Estimating seismic impacts on lifelines: an international review for RiskScape

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ABSTRACT: In this paper an international overview is provided about the main methods and computational tools available for the development of seismic damage scenarios and for the assessment of the ensuing loss of functionality of selected geographically distributed lifelines, namely transportation networks, electric power systems and potable water systems. The final objective of the study is to provide the Regional RiskScape programme in New Zealand with an engineering basis upon which the losses incurred by lifeline systems can be assessed under the action of different natural hazards. To this aim reliable and worldwide implemented methods have been investigated in order to understand: 1) the parameters adopted for the representation of the ground shaking; 2) the classification system and the asset attributes considered for the implementation of the exposure analysis; 3) the assumed spatial data representation; 4) the technical basis upon which vulnerability, fragility curves, loss and restoration have been developed. The feasibility of implementing the models presented for the seismic performance assessment of lifelines in New Zealand is finally discussed with reference to a study-case.

1 INTRODUCTION

The study “Multi-hazards performance of geographically distributed systems” has been jointly promoted and funded by the Crown Institute GNS Science and by the Earthquake Commission, EQC, in order to provide the regional RiskScape programme (funded by the Foundation for Research Science and Technology) with an engineering basis upon which the losses incurred by selected geographically distributed lifeline systems can be assessed under the action of different natural hazards. To this aim, the technical basis upon which vulnerability, fragility curves, loss and restoration curves have been developed within international literature and on–going research projects have been investigated. This paper summarises the preliminary results of the research, focusing on the seismic performance of transportation networks, electric power systems and potable water systems. Table 1 provides the acronyms of pertinent methods and of on–going research projects that have been judged relevant and reliable for the seismic performance assessment of lifelines in New Zealand.

Table 1. Assessment methods and on-going research projects on the seismic performance of lifelines.

<table>
<thead>
<tr>
<th>TRANSPORTATION</th>
<th>WATER</th>
<th>POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZUS</td>
<td>HAZUS</td>
<td>HAZUS</td>
</tr>
<tr>
<td>MIRISK</td>
<td>ALA</td>
<td>ALA</td>
</tr>
<tr>
<td>REDARDS</td>
<td>LESSLOSS</td>
<td></td>
</tr>
</tbody>
</table>

ALA – American Lifelines Alliance; HAZUS – Multi-hazard loss estimation methodology; LESSLOSS – Risk mitigation for earthquake and landslides integrated project; MIRISK – Mitigation Information and Risk Identification System; REDARDS – Risks from Earthquake Damage to Roadway Systems
In this paper, the methods proposed by HAZUS (FEMA 2007) and by ALA (ALA 2001) are discussed in Sections 2 and 3 while relevant on-going research projects are summarised in Section 4. The feasibility of implementing existing assessment methods in New Zealand, relying on available data, is discussed in Section 5, making reference to the electric power system in the Christchurch area.

2 HAZUS-MH - EARTHQUAKE MODEL

The HAZUS-MH Earthquake Model provides estimates of damage and loss to buildings, and essential facilities, including transportation and lifelines utilities such as electric power systems and potable water systems. HAZUS-MH allows the evaluation of the expected physical damage, in terms of fragility curves and damage ratio, to lifeline components and sub-components. Based on the estimation of the physical damage, the economic losses and the restoration times (component functionality) are inferred. HAZUS-MH is coupled with Geographic Information Systems (GIS) technology allowing the representation of estimated seismic-related damage scenarios before, or after, an earthquake occurs.

A feasibility study has been conducted in order to understand the potential and limitations for the implementation of HAZUS-MH fragility models in New Zealand. The definition of hazard parameters, asset attributes and the level of spatial data aggregation to be included in the RiskScape platform implementation of HAZUS-MH models are briefly summarised in the following.

HAZUS-MH aggregates and models spatial data as points, lines and polygons. For example, for water systems, the distribution pipelines are represented as linear components, with nodes located where attributes change, the reservoirs as polygon components, and the storage tanks as point components.

