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ENHANCING RESILIENCE OF CRITICAL ROAD INFRASTRUCTURE: BRIDGES, CULVERTS AND FLOOD-WAYS UNDER NATURAL HAZARDS

Annual project report 2016-2017

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Cover: Kapernicks bridge, Lockyer Valley area - by Hessam Mohseni

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ABSTRACT

ANNUAL PROJECT REPORT 2016-2017

In the funded first stage, the project aimed to develop vulnerability models for critical road structures: bridges, culverts and floodways under natural hazards of flood, bush fire and earthquakes. In the second stage of the project, optimized maintenance and strengthening regimes required to enhance resilience of critical road structures will be identified and a decision making tool will be developed.

During the past year, the research focused on analysis of the case studies available from end user partners and development of the methodology for vulnerability modeling of bridges and floodways under natural hazards of flood, earthquake and bushfires. Three case studies were analysed to further establish the methodology and a reliability based approach was established to account for the variability of the frequency and the intensity of disasters. A field study was undertaken to understand the economic impact due to failure of road structures during the 2011 and 2013 floods in the Lockyer Valley region in Queensland.

Three major workshops and a number of informal meetings were held during the past year with excellent participation of end users and researchers. A workshop has also been organized on 24 July 2017 to plan the work program for the second stage of the project and develop the utilization plan.

Six Ph.D candidates are progressing their research funded by APA, RMIT and IPRS scholarships. Three of the students secured CRC top up scholarships as well. One Master by research student completed in 2016 and one PhD will complete in 2017. Each of the four strands of the project has recruited a researcher to engage in the project and also utilized final year undergraduate projects to contribute to the research project.

Major outcomes during the past year can be summarized as development of the vulnerability modeling methodology for critical road structures exposed to extreme events and demonstration of the methodology using four case studies. This work has been published in number of journal papers and conferences and posters published in highly regarded journals and conferences. Members of the team also has been successful in winning awards for their work.

END USER STATEMENT

Martine Woolf, Geoscience Australia

Understanding the vulnerability of road infrastructure is critical in enhancing resilience of community resilience to natural disasters. Functional road infrastructure means connectivity is retained throughout the preparation, response and recovery phases of a disaster event, limiting the impact of disasters. Moreover, road damage itself currently forms a significant part of the costs from natural disasters. This project will deliver a significant contribution to a national ability to improve resilience of road infrastructure, and by extension to the communities connected by this infrastructure. The project covers different elements of road infrastructure, building a detailed picture of vulnerability and options for resilience. The continued involvement of end-users from the practitioner end of the user-spectrum ensures the project retains an ambitious yet practical focus as it develops. The project has progressed extremely well in this past year, and continues to create a range of robust outputs through peer-reviewed publications. The value of this project is evidenced also through the utilisation projects proposed directly applicable to (or proposed by) its end-users. This project is set to deliver a highly significant input to improving national disaster resilience across Australia.

INTRODUCTION

What is the problem?

Increasing frequency and intensity of natural hazards in Australia has led to scenarios where the infrastructure is subjected to loading regimes beyond those prescribed in the current design codes. Australia relies very heavily on its road network, which plays a vital part in the national economy as well as reducing the vulnerability of the community at large before, during and after extreme climate events [1]. Questions which require answers are: how does the road network - especially critical road structures such as bridges, culverts and floodways – cope with extreme natural hazards and how can the resilience of these be improved? This project aims to fill a major gap in critical road infrastructure research related to risk identification, assessment and monitoring using an integrated multi-hazard approach.

This project will take a hardening mode approach and for critical road structures this requires consideration of three aspects:

1. Vulnerability modeling of structures under extreme events, considering the design loads, standards and recently observed variability in intensity and frequency of disasters
2. Methods of enhancing resilience of road structures using optimised maintenance and strengthening
3. Understanding the effect of vulnerability of road structures on the community resilience before, during and after an extreme event.

Why is it important?

