A framework to assess the impact of seismic shocks on complex urban critical infrastructure networks

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SUMMARY:
The financial sector requires an understanding of the seismic performance of critical infrastructure and their interdependencies as they are central to the evaluation of financial risk due to earthquakes. Supported by the Willis Research Network, the EPICentre team at University College London is embarking on a project to develop an infrastructure vulnerability model that meets these needs. This paper provides a review of the literature and current thinking in the field and establishes gaps in knowledge and opportunities for further research. Based on the review outcomes it conceives a methodological framework for the assessment of infrastructure vulnerability accounting for interdependencies and discusses the forthcoming stages of the project, which will identify sources of input data and modelling techniques appropriate for the final methodology.

Keywords: lifelines, networks, interdependencies, loss estimation

1. INTRODUCTION

In earthquakes, although most of the human losses derive from damage to urban housing, the economic impact can instead arise from damage to critical infrastructure such as transport, energy and other utilities and the knock-on effects of disruption to their functionality. Furthermore, significant interdependencies can exist between infrastructure systems in an urban area, meaning that damage to one system may result in disruption to other critical infrastructure. The financial industry requires improved understanding of infrastructure behaviour under seismic shocks in order to establish the appropriate financial tools for their management. The evaluation of financial risk due to earthquakes therefore requires methodologies that account for the physical fragility of single elements of infrastructure (e.g. a single pipeline), the performance of an infrastructure system, (e.g. the water supply network) and also the interdependencies between systems (e.g. the effect of electricity disruption on water supply). At University College London (UCL), the Earthquake & People Interaction Centre (EPICentre) are embarking on a new project to develop such a tool in collaboration with the Willis Research Network (WRN). The project began in September 2011 and this paper reports on the progress made in developing the methodological framework for the tool.

Critical infrastructure networks are commonly referred to within the earthquake engineering and civil protection fields as *lifelines*, reflecting their role as lifelines to recovery. Lifelines can be defined as “systems or networks, which provide for the circulation of people, goods, services and information upon which health, safety, comfort and economic activity depend” (Platt, 1991). However, it is a matter for debate as to which infrastructure are classified as lifelines. In the absence of an agreed supranational list, different authorities and engineers have been left to assemble their own. A selection of these is shown in Table 1. This selection suggests that there is a core group of infrastructure that are widely recognised as being lifelines: electricity, telecommunications, transportation, water supply, wastewater treatment, oil delivery and natural gas delivery. The common factor amongst these infrastructure is that although there is some human interfacing to support their operation, they are largely physical systems. The exception is public transport, although even in this case human input is defined by operational rules – e.g. traffic laws, pre-defined routes – so there is limited scope for independent decision-making or emotion to affect their performance. For the majority of 'non-core' infrastructure, the situation changes. Most of these are primarily human systems which rely more heavily on emotion and decision-making in their operation. Such systems can be described as *socio-technical* systems. Table 1 indicates that these systems have been poorly studied but this does not mean that they are any less critical after hazardous events. More likely is that due to their deeper human context they are more complex to model and so have been consciously neglected. Even for the financial industry though, socio-technical systems can be very important. Disruption to healthcare systems for example could have subsequent economic impacts due to higher casualty rates and longer convalescence times reducing available human resources for civil reconstruction.