The inventory data required by HAZUS-MH for the representation and the analysis of lifelines subjected to earthquakes include the: 1) geographical location (Latitude and Longitude); 2) classification (attributes) of components and sub-components; 3) replacement costs of components and sub-components.

Dependant on a components’ vulnerability, different ground motion parameters are considered for the hazard representation, including: peak ground velocity, PGV; peak ground acceleration, PGA; permanent ground deformation, PGD; and spectral acceleration for different fundamental periods, Sa[T].

Tables 2 to 4 summarise HAZUS-MH input requirements for the different components respectively of transportation, water and power systems.

HAZUS-MH allows the assessment of different outputs, including: 1) the probability for the components of being in a certain damage state (Section 2.1); 2) damage ratio (Section 2.2); 3) economic losses [$$]; and 4) restoration time [days] (Section 2.2). All the outputs resulting from the implementation of HAZUS-MH can be displayed as GIS maps.

Table 2. Inventory data for transportation systems after HAZUS –MH (FEMA 2003).

<table>
<thead>
<tr>
<th>Components</th>
<th>GIS</th>
<th>Classification</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>road</td>
<td>line - coordinates at end nodes</td>
<td>interstate/state highways, urban roads</td>
<td>PGD at roadway links</td>
</tr>
<tr>
<td>bridge</td>
<td>point - coordinates at bridge</td>
<td>parameters i.e.: a) seismic design; b) number of spans; c) structure type; d) pier type; e) abutment type and bearing type; f) span continuity</td>
<td>PGA/PGD/Sa[0.3]/Sau[0.1] at bridge</td>
</tr>
<tr>
<td>tunnel</td>
<td>point - coordinates at tunnel</td>
<td>bored/drilled or cut &amp; cover</td>
<td>PGA/PGD at tunnel</td>
</tr>
</tbody>
</table>
Table 3. Inventory data for potable water system after HAZUS –MH (FEMA 2003).

<table>
<thead>
<tr>
<th>Components</th>
<th>GIS</th>
<th>Classification</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>transmission, aqueducts, and distribution pipelines</td>
<td>line - coordinates</td>
<td>ductile or brittle</td>
<td>PGV/PGD at aqueduct/pipeline links</td>
</tr>
<tr>
<td>reservoirs, water treatment plants, wells, pumping stations and storage tanks</td>
<td>point/polygon - coordinates at facilities</td>
<td>parameters: a) capacity; b) anchorage*</td>
<td>PGA/PGD at facilities</td>
</tr>
</tbody>
</table>

Table 4. Inventory data for electric power systems after HAZUS –MH (FEMA 2003).

<table>
<thead>
<tr>
<th>Components</th>
<th>GIS</th>
<th>Classification</th>
<th>Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>substations</td>
<td>point - coordinates at facilities</td>
<td>parameters: a) low, medium, or high voltage; b) with anchored or standard components</td>
<td>PGA/PGD</td>
</tr>
<tr>
<td>distribution circuits</td>
<td>point - coordinates at facilities</td>
<td>parameters: a) seismically designed or b) standard components</td>
<td>PGA</td>
</tr>
<tr>
<td>generation plants</td>
<td>point - coordinates at facilities</td>
<td>parameters: a) small or medium/large, b) with anchored or unanchored components*</td>
<td>PGA</td>
</tr>
</tbody>
</table>

*anchored components refers to equipment designed with special seismic tiebacks to meet seismic criteria.

2.1 Damage States and Fragility Curves in HAZUS-MH - EARTHQUAKE MODEL

A total of five damage states are usually defined by the HAZUS-MH model for lifelines system components, corresponding to: D₁= no damage; D₂= slight/minor damage; D₃= moderate damage; D₄= extensive/considerable damage; D₅= complete damage.

Damage functions or fragility curves for lifelines system components are modelled as lognormally distributed functions, giving the probability of reaching or exceeding different levels of damage for a given level of ground motion. The lognormally distributed functions are defined by a median ground motion parameter and a dispersion provided by HAZUS-MH for each one of the lifelines components considered for the system. As an example, the damage functions in the form of lognormally distributed functions curves are presented for medium voltage substation in Figure 1.

