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A component level approach to the earthquake vulnerability of critical infrastructure facilities

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ABSTRACT: Communities and their economic activity rely heavily on critical infrastructure. Utility infrastructure facilities are usually comprised of a range of interconnected components characterised by varying degrees of operational criticality and vulnerability to earthquake ground motion. The severity of damage to these components in an earthquake has complex implications for post-event functionality, repair cost and recovery timeframe of facilities. This paper describes how an integration of physical component vulnerability, associated component functionality, and a system model of the facility have been used to understand the seismic vulnerability and mitigation opportunities associated with a thermal power station. System behaviour of the facility has been analysed using a network model to evaluate facility performance and to assess component criticality. An application has been developed that integrates these elements in a Monte Carlo simulation that enables the outcomes of a broad set of events to be assessed, and is used to develop facility-level fragility models. Finally, the benefits of this approach to the process of assessment of vulnerability of legacy assets and identification of mitigation opportunities are demonstrated.

1 INTRODUCTION

The nature of Australian communities and the infrastructure that supports them is complex. Historically, natural disasters have directly impacted communities causing physical damage, injury and disruption to economic activity. An example of this is the Newcastle Earthquake of December 1989. Natural hazards have also caused indirect impacts due to the dependencies of households, businesses and institutions on critical infrastructure (CI). Modern CI systems are inherently interdependent and, when impacted, can cause widespread consequences beyond the assets immediately impacted due to cascading effects. An example of this can be seen in the work by Buldyrev et al. (2010) based on real-world power network and internet network data. Electricity supply is arguably the most central utility as most other services are dependent upon reliable supply. A prolonged outage will lead to widespread disruptions of community life and processes.

Seismicity in particular can pose a significant hazard to certain types of electricity infrastructure. Electricity generation and switching assets have components that have poor ductility and, if of older vintage, may not have been designed considering earthquake hazard. Furthermore, as the components of these assets must function as a system, physical components may have criticality for facility operation due to single points of system failure and long lead times for restitution. Vulnerability assessments to assess mitigation investment options need to capture all of these factors.

In this paper a hypothetical power station is used to demonstrate the methodology. Separately, the approach has been used in an Australian Aid program on specific facilities to assist developing countries derive information on electricity facility vulnerability. The methodology considers the vulnerabilities of the various components of facilities to earthquake, their system functionalities and the logistics of their repair. The integration of these into facility level models has enabled an understanding of the contribution of components to overall facility vulnerability and of the opportunities to reduce this.

2 CONCEPT OVERVIEW

Urlainis et al. (2014) noted that insufficient preparedness of critical infrastructure was responsible for the amplification of the consequences of extreme events, especially considering the cascading effects due to the complex interdependence of the CI. This was based on detailed surveys by the researchers of critical infrastructure damage caused by eight man-made and natural hazards between 1995 and 2011. Preparedness, in the context of CI, is commonly understood as a conjugation of three alternative measures: robustness, resilience, and redundancy. The proposed methodology recognises this reality, and provides a way to analyse the robustness of CI assets to earthquakes, taking into account the interdependence of the components comprising an asset, whether it be a facility or a network. It captures the robustness of the facility within a fragility model, and the resilience and related redundancy as the restoration prognosis model. The degree of assessed robustness and resilience of the assets can provide an evidence base for decision-makers to consider where redundancy might be necessary or advisable. The resilience of the system is assessed in terms of current and hypothetical levels of resourcing to effect restoration of damaged assets.

Fragility models currently available for power stations and other facilities have typically been developed based on empirical data derived from a limited number of events in specific regions, and expert judgement. In many cases these are generalised for broad asset classes that incorporate a very wide range of capacities and, in the case of power stations, generation technologies. Therefore, the applicability of such models to specific areas, and specific facilities is uncertain.