Table 1 – Alternative definitions of lifelines presented in current literature

	HAZUS (NIBS, 2003)	ATC-25 (ATC, 1991)	RISK-UE (Pitilakis et al., 2006)	Reed et al. (2009)	SYNER-G (Franchin et al., 2011)	Menoni et al. (2002)	O'Rourke (1996)	Kameda (2000)	Rinaldi et al. (2001)	Chang et al. (2006)	Brown et al. (2006)	Porter and Sherrill (2011)	Opricovic and Tzeng (2002)
Electricity	X	X	X	X	X	X	X	X	X	X	X	X	X
Telecommunications	X	X	X	X		X	X	X	X	X	X	X	X
Transportation	X	X	X	X	X	X	X	X	X	X	X	X	X
Water supply	X	X	X	X	X	X	X	X	X	X	X	X	X
Wastewater treatment	X		X	X	X	X	X	X			X	X	
Oil delivery	X	X		X	X		X	X	X	X	X	X	X
Natural gas delivery	X	X	X	X	X	X	X	X	X			X	X
Building services				X						X	X		
Business				X					X	X	X		
Emergency services		X		X	X				X	X	X		
Financial systems				X					X	X	X		
Food supply				X					X	X	X		
Government				X					X	X	X		
Health care		X			X	X			X	X	X	X	
Solid waste								X			X		
Education									X				
Space									X				
Commodities									X				
Nuclear power											X		
Dams												X	

Yet further complexity is added by consideration of interdependencies between two or more networks. A distinction is drawn between *dependent* and *interdependent* networks (Rinaldi et al., 2001). Dependency describes the unidirectional relationship whereby one infrastructure network is dependent on another for its performance. An example might be the requirement of electricity in order for railways to function. Interdependency describes bi-directionality in infrastructure relationships, e.g. water supply requiring electricity for power but at the same time, electricity generation might require water for cooling. In reality, the relationships between infrastructure systems are of a much higher order than a simple two-way relationship. There is a complex web of these bidirectional relationships across all infrastructure networks with the consequence that a shock to one network can have a significant impact on another network that previously appeared unrelated, which in turn has an impact on a third network and so on, resulting in cascading infrastructure failures. Alongside the complexity of human interfaces with networks, the modelling of interdependent behaviour represents one of the most intriguing challenges for understanding lifeline network performance.

2. LITERATURE REVIEW

The literature review on lifeline response to seismic shocks has been broadly be divided into four categories: estimation of the damage to infrastructure components; estimation of infrastructure system performance; estimation of the economic losses associated with the response; and decision support methodologies for prioritising infrastructure investment. Loss estimation, both direct and indirect (e.g. business interruption), is the primary focus of the financial industry in relation to lifeline response, whilst investment in infrastructure is important to improve its resilience and in doing so attempt to minimise potential economic losses and reduce premiums. Estimation of damage to infrastructure components and system performance are needed to inform the loss estimation exercise. Component damage will primarily relate to direct losses while system performance will relate more to indirect losses. The literature review is an evolving process but the following sections report on the progress thus far.

2.1. Infrastructure Fragility

Since the model is being tailored for the financial industry, it is anticipated that the focus will be on hard infrastructure although opportunities to incorporate some of the socio-technical systems will be explored. Currently the review of literature on fragility has focused on electric power, water, wastewater and gas.

The most thorough source of information on infrastructure fragility is HAZUS MR4 software (NIBS, 2003). Although it has been developed specifically for the United States, it is used as a reference globally and as a basis for similar projects in Europe, e.g. RISK-UE (Pitilakis et al., 2006) and SYNER-G (Franchin et al., 2011). HAZUS includes empirical fragility curves for components of seven infrastructure systems: electricity, telecommunications, transport, water supply, wastewater, oil delivery and natural gas delivery. Beyond HAZUS there are some studies that have looked at individual infrastructure systems such as electricity (Vanzi, 1996) and water supply (O'Rourke and Ayala, 1993) for example.

As part of the EU funded SYNER-G project (Franchin et al., 2011), a comprehensive exercise has been undertaken to review existing fragility curves for their applicability to Europe. The infrastructures considered by SYNER-G are listed in Table 1. A list of fragility curves for the electric power, water, wastewater and gas networks are inlcuded in the SYNER-G documentation (Alexoudi et al., 2010; Gehl et al., 2010; Pinto et al., 2010) and are not replicated here. To summarise the project, the majority of system components are dealt with using discrete damage states, as is the convention with structural elements. The exception is pipelines, for which damage is measured by repair rate per unit length. The use of discrete damage states will have implications for the model when it comes to measuring system performance, particularly for flow analysis. Many of the studies in SYNER-G focus on individual components within a system rather than all system components, meaning that for a given system, fragility curves may need to be taken from multiple sources for different components and should be checked for relevance to the assessed location and compatibility. The latter is not a simple consideration, as the sources of the curves vary: the proposed fragility curves having been generated empirically, analytically, by Bayesian methods or by fault-tree analysis. Furthermore, limited documenting of lifeline damage in past earthquakes means that the empirical curves are based on a very small number of events.

