Key elements for effective study of seismic vulnerabilities of lifeline infrastructure to develop informed mitigation strategies: trust, collaboration, and a generalised infrastructure model

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1. Geoscience Australia

Abstract

Critical infrastructure systems provide essential services central to the functioning of Australian communities and the economy. Research into historic catastrophic failures of infrastructure suggests two factors have the strongest influence on such failures: system complexity and tight coupling within such systems. While complexity of these lifeline systems is recognised, the latter factor is often not well-understood, especially in the context of severe natural hazards.

Proposed in this paper is a methodology to study the performance of lifeline infrastructure under hazard impact, where key component parameters of complex lifeline systems, along with component interactions, are integrated within an executable model. This model can then be subjected to any number of virtual hazards to assist in identification of non-obvious failure mechanisms, quantify post-hazard system performance, and conduct experimentation with alternate mitigation measures.

This process allows for investigating the combined effect of various parameters including component fragilities, system topology, restoration times and costs with their uncertainties, redundancies, and the expected hazard. Much of this information is commercially sensitive or only accessible to specialist groups. Ensuring access to, and effective combination of, such information requires a trusted information-sharing collaboration framework between cross-sectoral experts. This collaboration requires participation from infrastructure operators, researchers, engineers, and government entities. This paper outlines a methodology and tools that have been utilised within such a collaborative project, and documents key learnings from the effort, along with observations on improvement strategies.

1. INTRODUCTION

Research from the domains of behavioural science and economics have observed that people tend to incorrectly perceive "the threat posed by low-probability/high-impact natural disaster risks," leading both individuals and governments underpreparing for the potential impacts of such events. The threshold model heuristic, for example, suggests that "people ignore the probability of disaster risks if the probability is judged to fall below a threshold level of concern" (Robinson, 2019). In the context of lifeline infrastructure, this issue is further accentuated by the increasing complexity and interconnectedness of such systems.

The Normal Accident Theory hypothesises that within systems that are complex with tightly coupled components, catastrophic failures are inevitable (Perrow, 1999). This notion is technologically deterministic, and does not consider the effects of structuring the system deliberately to contain error propagation, or interventions to reduce failure likelihood of key components, or crucially, human intervention (Hopkins, 1999). The combined lesson from these theories, and from research into catastrophic failures generally, is this: hazard impacts on systems or components that are perceived to be resilient often have unrecognised vulnerabilities that can initiate failures that propagate in unexpected ways, and lead to major disasters. This can be considerably mitigated with systematic efforts in understanding the hazard threats facing the system components, identifying direct and indirect potential failure points, and using that information to inform mitigation measures.

These ideas form the motivation for a generalised methodology that acknowledges and addresses the nature of this challenge facing complex lifeline infrastructure. Practical tools need to be made available to apply this methodology for systematically identifying potential failure points, with a view to developing mitigation options. This paper briefly describes the development of a software tool for infrastructure seismic vulnerability analysis, and its applications in the Asia-Pacific region and in an Australian context.

2. THE CONCEPT AND THE SIMULATION PLATFORM

A methodology that can address the key issues discussed above needs three key characteristics: the method needs to be applicable for different infrastructure sectors, the method should allow the ability to incorporate a wide range of assets and systems of arbitrary degrees of complexity (in terms of both topology and component attributes), and the method needs to be hazard agnostic or at least be able to accommodate different kinds of hazards. The approach developed has a few key aspects:

1. Topology of all infrastructure systems, including facilities and networks, are represented as connected directional graphs.
2. Attributes of components have associated costs, physical damage state definitions, fragility algorithms, recovery times, and functionality thresholds,.
3. In line with the concept of Model-Based Systems Engineering, all models are built as executable models of sufficient complexity for the required level of analysis. The emergent behaviour of the components within the system context are elicited through the simulation of damage to components and simulation of system functionality with those damaged components.

