A METHODOLOGICAL HIERARCHY FOR MODELLING LIFELINES INTERDEPENDENCIES IN RISK MANAGEMENT

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Abstract: This paper briefly summarises the process for seismic risk assessment of a single lifeline with reference to different levels of methodological complexity for hazard, exposure, fragility and performance. It goes on to describe two paradigms for modelling interdependencies between lifelines: integrated modelling which is resource-intensive since interdependencies are analysed at element-level at the precise interfaces between systems, and coupled modelling which simplifies the problem by analysing interdependencies at system-level based on measures of the strength of the interaction between the systems. The paper proposes two interdependency parameters, the coupling strength and associated adjustment factor, that can be used quantify the strength of interaction in coupled models and then presents a hierarchy for modelling interdependencies. The hierarchy consists of integrated modelling at the highest level and then four applications of coupled modelling, based on increasingly simplified methods for estimating the interdependency parameters.

Introduction

Critical Infrastructure systems, which are also commonly known as lifelines, can be defined as the systems or networks, which provide for the circulation of peoples, good, services and information upon which health, safety, comfort and economic activity depend (Platt, 1991). Lifelines systems include utility networks such as energy, water and telecommunications; transport systems such as roads; or discrete critical facilities such as hospitals, ports and airports. They are essential to the routine functioning of society and play an important role in emergency relief, reconstruction and recovery after catastrophic events such as earthquakes. Despite the seismic fragility of elements within lifeline systems and the significance of the direct and indirect consequences that loss of functionality might have on large communities, analysis of the seismic performance and the post-earthquake management of lifelines has been is often given limited consideration. This is partly due to the main focus being typically given to building damage, since this more directly impacts on life safety, and partly due to the paucity of comprehensive data on earthquake-induced damage and loss of functionality of lifelines, which has made it difficult to create empirical damage models or calibrate analytical models.

When an earthquake occurs, damage to lifelines can be caused directly by the hazard (e.g. ground shaking causing structural failure of a component) or indirectly due to interdependencies with other disrupted systems with which it is connected (e.g. loss of electric power could disrupt water supply infrastructure if no back-up supply is available to power pumping facilities). Furthermore damage to lifelines has two impacts, firstly the cost associated with repair of physical damage and secondly the impact on people and businesses due to service interruption. This means that whilst the resilience of buildings can be measured by analysing their structural soundness, the resilience of lifelines depends on both structural performance and their capacity to provide their services. Investigating the resilience of a lifeline system therefore requires a complete understanding of its

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characteristics, including the structural vulnerability of its constituent components; the topology of the system and connections between constituent components; and the interdependency relationships with other lifeline systems and services. Damage to lifelines can have both social and economic consequences for an affected community and it is therefore important that the risk to and resilience of these systems are understood for effective decision making in relation to risk management, emergency planning and disaster mitigation.

Being able to forecast the potential impact that a future earthquake might have on the performance of a lifeline is a critical to understanding and enhancing its resilience. Although models for predicting lifelines damage are few in number, the general procedure is well-established as it is broadly similar to that used for seismic risk assessment with some adaptations specific to infrastructure. However this procedure takes seismic risk assessment of lifelines up to the stage of predicting damage to discrete elements. When considering the systemic impact of damage to lifelines there is greater variation in methods used. This is particularly the case for modelling interdependencies between systems since the complexity of the problem has led to numerous different approaches being proposed in an attempt to simplify the problem and make interdependency modelling tractable for widespread application. The alternative approaches reflect the fact that different sectors that are interested in interdependencies have different needs in terms of accuracy and detail; varying resources to allocate to the task; and different levels of access to model input data. Consequently, the procedure for seismic risk assessment of lifelines should not be reduced to a single approach. Instead it is proposed that the selection of methodology should be influenced by the needs of the modeller and the constraints imposed upon them. The concept of a methodological hierarchy can be applied throughout the seismic risk assessment process as shown in Table 1. The objective of this paper is to extend Table 1 by proposing an equivalent methodological hierarchy for modelling interdependencies between lifelines systems.

