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Are we ready for the next big shake? : Evidence to inform risk mitigation

Mark Edwards

Section Leader, Geoscience Australia

Abstract

Natural disasters impact Australian communities every year. They disrupt communities and, on average, cause billions in losses annually in response activity, recovery needs and economic disruption. While the more frequent flood and wind events feature prominently, Australian earthquakes can cause catastrophic consequences that are generally not well understood and can be difficult to manage when they occur. Do we understand the demands they can impose? Are we adequately informed as to the options for reducing this risk? Are we really ready for the next big shake?

Earthquake risk is the combination of the hazard severity, the assets exposed and the susceptibility of these to severe ground motion. In bringing these three components together an understanding can be developed of the potential impacts of credible earthquake events that are presently beyond Australia's settled experience. For emergency managers it can provide insights into events they have not encountered to enable planning for the management of similar. They can also provide information in a quantified form that can inform decisions and incentives to invest in changing earthquake risk through vulnerability reduction and improved community resilience. There is a particular need for targeted investment as earthquake hazard has not been considered in the design of both buildings and critical infrastructure for most of Australia's settled history.

This paper describes collaborative research being undertaken to better understand more holistically the consequences of the next big shake. The very non-linear nature of impact severity with longer average recurrence intervals is highlighted and how this information is supporting emergency management planning is described. The paper also describes how this research is developing knowledge of the factors behind the vulnerability in the built environment and the opportunities to mitigate this. The software tool named System for Infrastructure Facility Resilience Analysis (SIFRA) is described. It enables infrastructure facility components to be examined in the context of earthquake vulnerability, system criticality, repair cost and restoration time. The sensitivities in developing information with infrastructure managers are outlined and how these are being addressed is discussed in gaining access to and sharing data, information and specialist expertise. Finally, a research project focussed on earthquake mitigation strategies for vulnerable buildings is highlighted as an example of local engagement in addressing community risk.

Keywords: earthquake, vulnerability, risk, mitigation, infrastructure, community

1. INTRODUCTION

Australians are all too familiar with natural disasters. Annually Australian communities are impacted by damaging events which include severe storms, floods and bushfires. The regularity of such severe weather related events translates to an increased awareness of these hazards and, where appropriate, built environment regulation has for many decades enforced provisions to limit the vulnerability of community assets to minimise the associated risks. This has not been the case for geological hazards which, while less frequent, can exhibit severities that are disastrous for communities. For earthquakes in particular, the failure to broadly recognise this environmental hazard in intraplate Australia has resulted in a significant legacy of vulnerable elements in our communities which, if damaged in a rare event, can present catastrophic consequences.

In this paper the nature of earthquake hazard versus the meteorological hazard of severe wind is contrasted in terms of the structural demands. This difference is further illustrated in scenario modelling undertaken to support emergency management planning by the Australian Government. The nature of our vulnerable legacy is described, including some insights into the transport sector. Collaborative efforts with industry to understand the directly related risk and mitigate it are outlined, including information management arrangements to address the sensitivities of industry while maximising the opportunity to inform risk management and reduction. In particular, the application of the tool SIFRA (http://geoscienceaustralia.github.io/sifra/index.html) to utility facilities comprised of various components is described. Finally, a research utilisation project under the Bushfire and Natural Hazards Collaborative Research Centre (BNHCRC) focussed on earthquake mitigation strategies for buildings is highlighted as an example of a community engaged initiative to prepare for the next big shake.

2. THE NATURE OF EARTHQUAKE HAZARD

Regulations for the design and construction of the built environment seek to ensure that the resilience of our community infrastructure is compatible with the local natural hazards. They aim to ensure that the likelihoods that key performance objectives such as amenity and life safety do not exceed those considered acceptable to society. While natural hazards such as wind, earthquake and riverine flooding vary spatially, provided that the compatibility between infrastructure resilience and local hazard severity is maintained the “risk” is taken to be effectively the same. The increased consequences of more severe, rarer events are considered acceptable as performance expectations are moderated by the reduced likelihood of these occurring. For buildings the hazard exceedance likelihoods for design are stipulated in the National Construction Code (ABCB 2016) with adjustments provided for the importance class of proposed building use. This pragmatic approach to regulation presents some cross-hazard challenges that are illustrated by a comparison of severe wind and earthquake hazard in Perth, WA.

In Table 1 the design wind speed specified in the current wind loadings standard (Standards Australia, 2011) is presented for a range of average recurrence intervals (ARIs). The wind speed is in terms of a 0.2s gust at a 10m height in level open countryside with few obstructions. Alongside this is the equivalent gust wind speed for central Perth as assessed by an extreme value analysis of the combined weather observations of the Guilford and Pearce weather stations in Perth as undertaken by Holmes (2018). The two sets of wind hazard values indicate that the wind speeds for “Region A” in the wind loadings standard are conservative for Perth. If the probabilistic wind hazard assessment (PWHA) gust speeds by Holmes in Table 1 are translated into the stagnation wind pressure using the code approach and normalised by the 500 year ARI gust pressure, it can be noted that the wind loadings increase only gradually with lengthening ARI. Structural loadings for a storm generating the 2,500 year ARI wind speed locally are only 14% greater than those for a 500 year ARI. In Table 1 the latest NSHA18 assessed peak ground acceleration (PGA) values for Perth on rock (Allen et al, 2018) have been normalised in a similar fashion to the wind loads (corresponding to k_p in AS1170.4 (Standards Australia 2007)). The contrast between the two natural hazards is stark, with the seismic demands of a 2,500 year ARI ground motion being 2.6 times those of the 500 year ARI hazard. Other state capital values are larger with Melbourne 2.7, Sydney 2.8, Hobart 3.2, Adelaide 3.5 and Brisbane 3.6 times larger.

Table 1:- Comparison between severe wind hazard and earthquake hazard related structural loadings for the Perth metropolitan area.

Average Recurrence Interval [years]	**Gust Wind Speed in Airport Conditions**		**Normalised Wind Loading**	**NSHA18 Earthquake Loading**
	AS/NZS 1170.2:2011	**PWHA by Holmes**		
100	41	38.3	0.90	0.32
250	43	39.2	0.94	0.63
500	45	40.4	1.00	1.00
1,000	46	41.6	1.06	1.53
2,500	48	43.1	1.14	2.58
5,000	50	44.4	1.21	3.77

The comparison between the latest understanding of wind and earthquake hazard in Perth illustrates a fundamental difference between these natural phenomena. While the footprint of severe wind events may increase with rarity, the weather system does not deliver greatly increased wind loads as the ARI lengthens. In contrast, the earth’s crust delivers steadily increasing severities of ground motion. This is particularly an issue in intraplate Australia where tectonically derived strain energy, when released, can deliver greater shaking severity than that at tectonic plate boundaries (k_p = 2.6 for Perth versus 1.8 for Wellington (Standards New Zealand, 2004)). Conversely, from Table 1 it can also be noted that the more likely (shorter ARI) intraplate earthquake shaking has relatively small demands when compared to severe wind. The 115 continental Australian earthquake events between M_L 3 and M_L 5 in 2017 (https://ga.gov.au) caused no damage, even when close to exposed community assets. This further elucidates why earthquakes characteristically do not feature regularly as damaging events in the same way as do severe wind events.