In recent years there has been significant damage to road networks throughout Australia from floods and bushfires that have cost both State and Federal governments millions of dollars to repair. The effect of damage to road networks from natural hazards goes far beyond the immediate damage incurred by people whose homes and businesses are directly affected, and if the damage is widespread it can have an impact on the regional and national economy. The cost of repairing the road network alone is huge. For instance, the 2010-2011 floods in Queensland severely damaged 9,170 kilometres of road network including bridges, flood ways and culverts and cost the State and Federal government hundreds of millions of dollars to repair [1]. In Victoria, VicRoads spent over $17 million on repairing the road network after the bushfires in 2009 and over $200 million repairing the road network after the 2011 flood [2]. Creating a road network that can better withstand future natural hazards and better understanding of the impact on community will be of great importance in reducing the cost to the community and road authorities as well as local councils.

One of the seven goals of Sendai Framework for disaster risk reduction (2015-2030) is reduction of damage to vulnerable critical infrastructure by enhancing resilience of these. With international collaboration, the project will align well with the Sendai Framework.

Often during the reconstruction period, neither the road authorities nor the governments have adequate funding, technological knowledge and resources to build better. Optimised decision making requires front end planning to ensure community resilience at the next disaster event. We need to move from a reactive decision making approach to a proactive approach where the vulnerability is known, challenges are known and the disaster recovery is well planned so that we can build better. Current reactive approach has raised concerns that the Engineering profession is detached in enhancing resilience of the community during disasters.

Quantifying vulnerability of road structures considering the variability of frequency and intensity of disasters will enable managing authorities and funding bodies to make informed decisions on when, where and what to invest in.

How are we going to solve it?

The research program was planned for a 6.5 year period. Outcomes will develop tools and techniques to model the vulnerability of bridges, floodways and culverts leading to a better understanding of the cost of reconstruction and the impact of the failures on the community. Outcomes of the research will contribute to improving design and maintenance regimes of bridges, floodways and culverts so that they are more resilient under natural hazards. The generic research methodology developed can be used for other critical structures such as transmission towers or water mains considering the interaction between the natural hazard, the infrastructure and the community.

Specific objectives will include:

- Understanding the vulnerability of road structures to potential multi-hazard impacts (eg: floods, bush fires, earthquakes and climate change) taking into account current maintenance and design regimes as well as geographic location and local context.
- To develop a vulnerability assessment framework for different sections of the community, and produce guidelines that increase community resilience before, during and after an extreme event (towards communities that are better prepared and more self-reliant).
- Capturing impact of failure of critical road structures on the community as well as the managing authority.
- Develop analytical methods to evaluate impact of hazards on critical road structures.
- Develop an assessment framework for community resilience based on what type of impact on infrastructure affects which community groups and in what ways e.g. tourism operators vs actual tourists. Resilience measures will differ for each grouping.
- Developing performance thresholds for road structures based on structural performance, economy and community resilience.
- Developing optimum maintenance, refurbishment and design regimes for critical road structures.

BACKGROUND

Australia's variable climate has always been a factor in natural disasters that have had significant impact on an evolving road infrastructure and on the communities that rely on the roads. The following figure (Fig. 1) shows the average annual cost of natural disasters by state and territory between 1967 and 2005.

State and territory	Flood	Severe storms	Cyclones	Earthquakes	Bushfires	Total
	Cost ($ million in 2005 Australian dollars)[a]					
NSW	172.3	217.1	0.6	145.7	23.9	559.6
VIC	40.2	23.8	0.0	0.0	36.7	100.6
QLD	124.5	46.7	99.3	0.0	0.7	271.2
SA	19.3	16.7	0.0	0.0	13.0	49.0
WA	4.7	13.0	43.3	3.1	4.6	68.7
TAS	6.9	1.2	0.0	0.0	11.5	19.5
NT	9.1	0.4	138.5	0.3	0.0	148.3
ACT	0.0	0.5	0.0	0.0	9.7	10.2
Australia	**376.9**	**325.2[b]**	**281.6**	**149.1**	**100.1**	**1232.9**
Share of total *(per cent)[c]*	30.9	26.7	23.1	12.2	8.2	100.0

a. These figures exclude the cost of death and injury.
b. Figure includes costs associated with a storm involving several eastern states ($216.7 million) which has not been allocated to any individual state data in the table.
c. Figures may not add to totals due to rounding.
Source: BITRE analysis of Emergency Management Australia database <www.ema.gov.au>.

