Bridge-Utility Systems: Learnings from the Canterbury Earthquakes (2010-11)

A. Rais, S. Giovinazzi, A. Palermo & P. Lee

Department of Civil Engineering, University of Canterbury, Christchurch

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ABSTRACT: Bridges are not only linkages in the road network infrastructure, but also serve as linkages for utilities, such as potable water and waste water pipes and power and telecommunication cables, housed along the bridge decking system. Damages observed during the Canterbury Earthquakes (2010-2011) have highlighted significant seismic susceptibility of Bridge-Utility Systems (BUS). Despite that, there are no national codes of practice or specifications that account for the seismic interaction between the bridge and utility systems. There is therefore an urgent need, to advance knowledge and practice towards a performance based integrated design and assessment approach for BUS systems. This paper reports, first of all, on the impact on BUS observed after the Canterbury Earthquakes (2010-11). Focus is given in particular to physical damages observed in waste water, potable water and electricity power networks at bridge linkages. Secondly, the paper proposes an analysis framework towards the development of performance-based design and assessment approach to mitigate earthquake-induced physical and functional impacts on BUS. The framework includes a four-phase approach including simplified and advanced analytical modelling and of BUS prototypes in conjunction with the seismic risk assessment at network level.

1 INTRODUCTION

Bridges function not only as integral linkages for the transportation infrastructure but also serve as host structures, for carrying utilities over river crossings. Utilities, such as waste water, potable water, electricity and telecommunication lines, are usually supported at the side of the deck, openings embedded in the deck or through openings in piers (under the deck). The need for mounting utility lines on bridges is usually addressed when buried utility lines are required to crossover an obstacle, such as rivers, streams, railway lines, etc. This is achieved by either mounting the utility line on an existing host bridge or on a new dedicated bridge. Dedicated bridges are usually expensive and time demanding options to implement, hence, most utility operators utilize existing host bridges to mount crossing over utility lines (ASCE 1996).

This study focuses on Bridge-Utility Systems (BUS) concerned with host bridges. The integrated BUS comprises of several components, including: the host bridge; utility line (pipeline and/or cable); and the connectors. Each component and the interaction between different components define the seismic performance of the whole system. Figures 2 show the schematic representation for the integrated BUS, highlighting the usual locations and connections of the utilities with the host bridge components.

The Canterbury Earthquake Sequence 2010-2011 (CES) triggered significant impact at these bridge-utility linkages. Several impacts to bridge-crossing utilities were, in fact, reported (Table 1), even though the structural performance of bridges proved to be good, with very low count of moderate to extensive damage occurrences (Palermo et al. 2010, 2011). These impacts on bridge-crossing utilities included: leakages in potable water and waste water pipes due to connection failures with the bridge deck; failure of power cables (Fig. 1) due to insufficient rotational ductility capacity at the bridge ground transitions (Eidinger and Tang 2012); and other observed damage mechanisms, as defined in the following section.

The damage observed to BUS after the CES highlighted the need to develop a performance based approach to mitigate their seismic risk. As a matter of fact, the current national (NZTA Bridge manual 2013) and international codes (AASHTO 2009, Eurocode 8:part2 2005) of practice do not address the design provisions for the bridge crossing utilities. Moreover, studies focusing on the integrated system itself were found to be very scarce, with very limited discussions on the topic itself (Bharil et al. 2001). Whereas, design guidelines for bridge-utility crossings as developed by Bharil et al. (2001) and by FEMA (1991, 1992a) address the issue vaguely, without quantitatively defining the provisions.

In this paper, a framework is proposed, in the following sections, to assess the seismic performance of the Bridge-Utility Systems (BUS), in the Canterbury region; to implement a performance based approach for integrated design of new BUS, retrofitting of existing BUS and for the identification of risk mitigation strategies. The framework focuses on the interaction of bridge-linkages in pipe and cable networks and their effects during earthquakes. The approach would take into account lifeline interdependencies, highlighting the risk due to physical impact and functionality issues over the whole system network. This would assist the authorities in planning for pre and post earthquake retrofit, design or repair prioritization. This can then be generalized to other city infrastructures such as Wellington and Auckland, or national road networks (NZTA, Kiwi Rail). The implementation of advanced physical models for the integrated bridge-utility system into existing risk assessment platforms will allow better understanding considering the interdependencies amongst various infrastructure sectors (water, waste water, power and telecommunication).