A modelling framework and associated software has been developed to test and apply this methodology on real assets in partnership with industry. This tool is called SIRA (Systemic Infrastructure Resilience Analysis). At the core of this code is a metamodel of a generic infrastructure network. Sector-specific facilities and networks are built as child classes of this metamodel class, e.g. thermal power stations, electric substations, potable water treatment plants, wastewater treatment plants, pumping stations, etc. This allows for additional functionalities and behavioural complexity to be built for system models as necessary, and as relevant to the research questions being investigated. The design focus of this methodology has been on usability, adaptability and applicability across a wide range of infrastructure sectors and assets.

In the case of seismic hazard, the impact of ground shaking on a given infrastructure is simulated through a Monte Carlo process:

- A target asset is impacted by ground motion of a given intensity several thousand times (until a steady state is reached where the variance for additional samples is negligible).
- For each instance of this, a variable damage to each component is calculated, and

- The overall system operational capacity, i.e. ability of the system to continue producing its expected outputs, is calculated for the unique damage scenario through a flow calculation algorithm. The default option calculating this system flow is the 'max flow' calculation method as implemented in the *igraph*[1] graph modelling package. But custom flow calculation methods for specific network types can also be implemented.

Details of the approach and its implementation can be found online[2].

The necessary compromise to this approach is that SIRA models incorporate a lesser degree of sophistication in its flow analysis (i.e. analysis of performance of the impaired system) when compared to more specialised tools. Some of these tools are built for specific sectors (e.g. water), or a single type of problem (e.g. pipe failure), or designed to be used exclusively for detailed engineering analysis, or for use by specialised researchers. For example, Cavalieri, Franchin, Buriticá Cortés, and Tesfamariam (2014) undertook a comparative assessment of power network seismic vulnerability models where they classified available models into five categories (M1-M5) of increasing complexity. The simplest two models considered only connectivity, while the latter ones incorporated increasing degrees of sophistication in power flow analysis, with the most advanced version modelling iterative short-circuit propagation within substations and through the entire network.

SIRA seeks a middle ground where it offers the ability to undertake connectivity and generic flow analysis, along with centrality metrics for components to understand their relative criticality within the system. This allows network operators and researchers to combine their mutual strengths (in asset-specific knowledge and seismic vulnerability, respectively) to collaboratively build and test models of real assets to identify key vulnerabilities of the system and build an understanding of the implications of different damage scenarios for network operability. The utility of this tool is supplemented by a restoration prognosis model that assists the research team to explore the effectiveness of different restoration strategies, and also test the effects of retrofit options on the resilience and recovery of the target assets.

3. COLLABORATION FRAMEWORK FOR IMPLEMENTATION

The nature of this work necessarily requires expertise from several disparate disciplines, as illustrated in Figure 1. This has been the experience of the authors in undertaking seismic vulnerability assets projects in Australia, and in South-East Asia. A recent project that Geoscience Australia (GA) has been leading closely followed this structure. It involved active participation and data-sharing between state emergency management bodies, science agencies, and lifeline utility network operators from three sectors. The Global Earthquake Model Foundation[3] (GEM) has been a valued partner in this work. Their *OpenQuake* earthquake hazard modelling platform and expert advice have been important in ensuring

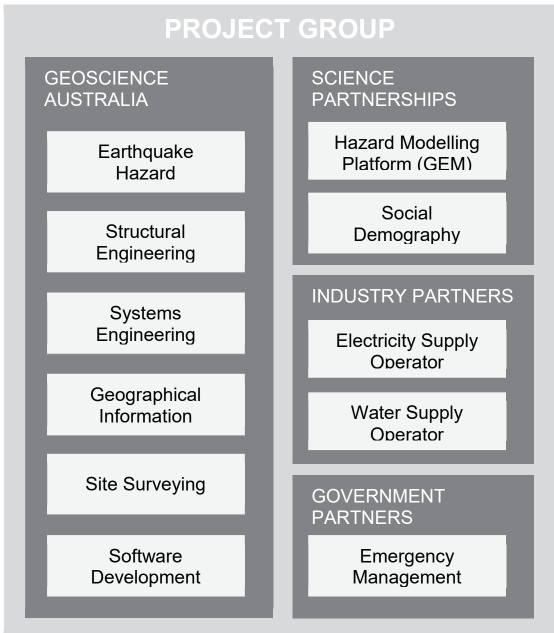

Figure 1. Sector and domain specific expertise utilised in a multi-sector infrastructure vulnerability project.