Table 1. Examples of methodological hierarchy in lifelines risk analysis

Hierarchy Level	Exposure	Hazard	Fragility	System Performance
Low	Key facilities only	None, ‘what-if’ scenarios	Expert judgment	No systemic analysis
Medium	Up to distribution level or equivalent	Single scenario earthquake	Empirical	Connectivity analysis
High	Detailed to property level	Probabilistic assessment	Analytical	Serviceability analysis

Seismic risk assessment of lifelines

Lifeline systems are made up nodal elements (known as nodes or vertices), such as substations or treatment plants, and linear elements (known as links or edges), such as pipelines or cables. These elements are arranged such that they form either a hierarchical or mesh network (or hybrid of these two) (Lakervi and Holmes, 1995). Hierarchical networks are those in which a physical resource is supplied from a source managed by a utility company to a customer (or reverse in the case of waste water). The number of nodes and links increase exponentially from the input (e.g. power generation plant) as the network branches out. These types of network are efficient in their equipment requirements but have very low levels of redundancy so that they run a high risk of system failure. In mesh networks (e.g. roads, telecoms) the objective is to link customers together. There are many more interconnections between nodes at all levels, which increase redundancy and reduce the risk of system failure. Illustrative examples of hierarchical and mesh networks are shown in Figure 1.

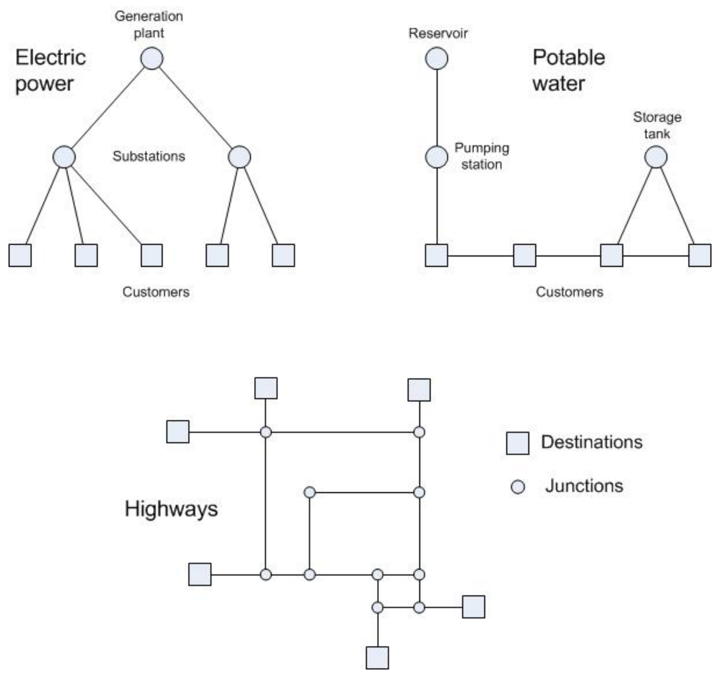

Figure 1. Illustrative examples of hierarchical (electric power and potable water) networks and mesh networks (highways)

The modelling of the consequences to a lifelines system after an earthquake can be described as a seven-step process, summarised in Figure 2, equivalent to that used for the seismic risk assessment of buildings. The first step is to produce a classification of lifelines and their constituent components so that elements that are expected to behave similarly are considered uniformly. The second step is to define the appropriate scales for classifying damage of each component. The third step is to determine the appropriate earthquake hazard parameters against which damage should be evaluated. The fourth step is to generate the seismic hazard intensities necessary to predict damage. The fifth step is to identify an appropriate hazard-damage relationship and assign damage to each component based on the hazard intensity. The sixth step is to assess the performance of the whole system based on the damages that have been assigned to each component within it. The final step is to model the restoration of the system in terms of how the system performance changes with time after the earthquake. The outputs from system performance and restoration time modelling relate to the infrastructure resilience properties of robustness and rapidity defined by Bruneau et al. (2003) and hence could also be used to quantitatively measure the resilience of a system. This process models the consequences of a single earthquake however measures of risk should be probabilistic. Therefore the steps are repeated for multiple scenario earthquakes and the distribution of modelled consequences can be plotted in order to obtain a probabilistic view of potential earthquake impacts.