Differences in design philosophy between severe and earthquake compound this further. The earthquake risk in terms of economic loss and community disruption is greater for earthquake as the design strategy generally entails the utilisation of degrees of ductile response with attendant building damage to protect life. This contrasts with the elastic design approach for severe wind where the structural system is designed to remain elastic for the ultimate limit state. This subtlety between the design approaches is not always appreciated by asset owners. Together, the differences in hazard characteristics and design approaches raise the question of how well the current focus on a single ARI hazard for earthquake design manages the community risk at longer ARIs?

3. THE ISSUE OF LEGACY

The sporadic nature of damaging earthquakes in Australia has had a direct bearing on the recognition of earthquake hazard as a consideration in building design. An Australian design standard for earthquake loadings existed as far back 1979 (SAA) but it was essentially only used in the two States that had experienced significant damaging earthquakes prior to its release; Western Australia (WA) with the 1968 Meckering Earthquake, and South Australia (SA) with the 1954 Adelaide Earthquake (Griffith 1992). Furthermore, even in these two jurisdictions the standard was not widely used and with application largely limited to some public buildings. The Newcastle Earthquake of the 28th December 1989 was seminal in the context of this historical complacency. Clearly earthquakes could occur anywhere and needed to be considered in the structural design of buildings and other structures. The first nationally applied loadings standard was developed and implemented (Standards Australia, 1993) that has since been updated in 2007 and 2018 to improve its application in building design.

Similar regulatory development has taken place for other non-buildings elements of the built environment, though with some lag behind building regulations. This is illustrated with the design of bridge infrastructure in WA. In the last 53 years road bridge design procedures in WA have developed with a transition from working stress design to ultimate limit state. Earthquake hazard consideration also progressed, influenced by the 1968 Meckering Earthquake, from having specific earthquake hazard information in the Yilgarn only to eventually include the balance of WA. Most recently (Standards Australia, 2017), design standard development has attributed higher importance classes to many bridges and included displacement based seismic design options. Table 2 presents a summary of the six design documents used by the Department of Main Roads, WA, from 1965 to the present. While even the oldest regulations identified seismic hazard as a consideration, it was not routinely included in bridge design state-wide until the implementation of AS5100 in 2004 (Standards Australia). This pivotal year of 2004 for seismic design is also known to be the case for at least one other east coast state that has a similar range of seismic hazard across the jurisdiction to WA. While seismic considerations do not dominate for many bridge structures on stiffer sites with significant braking force considerations, as with buildings, other bridge structures do require seismic design.

The implication of the parallel histories of building and critical infrastructure design for earthquake as an environmental hazard is one of legacy. Early construction forms, with the exception of some uniquely Australian architectural types, have followed the building practices of the countries of our early migrants where the earthquake hazard is typically low. Typically critical infrastructure has lagged behind building regulation in its address of earthquake hazard with a present need for greater uptake of seismic design considerations in other engineering disciplines such as electrical, mechanical and chemical engineering. The interplay between architects and structural engineers on achieving structural regularity and on the installation of non-structural elements also can be improved. In our communities today both buildings and critical infrastructure contain elements that are inherently vulnerable to ground shaking. These represent a vulnerable legacy that will contribute significantly to the consequences of rare but credible earthquakes in the future. These vulnerable elements need to be addressed if we are to be ready for the next big shake.

Table 2:- Western Australian bridge design regulation development and application to earthquake hazard

Design Standard	**Effective Period**	**Design Approach**	**Stated Seismic Design Application in Standard**	**Comments**
NAASRA 1965 (NAASRA 1965)	1965 to 1969	Working Stress Design	"in regions where earthquakes of significant intensity may occur" (Cl 2.23)	Seismic hazard flagged but not routinely considered in design
NAASRA 1970 (NAASRA 1970)	1970 to 1975	Working Stress Design	As per above	As per above
NAASRA 1976 (NAASRA 1976)	1976 to 1991	Working Stress Design	Zones 1 and 2 (Cl 2.13.1 and Figure 2B.1)	Specific hazard information provided for the Yilgarn.
AustRoads 1992 (AUSTROADS 1992)	1992 to 2004	Ultimate Limit State Design	Ultimate Limit State design earthquake is a 1:2000 AEP event (Cl 2.13.3)	Later amended to cross reference hazard in AS 1170.4. Seismic design not routinely considered state-wide in design.
AS 5100 2004 (Standards Australia 2004)	2004 to 2016	Ultimate Limit State Design	All bridges	State-wide application of seismic design, where controlling.
AS 5100 2017 (Standards Australia 2017)	2017 to present	Ultimate Limit State Design with Displacement Based Design approach added.	All bridges	Higher bridge importance classes assigned.

4. ARRANGEMENTS FOR DEVELOPING INFORMATION ON CRITICAL INFRASTRUCTURE RISK AND MITIGATION

Efforts are being made in Australia to understand and address seismic risk across several critical infrastructure sectors. Critical infrastructure, as the name implies, is a vital part of our built environment. It has been defined by the Australian Government as:-

> *"those physical facilities, supply chains, information technologies and communication networks which, if destroyed, degraded or rendered unavailable for an extended period, would significantly impact on the social or economic wellbeing of the nation or affect Australia's ability to conduct national defence and ensure national security"* (Commonwealth of Australia, Department of Home Affairs, 2015).

While the performance of building assets has a more direct influence locally, the disruption of critical infrastructure by virtue of its systematic nature and interdependencies can have far reaching consequences. The failure of critical infrastructure in a rare earthquake event can have major impacts to communities and the economy as well as adding significantly to emergency management logistics.

Information Sharing Arrangements for Critical Infrastructure

Developing an understanding of the vulnerabilities of critical infrastructure (CI) systems to natural hazards requires industry working with government and external domain specialists. This is particularly challenging where much national infrastructure sits in government owned but privately operated corporations or is fully privately owned. The need for broad collective effort on CI issues is recognised internationally and various information sharing arrangements have been established to facilitate collaborative efforts through public-private partnerships. Examples are:-

> US - Office of Infrastructure Protection (IP): It's remit falls under the Department of Homeland Security. It "conducts and facilitates vulnerability and consequence assessments to help critical infrastructure owners and operators and State, local, tribal, and territorial partners understand and address risks to critical infrastructure" (Department of Homeland Security USA, 2015).
>
> UK - Centre for the Protection of National Infrastructure (CPNI): The UK's CPNI has protective security as its primary focus. However, one of its key drivers is to assist in implementing the government's policy for enhancing 'Resilience of Infrastructure from Natural Disasters'. It has a leading role in the cross-sector Critical Infrastructure Resilience Programme (CIRP) (CPNI UK, 2015).
>
> EU - European Network and Information Security Agency (ENISA 2011) presents advice for building and sustaining effective public, private partnerships (PPPs).
>
> AUS - Trusted Information Sharing Network (TISN): The TISN is a multi-tiered, sector-based network of government and private operators of critical infrastructure assets and services. It acts as the mechanism for exchange of expertise between public and private sectors, and across sectors.