The method proposed and trialled for this project considers the facility as a system comprised of components, with defined constraints around its input and output requirements. In defining the facility as a system, the method takes into account the generation technology of the facility, the original seismic design levels, the fragilities of the key components that comprise the facility, and the component configuration. The resultant model is comprised of four key elements, and associated input data: fragility algorithms, facility system model, a loss model, and a restoration model. The process of obtaining and assigning component fragility algorithms are covered in Section 3. The system model and the process of calculating system vulnerability are presented in Section 4. The system restoration model is discussed in Section 5. The hypothetical asset under study and an overview of the results are presented in Sections 6 and 7, respectively. A discussion of the findings and future directions is outlined in Section 8, and conclusions are presented in the final section.

3 COMPONENT LEVEL VULNERABILITY

As earthquake induced ground shaking at a facility increases in intensity, the individual components 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. For this research four sequential damage states have been used for facility components. The hazard parameter adopted is the peak ground acceleration (PGA) at the site.

The component level fragility models need to be representative of the assets they characterise. The models used in this project were developed 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.

The literature review and model compilation produced by the Syner-G Project (Pitilakis et al. 2014) sponsored by the European Commission was particularly useful for all steps in the development hierarchy above. The key references included works by Vanzi (1996), Anagnos (1999) and the HAZUS Technical Manual (FEMA 2003). It should be emphasised that these functions were adjusted based on the design standards applied in the construction of the assets, any manufacturer proof testing results, and the review comments by the asset operators. The adopted fragility models were log-normal in form and defined by a median (θ) and log standard deviation (β). Additionally, in assessing the operational state of the overall facility, a functional state for each component damage state and the time to effect repair to each component were attributed. The fragility curves adopted for a step-up voltage transformer, adapted for a nominal ground shaking of 0.35g, are shown in Figure 1. Note that the damage states are associated with specific damage types sustained by the component.

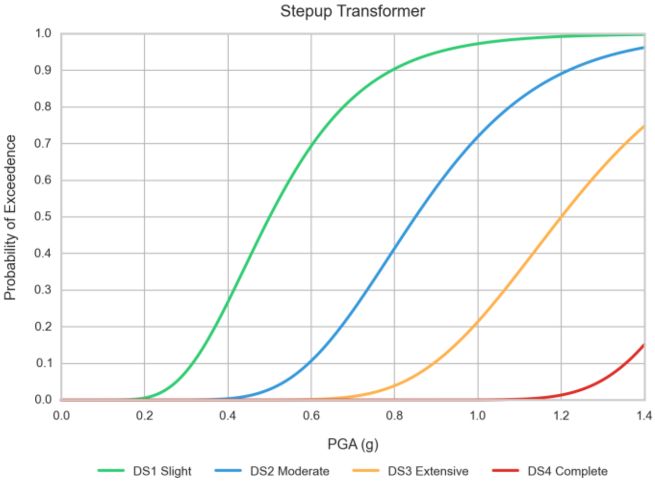

Figure 1. Fragility curve for a 230kV capacitive voltage transformer adapted from Anagnos (1999).

4 FACILITY SYSTEM MODEL AND SYSTEM VULNERABILITY

The facilities were modelled as a network of components. This had three distinct benefits: (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 this exercise map closely to the typology of *micro-components* and *macro-components* as defined in the 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 scheme, the components are represented as nodes. Based on their role within the system, these nodes, or components, are classified in four general categories:

i. *Supply nodes*: these nodes act as entry points into the system for required inputs or commodities. As for example, coal and water can be the required ‘commodities’ into a thermal power station. Hence, supply of these essential items need to be represented. In the case of the substation, required input is electricity from power stations or other substations.
ii. *Output nodes*: these nodes represent the exit points for the output of the system. For example, in the case of the power station, the output nodes act as dummy loads – representing the energy consumers – connected to each of the step-up transformers.
iii. *Dependency nodes*: these are the components that do not directly participate in the production of system output or handling of system inputs, but are critical for system operations in some other capacity, e.g. system management. The control building is an example of this.
iv. *Transhipment nodes*: these are nodes that transform, transport, or store system inputs to aid in production of the required outputs. Majority of the nodes within a system fall into this category.