Interdependencies

Lifeline systems do not operate in isolation. Rather there are interdependencies that exist between them, meaning that the performance of one lifeline is related to the performance of another. Rinaldi et al. (2001) summarised four main types of interdependent relationship: physical, geographical, cyber and logical. Physical interdependency refers to operational links between two systems in which the state of one system is dependent on the output of another, e.g. water supply system requires electric power to operate pumps. Geographical interdependency refers to the co-location of elements across two systems such that damage to one is likely to cause physical damage to the other, e.g. a pipeline traversing a bridge could potentially withstand earthquake forces but suffer damage due to collapse of the bridge. Cyber interdependency refers to systems connected by informational links; and

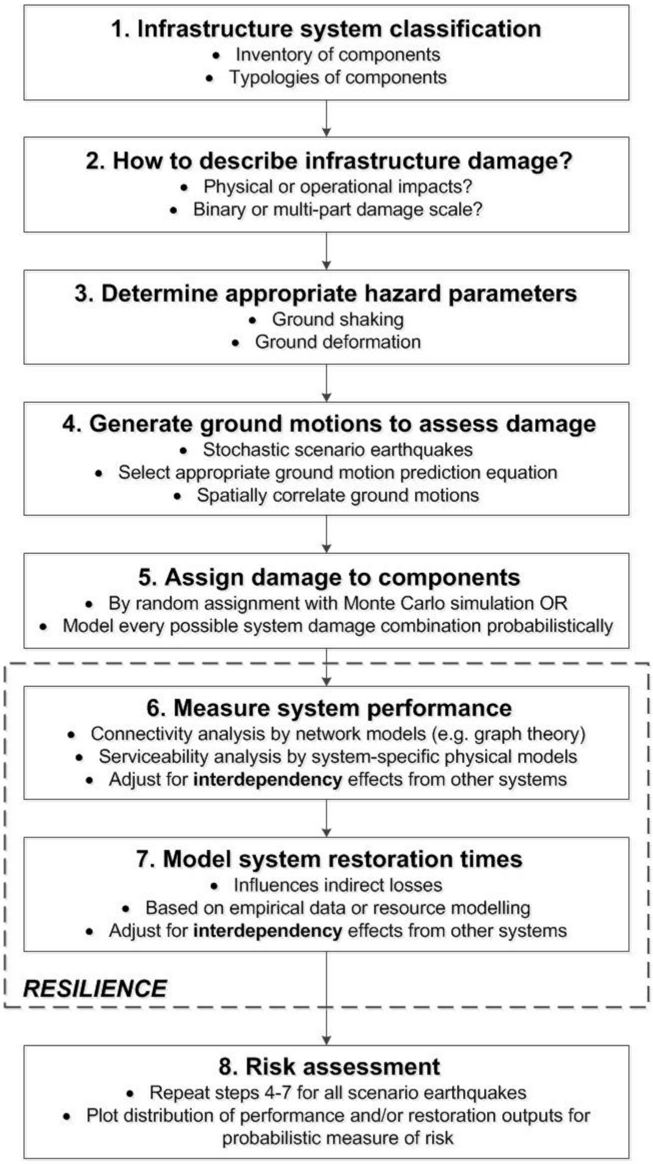

Figure 2. Flow chart for steps in seismic risk assessment of lifeline systems

logical interdependency refers to all other relationships not categorised by the other three types.
An example of a logical interdependency is the impact that damage to highways and telecoms can have on the ability of other infrastructures to implement repair and restoration works, by restricting the movement of personnel and communications with them. Whereas with other types of interdependency, the relationship between systems exists between physical elements of those systems, in this example the interdependency exists between a physical element (road or telecoms equipment) and a human/organisational element (engineering personnel). Given the potential for widespread damage and the urgent need to deploy resources for repair and restoration, this type of interdependency is especially important for emergency planning and disaster risk studies and should perhaps be described separately, rather than under the umbrella of 'logical' interdependencies. This was addressed by Duenas-Osorio and Kwasinski (2012) by referring to this as a 'logistical' interdependency.