Table 1. Utility losses observed at bridge linkages, during the Canterbury Earthquakes (2010-11) (University of Canterbury Bridge Damage Database).

Earthquake	Bridge	Utility type[1]	Damage mode
2010 Darfield	Kainga Road bridge	Sewer pipe	Pipe break
	Porrit Park footbridge	Pipe	Pipe break and translation
	Bateman Avenue footbridge	Pressure pipe	Pipe leakage
	South Brigthon bridge	Pressure pipe	Pipe break
	Gayhurst Road bridge	Pipes and cables	Buckled pipe and power cable
	Anzac Bridge	Drainage pipe	Pipe break
2011 Christchurch	Bateman Avenue footbridge	Pressure pipe	Pipe leakage
	Brooker Reserve footbridge	PVC pipe	Pipe fracture
	Summer Drain footbridge	Pipe	Pipe break at mid-span
	Avondale Road bridge	Pipe	Pipe break
	Fitzgerald Avenue bridge	Pressure pipe	Pipe break
	Barbadoes Street bridge	Pipe	Pipe break
	Ferrymead bridge	Pipes and cables	Extensive damage
	Opawa Road bridge	Pipe	Pipe leakage
	Beckford Road bridge	Pipe	Pipe break
	Worseleys Road bridge	Pressure pipe	Pipe bursting
	Old Main North Road bridge	Sewer pipe	Pipe break
	Durham Street Overbridge	300mm Ø pipe	Pipe break
	Westminister Street bridge	300mm Ø pipe	Pipe break

[1] **Details on material diameter and pipe type (gravity, pressure or siphon) are provided when available.**

2 PERFORMANCE OF BRIDGE-UTILITY COMPONENTS DURING THE CANTERBSUY EARTHQUAKES 2010-11

The following sub-sections highlight the performance of main components of the BUS, observed after the CES.

Figure 1. Utility failures at bridge crossings, after the CES; a) Partial failure of 66KV lines at Dallington Bridge (Eidingerand Tang. 2012); b) Damage to pipelines crossing over Avon River (Cubrinovski et al. 2011); c) Damage to lifelines at Gayhurst Road Bridge (Palermo et al. 2012).