5. EIRAPSI PROJECT

The project entitled "Earthquake Impact and Risk Assessment for Perth and Supporting Infrastructure" (EIRAPSI) is an Australian example of a collaboration between government, industry and research agencies. It is a two and a half year multi-partner project centred on the Perth Metro that is developing information, not only for the WA government agencies responsible for response and recovery, but also for the managers of critical infrastructure in the transport, electricity and water sectors. The six project partners are:-

Department of Fire and Emergency Services	Lead WA Government agency and coordinator of the project.
Geoscience Australia	Technical leader providing risk modelling, infrastructure facility vulnerability assessment and project management.
Global Earthquake Model Foundation	Science partner providing vulnerability and infrastructure network modelling support.
WA Department of Main Roads	Industry partner and collaborator providing transport sector data, information and expertise.
Western Power, WA	Industry partner and collaborator providing electricity sector data, information and expertise.
Water Corporation, WA	Industry partner and collaborator providing water sector data, information and expertise.

While the project is not being undertaken under the Australian TISN described above, the overarching project agreements (four in total) capture mutually agreed principles that are common to the aforementioned information sharing arrangements, including:-

> Any confidential information contributed to the project by any party must be kept confidential and not disclosed.
>
> Outputs derived using a combination of confidential and non-confidential data will be treated as confidential information, unless it is reviewed by the concerned parties and written approval is provided stating such outputs can be put in the public domain.
>
> The obligations of confidentiality imposed on a party will survive termination of the collaboration agreement.
>
> All parties agree to treat as confidential any information received from project partners marked as confidential, and will not publish or disseminate such information without written approval from the partners concerned.
>
> Analytical methods and software modelling tools and techniques, data model and typologies developed in the course of the project can be made available through open source and open data licenses.

The project is co-funded by the Global Earthquake Model Foundation (GEM) in Pavia, Italy, and Geoscience Australia. GEM is a non-profit research organisation which was incorporated in March 2009 and presently has 15 Public, 8 Private and 10 Associate Partners. GA is one of the public partners through which the Australian Government provides funds to GEM and, as in the EIRAPSI Project, can collaborate on projects of mutual interest.

Importantly, the role of the industry partners in this project has been an active one. Fundamentally, they are the experts on the operation of their assets and systems. As well as providing fundamental data, information and enabling facility inspections, the partners have provided access to their domain specialists to review and validate the research as it develops. Projects like EIRAPSI enable the bringing together of broader expertise along the full value chain of earthquake risk science which aids in a broader understanding of earthquake hazard, community exposure, vulnerability and risk mitigation. The aim is the development of trusted information that could not be developed by government or industry alone on credible earthquake impacts beyond present experience.

Scope

The broad project scope is summarised in Table 3 below.

Table 3:- Information development scope of the Earthquake Impact and Risk Assessment for Perth and Supporting Infrastructure (EIRAPSI) Project.

Industry Sector	Metric Category	Metric Component or Asset Type
Emergency Management	Vulnerability	Building damage, including those housing post disaster functions.
		Damaged building triage logistics.
		Persons rendered homeless.
	Casualties	Death and injuries
		Urban and Search and Rescue Logistics
	Socio-economic	Community resilience and recovery needs
Transport	Vulnerability and Mitigation	Bridges
		Tunnels
Electricity	Transmission/Sub-transmission	Terminal and switching
	Distribution	Zone substations
Water	Potable Treatment	Facilities
	Transmission Pumping	Pumping stations
All	***Interdependencies***	***Cross sector***

Hazard

The original scope for EIRAPSI comprised six scenarios. These events were scaled to generate bedrock shaking levels that matched three hazard likelihoods in two locations of interest as determined at a workshop with project partners convened on the 27th April 2017. The first epicenter was close to the Western Australian Cricket Association

(WACA) stadium at the eastern end of the Perth central business district, and the second was close to the community of Mundaring east of the Darling fault. Selected focal depths for the earthquake events were consistent with the regional geology. Events beneath the Perth Metro were necessarily deep to be below the sedimentary basin. Events at the second location east of the Darling Fault included a shallow event as the cratonic rocks could support a large shallow earthquake. The target bedrock hazard was the 2012 bedrock hazard developed by Geoscience Australia (Burbidge 2012) with later refinement to be made once the updated 2018 hazard assessment by Geoscience Australia is available (Allen et al, 2018). The scenario events that matched the 2012 hazard assessment are summarized in Table 4.

Table 4:- Earthquake scenario events matched to Geoscience Australia 2012 assessment of bedrock hazard (Burbidge et al).

Location	**Average Recurrence Interval [years]**	**Target PGA [g]**	**Moment Magnitude M_w**	**Focal Depth [km]**
Western Australian Cricket Association Stadium (The WACA)	500	0.045	4.2	25.0
	1,000	0.080	4.5	20.0
	2,500	0.135	5.0	16.0
	5,000	0.200	5.4	15.0
Mundaring Weir	500	0.060	4.2	15.0
	1,000	0.100	4.5	10.0
	2,500	0.175	5.0	8.0

Simulated bedrock ground motions corresponded with NEHRP Class B site conditions (Building Seismic Safety Council, 2004) and so were modified for the effects of regolith response. The process utilised the national classification of Australian regolith undertaken by Geoscience Australia which has been recently updated (McPherson 2017). The classification was undertaken using best available surface geology maps developed in each jurisdiction and mapped the surface soil types to the appropriate NEHRP class. In the figure the portion of this mapping in the Perth region is presented in Figure 1. The sediments of the coastal plain beneath Perth contrast with the stiff rock site conditions east of the Darling Fault.

Partway through the project an additional and rarer scenario event was added at the WACA location. This matched the 5,000 year ARI bedrock hazard and was developed to provide support to the then forthcoming *2018 East Asia Summit : International Disaster Assistance Workshop* (hosted in Perth from the 8 to 10 May, 2018). The simulated ground shaking severity in terms of Modified Mercalli Intensity on bedrock for this scenario is presented in Figure 2 and the corresponding surface shaking modified for regolith response in Figure 3. The region of strong shaking beneath the centre of Perth is very extensive and influenced by the soft alluvial deposits of the Swan and Canning Rivers. The physical consequences of this ASEAN scenario are discussed later.

