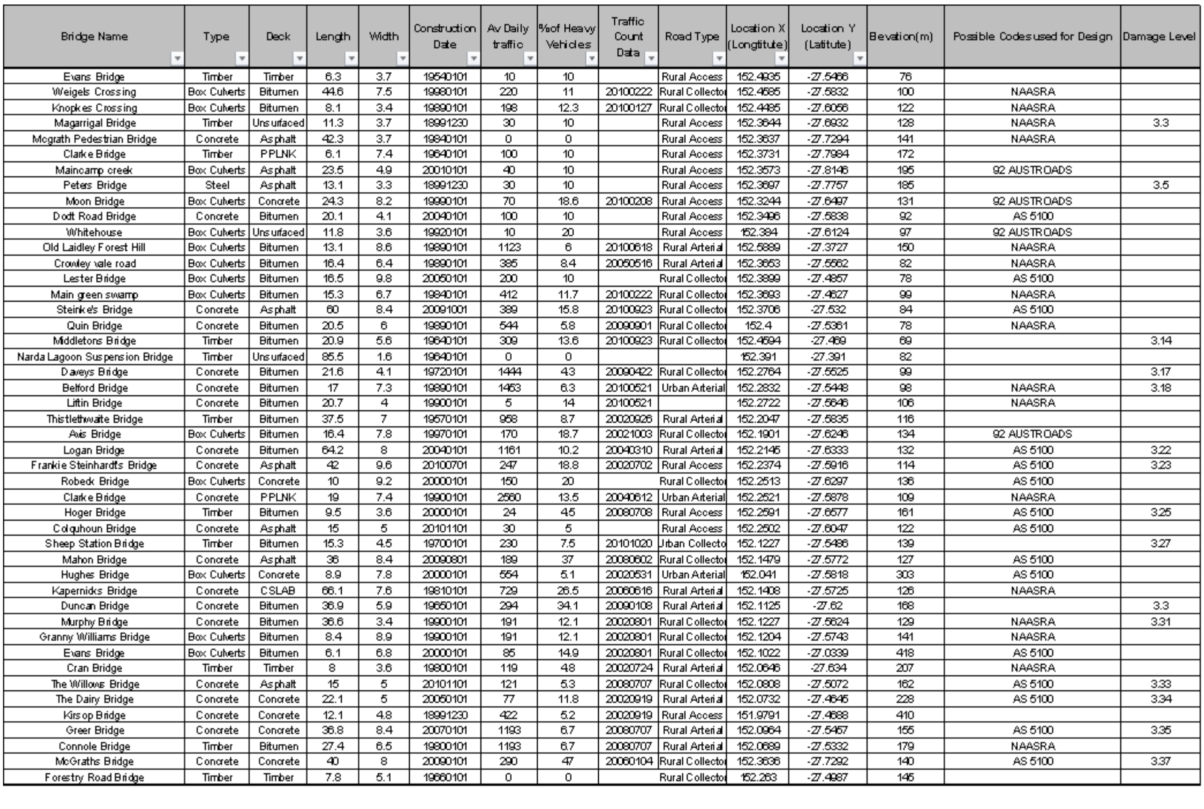
- Approaches
    - signs and delineation- missing, damaged or obscured
    - guardrails – missing or damaged
    - road drainage – blocked inlets/ outlets
    - road surface – missing or damaged, settlement or depression
- Bridge surface
    - Bridge surface – missing or damaged, scuppers blocked
    - Footpaths – damaged
    - Barriers/handrails – damaged, missing fixings, loose post base
    - expansion joints – loose or damaged, missing or damaged seal, obstructions in gap
- Waterway
    - debris against substructure
    - debris against superstructure
    - bank erosion
    - scour holes
    - damage to scour protection
- Substructure (abutments)
    - Movement of abutments
    - Movement of wing walls
    - Scour of spillthrough
- Substructure (piers)

  - Movement of piers
  - Rotation of piers
  - Scour around piers
- Substructure (bearings)
  - Missing, damaged or dislodged
  - Poorly sealed
- Superstructure (deck)
  - Damage
  - Debris on deck
  - Rotation of deck
  - Dipping of deck over piers
- Superstructure (girders)
  - damage

Each report further included about the damages to services by inspection 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.