The component configuration and redundancies are captured as edges connecting the nodes. Constraints on flow through specific paths, or sets of nodes, can be represented as capacities of edges connecting those nodes. An example of such a system representation is shown in Figure 3, and will be discussed later. As the edges represent a link or a process for maintaining ‘flow’ of goods or services within the system, their directionality is important. For the power station, the edges are unidirectional, since the inputs flow in one direction starting from the entry point into the system and are progressively transformed through the system to generate energy – the end product. However, in the case of the substation, it is an electrical network where electricity – the system 'commodity' – can flow in either direction through an edge as dictated by load demands and system constraints. Therefore, most of the edges in the substation are bidirectional.

Connection paths and 'production capacities' along those paths within a system are calculated as the maximum flow through those paths. The *igraph* Python package was used as the network modelling platform to calculate graph metrics for a post-hazard damaged system model. For a given value of PGA, a set of random samples is generated, and the damage state of each component is calculated for each random sample based on the fragility function of the given component. Given the assessed damage state of all the system components, the system functionality is assessed and system output level calculated. This process is run through a Monte Carlo process for the set of random samples to assess the system response at the selected ground shaking intensity. To obtain a characterisation of the system and develop fragility algorithms for the system (e.g. the power station) the process is repeated for a range of PGA values (e.g. 0g to 1.4g at 0.01g steps). This Process is shown in Figure 2.

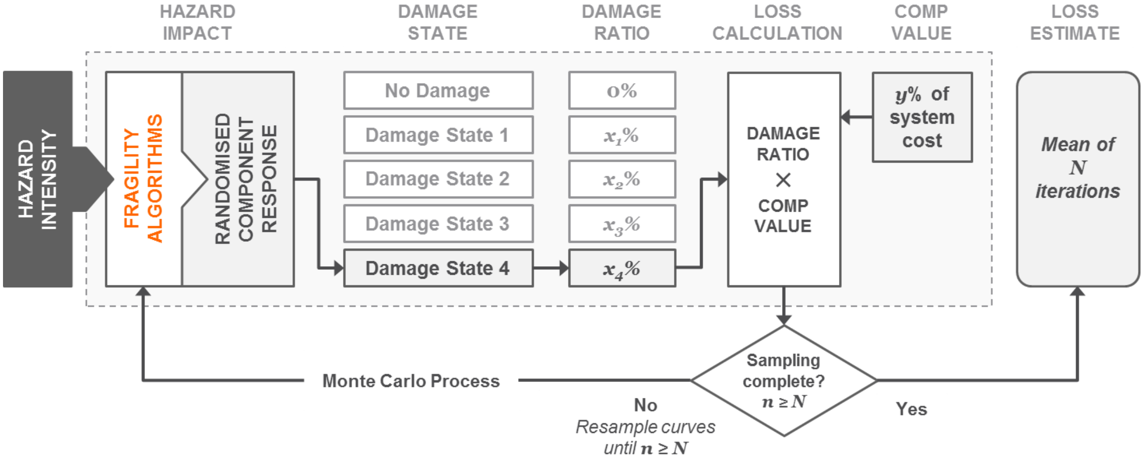

Figure 2. Schematic of Monte Carlo process to link component damage assessment to loss projection

Four discrete sequential damage states are used for assessing system fragility, similar to those used in HAZUS (FEMA 2003): DS1 Slight, DS2 Moderate, DS3 Extensive, DS4 Complete. The damage scale used for a power station is based on ranges of economic loss as a percentage of total system value. Please see Section 7 for the adopted damage scale boundaries.

5 SYSTEM RESTORATION MODEL

The restoration algorithms are defined as normal functions. An approximation of mean restoration time for each component at each damage level is attributed. The structural damage level definitions associated with the damage states are central to establishing a common understanding to facilitate the development of the restoration parameters.

The functionality F_C of component C at t time units after impact of an earthquake of PGA=x is calculated as a weighted combination of the probability of the components being in each of the S sequential damage states used in the model and the estimated recovery at time t for the components based of the restoration model:

$$F_{C|x}[t] = \sum_{i=0}^{S} P[ds_i|\text{PGA} = x] \times R_i[t] \tag{1}$$

where, i is the index of the damage state, $\{i \in \mathbb{Z} | 0 \leq i \leq S\}$. The 'None' damage state is i=0, and i=S is the complete or highest modelled damage state. $R_i[t]$ is the likely level of restoration of functionality at time t. Restoration level R_i can take on any value in the unit interval $[0,1]$.