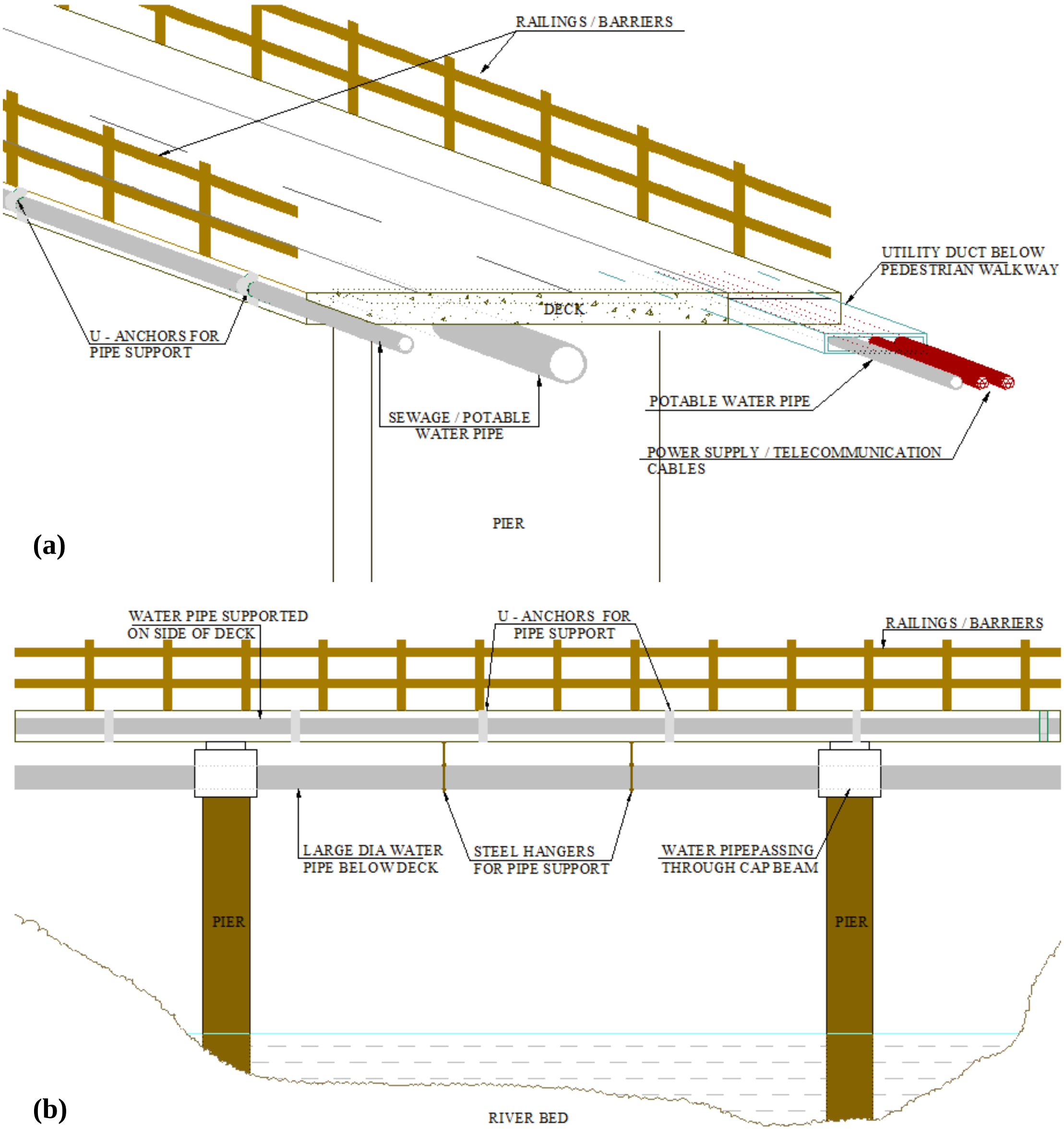

Figure 2. Schematic representation of the integrated BUS: a) Perspective view; b) Elevation view.

2.1 Bridges

The seismic performance of the host bridge is dependent on its structural form, which may vary according to the type of bridge. The University of Canterbury Bridge Damage Database (BDD), comprising of 223 bridges, is adopted as the study sample for this framework. These bridges are majorly classified as culvert bridges, arch bridges or girder-deck bridges. Figure 3 shows the composition of these bridges in terms of structural form, construction era and material.

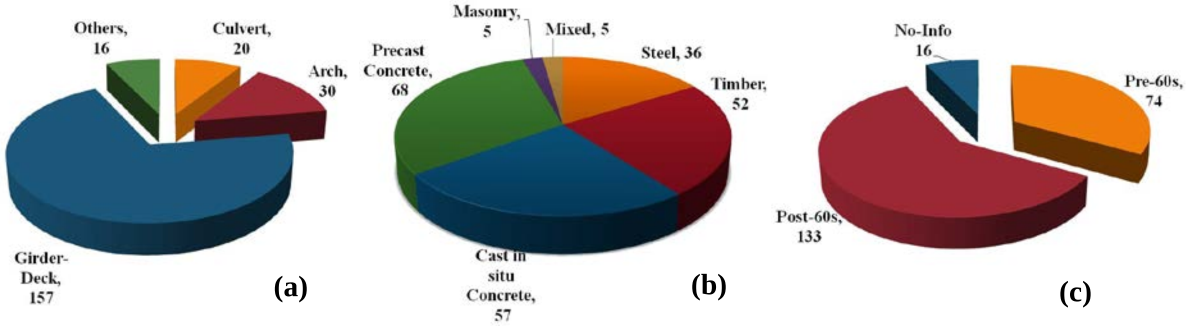

Figure 3. Canterbury bridges as for BDD; a) Structural form; b) Material; c) Construction era.

Most of the damaged observed to bridges was in regions that suffered liquefaction, during the CES. However, the general performance of the bridges was good, with low frequency of severe damages. In Christchurch, the observed damage was mainly attributed to lateral spreading effects, occurring in bridges spanning over the Avon and Heathcote rivers. The liquefaction induced damage to bridges included mainly: settlement and lateral spreading of approaches; back rotation and cracking of abutments; and pier damage (Palermo et al. 2012).