SKM completed such inspection reports for 46 bridges in the Lockyer Valley region. Oh et al. (2010) described that vulnerability of an infrastructure will depend on its physical characteristics such as bridge elevation, height, type of material and construction practice used. Having identified the importance of physical characteristics, an Excel sheet has been prepared by the authors to summarise finer details of the bridges such as bridge type, length, width, number of spans, location of the bridge, elevation, average daily traffic, level of damage and possible design codes used (Table 1). It has been observed from the given bridge inspection report that different bridges have different types of failure mechanisms. In a performance based design it is important to investigate the consequences of individual member behavior on the performance of the structural system (Bonstrom and Corotis, 2012). Some bridges have failed because of loss of bridge approach while some other bridges have failed due to scouring at the bridge pier or bridge abutment/wing wall etc. Table 2 illustrates different failure mechanisms for different bridges. It also describes the most common failure mechanisms of the bridge.

Table 1: Details of damaged bridges



Bridge Name	Type	Deck	Length	Width	Construction Date	Av Daily traffic	%of Heavy Vehicles	Traffic Count Data	Road Type	Location X (Longtitute)	Location Y (Latitute)	Elevation(m)	Possible Codes used for Design	Damage Level
Evans Bridge	Timber	Timber	6.3	3.7	19540101	10	10		Rural Access	152.4935	-27.5466	76		
Weigels Crossing	Box Culverts	Bitumen	44.6	7.5	19980101	220	11	20100222	Rural Collector	152.4685	-27.5832	100	NAASRA	
Knopkes Crossing	Box Culverts	Bitumen	8.1	3.4	19890101	198	12.3	20100127	Rural Collector	152.4485	-27.6056	122	NAASRA	
Magarrigal Bridge	Timber	Unsurfaced	11.3	3.7	18991230	30	10		Rural Access	152.3644	-27.6932	128	NAASRA	3.3
Mcgrath Pedestrian Bridge	Concrete	Asphalt	42.3	3.7	19840101	0	0		Rural Access	152.3637	-27.7294	141	NAASRA	
Clarke Bridge	Timber	PPLNK	6.1	7.4	19640101	100	10		Rural Access	152.3731	-27.7984	172		
Maincamp creek	Box Culverts	Asphalt	23.5	4.9	20010101	40	10		Rural Access	152.3573	-27.8146	195	92 AUSTROADS	
Peters Bridge	Steel	Asphalt	13.1	3.3	18991230	30	10		Rural Access	152.3697	-27.7757	185		3.5
Moon Bridge	Box Culverts	Concrete	24.3	8.2	19990101	70	18.6	20100208	Rural Access	152.3244	-27.6497	131	92 AUSTROADS	
Dodt Road Bridge	Concrete	Bitumen	20.1	4.1	20040101	100	10		Rural Access	152.3496	-27.5838	92	AS 5100	
Whitehouse	Box Culverts	Unsurfaced	11.8	3.6	19920101	10	20		Rural Access	152.384	-27.6124	97	92 AUSTROADS	
Old Laidley Forest Hill	Box Culverts	Bitumen	13.1	8.6	19890101	1123	6	20100618	Rural Arterial	152.5889	-27.3727	150	NAASRA	
Crowley vale road	Box Culverts	Bitumen	16.4	6.4	19890101	385	8.4	20050516	Rural Arterial	152.3653	-27.5562	82	NAASRA	
Lester Bridge	Box Culverts	Bitumen	16.5	9.8	20050101	200	10		Rural Collector	152.3899	-27.4857	78	AS 5100	
Main green swamp	Box Culverts	Bitumen	15.3	6.7	19840101	412	11.7	20100222	Rural Collector	152.3693	-27.4627	99	NAASRA	
Steinke's Bridge	Concrete	Asphalt	60	8.4	20091001	389	15.8	20100923	Rural Collector	152.3706	-27.532	84	AS 5100	