The simulation of the restoration prognosis is conducted based on a set of inputs and assumptions. The required data inputs to this process are:

- The system configuration
- The modelled scenario – seismic intensity value

- Impact simulation results – system component losses
- Restoration priority list – the order at which output lines should be recovered

The process assumes that restoration is undertaken in stages, subject to the level of resources that can be made available and the order of repairs. In regard to this, the concept of '*Restoration Streams*' is used—the maximum number of components that can be worked on simultaneously. This is effectively a proxy representing the deployment of trained personnel and material for the repair tasks. Additional optional offsets can be factored in to capture specific contexts: (i) *Restoration Offset* – this is a time allowance for assessment of damage to the system and for securing the site to assure it is safe for commencement of repairs; (ii) *Testing and Commission Interval*: this is a time allowance for testing conformity with operational and safety parameters for the system, or a part thereof.

Given a set of restoration parameters and the restoration plan, the consequent restoration time is calculated as follows:

1. Test if there is any available path between the set of required input (supply) node(s) and the output node with the highest priority to meet the demand at that node.
2. If no functional path is found, then identify the least expensive path(s) that needs to be restored to meet demand at the output node. Within each path, identify the functional status of the nodes (components), and generate a repair list.
3. Iterate through the ordered output list, repeating steps 1 and 2 above. Update the component repair list and produce a complete prioritised list of components to repair or replace.
4. Simulate an ordered restoration process based on the above list and user-specified resource constraints. If the process is using x resource constraints, then whenever a component is restored (and the number of unrepaired components is $\geq x$), the next component is added to the active repair list, so that at any one time x repair tasks are in progress. This process is repeated until all the paths are restored, i.e. until system output capacity is restored to normal levels.

It may be necessary to restore more than one path, i.e. connect an output node to multiple input nodes, in order to restore full capacity at an output node. For example: In the case of a thermal power station, the functioning of the generator depends on both the supply of fuel (as the source of energy to be transformed) and water (for cooling and for steam production to drive the turbines). In case of a substation, output node #1 may have a demand of 200MW, but it might be that there are three input nodes bringing in electricity from power plants that are rated at 100MW each. In that case output node #1 must be linked to at least two of the input/supply nodes to meet its demand.

In addition to the core process of approximating restoration time, a routine for simulating component cannibalisation within a facility or system has also been incorporated. Here we use cannibalisation to refer to an exercise whereby an operator may move an undamaged component from a low priority or redundant line to replace a damaged component on a high priority line. This exercise may allow the operator to eliminate the potentially long procurement or transportation time for a replacement unit, and thereby expedite the restoration of the high priority lines.

The outputs from the restoration model are: (a) a minimalist Gantt chart with each component needing repair, (b) restoration plot for each output line over time and the associated percentage of total system capacity rehabilitated, and (c) total restoration time for each output line for a given restoration scheme.

6 CASE STUDY ASSET

A hypothetical coal-fired power station was used as the primary focus of this study. It is similar to a specific facility studied under an Australian Aid funded project, but with key differences. It was comprised of two generation units and the design level of the entire plant was assumed to be 0.35g.

The identified components were assembled within a preliminary system diagram in the form of nodes and edges. Component fragilities were associated with the nodes and operational capacities were associated with the edges. The system configuration was iteratively refined to correctly capture the key operations, dependencies and redundancies. Figure 3 illustrates a representation of the model used in the simulations.