[1] https://igraph.org/c/doc/igraph-Flows.html. igraph – The network analysis package, Maximum Flows.
[2] https://geoscienceaustralia.github.io/sira/
[3] https://www.globalquakemodel.org

that the appropriate shaking intensities were obtained for scenarios that were relevant to the infrastructure owners and operators.

Effectiveness of projects of this nature depend to a very significant degree on access to asset-specific data. This data may relate to physical vulnerabilities of assets, or may include design information that is of a commercially sensitive nature. Hence, the operators of the lifeline infrastructure – which is often privately owned, or managed by private entities – are protective of their data. They justifiably are circumspect about who they share such data with, for what purpose, and under what assurances of confidentiality – of both the original data and analytical products derived from it.

For infrastructure vulnerability or risk assessment to succeed within collaborative projects there must be mutual trust, and an agreed framework for maintaining appropriate controls around access to and dissemination of sensitive data, its usage, and products or information derived from such data. There are excellent sources of research-based advice and guidance on building effective partnerships between public-private entities for work on infrastructure, e.g. publications by the European Union Agency for Cybersecurity (ENISA, 2011).

It is a significant challenge to develop damage state definitions or fragility algorithms that benefit from the technical expertise and historical knowledge of the engineers that operate and maintain the assets. To make that process workable, it is important to develop a common context where a diverse group of experts, e.g. hydraulic engineers, civil engineers, structural engineers, business continuity managers, and vulnerability researchers, can understand each other and are able to contribute in an informed manner. With this requirement in mind, and in consultation with key industry stakeholders, a 'governing definition' for each damage state for the system components was agreed to. This overarching definition was based on the recovery actions that would be required if a component were to suffer the structural damages linked to the component-specific damage state definitions. The component-specific structural damage state definitions are typically adopted from literature and adapted or modified by senior structural engineers within the project team so that they are applicable for the portfolio of assets that are being studied. This and other similar approaches used in the collaborative project facilitated meaningful contributions from individuals who are experts in their own fields, but may not have familiarity with the terminologies and processes of seismic vulnerability research.

4. APPLICATION FOR WATER TREATMENT PLANTS

A potable water supply system is comprised of several macro-level components: (i) water source, (ii) treatment facility, (iii) pumping station, (iv) storage, (v) conduits, (vi) Supervisory Control and Data Acquisition (SCADA) (Kakderi & Argyroudis, 2014).

Surveys of post-earthquake damages to water systems reveal that most of the damage is sustained by the pipework or conduits (Panico et al., 2015). The Water Research Foundation had sponsored a project (Eidinger & Davis, 2012) to reconnoitre the post-earthquake damages in Chile (City of Concepcion, 2010), Christchurch (2010-11) and Japan (2011). The observations of this investigation noted that in each of those events, there was extensive damage to non-seismic pipes. However, seismically designed pipes in all three of the affected areas performed remarkably well. Even for the Tohuku earthquake there were no reported failures of high-density polyethylene (HDPE) pipes in the affected areas.

The water sector partners consulted have noted that pipeline damages are relatively simple and quick to remedy. Pipeline damage due to accidental diggings, breakages, etc. is fairly common.

Water network operators generally have redundancy provisions, good processes and plentiful spares to respond to such issues through various measures, e.g. direct repair, alternate routing, delivery by road transport, temporary treatment measures in downstream storage tanks, etc.

Conversely, earthquake induced failure of critical nodes, such as key treatment facilities and pump stations are of significant concern for continuity of potable water supply to affected areas. These complex facilities, if significantly damaged, may require very long recovery times. Temporary measures are possible for short outage times, but long-term outages may not be manageable without degradation of water quality, major supply restrictions, or unsustainably expensive measures such as ongoing bulk water transportation on rail or by truck convoys. Given this background, it was decided that it would be most practical and useful to study the vulnerability of key treatment and pumping facilities. In addition, most modelling work into seismic risk or vulnerability of water supply systems have primarily focused on pipe networks where water treatment plants were explicitly excluded. This adds further rationale to the development of an analytical modelling process that encompasses the key functionalities and vulnerabilities of water treatment plants.