2.2 Potable Water Utilities

The Christchurch water supply is based on a comprehensive underground citywide network, with the distribution network comprising of 1700 km of watermain and 1000 km of submains. The network mains and submains are located along the roadways at shallow depths (within 0.8 m). The watermains and the submains are located typically under the carriageway and the footpaths, respectively. The prevalent pipe and fitting material varies depending on the installation timeline (Cubrinovski et al. 2014). The prevailing material composition is shown in Figure 4a, comprising of High Density Poly-Ethylene (HDPE), Asbestos Cement (AC), Medium Density Poly-Ethylene (MDPE80), Poly-Vinyl Chloride (PVC), Cast Iron (CI), Galvanised Iron (GI), Modified PVC (MPVC), Concrete Lined Steel (CLS), Ductile Iron (DI) and Steel (S) pipes.

The potable water network pipes showed good co-relation of high damage frequencies with high liquefaction zones in Christchurch, during the CES. There was also significant evidence of failures in pipes due to excessive pressure surges, resulting from Fluid Structure Interaction (FSI) coupling effects from seismic excitations. Where the high number of repairs caused loss of pressure, creating disruption in the water supply. Most of the damage observed was at pipe fittings, with minor damages observed in the pipes as well. Observed failure modes in pipes include blow-out (bursts) of pipe sections, cracking, circumferential split (cracking or splitting of pipe around its circumference), longitudinal split (pipe splits along its length), pinhole leaks, etc. Similarly, damages observed to joints and fittings include failure of couplers, failure of caulking, failure at bends and tees, failure of previous repairs, etc. (Cubrinovski et al. 2014).

2.3 Waste Water Utilities

The Christchurch waste water supply collection network is comprised of more than 1600 km of gravity waste water pipes and 900 km of gravity storm water pipes. Similar to the potable water utilities the pipe and fitting material composition varies through the network installation timeline. The prevailing material composition is shown in Figure 4b, comprising of Concrete (CONC), Earthen-

Ware (EW), UPVC, AC, PVC, MPVC, HDPE, and CI pipes (Cubrinovski et al. 2014). It is interesting to highlight that the flow transmission system changes to siphon or pressure flow in a ductile or plastic form of a pipe, at bridge crossings.

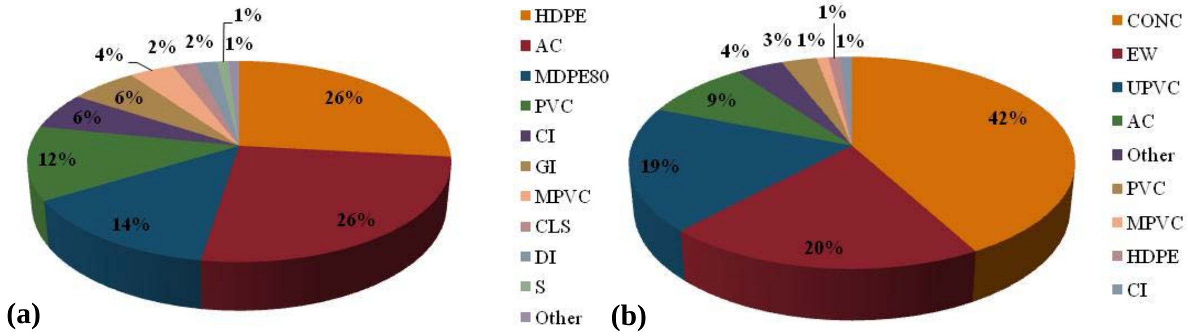

Figure 4. (a) Potable water network material composition; (b) Waste water network material composition.

The waste water network is largely composed of pipes made of brittle material, such as CONC, EW, AC, CI, etc., thus posing high vulnerability in the system. The observed failure modes include: breaks in the aeration pipes at the Waste Water Treatment Plant (WWTP) due to sloshing forces (probably due to FSI effects); fracture and rupture of pipes and joints due to liquefaction; loss of grade resulting in flow disruption due to liquefaction. (Eidinger and Tang 2012, Cubrinovski et al. 2011).Where, the extensive number of repairs caused high disruption in the sewer, blocking the sewers with sand and silt, making them unusable.