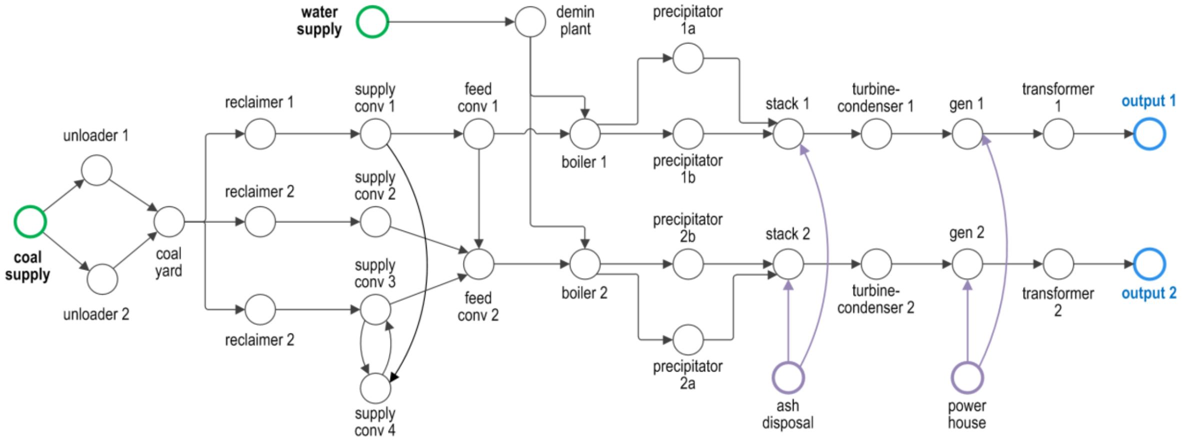

Figure 3. Graph-theoretic system diagram of the power station that was subject of the study

7 RESULTS

The model calculates direct economic loss as a consequence of hazard impact. Loss calculations were made for each component within the system, and for each realisation of the Monte Carlo process. The results were aggregated by component type, and the contribution of each component type to the overall loss incurred by the system was assessed. The damage scale thresholds applied in producing the fragility functions for the system of interest were based on the direct economic loss sustained by it:

- Slight damage is defined as loss of ≥1% of total value of facility,
- Moderate damage state is defined as a loss of ≥15%,
- Extensive damage state is defined as a loss of ≥40%, and
- Complete damage is assumed for losses exceeding 80%.

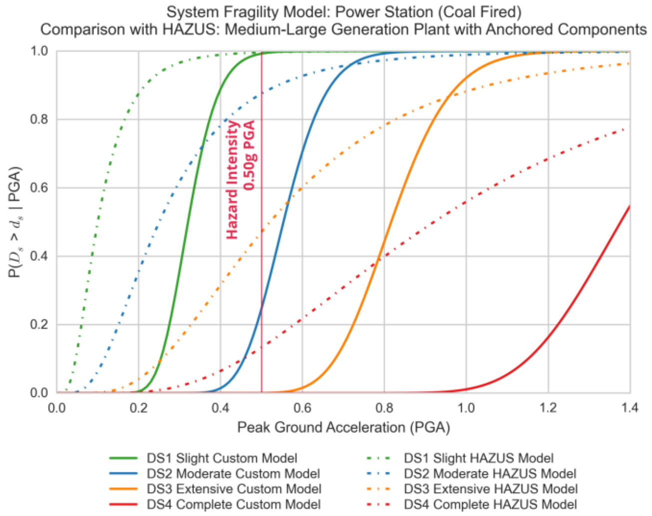

Figure 4. Fitted model for case study power station, and comparison with HAZUS curves for the same class of asset (EPP3)

Table 1. Fragility algorithm parameters for the case study power station*.

Damage State	Median*	Log Std Dev*
Slight	0.32	0.18
Moderate	0.55	0.15
Extensive	0.82	0.14
Complete	1.38	0.14

* The function used in Log-normal Cumulative Distribution Function (CDF). Design level of the asset is 0.35g.

The initial results were reviewed for congruence of the assessed system response with historical events and recorded damage to the system. The derived fragility curves are illustrated in Figure 4 and the function parameters are tabulated in Table 1. The figure indicates that the generic HAZUS model significantly overestimates the likely damage to the power station, and also indicates that the plant would have in excess of 10% likelihood of being in a complete damage state at the intensity of the simulated 0.5g PGA event. It is of note that the derived curves have significantly lower dispersion when compared to HAZUS curves. This can be attributed to the fact that these curves reflect the fragility of a single facility of a specific generation technology as opposed to the very broadly categorised facilities of multiple generation technologies that the more generic models cover.