Two further observations can be drawn from the SYNER-G work. Firstly that for a number of infrastructure components HAZUS or other non-European derived relationships are identified as the most appropriate for use, often without justification being presented (Alexoudi et al., 2010; Gehl et al., 2010; Pinto et al., 2010). The second observation is that studies on infrastructure vary in terms of the resolution at which they divide the system into components. In modelling electricity networks for example, HAZUS focuses on large visible components (presumably those that generate the highest repair costs given its focus on direct economic costs), while others go to the level of detail of sub-station 'micro-components' (Vanzi, 1996). Higher resolution is likely to improve accuracy but may also increase the complexity to a level that is not appropriate for the needs of the financial industry and reduce transferability to other locations.

2.2 Network Reliability

Methodologies for predicting network reliability fall into two categories: simulation-based models and analytical (or exact) methods (Kim et al., 2010). Simulation-based models involve the use of random sampling techniques and Monte Carlo simulation to approximate system functionality following an earthquake. When such methods are used, a metric for functionality is needed. Metrics used in the literature include availability and serviceability (Javanbarg and Takada, 2009) and fragility, quality, robustness and resilience (Reed et al., 2009). In these examples, availability is defined as the ratio of available pressure to required pressure in a water system; serviceability is the ratio of available flow to required flow in a water system; fragility is the percentage of outages relative to number of customers per area for an electricity network; robustness is ratio of post-event capacity to normal capacity for an electricity network; quality is a function of robustness, time and recovery rapidity; and resilience is the integral of quality over time.

Analytical methods do not require repeated sampling and therefore in theory allow for more rapid computations. These methods assume that infrastructure components behave in a binary fashion, i.e. a component is either completely failed or fully operational. Whereas simulation methods can account for partially functioning components, analytical methods cannot. Consequently analytical methods cannot measure functionality, only connectivity, and cannot inform socio-economic impacts to the same degree as simulation-based methods (Song and Ok, 2010). Notably simulation methods can derive both functionality and connectivity. Recently studies on lifeline response to earthquakes have focused on analytical methods and hence connectivity. Methods include heuristic minimal path sets (Javanbarg et al., 2009a), ordered binary decision diagrams (Javanbarg et al., 2010) and matrix-based system reliability (Chang and Song, 2007; Kang et al., 2008; Kim et al., 2010; Song and Ok, 2010; Kang et al., 2012).However, analytical methods can have problems dealing with large-scale networks since the computational effort increases exponentially as networks increase in size, although Chang and Song (2007) claim that this can be overcome by taking a multi-scale approach or by sub-dividing the system into multiple disjoint link sets or cut sets.

A general issue with network reliability assessments is spatial correlation of seismic intensities. To estimate intensity and damage, two components which are close together cannot be treated independently. There will be some correlation and statistical dependence between them which should be accounted for. However, research into this area has only recently developed and few studies exist. Spatial correlation has been investigated through the determination of correlation distance from wave propagation characteristics and local site conditions (Adachi and Ellingwood, 2009) or by empirically deriving a correlation model from past earthquakes (Jayaram and Baker, 2009). Jayaram and Baker (2010) found that not considering spatial correlation can lead to the impacts of earthquakes being underestimated, so it is important for it to be addressed in seismic risk assessments.