The HAZUS-MH fragility functions (fragility curves) result from a combination of expert judgement models and empirical models based on statistical analysis of damage data from previous events.

When necessary (i.e. substations, generation power plants, etc.) HAZUS-MH fragility curves account for the probabilistic combination of subcomponent damage functions, using Boolean expressions to describe the relationship between components and sub-components. The Boolean approach involves evaluation of the probability of each component reaching or exceeding different damage states, as defined by the damage level of its sub-components. It should be mentioned that the Boolean logic is implicitly presented within the definition of a particular damage state. For example, the moderate damage state for substations is defined as the failure of 40% of disconnect switches, OR the failure of 40% of circuit breakers, OR the failure of 40% of transformers, OR by the building being in moderate damage state. Therefore, the fault tree for moderate damage for substations has 4 primary OR branches: disconnect switches, circuit breakers, transformers, and building. Within the first 3 OR
branches (i.e., disconnect switches, circuit breakers, and transformers) the multiple possible combinations are considered. These evaluations produce component probabilities at various levels of ground motion. In general, the Boolean combinations do not produce a lognormal distribution, so a lognormal curve that best fits this probability distribution is determined numerically and provided by HAZUS-MH.

Damage ratios, defined in terms of fraction of the component replacement cost, are provided by HAZUS-MH for each components of the lifeline systems and for each damage state DR\(_i\) (i = 1 to 5). When necessary (i.e. substations, generation power plants) the damage ratios are evaluated accounting for the sum of the damage ratios of all the subcomponents, multiplied by their respective percentages of the total component value.

The assessment of the expected economic losses, for each component of the lifeline system, requires, as a first step, the computation of a compounded damage ratio DR\(_c\), evaluated as the probabilistic combination of damage ratios for different damage state DR\(_i\) (i = 1 to 5), as follows:

\[
DR_c = \sum_{i=2}^{5} DR_i P[D_i | PGA]
\]

where DR\(_i\) is the damage ratio for each damage state provided by the HAZUS-MH model; P[D\(_i\) | PGA] is the probability of being in a certain damage state D\(_i\) (i = 1 to 5) given a certain PGA. The value of P[D\(_i\) | PGA] can be straightforwardly assessed from the fragility curves (Par. 2.1). It is worth noting that no losses are associated with damage state D\(_1\), therefore, the summation in Equation 1 is from 2 to 5.

The expected economic losses are evaluated multiplying the compounded damage ratio, DR\(_c\), by the replacement value. It is worth underlining that most of the replacement value data reported in HAZUS-MH comes from ATC-13 (1985) and ATC-25 (1991). These replacement values are rough estimates and should only be used as a guide. It is expected that the user will input replacement values based on specific knowledge of the lifeline components in the study area.

Restoration curves are also provided by HAZUS-MH, for each component of the lifeline system, calibrated on different set of data or based on expert judgement. As an example, for electric substations and distribution circuits, restoration curves are based on G&E report (1994), while restoration curves for generation facilities are obtained using the data for mean restoration times reported in ATC-13 (1985). Restoration curves are provided either in terms of means and standard deviations, in order to draw smooth continuous curve, or as approximate discrete functions (Fig. 2a).
In order to check their reliability, the damage ratio curves resulting from HAZUS approach have been compared with the ones resulting from observed damage data. For the specific case of electric power systems, damage ratio curves, resulting from the statistical processing of observed data (Cousin 2008), have been compared with the ones resulting from the implementation of the HAZUS approach after assuming the correlation between the macroseismic intensity $I_{MMI}$ and the peak ground acceleration PGA, by Murphy and O’Brien (1977). The obtained results, presented in Fig. 2b seem reasonable; damage ratio curves resulting for pole mounted cables and transformers from the observed data processing implemented by Cousin (2008) represent a sort of medium curve for the damage ratio curves resulting from HAZUS-MH approach for anchored and unanchored components.