The simulated damage sustained by the components types for the hypothetical 0.5g event, and their respective contribution to the overall loss of the system, are shown in Figure 5. It can be seen that the boiler and coal handling equipment represent the greatest component and overall losses. Given a restoration scheme allowing for ten simultaneous repair tasks, the restoration routine approximates 81 weeks for the restoration of the priority unit (*output_2*) and 131 weeks for the remaining unit (*output_1*). This result, along with the sequence of the restoration operations, is illustrated in Figure 6.

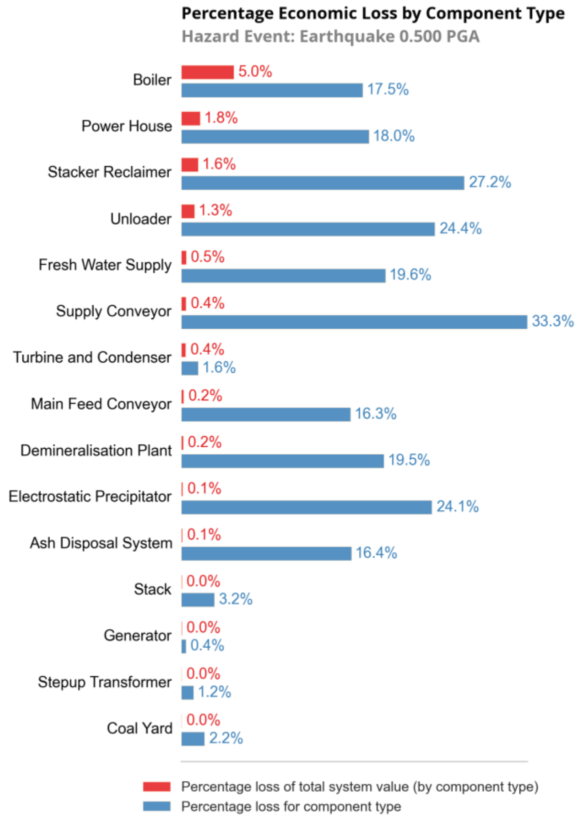

Figure 5. Losses sustained by the power station – by component types.

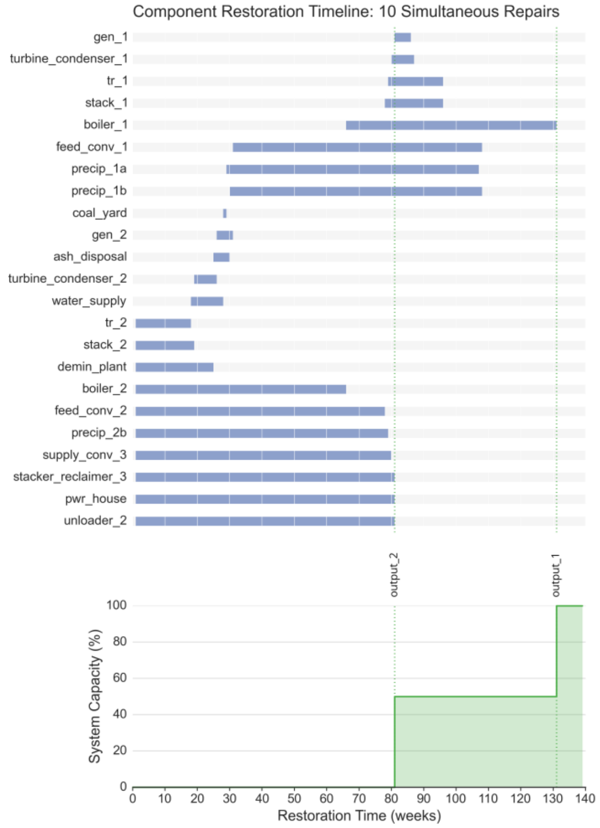

Figure 6. An illustration of the restoration schema for the ten simultaneous repair streams.