2.4 Electricity Power Supply Utilities

The main power transmission and sub-transmission system in Christchurch comprises of three voltage levels, namely 66 kV, 33 kV and 11 kV. There are four main types of cables that are used in the underground power transmission and distribution cable systems, including Paper-Insulated Lead Covered Armoured (PILCA), PILCA-HDPE, cross-Linked Poly-Ethylene (XLPE) and Oil-filled cables. These cables are mostly flexible, with varying about of flexibility, but all with limited rotational capacity. At the time of the earthquakes there were about 2157 km of 11 kV transmission cables in Christchurch power network (Kongar et al. 2014).

Impact induced by the CES was severe on all levels of transmission networks, mainly due to liquefaction. 50% of the 66 kV cables were damaged, leading to power outages in the area, while 15% cables with more than 1000 faults were identified in the 11 kV cables (Kongar et al. 2014 Eidinger and Tang 2012, Giovinazzi et al. 2011). The physical failure mechanism in cables was attributed to the development of bending stresses (from shear waves and ground deformations) in the weak concrete backfill. This resulted in backfill failure due to tensile bending stresses; at the same time inducing high compressive bending stresses in the cables, leading to buckling in the cable, with double curvatures. (Figure 5) (Eidinger 2012).

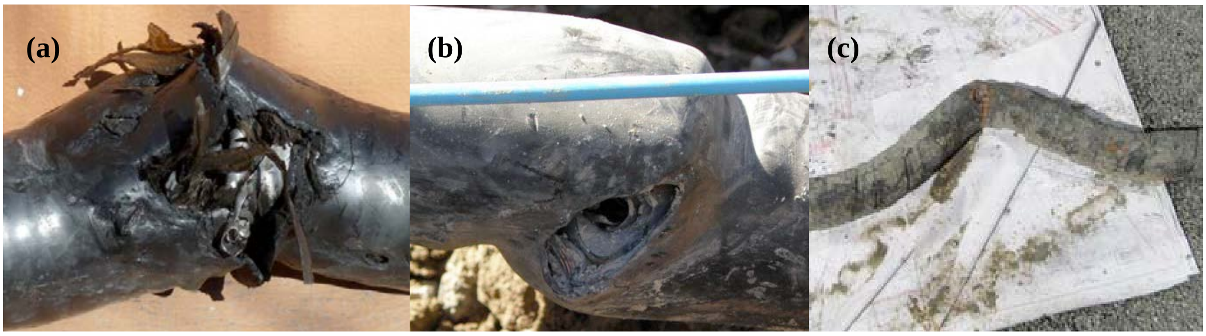

Figure 5. Damages to cables during the CES; a) Failure of 66 kV oil filled cable (Eidinger 2012); b) Failure of 66 kV XLPE cable (Eidinger2012); c) Failure of 11 kV cable (Eidingerand Tang 2012).

2.5 System Performance

There are more than 124 bridges in Christchurch that carry single or multiple utility lines from one or more infrastructure networks. Utility lines are carried by all structural forms of bridges, as shown in Figure 6a. Damages to BUS during the Canterbury Earthquakes (2010-11) were significant in areas prone to liquefaction or lateral spreading. Damages as included in the BDD are summarised in Table 1, however, there have been a higher amount of damages to BUS, as resulting after an extensive data collection and on-going collation and processing by the author.

The dominant failure mechanism in BUS was due to lateral spreading, which tends to expose the upper part of the bridge abutment piles, or it may cause settlement of the bridge embankment. Piles in the exposed region may undergo buckling which causes the abutments to rotate. Therefore, if a utility line was passing through the abutment, it would experience high stress concentration at the abutment-deck interface (Fig. 6b), where the abutment would induce high curvatures in the utility line due to its own rotation. Similarly, if the embankment undergoes settlement, due to lateral spreading, the utility line would experience high stress concentrations at the embankment-abutment interface, where the embankment would impose high shearing stresses in the gravity direction.