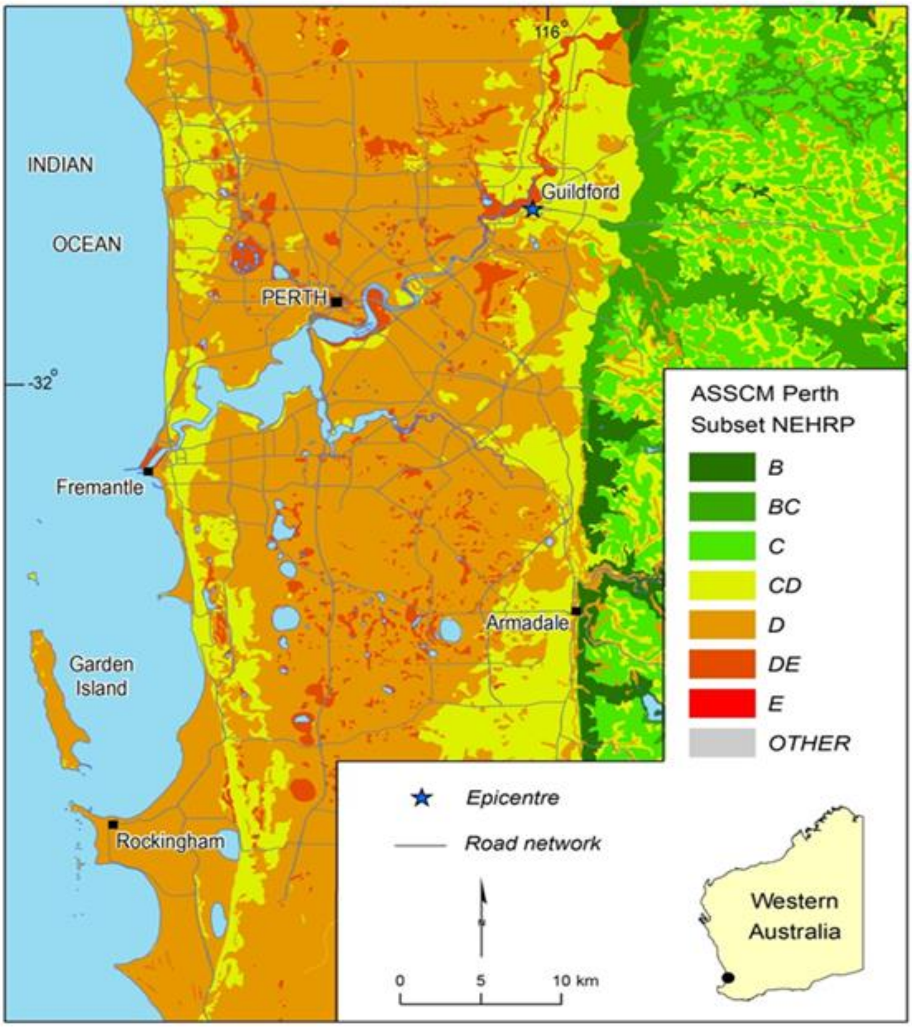

Figure 1:- Mapping of surface geology to NEHRP site response classes using surface geology by McPherson (2017)

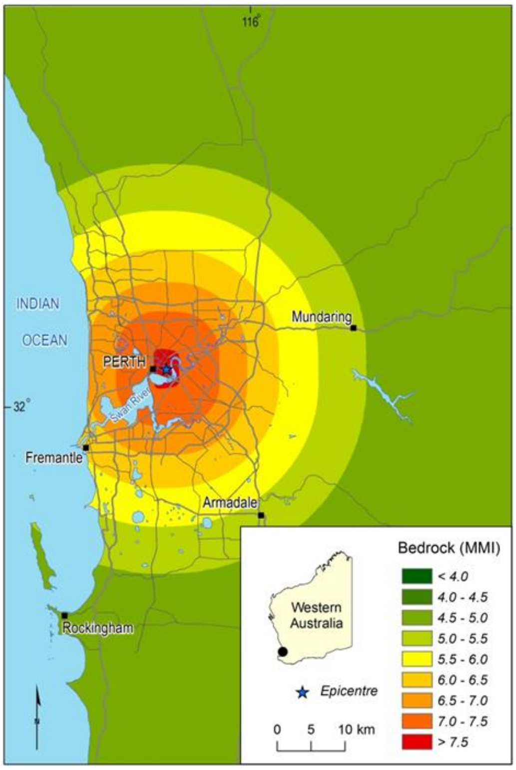

Figure 2:- Modelled severity of earthquake shaking on rock in terms of the Modified Mercalli Intensity for the 5,000yr ARI hazard matched event centred on the eastern end of the Perth central business district.

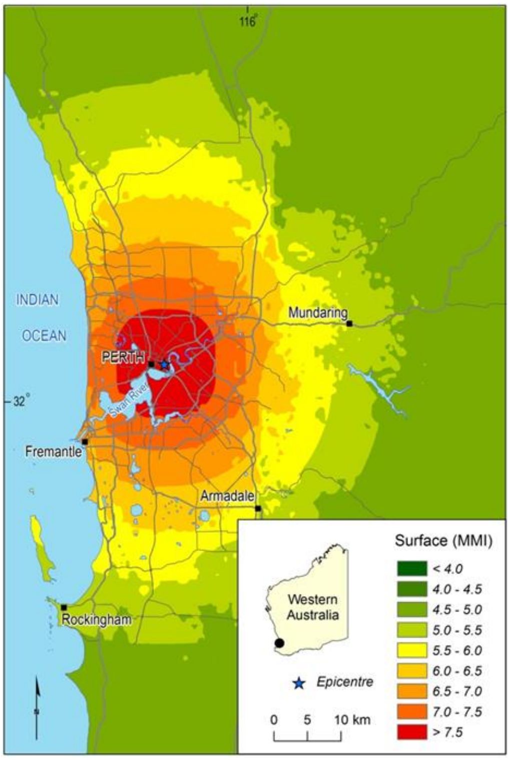

Figure 3:- Modelled severity of earthquake shaking on surface soil in terms of the Modified Mercalli Intensity for the 5,000yr ARI hazard matched event centred on the eastern end of the Perth central business district. The simulation of the event predicts extensive areas of the central city experiencing MMI 7.5+ severity shaking.

The scenario events are presently being refined to match the latest bedrock hazard assessed in the NSHA18 probabilistic seismic hazard assessment (Allen et al, 2018) by Geoscience Australia.

Exposure

The project utilised the National Exposure Information System (NEXIS) developed by Geoscience Australia as the basic definition of Perth community exposure. NEXIS provides nationally consistent building, demographic, business and some CI information through the integration of information and data maintained by other custodians. It also includes information captured by Geoscience Australia through post disaster and exposure survey work linked to other projects. The information is at building level and can be accessed online from the GA website at an aggregated level with user defined geographic boundaries and theme selections through the Australian Exposure Information Platform (https://www.info.aeip.ga.gov.au/).