Quin Bridge	Concrete	Bitumen	20.5	6	19890101	544	5.8	20090901	Rural Collector	152.4	-27.5361	78	NAASRA	
Middletons Bridge	Timber	Bitumen	20.9	5.6	19640101	309	13.6	20100923	Rural Collector	152.4694	-27.469	69		3.14
Narda Lagoon Suspension Bridge	Timber	Unsurfaced	85.5	1.6	19640101	0	0			152.391	-27.391	82		
Daveys Bridge	Concrete	Bitumen	21.6	4.1	19720101	1444	43	20090422	Rural Collector	152.2764	-27.5525	99		3.17
Belford Bridge	Concrete	Bitumen	17	7.3	19890101	1463	6.3	20100521	Urban Arterial	152.2832	-27.5448	98	NAASRA	3.18
Liftin Bridge	Concrete	Bitumen	20.7	4	19900101	5	14	20100521		152.2722	-27.5646	106	NAASRA	
Thistlethwaite Bridge	Timber	Bitumen	37.5	7	19570101	958	8.7	20020926	Rural Arterial	152.2047	-27.5835	116		
Axis Bridge	Box Culverts	Bitumen	16.4	7.8	19970101	170	18.7	20021003	Rural Collector	152.1901	-27.6246	134	92 AUSTROADS	
Logan Bridge	Concrete	Bitumen	64.2	8	20040101	1161	10.2	20040310	Rural Arterial	152.2145	-27.6333	132	AS 5100	3.22
Frankie Steinhardt's Bridge	Concrete	Asphalt	42	9.6	20100701	247	18.8	20020702	Rural Access	152.2374	-27.5916	114	AS 5100	3.23
Robeck Bridge	Box Culverts	Concrete	10	9.2	20000101	150	20		Rural Collector	152.2513	-27.6297	136	AS 5100	
Clarke Bridge	Concrete	PPLNK	19	7.4	19900101	2560	13.5	20040612	Urban Arterial	152.2521	-27.5878	109	NAASRA	
Hoger Bridge	Timber	Bitumen	9.5	3.6	20000101	24	45	20080708	Rural Access	152.2591	-27.6577	161	AS 5100	3.25
Colquhoun Bridge	Concrete	Asphalt	15	5	20101101	30	5		Rural Access	152.2502	-27.6047	122	AS 5100	
Sheep Station Bridge	Timber	Bitumen	15.3	4.5	19700101	230	7.5	20101020	Urban Collecto	152.1227	-27.5486	139		3.27
Mahon Bridge	Concrete	Asphalt	36	8.4	20090801	189	37	20080602	Rural Collector	152.1479	-27.5772	127	AS 5100	
Hughes Bridge	Box Culverts	Concrete	8.9	7.8	20000101	554	5.1	20020531	Urban Arterial	152.041	-27.5818	303	AS 5100	
Kapernicks Bridge	Concrete	CSLAB	66.1	7.6	19810101	729	26.5	20060616	Rural Arterial	152.1408	-27.5725	126	NAASRA	
Duncan Bridge	Concrete	Bitumen	36.9	5.9	19650101	294	34.1	20090108	Rural Arterial	152.1125	-27.62	168		3.3
Murphy Bridge	Concrete	Bitumen	36.6	3.4	19900101	191	12.1	20020801	Rural Collector	152.1227	-27.5624	129	NAASRA	3.31
Granny Williams Bridge	Box Culverts	Bitumen	8.4	8.9	19900101	191	12.1	20020801	Rural Collector	152.1204	-27.5743	141	NAASRA	
Evans Bridge	Box Culverts	Bitumen	6.1	6.8	20000101	85	14.9	20020801	Rural Collector	152.1022	-27.0339	418	AS 5100	
Cran Bridge	Timber	Timber	8	3.6	19800101	119	48	20020724	Rural Arterial	152.0646	-27.634	207	NAASRA	
The Willows Bridge	Concrete	Asphalt	15	5	20101101	121	5.3	20080707	Rural Collector	152.0808	-27.5072	162	AS 5100	3.33
The Dairy Bridge	Concrete	Concrete	22.1	5	20050101	77	11.8	20020919	Rural Arterial	152.0732	-27.4646	228	AS 5100	3.34
Kirsop Bridge	Concrete	Concrete	12.1	4.8	18991230	422	5.2	20020919	Rural Access	151.9791	-27.4688	410		
Greer Bridge	Concrete	Concrete	36.8	8.4	20070101	1193	6.7	20080707	Rural Arterial	152.0964	-27.5467	155	AS 5100	3.35
Connole Bridge	Timber	Bitumen	27.4	6.5	19800101	1193	6.7	20080707	Rural Arterial	152.0689	-27.5332	179	NAASRA	
McGraths Bridge	Concrete	Concrete	40	8	20090101	290	47	20060104	Rural Collector	152.3636	-27.7292	140	AS 5100	3.37
Forestry Road Bridge	Timber	Timber	7.8	5.1	19660101	0	0		Rural Collector	152.263	-27.4987	146		