Besides the dominant damage observed due to rotation of abutments, there have been instances where other failure modes were also observed. These include: failure of pipe at mid-span that may be possible due to ground shaking, as reported at the Durham Street Overbridge (CES); buckling of pipe, as reported after the 1994 Northridge Earthquake (Schiff 1997); failure of primary and secondary connections that may be attributed to perturbations induced through FSI effects and ground shaking, etc., as reported at the Rokko Island bridge (1995 Kobe Earthquake, (Schiff 1998)) and at Bateman Avenue footbridge (CES).

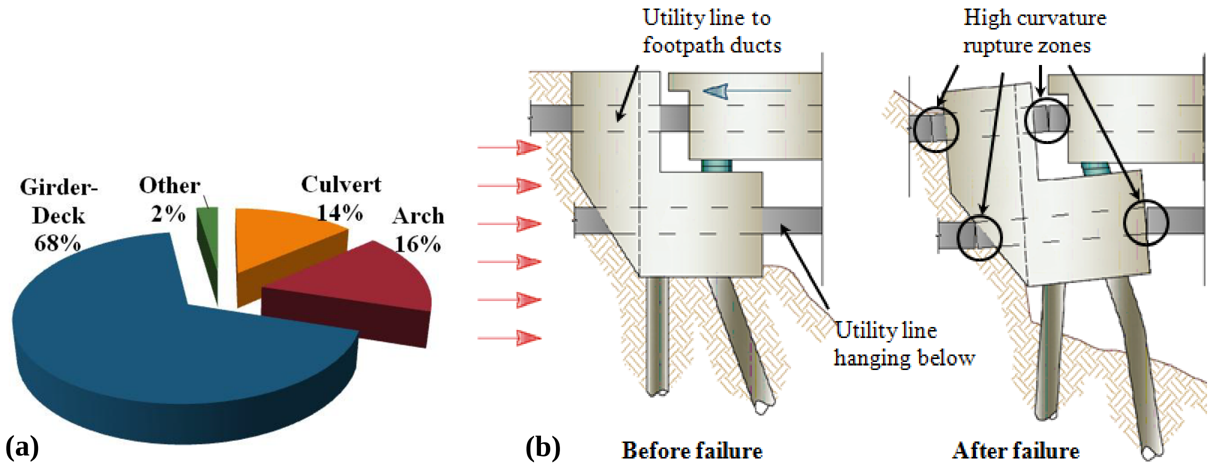

Figure 6. (a) BUS composition by bridge form; (b) Failure mode of utility lines at abutment interface (schematic-representation courtesy of Brando (2011)).

3 LOSS ESTIMATION AND MITIGATION FRAMEWORK

A framework is herein proposed (Fig. 7), consists of four phases, each providing a unique output. The four objectives are inter-related and contribute to provide the final objective, namely Objective 5 'To develop simplified performance based analytical tools for the design and mitigation of new and existing Bridge-Utility systems'. The first phase is to collect and collate exhaustive data on bridge-utility integrated systems in the Canterbury region, and detailed damage reports from the Canterbury Earthquakes 2010-11. The second phase involves simplified numerical analysis of the integrated BUS, developing the understanding of the basic seismic response of the system and the underlying uncertainties associated with it. The third phase focuses on detailed numerical analysis of the system, by incorporating results from FEM modelling of components integrated with Fluid Structure Interaction (FSI) effects into the global model of the integrated BUS, to develop fragility functions;

highlighting the resilience of the system against ground shaking and liquefaction phenomenon. The final stream is to combine the fragility formulations and taxonomies, generated for the integrated BUS, with existing risk models to assess the functionality and socio-economic risk of the infrastructure networks, due to ground shaking and liquefaction susceptibility at bridge linkages. The following sub-sections provide an overview for each phase and relative objective included in the proposed framework.