3 ALA - AMERICAN LIFELINES ALLIANCE

The American Lifelines Alliance, ALA, is working since 2001 in the preparation of Guidelines for assessing the performance of lifelines in natural hazard and human threat events. The purpose of ALA guidelines and of the accompanying commentaries is to provide a multilevel process by which the performance of electric power system (ALA 2005a), water system (ALA 2001 and ALA 2005b) and wastewater system (ALA 2004) in natural hazards and human threat events can be assessed. The natural hazards addressed by ALA guidelines include earthquakes, together with floods (riverine and coastal), windstorm (extreme winds and tornado), icing and ground displacements.

ALA guidelines provide specifics steps to be performed for the assessment of lifeline systems performance plus the relative level of effort required to address specific inquiry and the types of expertise needed. In particular, ALA (2001) provides detailed procedures that can be applied to any water transmission system in order to evaluate the probability of damage from earthquake hazards to various components of the system, including: 1) the inventory information to be collected and the required inputs in term of location and hazard parameters are provided; 2) fragility curves for each type of component; 3) observed damage and repair data from real events used to define the proposed fragility curves; 4) description of the statistical analysis methods used in developing the fragility curves; 5) comparisons of the fragility curves with those prepared by other researchers in the past; 6) examples of application of the methods. It is worth noting that the fragility curves proposed within ALA guidelines, consider both uncertainty and randomness from both the characterization of the earthquake hazard as well as the performance of the component itself to a particular level of hazard. Equations 2 and 3 provide generic examples of the parameters accounted for in the formulation of vulnerability and fragility curves for potable water systems according to ALA (2001).

\[ DM = f(D, t, d, J, M, E, S, XX) \]
where DM is the damage measure, D pipe diameter, t pipe wall thickness, d depth of soil cover, J joint type, M material, E Earthquake hazard measure, S site characteristics, XX other parameters to be determined.

\[ PD = f(H,D,t,M,F,A,E,S,YY) \]

where PD=probability of damage state occurring, H height, D diameter, t wall thickness, M material, F fluid, A anchorage, E Earthquake hazard measure, S site characteristics, YY others parameter to be determined.

As an example, Fig. 3 provides the recommended “backbone” pipe vulnerability functions, intended to represent the average performance of all kinds of pipes in earthquakes, for peak ground velocity, PGV, and permanent ground deformation, PGD, mechanisms. The damage algorithm for buried pipe is expressed as a repair rate per unit length of pipe. RR.

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Vulnerability Function</th>
<th>Lognormal Standard Deviation, ( \beta )</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Propagation</td>
<td>RR=0.00187 * PGV</td>
<td>1.15</td>
<td>Based on 81 data points of which largest percentage (38%) was for CI pipe.</td>
</tr>
<tr>
<td>Permanent Ground Deformation</td>
<td>RR=1.06 * PGD^{0.319}</td>
<td>0.74</td>
<td>Based on 42 data points of which largest percentage (49%) was for AC pipe.</td>
</tr>
</tbody>
</table>

Figure 3. Buried Pipe “backbone” Vulnerability Functions after ALA (2001).

The “backbone” vulnerability functions are proposed in ALA (2001) for cases where there is no knowledge of pipe materials, pipe joinery, pipe diameter or soil corrosion status, etc. of the pipe inventory and when the evaluation is intended to be performed for a reasonably large inventory of pipelines comprising a water distribution system. Throughout ALA report (2001) and related Appendix, the possible behaviour of various pipe types in earthquakes is addressed. Recommendations on how to apply “backbone” curves to particular pipe types (where more precise information are specified i.e. pipe diameter, material, joint type, soil condition, etc.) are provided.

It is worth highlighting that the development of damage algorithms for buried pipe is primarily based on empirical evidence (i.e. data collected about how many miles of buried pipe experienced what levels of shaking, and how many pipes were broken or leaking because of that level of shaking) tempered with engineering judgment and sometimes by analytical formulations.