In developing the model for the potable water treatment plant (PWTP), the following process was used:

- Site inspection
- Study of design diagrams for the plant and its components, including subsidiary systems, electricals, and backup systems.
- Identification of key components – 23 specific components were used
- Compilation of fragility data for water assets – the primary sources of fragility data were NIBS (2009) and Kakderi and Argyroudis (2014).
- Adjustments of component fragilities based on design documents, fundamental structural analysis, calibration against historical data, study of geotechnical reports, and consultation with subject matter experts within the organisation.

For the water treatment plant components, the project partners agreed on four damage state levels with the following recovery-related ‘governing definitions’:

DS1 Minor	can be allowed back in service after inspection
DS2 Moderate	will need significant repair and parts may need replacement
DS3 Extensive	extensively damaged, will require extensive repair, but is still economical to restore
DS4 Complete	will need to be replaced or rebuilt

All the identified component types were assigned structural damage definitions linked to this set of governing criteria. Due to the size limitations, they are not presented in this paper.

The plant studied is considered of a small size, according to the HAZUS size classification criteria for PWTP’s (10 mgd to 50 mgd, i.e. between approximately 38 and 189 ML/day). The basins and critical equipment such as pump motors and transformers within the studied facility were found to be resilient against major (extensive) damages. The modelling produced damage outcomes for Slight and Moderate levels that are very similar to levels suggested by the fragility curves published by the widely used hazard and risk assessment platform HAZUS (NIBS 2009) for water treatment plants with unanchored components (see Table 1). However, for a small plant designed and built within the past decade, the modelling indicates that far greater degrees of excitation are required for the plant to enter into extensive and complete damage states (Figure 2).

For the "complete" damage state specifically, historical damage data seems to support the above outcome. Panico et al. (2015) in their analysis of damage data for 31 affected plants for 15 separate earthquake events found that there were no observations of complete failure for any of the events, even for peak ground acceleration values exceeding 0.8g.

Table 1. (a) Parameters of proposed fragility models for a modern "small" potable water treatment plant, as derived through simulation. (b) HAZUS parameters for a WTP with unanchored components. (Parameters are for a lognormal distribution and the measure of shaking intensity is peak ground acceleration.)

	(a) SIRA derived parameters		(b) HAZUS parameters	
Damage States	**Median (g)**	**Beta**	**Median (g)**	**Beta**
DS1 Slight	0.14	0.17	0.16	0.40
DS2 Moderate	0.26	0.14	0.27	0.40
DS3 Extensive	0.75	0.12	0.53	0.60
DS4 Complete	1.56	0.16	0.83	0.60

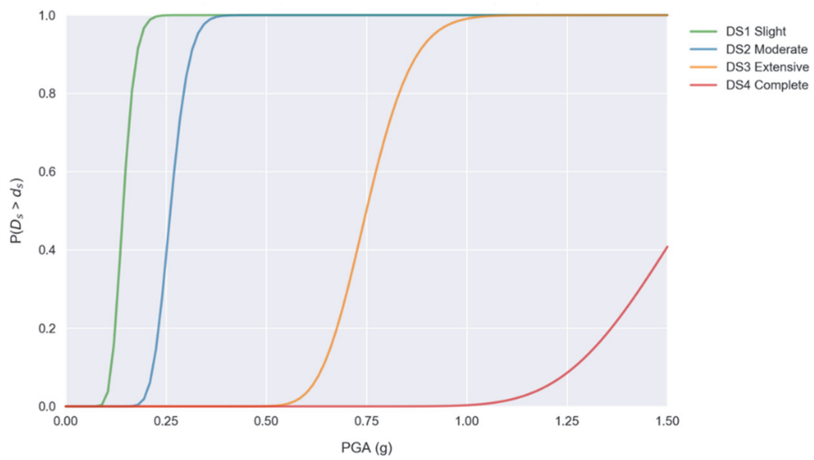

Figure 2. Proposed fragility algorithm for a modern small water treatment plant, based on simulated impacts on a real facility.