Within seismic risk assessment interdependencies are considered in the calculation of system performance at step 6 and also when assessing restoration times in step 7. An infrastructure element can fail after an earthquake in two ways. One is that the element may suffer physical damage as a direct result of seismic forces. If elements in different systems fail in this way due to the same earthquake, this is an example of common cause failure (Rinaldi et al., 2001) or inherent failure (Han and DeLaurentis, 2013). However an element may be able to withstand the initial shock yet stop functioning because it is no longer receiving some input from another system which it requires to operate normally, e.g. when a water pump loses its power supply. Han and DeLaurentis (2013) refer to this as a propagating failure, although Rinaldi et al. (2001) make a distinction between the case where failure in one system causes failure in a second system – cascading failure – and the case where failure in one system exacerbates an existing failure in a second system – escalating failure. Whilst steps 1 to 5 in Figure 2 summarise the procedure for predicting inherent failures to infrastructure elements, to correctly model system performance in step 6 it is also necessary to account for propagating failures resulting from physical, geographical and cyber interdependencies. At step 7, when calculating restoration times, it is important to understand the geographical and logistical interdependencies that may slow down repair activities and also the physical interdependencies that prevent otherwise undamaged elements in one system from operating until a damaged element in another system is repaired. However, from hereon, this paper focuses on system performance interdependencies.

There are many different techniques that can be utilised to model lifelines interdependencies (Kakderi et al., 2011) but collectively they fall into two paradigms, described by Eusgeld et al. (2011) as the integrated and coupled approach. The primary distinctions between these two paradigms relate to the scale at which interdependency is modelled and the stage at which interdependencies are considered in the analysis. The differences in approach are summarised schematically in Figure 3 for a fabricated pair of lifeline systems: an electric power network and a water supply network with identical layouts to those presented previously in Figure 1. In this example, there is interdependency between the systems because a pumping station in the water supply network relies on electric power.

Integrated interdependency modelling

In the integrated approach the interdependency is defined at the element-level. This means the specific elements between which the interdependency exists are identified and represented in the network model. In the schematic in Figure 3, this is represented by the dashed line between the pumping station and the substation on which it is reliant for power. Defining these specific interfaces effectively integrates the individual lifelines together into one single system, within which each lifeline is just a sub-system. Once the interdependencies are identified, inherent failures are identified using fragility functions (an interdependency link may also have a fragility associated with it if it is representative of physical equipment) and then propagated through the integrated system. In the trivial example in Figure 3, the propagation of failures is straightforward, i.e. all elements downstream of the inherent failures are assumed to be non-operational unless they have a back-up or secondary input. However in more complex exercises, such as where more than two lifelines are being assessed or where there is a two-way interdependency between two lifelines, there is a possibility of an inherent failure propagating through a feedback mechanism back into the system in which it first occurred.