In addition to correlation of intensities, a further consideration is correlation between the infrastructure components themselves. This can manifest itself in different ways, such as components sharing characteristics (common causes of failure), geographical co-location or propagation of malfunction (cascading failure). An example of common causes of failure could be the failure of a particular group of components, which were manufactured within the same batch and therefore shared a common fault. Correlation due to geographical co-location is important due to the possibility that physical damage to one component could cause damage to another in its proximity, e.g. damage to a highway overpass causing blockage of a road passing underneath. Finally, there is the potential for a fault in one component to propagate to an adjacent component and begin a cascading failure, e.g. the propagation of a short circuit within the electric power network. Page and Perry (1989) and Javanbarg et al. (2009b) have both developed models to account for common causes of failure by decomposing the system analysis into multiple simpler problems using Bayes' Theorem. There are also a number of models which seek to account for cascading failure either generally, (Motter and Lai, 2002; Watts, 2002; Crucitti et al., 2004; Wang and Kim, 2007) or for specific lifelines (Carreras et al., 2002; Pinto et al., 2011; Kinney et al., 2005).

2.3. Economic impacts

The key methodology for lifeline loss estimation is HAZUS MR4 (NIBS, 2003). HAZUS uses fragility curves for discrete infrastructure components combined with information on the replacement value and the damage ratio (ratio of repair cost to replacement value). However HAZUS has limitations for global application as it is derived from US data, and therefore it is questionable whether it should be applied elsewhere. Also, HAZUS only considers direct losses associated with the repair or replacement of the infrastructure component. Indirect losses due to level of service are not considered. Furthermore, developed in 2003, the software only accounts for 'traditional' infrastructure and does not yet consider emerging technologies such as solar power or wind farms.

RISK-UE (Pitilakis et al., 2006) was an early attempt to establish a European equivalent to HAZUS, but more recently it has been superseded by SYNER-G (Franchin et al., 2011), the outcomes of which are yet to be published. It is not currently clear what specific outputs the SYNER-G model will generate in terms of economic impacts although the Work Plan suggests a strong focus on socio-economic rather than financial impacts. Alternative loss estimation models have been developed empirically, and in particular there exist a number simple models which take into account indirect losses (Chang, 2003; Rose and Lim, 2002; Tatano and Tsuchiya, 2008), not currently within the capabilities of HAZUS. The importance of determining indirect losses is underlined by Chang (2003), whose loss estimation methodology was tested on the water supply system in Portland, US. They found that indirect losses outweighed direct losses by 100 times. Furthermore, Tatano and Tsuchiya (2008) tested their methodology, including spatial distribution of losses, on the 2004 Niigata earthquake and found that the highest losses did not occur in the local Niigata region but in the more heavily industrialised Kanto region.

2.4. Decision Support Methodologies

Decision support methodologies can be used to assist authorities with the task of prioritising infrastructure investment for disaster mitigation or prioritising emergency response and recovery activities. Inputs into a decision support model might include network reliability. Optimisation for prioritisation can be made on the basis of economics (Chang, 2003), downtime (Cagnan et al., 2006; Xu et al., 2007) or multi-criteria analysis (Opricovic and Tzeng, 2002; Javanbarg et al., 2008). There may also be scope to optimise for social impacts.

2.5. Interdependencies

Most of the studies in the review focus on single infrastructure networks and only a few of these look at interdependency. The latter propose methodologies that are still at an early stage of development (Kakderi et al., 2011). One of the most in-depth studies on interdependency is Rinaldi et al. (2001), which provides a framework to act as a starting point for considering network relationships. Four types of interdependency are classified: physical, cyber, geographic and logical. 'Physical' refers to an actual physical link between two networks; 'cyber' refers to networks connected by informational links; 'geographic' refers to links by proximity (there is no operational link between the two networks but proximity means that damage to one might have repercussions on the other); and 'logical' refers to all other relationships, (e.g. a shock to the financial system could have long-term impacts on the highways network due to reduced investment). Logical relationships may be particularly important when considering socio-technical systems due to the human element. There are only a limited number of studies in the review which consider interdependency analytically rather than just qualitatively (Duenas-Osorio et al., 2004; 2007; Reed et al., 2009; Kim et al., 2010; Poljansek et al., 2011).