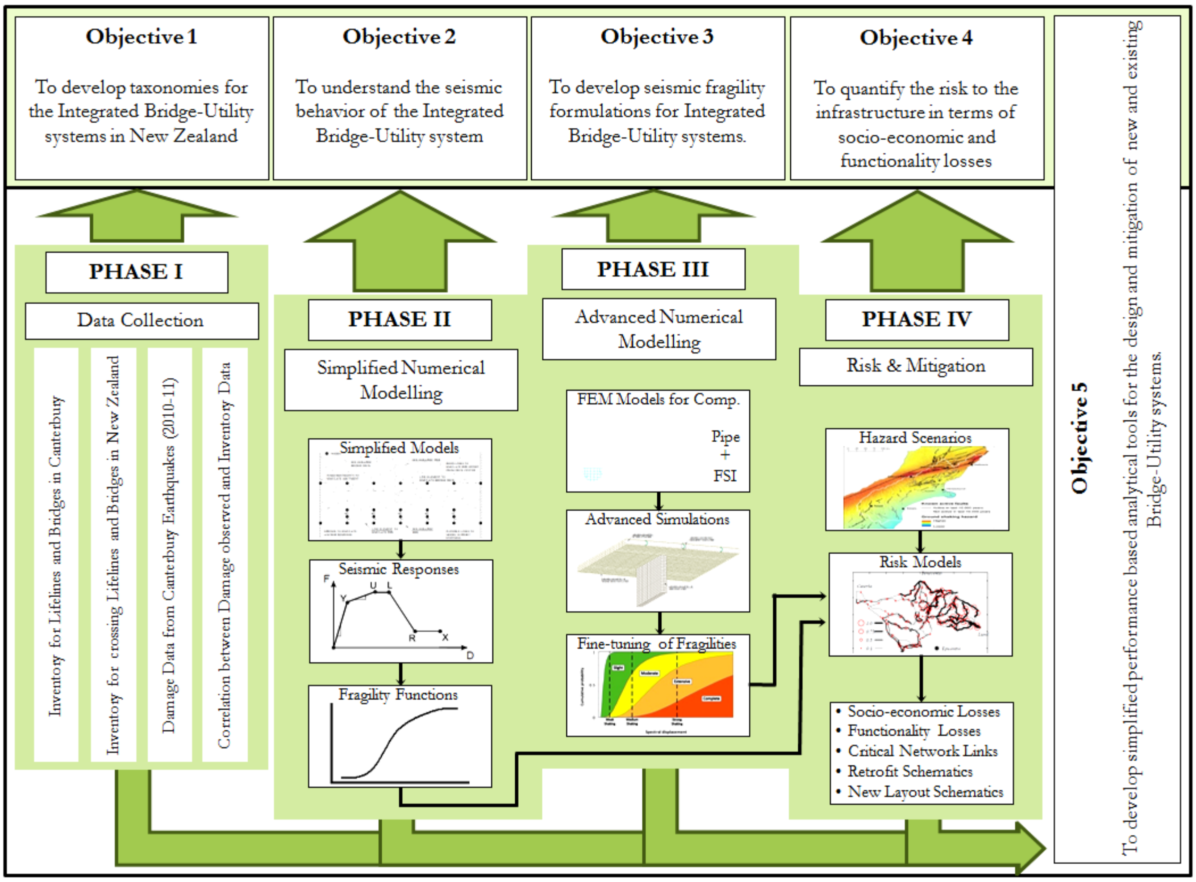

Figure 7. Schematic overview of the framework and objectives.

3.1 Phase I: Data Collection

The initial phase aims to develop comprehensive asset inventory for the existing BUS in Christchurch, based on exhaustive data collection and collation. The database will include the parameters required for estimating the seismic engineering and risk demands for the prevalent bridge-utility systems and components, along with observations and repair strategies employed during the Canterbury Earthquakes (2010-11). The following methodology is proposed to meet the needs:

- Development of a comprehensive asset inventory system would require valuable data inputs and collaboration from the asset and risk holders, along with field surveys and inputs through various other sources, to ensure the integrity of the data.
- Taxonomies will be developed from the inventory and the damage date collected, considering the parameters that would reflect on the structural response of each taxonomy.
- A preliminary correlation will be applied to develop vulnerability indices for the BUS component taxonomies, from the damages observed during the Canterbury Earthquakes (2010-11) and the existing asset stocks.

3.2 Phase II: Simplified System Level Simulations

Simplified Simulations are proposed to be carried out to estimate the basic response of the BUS against seismic ground motions and deformations. Alongside the results from these simulations will be used to develop limit states as per engineering and risk demands, to estimate the fragility formulations for the BUS, that would be useful to carry out risk assessment for physical and functionality losses for retrofit of existing and planning of new assets.