4 ON–GOING RESEARCH PROJECTS ON SEISMIC PERFORMANCE OF NETWORKS

4.1 MIRISK - Mitigation Information and Risk Identification System

The “Mitigation Information and Risk Identification System”, MIRISK platform (Mina et al. 2008), created by the Research Centre for Disaster Risk Management, at Kyoto University, provides a tool for the assessment of the performance of building and transportation network under natural hazards and for supporting the decision making about risk mitigation strategies (Fig. 4a). MIRISK project has been funded by the World Bank in agreement with AGORA, Alliance for Global Open Risk Analysis (www.risk-agora.org) and is intended to support the work of decision makers by: 1) identifying natural hazards affecting a region; 2) defining the kinds of infrastructure that make up typical development projects; 3) describing the vulnerability of these assets to natural hazards, and how vulnerability can be reduced; 4) analyzing the natural hazards and vulnerability data, to assess whether projects should follow normal design practices, or whether the cost of some enhanced design for natural hazards is justified by the benefits (of avoided losses).

When dealing with earthquake, MIRISK’s basic purpose is to allow a decision maker to quickly understand if the seismic risk is very significant in a region where the decision maker is considering development. If so, MIRISK provides information on what can be done, and permits estimation of the
added cost to guarantee a moderate level of seismic protection. Furthermore an “optimum” level of enhanced construction can be estimated by MIRISK, based on the degree of hazard, the type of facility, and the project’s benefit cost ratio (where benefit, including some monetised estimate of future social benefits, is divided by the total component cost, including indirect costs of damage).

4.2 REDARS - Risks from Earthquake Damage to Roadway Systems

Since the mid-1990s, the Federal Highway Administration’s, FHWA, in USA has sponsored multiyear seismic-research projects at the Multidisciplinary Centre for Earthquake Engineering Research, MCEER, that have included development and programming of the tool “Risks from Earthquake Damage to Roadway Systems”, REDARS™. The tool has been released for public use in March 2006 (Fig. 4b).

REDARS™ uses state-of-knowledge models to estimate: a) the seismic hazards (ground motions, liquefaction, and surface fault rupture) throughout the system; b) the resulting damage states (damage extent, type, and location) for each component in the roadway system; and c) how each component’s damage will be repaired, including its repair costs, downtimes, and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake). Secondly, REDARS™ incorporates these traffic states into a highway-network link-node model, in order to form a set of system-states that reflect the extent and spatial distribution of link closures at various times after the earthquake. Finally, REDARS™ applies network analysis procedures to each system-state, in order to estimate how these closures affect system-wide travel times and traffic flows.

Figure 4. Earthquake impact on transportation networks: a) estimation of bridge damage in MIRISK (Mina et al. 2008); b) traffic and costs impacts from REDARS™ (Werner et al. 2004).

4.3 LESSLOSS - Risk mitigation for earthquake and landslides integrated project

The EU funded “Risk mitigation for earthquake and landslides” integrated project, LESSLOSS, has targeted the analysis and assessment of the impact of earthquake and landslides on lifelines utility systems. The focus of the LESSLOSS project has been to make earthquake engineers familiar with the main methods and computational tools needed for developing scenarios of earthquake ground motion and the related scenario damage to representative urban lifelines system as well as with illustrative examples of application to cities in Europe and neighbouring countries. In addition to describing tools for practical construction of damage scenarios, The LESSLOSS project has highlighted some innovative research, especially methods leading to the estimation of pipeline damage on the basis of the peak ground strains generated by the propagation of seismic waves, which in turn needs the support of advanced 2D or 3D wave propagation modelling. The results obtained within the LESSLOSS Project have been reported in several technical reports and technical dissertations further to scientific papers (Ansal et al. 2007a/2007b; Selçuk and Yücemen 2000; Toprakw and Taskin 2007).
5 CRITICAL ANALYSIS OF LIFELINES EXISTING DATA IN NEW ZEALAND