Consider an example where a substation receives power from a gas-fired power plant. If the substation fails due to earthquake damage, that failure may propagate into a pumping station, which in turn prevents a key gas processing facility from operating, since water is needed for fire safety. If that particular gas facility is critical to the operation of the generation plant, then the generation plant may fail also, so the failure of the substation has propagated back into the electric power network. Where feedback mechanisms such as this exist, the initial failures must be repeatedly propagated through each system until they are prevented from progressing any further (e.g. because the next downstream element has already failed), which depending on the complexity of the systems and their interdependencies, may take

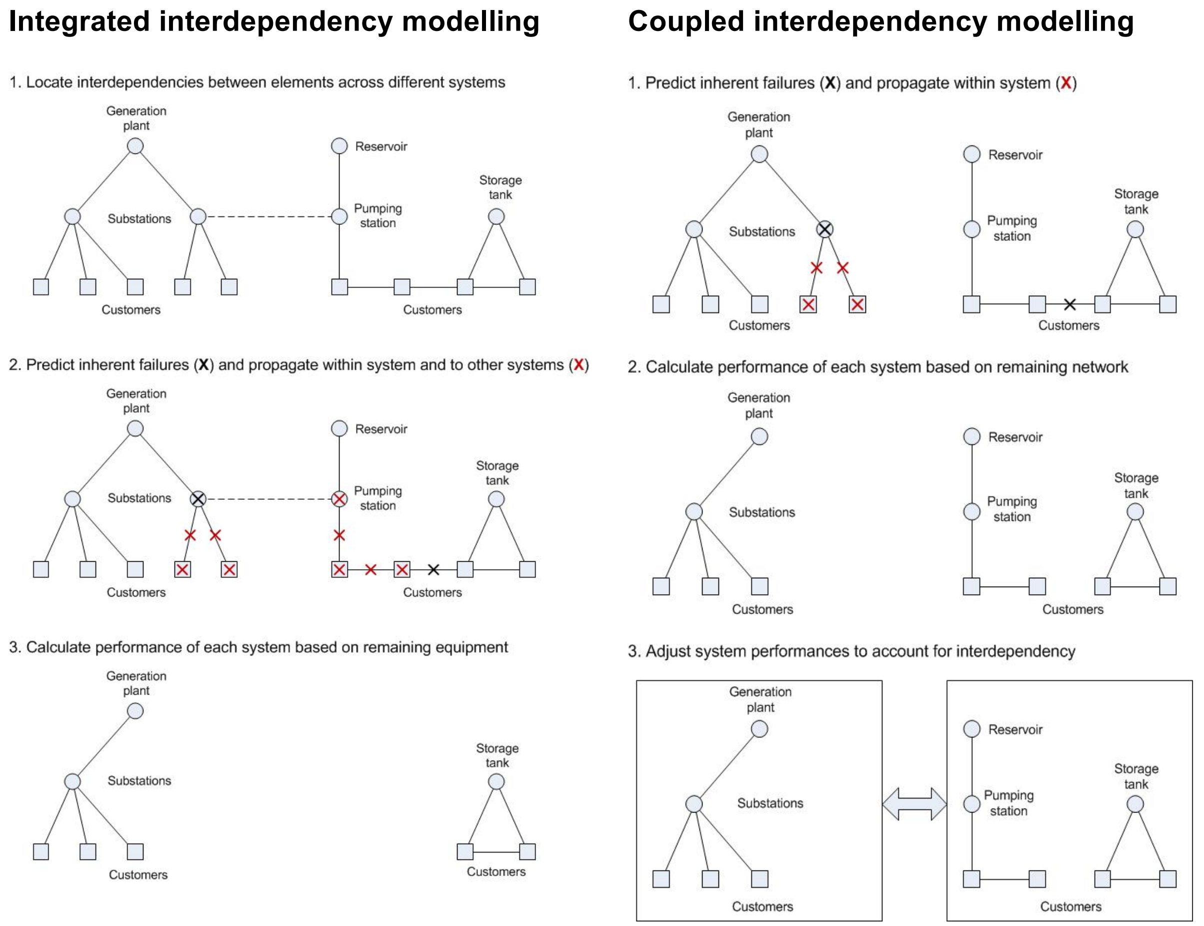

Figure 3. Methodologies for high-resolution (integrated) and low-resolution (coupled) interdependency modelling illustrated with example of electric power and potable water systems

many cycles. Once all the failed elements are identified, they are removed from the model and the integrated system is disaggregated back into the individual lifelines, and the remaining functional elements are used to evaluate the performance of each system.