The following methodology is proposed to meet the needs:

- The preliminary simulations of the BUS to develop the basic (but non-linear) seismic response would require to construct 3D models based on frame line elements of the BUS. Where the component characteristic properties can be defined as estimated bi-linear load deformation curves (crude), developed by simple spreadsheet calculations. The component properties can be calibrated through the observations from the Canterbury Earthquakes (2010-11).
- Fragility curves require the development of appropriate limit and damage states, in terms of the mechanical damage sustained by the utility element. The limit and damage states can then be used to evaluate the probability of exceedance against the seismic intensity parameters.

3.3 Phase III: FEM Simulations

A rigorous form of simulation is proposed at a later stage to simulate the detailed response of the BUS components via FEM analysis, that would enable to define the parametric response of the components and permit to include the variations in the component taxonomies. Alongside, the results will be used to compute global fragility functions, enabling to accommodate the parametric change in the fragility functions that would reflect the consequences in the risk and loss estimates. The following methodology is proposed to meet the needs:

- FEM simulations of pipe and cables would be required to carry out for parametric and detailed non linear response. Pipes will be analysed coupled with the fluid interaction (FSI), to account for the excessive pressure surges due to Poisson, friction and junction couplings, that may drastically alter the response of the pipe due to seismic excitations. The outputs of the FEM analyses will then be incorporated in the 3D models developed in the previous phase to obtain a more refine response of the BUS.
- Fragility relations would be correlated with the parametric response of the BUS obtained from the rigorous simulations to evaluate a global fragility function that would account for all the uncertainties associated in the BUS and component taxonomies, so that the application is compatible for other BUS taxonomies outside New Zealand as well.

3.4 Phase IV: Risk Estimations and Mitigation Strategies

The estimated fragility functions from the previous phases would be used in existing risk models and tools to assess the GIS based probabilistic and deterministic risk associated with the physical damage of the BUS on the monetary and functionality loss of the utilities. The estimates can then be compared with the actual observed losses, after the CES, to evaluate any associated uncertainties in the outputs. Furthermore, the risk associated with the functionality loss on the performance of the utility infrastructure network will be assessed simultaneously to develop critical path mitigation strategies. The risk and loss estimates can then be used in consideration for mitigation techniques for retrofit prioritization of existing and planning of new BUS.

- Existing programmable risk and loss assessment tools such as OOFIMS® (developed under the SYNER-G framework (Pitilakis et al. 2014)) would be used to evaluate GIS based probabilistic and deterministic loss estimation estimated for seismic ground shaking and liquefaction. These tools would enable to estimate the flow requirements and losses in the utility infrastructure networks, providing a more precise understanding of the associated risk, through evaluation of various runtime performance indicators.

- The performance indicator would then be used to assess the possible mitigation strategies by optimizing the risk by proposing improvements in the BUS network layout and by proposing performance based guidelines for planning and designing of installations of utilities on host bridges. Thus, enabling the asset manager to select the optimum technique as per need.

4 CONCLUSION

The Darfield Earthquake 2010 and the Christchurch Earthquake 2011 proved to be severely devastating for the built infrastructure of Christchurch, including the bridge-utility systems. Damage to utilities crossing over bridges was significant in lateral spreading regions, due to excessive stresses concentrating at the settled embankment or at the abutment face causing high rotational demand in the utility lines. A framework has been defined to address the design and mitigation of new and existing bridge-utility systems. The study progress is summarized below:

- Phase I is on the verge of completion, currently. Exhaustive data collection was undertaken and has been processed by the author. Preliminary analysis results will be included in an upcoming publication (Rais et al. 2015 'Pipelines at bridge crossings: empirical based seismic vulnerability index')
- Phase II will be commencing in the first half of 2015. It is expected to initially progress with developing and analysing the 3D system models on OPENSEES or RUAUMOKO. This will be followed by progressing on the fragility functions and curves.
- Phase III is scheduled to commence in the second half of 2015. FEM tools such as TNO - DIANA® or ABAQUS® will employed to model the prevalent component types. The analysis results will then be used for parametric evaluation study for developing characteristic response and fragility functions.
- Phase IV is scheduled to commence in the first half of 2016. Preliminary understanding of the risk assessment tool OOFIMS has been already gained. Therefore, fragility curves from the previous phases will be incorporated in the tool for assessment. Thereafter, mitigation strategies will be developed based on the results from the analysis.

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