The specific WA government residential building information recently integrated into NEXIS significantly improved the definition of residential building construction as to age, wall type and roof type. The building stock data also highlights an interesting feature of WA residential building construction which contrasts with that of the eastern states. Unreinforced masonry is the preferred form of construction with 84% of the WA residential building stock being of this form. While eastern states experienced a shift to brick veneer construction from the 1960’s onwards, WA experienced the opposite trend. During the 1980s and 1990s over 90% of new homes built in WA were unreinforced masonry as seen in Table 5. Contemporary unreinforced masonry, while of improved materials and robustness when compared to older masonry construction, is more readily damaged in earthquake shaking as highlighted by analyses of damage loss from the Newcastle and Kalgoorlie Earthquakes (Maqsood et al, 2014). This exposure related earthquake vulnerability factor was included in the scenario modelling.

The NEXIS derived exposure information was further augmented with specific attributes for buildings poorly defined or of particular interest to emergency services through the following:

- Desktop survey of 599 multi-storey apartment buildings.
- Desktop survey of 340 hospital buildings across 29 campuses.
- Inclusion of 7,410 school buildings across 663 campuses by means of a sample desktop survey of 2,035 buildings in the epicentral regions of the scenarios and subsequent statistical attribution across the balance of Perth.
- Desktop survey of 64 emergency services buildings.
- Inclusion of detailed information for 745 buildings field surveyed in the Perth central business district by Geoscience Australia for the Australian Reinsurance Pool Corporation.
- The inclusion of specific information for 461 road bridges and 1 road tunnel as provided by the WA Department of Main Roads.
- Detailed information on key electricity and water sector facilities provided by Western Power WA and Water Corporation WA.

The resultant exposure database is the most robust that Geoscience Australia has used for a city level study to date and has enabled a detailed mapping of vulnerability models.

Table 5:- Percentage unreinforced masonry wall construction in the Western Australian residential building stock by building age category.

Period Built	**Number of WA Residential Buildings**	**Percentage that have Unreinforced Masonry Walls**	
		Narrow Age Bands	**Broad Age Categories**
1788-1839	3	57.8	57.8
1840-1890	139	77.7	
1891-1913	5,343	58.2	
1914-1946	40,799	57.7	
1947-1951	15,203	48.3	75.5
1952-1961	36,593	53.0	
1962-1971	91,928	73.3	
1972-1981	145,843	85.4	
1982-1991	149,365	91.1	90.1
1992-2001	165,622	91.2	
2002-2011	194,596	90.5	
2012-2016	43,220	87.8	
Total	***859,680***	***84.0***	***84.0***

Vulnerability

On the basis of available NEXIS information, a total for 31 building types covering three building usages have been identified and subdivided into two age related vulnerability classes. Earthquake vulnerability models (18 in total) were mapped to these with a one to many mapping in many cases. Four of the vulnerability models were empirically derived from Australian earthquake damage data (Maqsood et al, 2016) and the rest were based on US models (FEMA 2003) with some heuristic adjustments.

For bridge vulnerability, selections from a suite of 28 US bridge vulnerability models (FEMA 2003) were utilised in a mapping to the Perth bridge stock. This mapping was subsequently refined through a bridge sector specialist workshop on the 31st August 2018. A similar mapping of US vulnerability models was undertaken for the 76 electricity substations in the greater Perth area.

For selected key electricity and water sector facilities, specific vulnerability models are being developed and used to assess current vulnerability and mitigation opportunities. These models are being developed using an application called System for Infrastructure Facility Resilience Analysis (SIFRA) as described later in this paper.

Impact and Risk Assessment

Quantitative impact and risk assessment requires the integration of the elements of hazard, asset exposure and vulnerability (or susceptibility). The approach used by the project team corresponds with the convolution of these elements routinely used actuarially in the financial sector, though with a broader range of impact and risk metrics for this project. The integration tool was *OpenQuake*, a freely available earthquake impact and risk assessment software developed by GEM (Silva et al, 2014). In this project GA is using *OpenQuake* for the first time for impact and risk assessment, in place of the corresponding tool GA developed previously for this work, EQRM (Robinson et al, 2003).

Table 6:- Impact metrics for the four WACA centred earthquake scenario events and three events centred on Mundaring.

Impact	**Mundaring Weir Scenarios**			**WACA Perth CBD Scenarios**			
ARI	***500yr***	***1,000yr***	***2,500yr***	***500yr***	***1,000yr***	***2,500yr***	***5,000yr***
Damaged Buildings	34,000	83,000	185,000	114,000	186,000	331,000	493,000
Building Triage	17,000	42,000	98,000	59,000	100,000	199,000	347,000
Uninhabitable Buildings	140	900	6,400	2,900	8,500	41,000	122,500
Homeless Population	400	2,500	28,100	8,100	23,800	114,700	345,600
Slightly Injured	60	150	360	220	410	1200	4,050
Moderately Injured	5	20	120	60	170	800	2,520
Severely Injured	-	-	-	-	-	5	75
Dead	-	-	-	-	-	10	140

The key impact metrics developed for the three Mundaring centred and four WACA centred earthquake scenarios are summarized in Table 6. Other impacts were also simulated but not presented here which included infrastructure and urban search and rescue logistics. It can be noted that exposure has a clear influence. The respective ground motion hazards are similar for each location but the WACA consequences at each ARI are several times larger than those for Mundaring Weir due to the greater exposure in central Perth. Secondly, it can be clearly seen that the severity of the impacts increase significantly with the stepwise increase in the ARI. This is a direct reflection of the nature of this geological hazard which increases steadily with increasing rarity, as contrasted with severe wind earlier. Finally, it can be noted that the 5,000 year ARI logistics are overwhelming with most buildings in the Perth Metro damaged, an enormous triaging exercise required and 350,000 people requiring temporary housing.

6. ASEAN SUMMIT ON INTERNATIONAL DISASTER ASSISTANCE

Australia is a strategic partner of the 10 member community of the Association of Southeast Asian Nations (ASEAN). Arrangements exist for these nations to assist one another when a major natural disaster occurs that exceeds the capacity of the impacted nation to manage. While Australia is able to draw upon its resources to assist in the region, there is the reciprocal situation in which Australia may be faced with such a catastrophic event that it needs ASEAN neighbours to quickly assist in key capability areas. The arrangements for this eventuality were the subject of a summit convened in Perth from the 8th to the 10th of May this year as an initiative between the Australian and Indonesian governments. An earthquake event beneath Perth occurring in concert with heatwaves and bushfires in the south eastern states and a threatening tropical cyclone off the Queensland coast was chosen as a backdrop for this summit.

In support of the ASEAN summit, the original six scenario scope for EIRAPSI was augmented with a fourth earthquake event centred on the Perth CBD. As can be seen from Table 6, and as characteristic of earthquakes in intraplate Australia, the 5,000yr ARI event provided overwhelming consequences for Australian emergency management in the context of other emergency management demands elsewhere in the country. This EIRAPSI component provided an evidence based reference against which Australian needs were assessed in the context of existing arrangements. The result will be improved ASEAN support arrangements so Australia can be ready for a catastrophic disaster, including a large earthquake.