Since the integrated approach models interdependencies between specific elements, it is a low-level high-resolution approach. If the functional relationships between interdependent elements are deterministic and accurately defined, then this is an exact method for modelling interdependency (though uncertainty remains in hazard and fragility). The integrated approach is the most realistic representation of the true conditions but is associated with long development times, greater problems with data availability, long simulation times and non-trivial validation (Eusgeld et al., 2011). This is because as the number of systems being analysed increases and as the systems themselves become larger, so the feedback mechanisms become more complex. Whilst for some purposes the resources to carry out such an intensive exercise may be justified, there is a need also for less resource-intensive methods for practitioners who require rapid assessment or for whom there are likely to be problems acquiring data. The insurance and catastrophe modelling sectors fall into this category.

Coupled interdependency modelling

In the coupled approach, interdependencies between specific elements are not considered. Instead interdependencies are considered at the system-level and hence it is a high-level low-resolution approach. The advantage of coupled approaches is that they are less resource-intensive than the integrated approach, but this is potentially at the cost of some precision. In coupled models inherent failures are identified and propagated only within each individual lifeline. The failed elements are removed from the model and the performance of each system is evaluated based on the remaining elements within each system. No interdependencies have been considered yet so the performance that has been evaluated is the isolated system performance. To account for interdependencies, the isolated system performances are used as inputs into a higher-level 'system-of-systems' model. In the high-level model, each lifeline is represented as a single node with an initial value (the isolated system performance) associated with it. Interdependencies between systems are represented by links between the nodes (with separate links for each direction of dependency if the relationship between a pair of systems is two-directional). Associated to each link is a quantitative measure of the strength of the dependency between the two systems and this measure can be used to 'adjust' the initial isolated performance of the dependent system to account for the state of the controlling system. Quantitative system dynamics modelling (causal loop diagrams) and Leontief input-output models are examples of a coupled approach to interdependencies.

The challenge associated with the coupled approach is the definition and derivation of strength of interdependency. Defining the strength of interdependency is somewhat subjective since this may vary depending on how system performance is defined and measured and what the objectives of the analysis are. Therefore this paper proposes two parameters to define and model interdependency: the coupling strength and the adjustment factor. Consider two lifeline systems, **A** and **B**, where **A** is dependent on **B** and where the system performances, *SP,* are measured as proportions (0 to 1) of normal operation. The coupling strength between **A** and **B**, CS_{AB}, is defined here as the ratio between the reduction in the performance of system **A** due solely to its interdependency with system **B**, ΔSP_{AB}, and the reduction in the performance of system **B** due to the earthquake, ΔSP_B. These are summarised in equations 1 to 3, where SP_A is the performance of **A** accounting for failures from both physical damage and interdependency effects; $\Delta SP_A'$ is the performance of **A**, accounting only for failures from physical damage (the isolated system performance); and SP_B is the performance of **B** accounting for all failures.

$$CS_{AB} = \frac{\Delta SP_{AB}}{\Delta SP_B} \tag{1}$$

$$\Delta SP_{AB} = 1 - \frac{SP_A}{SP_A'} \tag{2}$$

$$\Delta SP_B = 1 - SP_B \tag{3}$$

This definition of coupling strength is a measure of how much the performance of **A** reduces because of **B**, as a proportion of the reduction in performance of **B**. For example, say that after an earthquake the isolated performance of **A** is 1.0 (i.e. there are no inherent failures) but the isolated performance of **B** reduces by 0.4 to 0.6. A coupling strength of 1 between **A** and **B** would mean that the isolated performance of **A**, reduces by an additional factor of 0.4 (the coupling strength multiplied by the reduction in performance of **B**) to 0.6 due to interdependencies. A coupling strength of 0.5 would mean that the initial performance of **A**, reduces by an additional factor of 0.2 to 0.8. The purpose of measuring coupling strength as a ratio (relative to the performance reduction of **B**), is to allow for coupling strengths greater than one, which is representative of the case where the effect of interdependency is disproportionately large, i.e. the impact on **A** due to failures in **B** is greater than the impact on B itself, for example, a 0.5 reduction in performance of **B** causing complete failure of **A**.