The simulation results indicate that modern treatment plants can be expected to be quite resilient in regards to their core components. Figure 3 shows the relative direct losses incurred by the different component types of the plant due to ground shaking of a 5000-year return period intensity at the plant location (based on the significant reductions in predicted hazard according to the revised National Seismic Hazard Assessment for Australia (NSHA 2018)). The expected damage is virtually negligible.

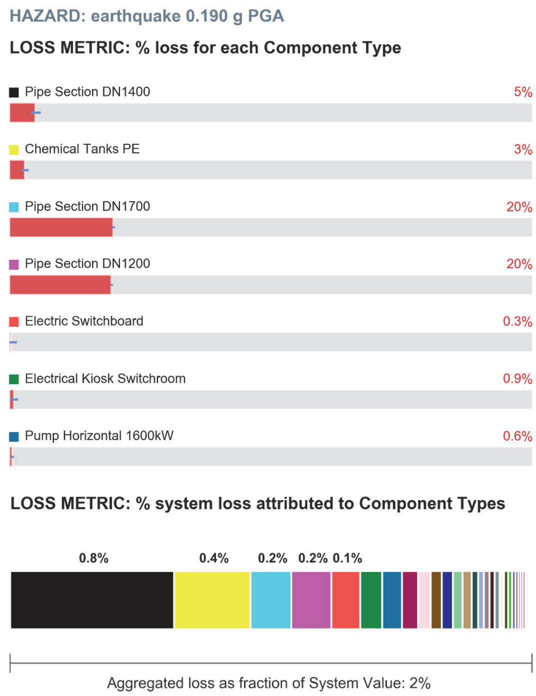

Figure 3. Simulated loss data for components in the treatment plant, ranked by the greatest contribution to total losses suffered at the plant due the modelled event.

This positive result, however, needs to be tempered with an important observation. The process of designing the system model, based on the design documents and inspections, often reveals potential issues with the peripheral support systems provided by third-party suppliers. This is indicative of a familiar systems issue, where often failures are not caused by the components within the primary systems, but rather failures are initiated from components (often deemed non-critical) at boundaries of the system and then propagate inside.

5. APPLICATION FOR ELECTRICAL SUBSTATIONS

Bastami (2008) reviewed historic damage data for 58 medium and high voltage substations from 43 earthquakes. He noted that while disconnect switches had the highest *occurrence* of damage reports, as a *percentage of the total population* of exposed components of this type, they performed better than most other components. Another interesting finding was that the same substation component – depending on its specific type or design – can have hugely varying seismic performance. For example, the data indicates that live-tank circuit breakers had the worst seismic performance with about 32.3% failing, while dead-tank circuit breakers performed the best (2.5% failure rate). This observation of vulnerabilities circuit breakers of different types is confirmed by Fujisaki, Takhirov, Xie, and Mosalam (2014). This illustrates the importance of working with power network owners/operators to understand the historical design practices in the area of interest and the prevalence of specific types of components in use within their systems.

Three types of substations were studied:
1. 330kV terminal station (medium voltage transmission substation),
2. 132kV terminal station (low voltage subtransmission substation), and
3. 132kV zone substation.

Across these three types of facilities, 21 different types of components were modelled that included autotransformers, buses, circuit breakers, disconnect switches, capacitor voltage transformers, current transformers, voltage transformers, combined current voltage transformers, lightning arresters, transformers of different types and capacities. The vulnerabilities of control equipment and control buildings were also modelled. A similar process to that used for the water treatment plant was used in building the models. Publications for US HAZUS (NIBS, 2009) and the European *Syner-G* project (Pinto et al, 2010) were very helpful in making the initial selection of fragility algorithms for the more common types of components. However, these were revised based on inspections of the assets in the yards. For instance, the design standards used in the construction of the concrete support for circuit breakers and disconnect switches in the facilities were studied (see Figure 4), and structural analysis was conducted for them. The resulting body of knowledge was used to customise the fragility curves used for those components.

Figure 4. Concrete support of 132kV circuit breakers (photo credit: Edwards, M.).