FIGURE 1: AVERAGE ANNUAL COST OF NATURAL DISASTERS BY STATE AND TERRITORY, 1967-2005 (BITRE, 2008:44)

From these data it can be seen that during this period severe storms and cyclones inflicted the most economic damage, followed by flooding. The data are strongly influenced by three extreme events - Cyclone Tracy in NT (1974), the Newcastle earthquake in NSW (1989) and the Sydney hailstorm also NSW (1999), as well as three flood events in Queensland (South East Qld, 2001: Western Qld, 2004; and the Sunshine Coast, 2005). Climate change has increased the risk from extreme events and the update of this table that includes data for the years 2007 to 2013 - during which there were extreme climate events in Qld, Vic, SA and NSW.

The recent flood events in Queensland, Australia had an adverse effect on the country's social and economic growth. Queensland state controlled road network include 33,337 km of roads and 6,500 bridges and culverts [3]. 2011-2012 flood in Queensland produced record flood levels in southwest Queensland and above average rainfall over the rest of the state [4]. 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 [5]. Theodore in Queensland was flooded three times within 12 months in 2010 and it was the first town, which had to be completely evacuated in Queensland. 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 [6]. Approximately 18,000 residential and commercial properties were significantly affected in Brisbane and Ipswich [7] 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 organisations. Furthermore, more than $12 million in concessional loans to small businesses and primary producers have been provided (Rebuilding a stronger, more resilient Queensland, 2012). The Australian and Queensland governments have committed $6.8 billion to rebuilding the state.

Pritchard [4] identifies that urban debris, such as cars, and the insufficient bridge span for debris to pass through are main causes for damaging bridges in the aftermath of 2011/2012 flood in Queensland. Using 2013 flood event in Lockyer Valley, Lokuge and Setunge [8] 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 requires consideration in designing of bridges to be resilient to extreme flood events.

THE PROJECT

Vulnerability modelling at a detailed level which aids managing authorities of road structures to prioritise hardening of structures, considering the intensity of disasters, vulnerability of structures and the impact on community resilience is not available to date. The project aims to deliver following outcomes over the first stage of 3.5 years currently funded by the BNH-CRC.

- Advancement in understanding input hazard parameters for quantifying impact of hazards on road structures
- Understanding failure mechanisms under different hazard types and vulnerable structural forms – clustering of structural forms according to vulnerability
- Developing a method for quantifying community impact of failure of critical road structures
- A methodology for vulnerability modelling of bridges under variable intensities of hazards

The hazards considered include flood, earthquake and bush fire.

In the second stage of the project, the derived vulnerability models for the two case study regions will be used to develop a tool which can be used for vulnerability modelling of any given region in Australia. This will be further developed as a GIS based software tool. Thus the outcomes of the second stage will be:

- GIS based software tool for vulnerability modelling of road structures for a given region with required input parameters

- Road infrastructure retrofitting options and optimisation strategies
- Generic framework for vulnerability assessment of infrastructure

To achieve the above outcomes, following approach will be adopted by the researchers.

1. Stage 1: Vulnerability Modeling
    a) Analysis of case studies of failure – Lockyer Valley and critical regions in Victoria
    b) Input exposure parameters for multi hazard analysis will be sourced
    c) Critical failure mechanisms and modes will be established
    d) Community Impact of failure of road structures will be quantified
    e) Australian design standards for road structures will be examined and gaps in design practice will be identified
    f) A methodology for vulnerability modeling of road network to understand the risk of failure of road structures will be developed.
2. Stage 2: Prototype tool for vulnerability of road structures and optimised strengthening
    a) Develop a GIS tool to map vulnerability
    b) Calibrate the vulnerability models with two other case study areas
    c) Identify strengthening methods
    d) Deliver a methodology and a tool for optimised strengthening of structures

PROGRESS TO DATE

RESEARCH ACTIVITIES

During the past year the research methodology has been further refined and presented to the end users. Specific activities associated with this are summarised below:

1. Vulnerability modelling of the road structure under natural hazards has been investigated and a draft report no. 5 was prepared.
2. Vulnerability modelling has been completed for the hazards of Flood, Bush Fire and Earthquakes with two case studies of bridges and one case study of floodway failure completed.
3. Australian design standards for bridges and floodways have been examined and a comparative study of international standards have been undertaken to ensure that we are using the best available knowledge in vulnerability modelling.
4. Report 4 on "Analysis of design standards and applied loads on road structures under extreme events" has been completed. Reviews have been received from end users and the report has been finalised.
5. GIS analysis integration potential has been initiated for the next phase of the project.
6. Three utilisation activities are finalised to transfer knowledge gained from the project to practice. These were guided by the significant end user engagement activities which happened during the year and will be fine-tuned and broken down during the project.
   - A software tool for optimised funding allocation for vulnerable road structures;
   - Implementation of the resilient floodway design guide as a technical note for local councils;
   - GIS interfaced prototype software tool for scenario based identification of damage to road structures.
7. A framework for calculating the economic impact of failure of road structures has been developed and progressed.

WORKSHOPS OF RESEARCHERS AND END USERS

During the past year, following end user engagement activities were completed:

- A disaster resilience seminar was organised with guest speakers from NZ & UK on 12/July/2016. Prof. Suzanne Wilkinson (University of Auckland) & Dr. Kelum Jayasinghe (University of Essex);
- A workshop to plan the utilisation activities for the project held on 16 Oct. 2016 at RMIT, Melbourne. Feedback from VicRoads, QRA, DELWP and RMS were used in developing the utilisation plan for the project.
- A workshop on "Decision making for resilient road structures & community adaptation" held at RMIT on 16th Dec. 2016. with attendance of RMIT researchers, consultants, road authorities and state government

agencies; Outcome of the above workshop has been collected and incorporated into the Building Resilience conference paper;
- A workshop with VicRoads and RMIT researchers on road congestion took place on 25th May 2017;
- A workshop with end-user stakeholders has been organised to be held on 24th July.

PLACEMENTS

Ph.D student: Ismail Qeshta completed a three month placement at VicRoads. Another PhD student placement opportunity with VicRoads is being explored.

CONFERENCES ATTENDED REPRESENTING THE BNH-CRC

1. International Conference on Bridge Maintenance, Safety and Management (IABMAS), July, 2016
2. 6th International Conference on Building Resilience, September, 2016
3. AFAC Conference, September 2016
4. Austroads Bridge Conference April 2017

PUBLICATION LIST (2016-2017)

1. Nasim, M., Setunge, S., Mohseni, H. & Robert, D. An Investigation to the behaviour of Water Flow on Bridge Pier in Flood Events, Austroads Bridge Conference, 2017
2. Dissanayake, A., Srikanth, S., Mohseni, H. & Setunge S. Numerical performance analysis of composite girder bridge structures subjected to hydrocarbon and bushfires. Austroads Bridge Conference 2017
3. Yazdanfar, Z. Robert, D., Mohseni, H., Setunge S. A parametric study of local bridge scour. Austroads Bridge Conference 2017
4. LOKUGE, W., GAMAGE, N. & SETUNGE, S. 2016. Fault tree analysis method for deterioration of timber bridges using an Australian case study. Built Environment Project and Asset Management, 6, 332 – 344. (Q3)
5. WAHALATHANTRI, B., LOKUGE, W., KARUNASENA W. & SETUNGE, S. Quantitative assessment of flood discharges and floodway failures through cross-cultivation of advancement in knowledge and traditional practices – a case study from regional Queensland, Hydrology and Earth System Sciences (submitted) (Q1)
6. PATHIRANAGE, T. & LOKUGE, W. Vulnerability assessment of bridges subjected to extreme cyclonic events, Natural Hazards, Springer (Revised version Submitted) (Q1)
7. LOKUGE,W., WILSON, M., TRAN, H. & SETUNGE, S. Predicting the probability of failure of timber bridges using Fault Tree Analysis, Journal of Bridge Engineering, ASCE (submitted) (Q1)
8. STAINWALL, H., WAHALATHANTRI, B., LOKUGE, W. & KARUNASENA W. Drag and lift forces acting on fully submerged box culverts using computational fluid dynamics (submitted for CRC approval)
9. FRASER, C., LOKUGE, W. & KARUNASENA, W. 2016. Vulnerability of bridges in extreme flood events based on element failure. AFAC and Bushfire & Natural Hazards CRC Conference 2016 (poster presentation)
10. WAHALATHANTRI, B., LOKUGE, W. & KARUNASENA, W. Evaluating the importance of flood loadings on structural performance of a floodway. AFAC and Bushfire & Natural Hazards CRC Conference 2017 (submitted for poster presentation)
11. ABBOTT, T., GAMAGE, N., LOKUGE, W. & SETUNGE, S. Predicting the remaining life of timber bridges, World Congress on Engineering Asset Management (WCEAM2017)- full paper accepted for publication and presentation
12. COHEN, J. & LOKUGE, W. Effect of snipe on the performance of timber bridge girders, 9th International Conference on Bridge Maintenance Safety and Management (IABMAS2018)- Abstract submitted
13. BORZOU, R. & LOKUGE, W. Rehabilitation of timber bridge piles using a wrapping system, 9th International Conference on Bridge Maintenance Safety and Management (IABMAS2018)- Abstract submitted
14. Akvan Gajanayake, Hessam Mohseni, Guomin Zhang, Tehmina Khan, Sujeeva Setunge. measuring social, environmental and economic impacts of road structure failure. 6th Building Resilience Conference
15. Amila P. Dissanayake, Srikanth Venkatesan, Sujeeva Setunge, Hessam Mohseni. PERFORMANCE ANALYSIS OF COMPOSITE STEEL GIRDER BRIDGE STRUCTURAL ELEMENTS SUBJECTED TO BUSHFIRES. Poster submitted at AFAC 2017.