The objective in the coupled model is to convert initial measurements of isolated system performance, SP_A', into measurements of the 'true' interdependent system performances, SP_A. Rearranging equation 2 and then substituting for equation 1 gives equation 4, for calculating interdependent system performance from isolated system performance. The term in the square brackets in equation 4 is defined here as the adjustment factor, AF_{AB}, and is the quantity associated with each interdependency link in the high-level coupled model. The adjustment factor may be a constant term or the output of some function relating the strength of dependency to variable system properties (e.g. system performance).

$$SP_A = SP_A' \times \left[1 - \left(CS_{AB} \times \Delta SP_B\right)\right] = SP_A' \times AF_{AB} \tag{4}$$

As with the integrated approach there is potential for feedback between systems and so it may be necessary to loop through a number of cycles of applying the adjustment factors before all systems arrive at a steady state. As well as complexity, the problem that feedback creates is the potential for system performance to escalate downwards if the relationship between two systems is negatively reinforcing, e.g. **A** causes a reduction in performance of **B**, which in turn causes a reduction in **A** and so on. This is particularly likely if both adjustment factors are constant terms, but may also occur with variable adjustment factors depending on the nature of the function. In such a case, after a number of cycles the performance of both systems will approach zero. Whilst in some cases two systems may genuinely be negatively reinforcing, in others this phenomenon may be a false consequence of the simplified high-level model, in which case system failures may be over-estimated. One way to overcome this is to limit the number of cycles rather than continuing to apply adjustment factors until equilibrium is reached. However this is indiscriminate and may result in genuine escalating failures not being elucidated by modelling. Alternatively the use of variable adjustment factors may reduce the likelihood of false escalating failures by accounting for interdependency with greater nuance than constant adjustment factors. The derivation of adjustment factors is therefore critically important in the coupled approach

Derivation of adjustment factors

Depending on the data available, there are different ways to derive the adjustment factors. Ideally the adjustment factor between a pair of systems would be derived from empirical data, i.e. take damage and system performance data from a past earthquake affecting the two systems and use equations 1 to 4 to derive the adjustment factor. There are barriers to this method however. It can only be used where an earthquake has occurred previously and recently so that damage and consequence data are likely to have been thoroughly recorded. Even for recent earthquakes however, the importance given to buildings over lifelines combined with difficulties in recording lifelines damage means that there may not be sufficient data available. Furthermore, even if sufficient data is available, it may only be available for one or two earthquakes, which may limit the exercise to deriving a constant adjustment factor – more data is needed to adequately fit a variable function. Adjustment factors could also be derived using data from earthquakes in other locations, either by itself or by supplementing location-specific data. However this assumes that the strength of interdependency between two types of lifeline would be similar, irrespective of location, i.e. the strength of interdependency between electric power and water systems is similar in Los Angeles or Istanbul or Tokyo. Considerably more research is required to test the validity of this assumption, yet in the absence of location-specific data this may be the most viable method for coupled interdependency modelling.

For certain pairs of systems there may be no empirical data available from any location. This is a problem for insurance companies since the need to assess risk exists regardless of whether there is empirical data available. If integrated interdependency modelling, which requires no historic data, is not feasible due to resource availability then alternatives to the empirical derivation of adjustment factors are necessary to implement the a coupled model.

To find alternative methods, it is helpful to draw a parallel between interdependency modelling and the derivation of fragility functions for seismic risk assessment. There are four techniques for deriving fragility functions: expert judgment, empirical, analytical and hybrid (Rossetto and Elnashai, 2003) and this paper proposes that the same framework can be applied to interdependency modelling. The integrated approach to interdependency modelling can be considered as equivalent to the analytical derivation of fragility functions, since it considers the specific interactions between infrastructure elements in detail. The two methods described for deriving adjustment factors for coupled interdependency modelling are equivalent to empirical derivation of fragility functions.