Table 2: Failure mechanisms of selected bridges

Name	**Type**	**Submerged**	**Mode of failures**	**Most affected bridge component**
Maggarigal	2 Span Deck Unit (Precast Concrete)	Yes	Deck and the bridge approach significantly damaged;Built up of mud and debris on the structure and approach	Bridge Approach and Deck/ Scouring or undermining
Peters	4 Span Precast Concrete Deck Unit	Yes	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
Middleton	4 Span Timber Deck	Yes	Scouring in front of North Abutment; Undercut beneath the southern abutment.	Abutments/ Scouring
Davey	2 Span Blade pier R/C vertical abutments	Yes	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
Belford	2 Span I Girder Bridge	Yes	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
Logan	4 Span Transversely stressed deck unit bridge	Yes	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
Frankie Steinhardt’s	Single Span precast concrete bridge	No Medium	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
Sheep Station	Single span precast deck unit	No Medium	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
Duncan’s	4 span deck unit	Yes	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
Murphy	Concrete Deck Unit	Yes	Significant build-up of debris on the deck Northern approach had scoured with road surface and pavement removed.	Bridge approach/scouring
The Willows	Single precast deck unit	Yes	Both approaches sustained substantial damage Bridge guardrails ripped off Upstream edge of the bridge broken	Both bridge approach/scouring
The Dairy	2 span timber girder - concrete deck	Yes	Loss of rip rap spill through protection with some minor undercutting of abutment headstocks	Abutments/ scouring or undermining
Greer	4 span timber girders with Concrete deck	No High	Scour protection has been washed away from the face of the spill through Scouring of spill through	Spill through/scouring
McGrath	3 Span Deck Unit bridge	Yes	Scour and erosion noted beneath both back spans One of the piles supporting pier appears to be leaning Pile not centred on the headstock	Approach embankments/ scouring or erosion

Clerk (Thorton)	3 Span Deck Unit	Yes	Edge delineation had been damaged by debris Some bank scour on the downstream side of the bridge	Wing wall or bank / Scouring

3.2 Major failure mechanisms

Inspection report for the bridges affected by recent flood event (January 2013) indicates different types of failure mechanisms for different bridges. The observed failure mechanisms are as follows:

- Deck and the bridge approach were significantly damaged
- Pier / Abutment scouring
- Significant built up of mud and debris on the structure and approaches
- Both run on slabs had been undermined
- Substantial crack in the abutment wing walls
- Abutment headstock not connected to piles.

Losses of road approach, embankment and pier and abutment scouring have been identified as major causes of failure for the bridges in Lockyer Valley region.

4.0 DISCUSSION

4.1 Scour effect

This happens mostly to bridges where the main criterion for design was mostly about the foundation capacity without considerations for possible scour effects. Fig 3 shows examples of bridges collapsed because of scour effects. This effect depends on many factors including the water/flood flow, flow speed, type and conditions of the river bed, width and depth of the river. Additionally, the defect can also happen as a local scour phenomenon at the bottom of the river, near the piers because of the surrounding water flow combination of a variety of factors as described above and also the shape and position of the structure, and its orientation with respect to the river flow.