Network, components and critical link attributes for the three geographically distributed systems under analysis (road system, electric power system, potable water system) have been collected and their geospatial representation has been performed for a pilot area identified within Christchurch City. The existing databases have been critically examined, in order to identify if the information available would allow the seismic performance assessment of the three lifelines under the impact of earthquake ground shaking, and the representation of the results in term of GIS maps. The data processing involved the following steps:

1. Identifying the basic components of the lifeline systems and their function in the overall system operation;
2. Clarifying which components are accounted for within existing loss estimation methods, and which ones are not, assuming that either they are not potentially vulnerable or that they are not critical to the overall system operation;
3. Reviewing the inventory of the data available for the pilot region, clarifying which components are represented, which information are associated to each component, the level of detail of the information, the model adopted for the geo-spatial representation of each component.

Results summarised here are in reference to the ORION power companies database that contains geospatial data and attributes for the electric power system in Christchurch City, including Banks Peninsula. The items identified within the ORION database and the associated information have been compared with the input requirements for the implementation of HAZUS-MH approach (Table 4). It has been observed, for instance, that, on one hand, the ORION database allows to distinguish between elevated crossing (overhead lines) and buried crossing (underground cables) distribution circuits, as required for HAZUS-MH. On the other hand, the presence of seismic design components or anchored components within distribution circuits required assumption of some inferences (Table 5). The inferences were established after analysis of the standards and codes used during the year of construction or during the year of replacement of the distribution circuit components. Similarly, inferences were established to allow identification of the transmission voltage for substations.

In conclusion, the information and spatial data in the ORION database are adequate and suitable for the implementation of a simplified loss estimation approach as for HAZUS-MH. Furthermore the geo-spatial representation of the ORION components is definitely appropriate for the implementation of GIS analysis and for the result representation in terms of GIS maps (Figure 5). It is worth highlighting that further information for the characterisations of electric power system components, additional to those required for the HAZUS-MH approach, are available within ORION database (e.g. information about the size and the material of the cables and lines). Reliable inferences can be made for the characterisation of the components and for the estimation of replacement and reconstruction costs that are not directly included in the ORION database. To reach this goal, it is critical to liaise with the administrators of the ORION Company.

<table>
<thead>
<tr>
<th>HAZUS classification</th>
<th>ORION database</th>
<th>Possible Inferences</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{LOW} = 115,KV$</td>
<td>incoming supply feeder voltage (11kv or 66kv)</td>
<td>$V_{LOW} \leftrightarrow$ incoming supply feeder 11kv</td>
</tr>
<tr>
<td>$V_{MEDIUM} = 230,KV$</td>
<td>Installation Year IY,</td>
<td>$V_{MEDIUM} \leftrightarrow$ incoming supply feeder 66kv</td>
</tr>
<tr>
<td>$V_{HIGH} = 500,KV$</td>
<td>Replacement year RY</td>
<td>anchored component $\leftrightarrow$ IY or RY$\geq2000$</td>
</tr>
<tr>
<td>anchored components</td>
<td></td>
<td>no anchored component $\leftrightarrow$ IY or RY$&lt;2000$</td>
</tr>
<tr>
<td>no anchored components</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6 CONCLUSION

In this contribution, an overview of methods and computational tools available for the damage assessment loss of functionality of geographically distributed lifelines due to earthquake has been given. Exhaustive, well documented and scientifically supported literature is available for the assessment of lifelines performance under seismic actions. In order to specify the assessment method to be implemented within RiskScape, the work will continue comparing the different methods and calibrating them with observed damage data. The analysis of attributes and spatial data available for the three geographically distributed systems under analysis (road system, electric power system, potable water system) in Christchurch City has provided positive results. The existing data would allow the implementation within the RiskScape platform of the simplified methods presented in the international literature and worldwide adopted for the assessment of lifeline systems seismic performance, provided that reliable inferences between existing data and some missing information will be established by liaising with the owners and the administrators of the lifelines companies.

7 ACKNOWLEDGMENTS

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