Continuing with the framework parallel, adjustment factors could be derived based on expert judgment, which would overcome the need for empirical data and also allow for variable adjustment factors. With fragility functions, it is usual for functions derived in this way to be based on the opinion of a number of experts (Rossetto and Elnashai, 2003). However in the case of lifelines there may not be a sufficient number of experts available, particularly given the possibility that the adjustment factor between two systems might be location-specific. In that case, potentially the only 'expert' with sufficient knowledge of the systems to make this judgment is the system operator. This increases the likelihood of bias in the judgment and furthermore, the engagement of system operators cannot always be guaranteed. If it is not possible to directly elicit the opinion of an expert, then a judgment could be based on publicly available information. For example in the Canterbury region in New Zealand, local lifelines operators collaborate for disaster preparedness purposes and amongst the published outputs from this work is a matrix outlining qualitatively the strength of interdependency between every pair of lifelines organisations in the region (CAE, 1997). Although not as robust as properly elicited expert judgment, this provides a starting point for a basic interdependency modelling exercise.

Finally, this paper proposes a new method for deriving adjustment factors equivalent to the hybrid method for deriving fragility functions. The issues associated with the analytical method are that its complexity and high-resolution analysis make it difficult to apply for certain uses. In loss estimation, it is common to run a Monte Carlo simulation requiring 10,000 or more possible earthquake scenarios in order to get a probabilistic view of risk accounting for uncertainty in the model. It is this large number of scenarios and the resources that this takes that makes the integrated approach impractical for insurance and catastrophe modelling. However for a small number of earthquake scenarios it becomes more practical to apply the integrated method. For a single simulated earthquake scenario with high-resolution integrated interdependency modelling, it is possible using predicted ground motion parameters and damage assignment to calculate both isolated and interdependent measures of performance for two infrastructure systems. Using these synthetically generated measures as inputs into equations 1 to 4, a value of the adjustment factor between the systems can also be calculated in the same way as the empirical methods. If this is repeated for a small number of further simulated earthquakes, then this data can be used to develop a variable function for calculating the adjustment factor. The function can then be used with the coupled interdependency method for the full Monte Carlo simulation with 10,000+ earthquakes. With this method, simulated earthquakes are used as a substitute for empirical data where it does not exist or to complement empirical data where it is limited. It is a hybrid approach because it ultimately uses coupled (empirical) methods to model interdependency in the loss estimation, but uses integrated (analytical) methods to help derive the adjustment factors needed to apply the coupled model.

Conclusions

The objective of this paper was to create a methodological hierarchy for interdependency modelling to allow end users to determine a method that is appropriate to their needs and resource availability. This is complementary to other stages of the seismic risk assessment process where decisions have to be made on the level of detail and complexity that is suitable. These options are summarised in Table 1 using a three-level hierarchy, but the number of levels in the hierarchy is subjective and this paper has proposed five methods for interdependency modelling of decreasing complexity, as summarised in Table 2.

Table 2. Hierarchy of interdependency modelling methods by complexity

Complexity	Interdependency model	Model derivation
V. High	Integrated	n/a
High	Coupled	Simulated event data
Medium	Coupled	Empirical data (local)
Low	Coupled	Empirical data (non-local)
V. Low	Coupled	Expert judgment

The next planned stage of this research is to test the proposed hierarchy with a real case study in Christchurch, New Zealand. For insurance purposes it is the simplified coupled models that have the greatest potential to be incorporated into catastrophe models and the aim of the case study will be to compare seismic risk assessment outputs from the four coupled models to outputs from a reference seismic risk assessment performed using an integrated model. This will help to determine the value of each of the four coupled methods in terms of balancing input data availability with output precision.

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