A three-level limit state model was used to balance the need to capture a sufficiently broad set of damage outcomes that reflect typical earthquake-induced damage, and the need to keep the model simple enough in cognizance of the challenges in developing pertinent fragility models. Damage state levels for substation components with the following recovery-related 'governing definitions' were used:

DS1 Minor	component can be allowed back in service after inspection
DS2 Extensive	component will need significant repair and parts may need replacement
DS3 Complete	component will need to be replaced or rebuilt

Substation models were built as a bidirectional flow network. Figure 5 illustrates a model of a transmission substation, with the components represented as nodes and arranged in bays. The damage functions for the three types of substations are shown in Figure 6, Figure 7, and Figure 8. The function parameters are listed in Table 2.

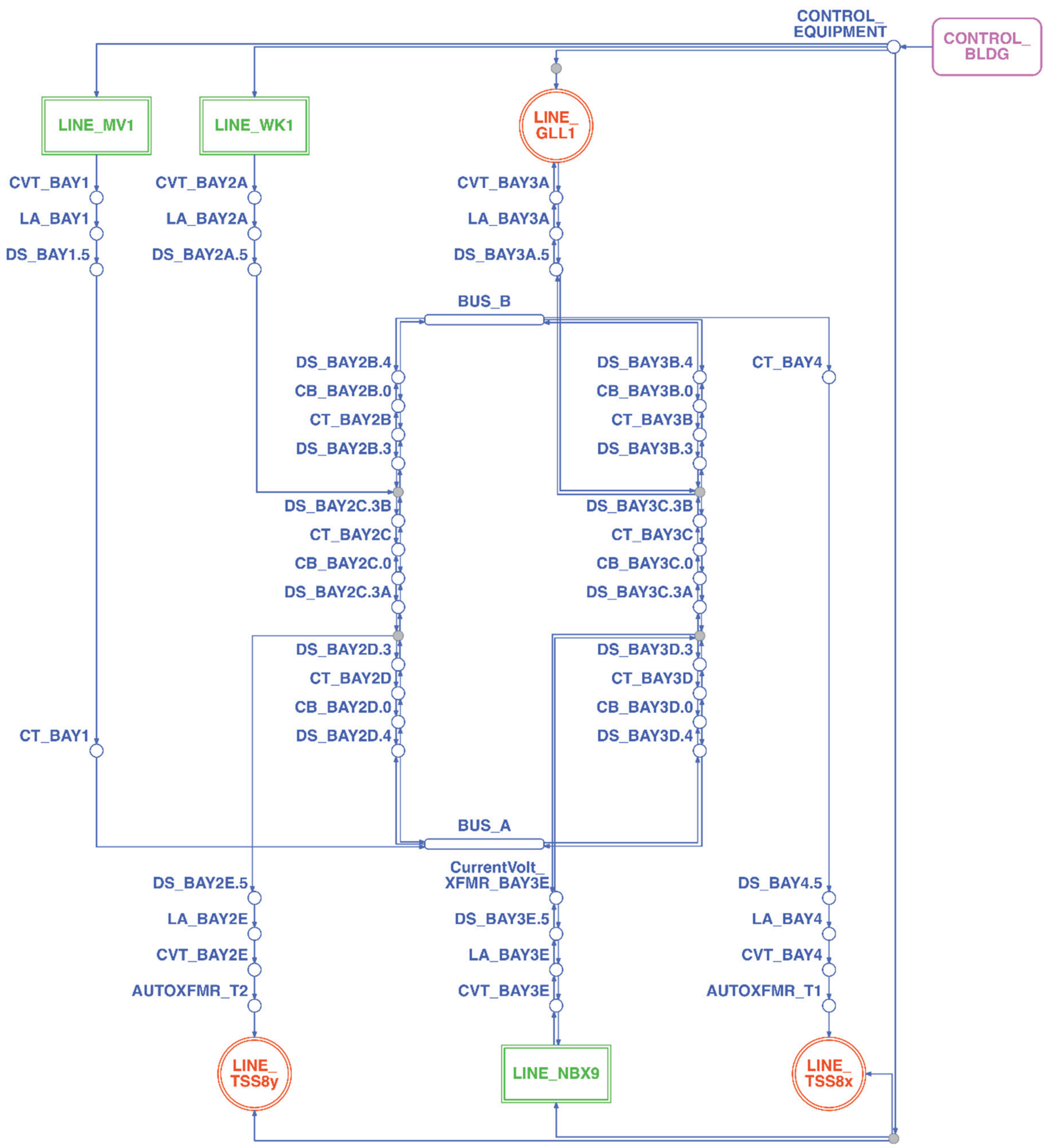

Figure 5. Topology of the model for a medium-voltage transmission substation, represented as a graph with bidirectional flow.