16. Ismail M. I. Qeshta, Rebecca Gravina, Hessam Mohseni, Sujeeva Setunge. Collapse Risk Assessment ofStrengthened Concrete Bridge Pier under Flood Loads. Poster submitted at AFAC 2017.
17. Maryam Nasim, Sujeeva Setunge, Hessam Mohseni, Shiwei Zhou. WATER FLOW PRESSURE CHANGES ON BRIDGES'CIRCULAR AND SQUARED SHAPE PIER UNDER FLOODVELOCITY INCREASING. Poster submitted at AFAC 2017.
18. Nilupa Herath, Lihai Zhang, Priyan Mendis, Tuan Ngo. RELIABILITY ANALYSIS OF DAMAGE ACCUMULATION INBRIDGE STRUCTURES SUBJECTED TO MULTIPLEEARTHQUAKES IN AUSTRALIA. Poster submitted at AFAC 2017.
19. Akvan Gajanayake, Hessam Mohseni, Guomin Zhang, Tehmina Khan, Sujeeva Setunge. MEASURING SOCIAL, ENVIRONMENTAL AND ECONOMIC CONSEQUENCES OF ROAD STRUCTURE FAILURE DUE TO NATURAL DISASTER. Poster submitted at AFAC 2017.

LIST OF CURRENT INTEGRATED TEAM MEMBERS

Researchers	Research Students	End Users
Dr. Buddhi Wahalathantri Prof. Chun Qing Li Dr. Damith Mohotti Prof. Darryn McEvoy Prof. Dilanthi Amaratunga Dr. Hessam Mohseni Dr. Jane Mullett Prof. Karu Karunasena A/Prof. Kevin Zhang Dr. Nilupa Herath Prof. Priyan Mendis Prof. Sujeeva Setunge Dr. Tuan Duc Ngo Dr. Weena Lokuge	Mr. Albert Zhang Mr. Amila Dissanayake Mr. Farook Kalendher Mr. Ismail Qeshta Ms. Maryam Nasim Ms. Zeinab Yazdanfar	Leesa Carson, Branch Head, Community Safety, Geoscience Australia, Lead end user. Dr. YewChin Koay, team leader, structural assets, VicRoads. Kieran Dibb, Director, technical services, QRA Ralph Smith, Branch Manager, Environmental Protection Branch, Department of Fire & Emergency Services WA Myles Fairbairn CEO, Lockyer Valley Regional Council

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8. Lokuge, W. and S. Setunge, *Evaluating disaster resileince of bridge infrastructure when exposed to extreme natural events*, in *International conference on disaster resilience*. 2013: Sri Lanka.