7. SIFRA

Critical infrastructure facilities are complex and incorporate a range of discrete components that must work together in concert to deliver services. The components often have varying vulnerabilities to earthquake ground motion, differ in criticality to the service delivery, have variable costs to repair and can have greatly varying timeframes for restoration. Some of the most vulnerable components can be legacy elements originally built as part of a much smaller facility that was subsequently enlarged to what exists presently. Furthermore, the geographic spread of key components in some facilities can mean that each component does not each experience the same ground motion in a given earthquake event as epicentral distances and soil classes may differ. Some earthquake vulnerability models are available in the literature for complete facility types (FEMA 2003) but these functions for facilities represent broad classes for facilities and provide little insight on what the drivers are behind overall earthquake risk. Facility information down to component level is fundamental for prioritising any earthquake mitigation efforts.

The software application called the System for Infrastructure Facility Resilience Analysis (SIFRA) has been progressively developed at Geoscience Australia to enable critical infrastructure facilities to be analysed from component level up. While the initial development of the capability was for assessing earthquake vulnerability and was directly linked to the earthquake event simulation software EQRM (Robinson et al, 2003), the old architecture has been revised in the development of SIFRA. The new architecture is hazard agnostic enabling other natural hazards, human threats, or techno-genic failures to be examined from a component level/system behaviour level. The current application of the tool has been for earthquake vulnerability and so is discussed in this context in this paper.

The SIFRA model is comprised of four key elements and associated input data: fragility algorithms, facility system model, a loss model, and a restoration model. Each of these is discussed below:-

Component Level Vulnerability

As earthquake induced ground shaking at a facility increases in intensity, the individual components that comprise it respond and sustain progressively more damage. Fragility functions are typically used to define this susceptibility to damage by quantifying the likelihood that a level of damage will be exceeded for a given level of shaking. This approach requires the definition of one or more earthquake damage states for each component and the selection of a ground shaking measure that is highly correlated to the component damage. In SIFRA up to four sequential damage states have been used for facility component fragility definition. The hazard parameter usually adopted is the peak ground acceleration (PGA) at the site. However, the software can accommodate fragility functions that have other earthquake hazard transfer parameters that may be more correlated to damage of the component in question. For example, peak ground velocity is better correlated to chimney stack damage than PGA.

The component level fragility models need to be representative of the assets they characterise. The models used have typically been established by GA using the following hierarchy of reducing certainty:-

1. Direct consultation with industry asset managers to reach agreement on component fragilities using the most appropriate published models and drawing upon construction specifications and observed earthquake performance (if possible).
2. Selection of the most applicable model from a literature survey of published models.
3. Heuristic engineering judgment in adapting damage models for other components assessed to have similar fragility.

An example of a fragility function of the second type representing a capacitive voltage transformer (Anagnos 1999) is presented in Figure 4.

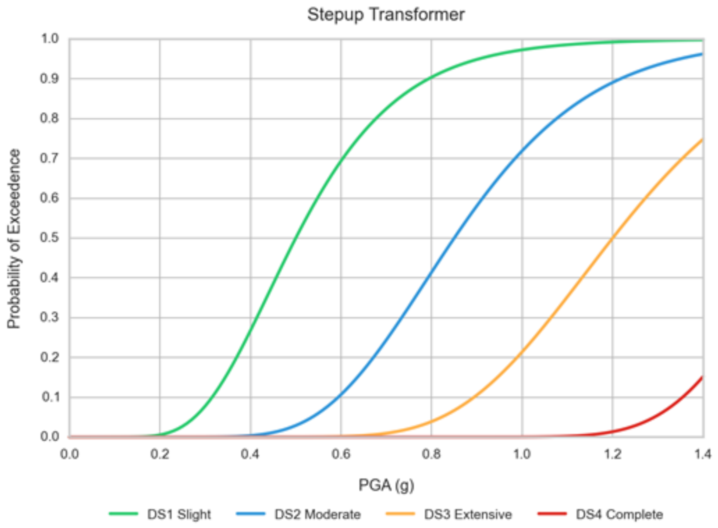

Figure 4:- Fragility curve for a 230kV capacitive voltage transformer adapted from Anagnos (1999).

Facility System Model and System Vulnerability

Facilities are interdependent systems and so are modelled in SIFRA as a network of components. This has three distinct advantages: (1) it allows for modelling the effect of impaired or destroyed components on the operational capacity of the system, (2) it allows for using graph theory to assess the graduated capacity degradation (and restoration) through modelling flow through the network, and (3) it allows for detection of the most efficient ‘paths’, or sets of components, through the network that need to be restored in order to establish a link between input and output nodes.

The concept of components and facilities used in SIFRA map closely to the typology of micro-components and macro-components as defined in the European Synerg-G program (Pitilakis et al. 2014), and align with the definition of subsystems and systems as defined in Rinaldi et al (2001). Under this approach, the components are represented as nodes. Based on their role within the system, these nodes, or components, are classified in four general categories; supply, output, dependency or transhipment. These are described in greater detail in a paper by Rahman et al (2015). The *igraph Python* package is used as the network modelling platform to calculate graph metrics for a post-earthquake damaged system model. An example of a facility translated into a network model is illustrated in the case of an Australian water treatment facility in Figure 5.

While a component fragility function gives the likelihood that a component will be in a particular damage state, for the SIFRA analysis of the facility an actual discrete damage state needs to be assigned for each component. The SIFRA process is run through a Monte Carlo process to sample the damage state of each component, and for each set of realised component damage states the operational status of the facility is assessed using the network model. The process is then repeated for a step-wise increasing range of hazard values (e.g. PGA of 0.01g to 1.40g in 0.01g steps). This process shown in Figure 6 which enables a characterisation of the system in terms of repair cost and facility fragility.