Bridges that have failed because of this phenomenon generally did not go through a proper design with proper considerations for hydraulic effects. Furthermore, their foundation design did not include such factors as the scour maximum depth, the river flow patterns and the basin features. When there is a potential for scour effects, it is recommended that a complete study be performed on the bridge showing the causes that may trigger scour and providing solutions to erosion and sedimentation effects that may affect the bridge. In the document, “Socavación y protección contra socavación (Scour and protection against scour),” taken from the Manual de Inspección Especial de SiPuCoL (Instituto Nacional de Vias of Colombia 1996), it is recommended that this study, as a minimum, must include the areas included in Table 3.

Table 3: Studies recommended to evaluate scour effect

Study	**Content**
Hydrologic	Hydrologic basin analysis. Flooding and raining analysis. Definition of flow design
Hydraulic	Definition of medium flowing speed and main flow. Definition of flowing lines. Sediment definition. Reduction effect in hydraulic section. Alignment of piers inside the river flow. Ground works protection of river flow.
Geologic	Secondary information taking and field information
Geomorphologic	Evaluation of Flow Stability. Use of airplane photography in the morphologic study of rivers.
Topographic	Recovering of existing information Field recognition Topographic detailing
Geotechnical Studies	Field recognition Schematic exploration of the bridge site. Sub soil investigation, perforations. Laboratory essays.

	Foundation solutions

Note: Source: Manual de Inspección Especial de SiPuCoL (Instituto Nacional de Vias of Colombia 1996).

The following are several scour effects that can potentially cause bridge collapse:

- General scour effects, because of local contraction occurring in curves.
- Differential settlement of piers and abutments.
- Hydraulic structures damaged and wrongly placed in the flow causing obstruction and increasing local scour effect.
- Obstruction in the river flow, see Fig. 4.
- Piles exposed because of scour effects and vulnerable to horizontal loads.
- Insufficient bridge length to the hydraulic area of river flow.
- Sedimentation and insufficient height to the bridge's deck.

4.2 Flood debris

It is a common practice to learn lessons from a disaster and incorporate them into building codes and construction specifications so that the future structure will perform better in an extreme event (Arumala, 2012; Lamond and Proverbs, 2009). AS 5100 (Standards Australia 2004) along with many other codes and standards worldwide assume typical rural flood events in designing bridges. It considers the effect of water flow, debris mat and log impact. Flood debris may contain large segments of the concrete river walk, shipping containers, vehicles, private pontoons, pressure vessels, traditional debris mats that include vegetation, trees etc. It is obvious that the recent flood event in Brisbane, Queensland was an urban flood event in contrast to the rural flood event as assumed in AS 5100: 2004 Bridge Design Code. Current tools and techniques available for risk-cost optimization do not take into account the increased loading conditions on the structures that are exposed to extreme weather events. On the other hand, rural debris loads experienced by the bridges in the recent floods are much higher than the loads recommended in the Design Code. Hence these design codes of practice should be updated to reflect these huge flood loads in future. It is also recommended that each authority or bridge owner must consider the actual location and context of the bridge to road hierarchy and provide design criteria accordingly (Pritchard 2013).

4.3 Bridge design codes

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 configuration. 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.

5.0 CONCLUSIONS

This research paper investigates the importance of bridges in enhancing community resilience during an extreme flood event. Using a case study from Lockyer Valley Regional Council for the performance of bridges during floods in Queensland, Australia in 2013, following observations are made:

- Major failure criteria for bridges were identified as 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.
- During and after an extreme flood event, the resilience of road infrastructure is extremely important for the resilience of the community. Therefore the vulnerability of the structures such as bridges will have an impact on the resilience of the community in these areas. This aspect of community impact requires further consideration in designing bridges.
- 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

depending on the construction time. 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. There could be different construction practices adopted during the construction of the bridges and possible strengthening after a previous disaster event. These aspects need to be further analysed.

A current research project is examining further the design loads that had been used to design the damaged bridges in this case study.

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