8 DISCUSSION

The vulnerability assessment methodology for critical infrastructure facilities presented here, and the tools developed to implement it, allows researchers and critical infrastructure operators to gain insights into the vulnerabilities of facilities. It has facilitated a criticality analysis of the target facility, which has led to 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. Work of this kind can assist in producing a demonstrable understanding of the likely benefits of different mitigation strategies. An inherent difficulty of implementing this process that should be noted is that it requires strong engagement from, and with, industry for data, operational knowledge of the systems, and validation of outcomes. This is necessary as the underlying purpose of the method is to produce directly actionable analytical products and not theoretical solutions.

The research tools used in this body of work can be improved in a number of areas. For future development, the propagation of uncertainty within the model needs to be managed and reported more methodically. The model can capture the collective contribution of all major components or subsystems within an asset in an operational context. However, it implicitly assumes that damage to one component is not directly correlated to other components. This may not always be the case, and it would be useful to undertake further research and testing to investigate methods to capture correlation of component damage across the system and, specifically, how this can help in effective risk management. Research by Jiang and Haimes (Jiang 2004) on the application of Leontief-based models for interdependent systems provides a promising technique for achieving this.

Finally, in order to calibrate and expand the capabilities of the tools, other electrical infrastructure facilities, generation technologies, and infrastructure sectors need to be studied. The adaptability of the method was successfully tested with transmission substations, but due to space constraints could not be covered within this paper. The core methods are generic enough that they can be expanded to investigate more geographically distributed facility assets and infrastructure networks that may experience variable ground motion in a single event. The methods can also incorporate other shaking severity measures for component types that are more correlated to their damage.

9 CONCLUSION

Critical infrastructure facilities are complex and interdependent. Differences in the nature and construction of facility components result in unique responses to ground shaking and vulnerabilities. These differences can, in part, be due to a staged development of the facility over time with stepwise increasing consideration of seismicity. Addressing legacy vulnerabilities is a key issue in which the subtleties of more vulnerable components need to be captured and understood. The methodology described significantly extends beyond the physical vulnerability of assets to directly assess the functional system implications of loss operation and the prognosis for recovery. Information of the breadth and detail afforded by this approach can inform investment to increase robustness, resilience and redundancy.

While the focus of the case study has been a thermal power station, the methodology can be applied to other facilities in other infrastructure sectors that are susceptible to earthquake ground motion. The generic nature of the approach is also applicable to other natural hazards including severe wind and flood. Collectively the information developed can lead to making CI more resilient and reduce associated community risk.

REFERENCES:

Anagnos, T. 1999. *Development of an electrical substation eqyuipment performance database for evaluation of equipment fragilities*. Department of Civil and Environmental Engineering, San Jose State University, San Jose, USA, for PG&E/PEER.

Buldyrev, S.V., Parshani, R., Paul, G., Stanley, H.E. & Havlin, S. 2010. Catastrophic cascade of failures in interdependent networks. *Nature*, 464: 1025-1028.

FEMA. 2003. *HAZUS-MH MR3 Multi-Hazard Loss Estimation methodology – Earthquake Model – Technical Manual*. Federal Emergency Management Agency. Washington DC, USA.

Jiang, P. & Haimes, Y.Y. 2004. Risk Management for Leontief-Based Interdependent Systems. *Risk Analysis*, 24(5): 1215-1229.

Pitilakis, K., Crowley, H. & Kaynia, A.M. (eds.) 2014. *Syner-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk*. Chapter 6: 157-186. Nettherlands: Springer.

Rinaldi, S.M., Peerenboom, J.P. & Kelly, T.K. 2001. Identifying, Understanding, and Analyzing Critical Infrastructure Interdependencies. *IEEE Control Systems Magazine*, 0272-1780/01: 11-25.

Urlainis, A., Shohet, I.M., Levy, R., Ornai, D. & Vilnay, O. 2014. Damage in critical infrastructures due to natural and man-made extreme events – A critical review. *Procedia Engineering*, 85: 529-535.

Vanzi, I. 1996. Seismic reliability of electric power networks: methodology and application. *Structural Safety*, 18(4): 311-327.

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