Table 2. Parameters of proposed fragility models for three categories of electrical substations in WA, as derived through simulations. Parameters are for a lognormal distribution and the measure of shaking intensity is peak ground acceleration.

	(a) 330kV Terminal		(b) 132kV Terminal		(c) 132 kV Zone	
Damage States	**Median (g)**	**Beta**	**Median (g)**	**Beta**	**Median (g)**	**Beta**
DS1 Minor	0.24	0.39	0.22	0.36	0.20	0.43
DS2 Extensive	0.40	0.16	0.47	0.11	0.43	0.16
DS3 Complete	0.60	0.19	0.68	0.11	0.60	0.22

Simulations indicated very low likelihood of exceeding even the Minor damage state for the hazard values for 2500- and 5000-year return period events at the substation locations. However, simulations also indicate that the control equipment are likely to experience damages even at low shaking intensities. The expected PGA at the location of the 132kV transmission substation was

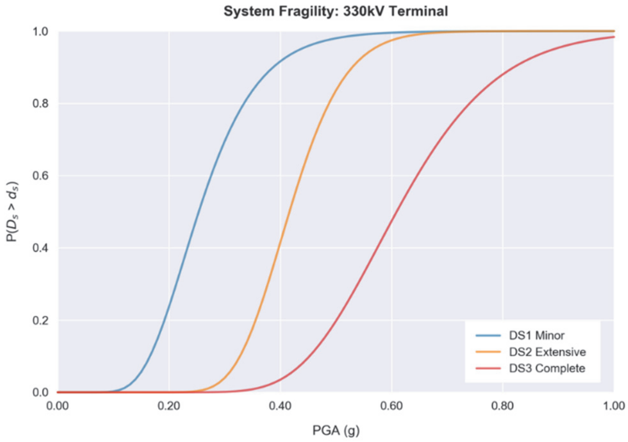

Figure 6. Fragility model for a 330kV terminal substation.

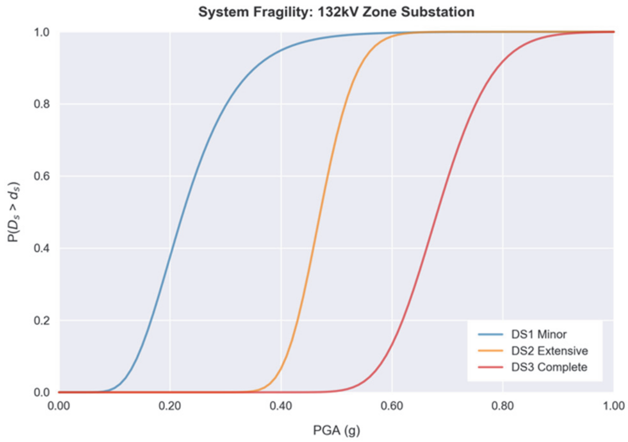

Figure 7. Fragility model for a 132kV zone substation.

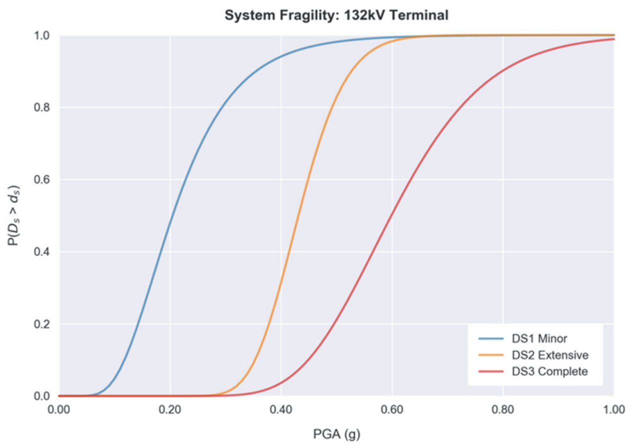

Figure 8. Fragility models for 132kV terminal substation.