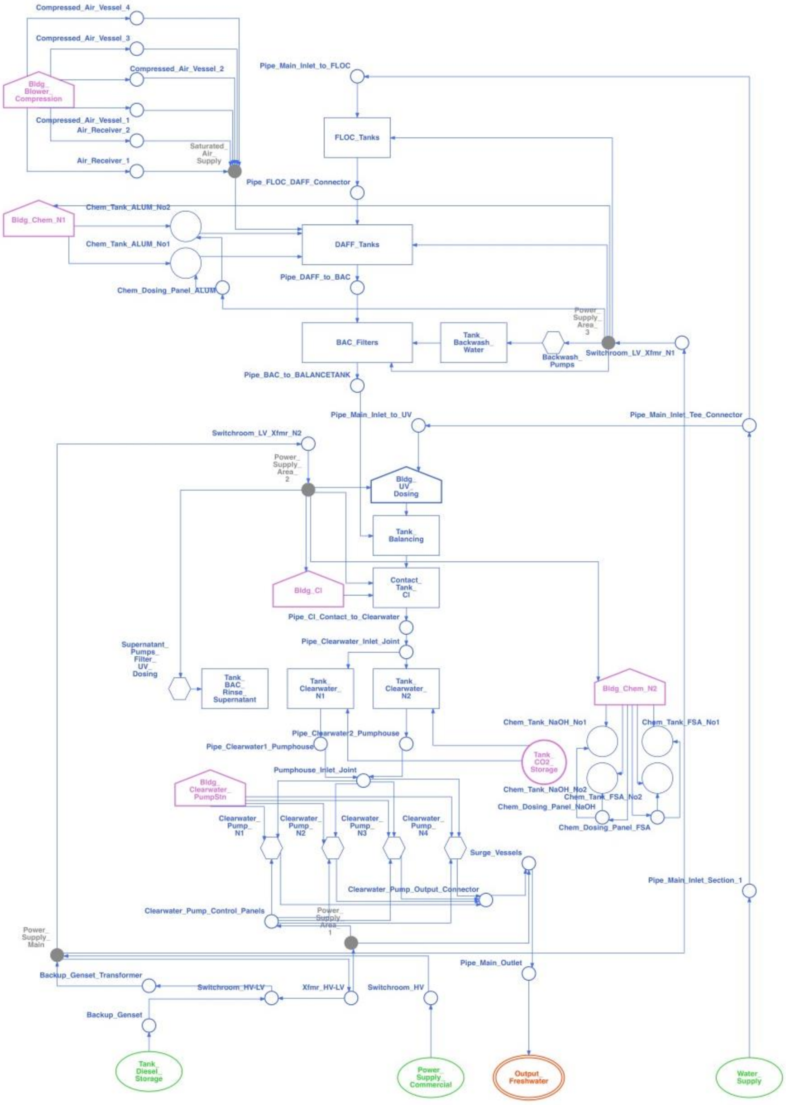

Figure 5:- Graph-theoretic system diagram of an Australian water treatment plant. The supply nodes are shown in green, the dependency nodes are purple, and the output node is orange.

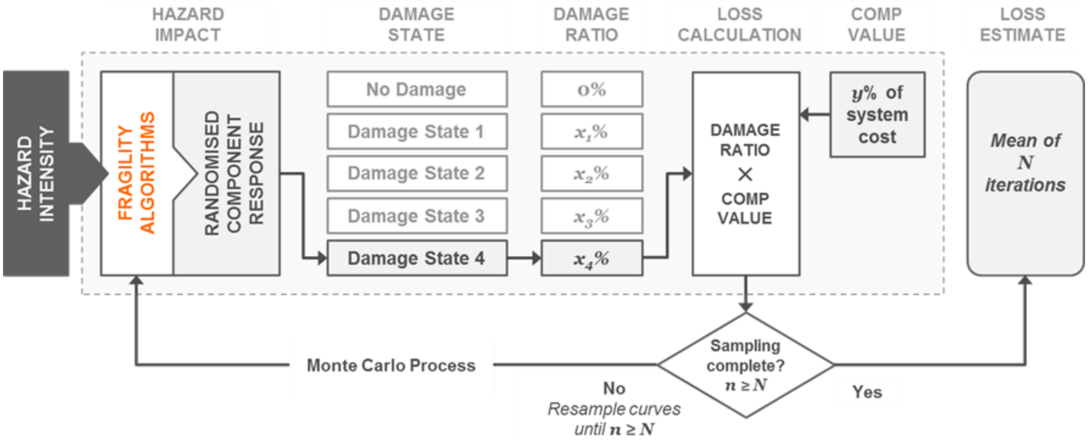

Figure 6:- Schematic of the SIFRA Monte Carlo process to attribute component damage associated damage loss.

System Restoration Model

It is assumed in SIFRA that the system restoration process needs to be undertaken in stages, subject to the level of reparation resources that can be made available and the sequence of repairs. The key assumptions needed for modelling restoration are:

- Restoration Streams: this is the maximum number of components that can be worked simultaneously. This is effectively a value representing the volume of work that can be simultaneously undertaken in a period of time, and acts as a proxy for the effect of the deployment of trained personnel and material to the repair tasks.
- Restoration Offset: this is the time allowance for assessment of damage to the system and for securing the site to ensure it is safe for the commencement of repairs.
- Testing and Recommissioning Interval: this is the time allowance for testing that the system, or a specific production line, or a specific component, meets operational and safety parameters before recommissioning.

In addition to the core process of approximating restoration time as outlined above, a routine for simulating component “cannibalisation” within a facility has also been incorporated. “Cannibalisation” refers to the moving of an undamaged component from a low priority or redundant line to replace a damaged component on a high priority line, eliminating potentially long procurement or transportation times and expediting the restoration.

A sample Gantt chart of recovery for a power station example is shown in Figure 7. The staged restoration efforts are shown along with the corresponding step-wise recovery of generation capacity

The simulation process enables the fragility of the entire facility to be simulated. It facilitates criticality analyses with the identification of components with the greatest vulnerabilities, longest restoration times, and financial losses. This process can be used to undertake virtual retrofits of systems to assess the sensitivity of facility resilience to upgrades. Most importantly, it can inform investment by industry in mitigation strategies to make facilities more resilient before a future severe earthquake.

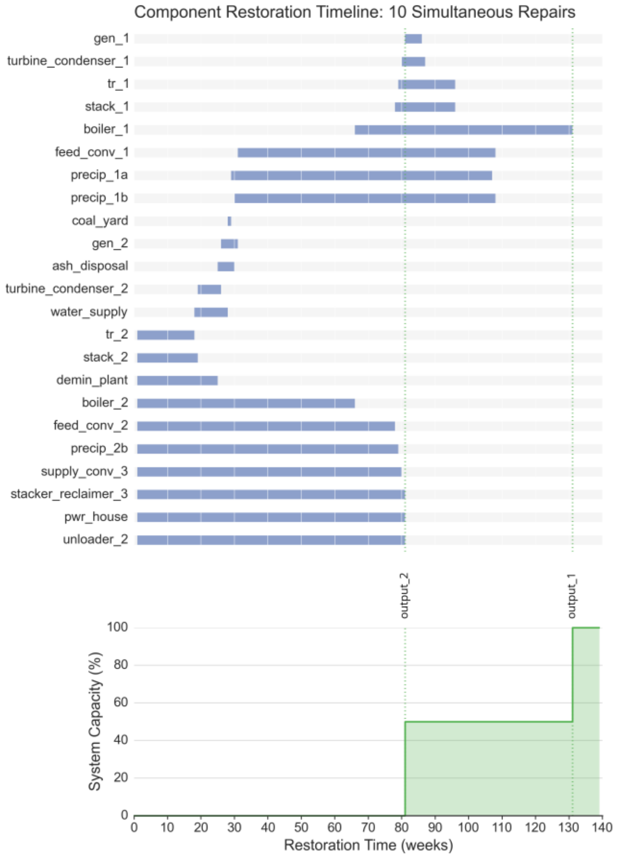

Figure 7:- Restoration schema for ten simultaneous repair streams for and earthquake damaged thermal power station.