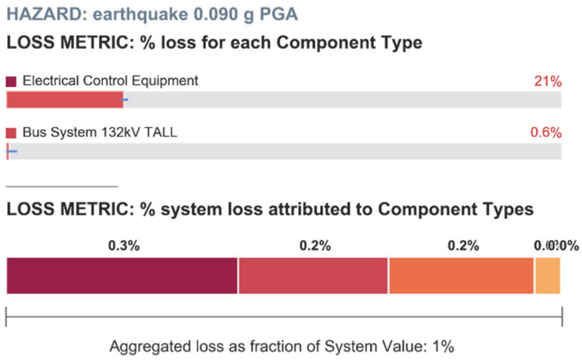

Figure 9. Simulated loss data for components in the 132kV transmission station, ranked by the greatest contribution to total losses suffered at the site due the modelled event.

approximately 0.09g for a 2500 return period. Even at this low level of shaking, the control equipment was expected to suffer significant damage, though other equipment in the yard was not likely to suffer issues of any significance (Figure 9). Control buildings, and the critical control equipment they house, have been found to be a general problem with substations. This has been the experience of the authors in studying substation vulnerabilities in Australia and in the Asia-Pacific.

Control equipment and instrument panels are often not appropriately designed for seismic effect, lacking spacers and/or adequate bracing. This poses a risk to these critical components, without which the substation cannot be safely energised even if the other components remain undamaged. Records of past earthquake damages also show that control equipment and buildings have experienced damages even in relatively weak earthquakes (Omidvar, Azizi, & Abdollahi, 2017). These assets are good candidates for a systematic review and, subject to findings, may benefit from a network-wide retrofit program.

6. CONCLUSION

Basic functions of our communities, the economy, and essential services are tightly coupled to the reliable and uninterrupted operation of our lifeline infrastructure. Therefore, the impacts of failures in critical infrastructure are potentially far more consequential. The recently released National Disaster Risk Reduction Framework (NDRRF) identified this interconnectedness and dependency as a driver for mitigation actions (Department of Home Affairs, 2018). It is proposed that it is valuable to have a tested methodology and associated tools for studying the systemic vulnerabilities of these complex interconnected assets. It allows us to model the effects of potentially high-consequence events – events that are plausible but beyond our lived experience – on our infrastructure. Application of SIRA in different contexts, sectors, and for different asset types thus far appear to produce results that are credible and consistent with records of historical events. The collaboration and contributions of the infrastructure operators were critical to the development and validation of this work. It was made possible by an explicit recognition of the concerns of the industry partners in regard to the confidentiality of their information, by formalising that through inclusion of carefully developed clauses within the collaboration agreements, through the maintenance of a data register, and through consultations and explicit agreements on how the work and results are disseminated.

The recent project with industry has found that many critical infrastructure assets are resilient given our seismic hazard context, but it has also uncovered a number of obscure vulnerabilities. The next stage of development will have a greater focus on the distribution assets of an electric power network which have exhibited greater damage in past events than transmission assets and have had higher contributions to recovery delays (Fujisaki et al., 2014). There are efforts underway to expand the scope of the research work beyond facilities to multiple interconnected networks, including water, electricity, and road transport networks. The work of Geoscience Australia in the field of engineering vulnerability and community safety has been focused on working directly with communities and industry to address real problems. Consistent with this approach, collaboration efforts with industry are underway to develop and apply the infrastructure vulnerability modelling capability to the study of seismic impacts on roads, rail, electricity, and water sectors, and critically, their interactions across the sector boundaries. The work will align with the strategic directions of the NDRRF, and will further highlight that the address of current and emerging risk requires a cross sector collaboration that will be a fundamental part of this project.

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