Application to EIRAPSI Partner Water Sector and Electricity Facilities

The SIFRA methodology is presently being employed to examine three electricity transmission facilities managed by Western Power. In additional, a major potable water treatment plant with associated water transmission pumping facilities is being examined with Water Corporation. Facility models have been developed and currently collaborative effort is being directed at improving the component level information to improve assessments of system behaviour and restoration prognosis. Where identified, options for mitigating vulnerabilities can be examined. The aim is to assist the managers of CI to identify and address current vulnerabilities ahead of a major earthquake.

8. YORK MITIGATION STUDY

York is the oldest inland town in Western Australia and is situated approximately 100 kilometres east of Perth in the Avon Valley. The town has many notable heritage buildings that today attract tourists to the town, thereby indirectly making a major contribution to the local economy. However, the presence of these valued older masonry structures in York is “two edged” in that it has also given the town an inherent vulnerability to earthquake ground motion. Figure 8 shows the York Town Hall built in 1911 which, while well preserved, has not been the subject of any targeted retrofit to improve its resilience to earthquake ground motion. The seismic hazard in York is at the threshold of moderate by world standards and the vulnerability of the community was highlighted in the 1968 Meckering Earthquake that caused widespread damage to York, located 38km from the epicentre. Earthquake hazard in York is further exacerbated by the soft alluvial deposits of the Avon River which runs through the centre of town. These reach thicknesses of 10 metres or more and serve to amplify earthquake ground motions.

Figure 8:- York Town Hall located at 81 Avon Terrace.

The vulnerability of York to future credible earthquakes is of concern to the Shire of York which would be greatly impacted locally, the WA Department of Fire and Emergency Services (DEFS) that would need to respond following an event, and the WA Department of Planning, Lands and Heritage which seeks to preserve these valuable structures. The interests of local stakeholders have prompted a research utilisation project under an overarching earthquake mitigation focussed project that is part of the current Bushfire and Natural Hazards Collaborative Research Centre (BNHCRC). Under Project A9 entitled *Cost Effective Mitigation Strategy For Building-Related Earthquake Risk* (https://www.bnhcrc.com.au/research/understanding-mitigating-hazards/244), a mitigation project led by the University of Adelaide and partnered with Geoscience Australia is developing earthquake mitigation strategies for masonry buildings in York. These will be virtually applied to the town to assess the most cost-effective approaches for making six common building types in York more resilient to future earthquakes.

The project is significant in the matter of preparedness to earthquakes in several areas:-

- It is the first time (to the author's knowledge) that a community scale approach is being taken to address legacy earthquake vulnerability in Australia. This includes the development of scalable information for a spectrum of decision makers ranging from building owners, to business owners, to local government, to state government with an interest in both emergency management and heritage preservation.

- The project is considering a very broad range of metrics which include injuries, health care costs and the impacts on businesses. It is also considering other metrics to better capture avoided intangible impacts. This element involves a second BNHCRC project that will be providing quantitative measures for these based on "willingness to pay".
- The project is assessing the effectiveness of mitigation strategies in economic terms as a fundamental input into what are investments in future resilience.
- The project is engaging with the insurance industry that, in the case of York, does not always price the standard cover for earthquake based on locality risk in the same way as it does for bushfire, severe wind and flood. This has implications for insurance affordability that can impact a community's ability to recover and on price signals to promote retrofit action.
- The project is seeking to inform strategies for incentivising mitigation action by stakeholders in an environment where Australian building regulation lacks the retrospective mandates that have recently been strengthened in New Zealand legislation.
- Scenarios for DFES are being simulated for present vulnerability and forecast reductions resulting from retrofit uptake into the future.
- The research is being developed to be readily transferable to other Australian communities with vulnerable masonry buildings, particularly smaller low growth regional towns.

The project will be completed by June 2019. To date the entire town has been surveyed, the predominant building stock has been reviewed and six key building types have been identified (Vaculik et al, 2018). From a stakeholder workshop convened in York on the 9th August a range of incentivisation initiatives have been identified and consensus developed on credible uptake rates for building retrofit to enable current and future community risk to be forecast.

9. SUMMARY

In Australia earthquake hazard has unfortunately been ignored in the development of the built environment for most of the country's settled history. Seismic considerations for critical infrastructure have taken even longer to address with an ongoing need to promote seismic design considerations with other engineering disciplines such as electrical, mechanical and chemical engineering. Collectively this has led to vulnerable elements being present in the Australian built environment. These represent a significant risk that needs to be systematically addressed

It must be noted that, not every community asset is vulnerable to earthquake, with many structure types either inherently resilient, or having more dominate loading conditions from another hazard, such as cyclonic wind. Hence, targeted action is the key to addressing those assets that represent the greatest risk, rather than broad scale initiatives.

Critical infrastructure represents a special risk due to the heavy dependency of communities on transport links and utility service delivery. The interdependency and connectedness of these systems can cause disruption to economic activity and services with footprints much larger and/or extending much further than the area of immediate damage. The value of partnerships between industry, government and other specialists in addressing vulnerability issues has been recognised as reflected in established arrangements for developing and sharing sensitive information to inform mitigation investment. Such partnerships provide insights that cannot be realised by any of these parties in isolation.

Earthquake hazard in Australia has characteristics that differ from meteorological hazards and tectonic plate boundary hazard. Rare intraplate earthquakes can be very severe and the consequences beyond the limited experience we have in Australia. As reflected in the reinsurance industry pricing of risk, rare earthquakes can be devastating. The wide gap between the severity of present design level ground shaking and the severity for rare credible events presents challenges for infrastructure regulation. It is not clear whether design approaches for tectonic plate boundary countries that have influenced Australian building regulation will prevent catastrophic loss of life in an event that should not cause structural collapse. Broader performance objectives such as collapse prevention may need to be explicitly addressed to ensure that community expectations are met. Furthermore, there is the broader issue of the avoidance of economic loss where current seismic design philosophy exposes property owners to greater financial loss than does design for severe wind.

Information is needed on existing vulnerability and the most cost-effective strategies to mitigate this. Given the finite resources that are available for retrofit, these strategies need to target those elements of communities that are contributing the most to earthquake risk to get the best outcome for the investment. This information should also draw upon the best available hazard science, including the incorporation of the significant uncertainties that are characteristic of our intraplate environment. Furthermore, this information needs to be communicated in a way that can enable a range of decision makers to make investment decision.

Emergency management (EM) has made significant strides in recent years at a range of scales to better plan for future earthquakes. While this paper has highlighted initiatives by DFES in WA and Emergency Management Australia (EMA) at a national level, a significant body of work has also been done in other jurisdictions that include South Australia, Victoria, New South Wales and Queensland. This is enabling EM to be better prepared for the next major Australian earthquake.

Arguably it could be said on balance that Australia is not ready for the next big shake. However, as illustrated by ongoing project initiatives with emergency managers, critical infrastructure operators and local communities with high risk community assets, progress is being made. With the development, communication, incentivisation and uptake of targeted measures, the next big shake may not be the inevitable disaster otherwise anticipated.

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