Within the SYNER-G project, five methods for modelling interdependencies have been identified: physics-based models, nodal analysis models, agent-based models, stocks-and-flows (input-output) models and network models (Kakderi et al., 2011). Physics-based models are highly simplified and define interdependencies as interaction coefficients using fault-tree analysis. Nodal analysis models use fault-tree analysis or reliability block analysis, but do not consider partial functionality of components. Agent-based models represent infrastructures as complex adaptive systems which can communicate with each other and they allow decision-making to be accounted for. Agent-based models are the most complex to develop and run. Stocks-and-flows models approximate physical interdependencies as economic input-output transactions of sectors (infrastructures). Network models treat interdependent infrastructure as a network of networks modelled as a single network, usually using graph theory to determine connectivity between networks

The Idaho National Laboratory (INL), part of the United States Department of Energy, has published a report to establish the state-of-the-art in interdependency modelling (Pederson et al., 2006). The report found that there were around 30 models, either existing or in development, to evaluate infrastructure interdependency. These models are not specific to earthquakes, but generalised to assess the impacts on interdependent infrastructure due to some small perturbation. These are seen to adopt a range of methods including input-output models and network analysis but the majority of models are agent-based simulations. A summary is provided for each of these in Pederson et al. (2006) and the report is useful in identifying existing products. However, the summaries offer only a basic overview of each model and are focused more towards software development issues rather than modelling processes. Also, whilst the models are described, no comment is offered on their efficacy. Few of the models are referenced in peer-reviewed academic journals and where references have been provided, these have tended to be independently published reports, many of which do not appear to be publicly available. This has made it difficult to acquire a better understanding of the processes underpinning these models.

2.6. Discussion

Many gaps are apparent in the approaches adopted so far for lifeline response to earthquakes. Issues relating to indirect losses, spatial correlation of seismic intensities, interdependencies, socio-technical systems and partial functioning of network components have already been discussed. Additionally the literature exhibits a strong bias towards the United States as a location for testing and applying new techniques. In this regard the development of the SYNER-G project with its European focus is promising. Amongst hard infrastructure systems there is also a focus on electricity and water supply networks and only limited research into other networks such gas and telecommunications for example. Finally the majority of techniques tested are purely physical models, with little or no input from lifeline managers and authorities. Only one study was found that explicitly sought the opinion of those working in the infrastructure sectors (Porter and Sherrill, 2011). Even where agent-based simulation has been used for interdependencies, it is not clear that the rules governing certain decision making processes have been derived first-hand from expert sources.

3. CONCEPTUAL METHODOLOGY

The primary goal of this project is to estimate financial impacts due to the effects of earthquakes on infrastructure. To do this, the performance of the infrastructure must be understood. There are three perspectives from which infrastructure reliability can be measured (Chang and Song, 2007). One can assess the reliability of a structural component, (i.e. its damage state); or the reliability of a connection between node pairs in the network, (i.e. connectivity); or overall system reliability, (i.e. functionality, for example maintaining minimum water pressure). The first of these perspectives looks at individual network elements discretely and thus tells us little about overall system reliability. The latter two perspectives appear to be more useful for infrastructure systems since they tell us whether a service can be provided between two points or what the overall level of service is.

In practice all three perspectives must be considered. Economic losses after an earthquake can be caused by structural damage to physical infrastructure that requires repair, or from business interruption due to service disruption. For the former, damage states must be known, and for the latter connectivity or functionality are the key parameters. Moreover, the damage states of individual components may be needed to inform the other perspectives. Both connectivity and functionality are important since whilst connectivity states whether a node is receiving a service, the level of service is unknown. Conversely functionality measures overall level of service, but may not necessarily be instructive as to how this is distributed across an affected region.

To fulfil these objectives, the final methodology will need to incorporate state-of-the-art tools for each measure. A framework for the methodology has been produced, which is divided into seven stages each with inputs, processes and outputs as summarised in Figure 1.

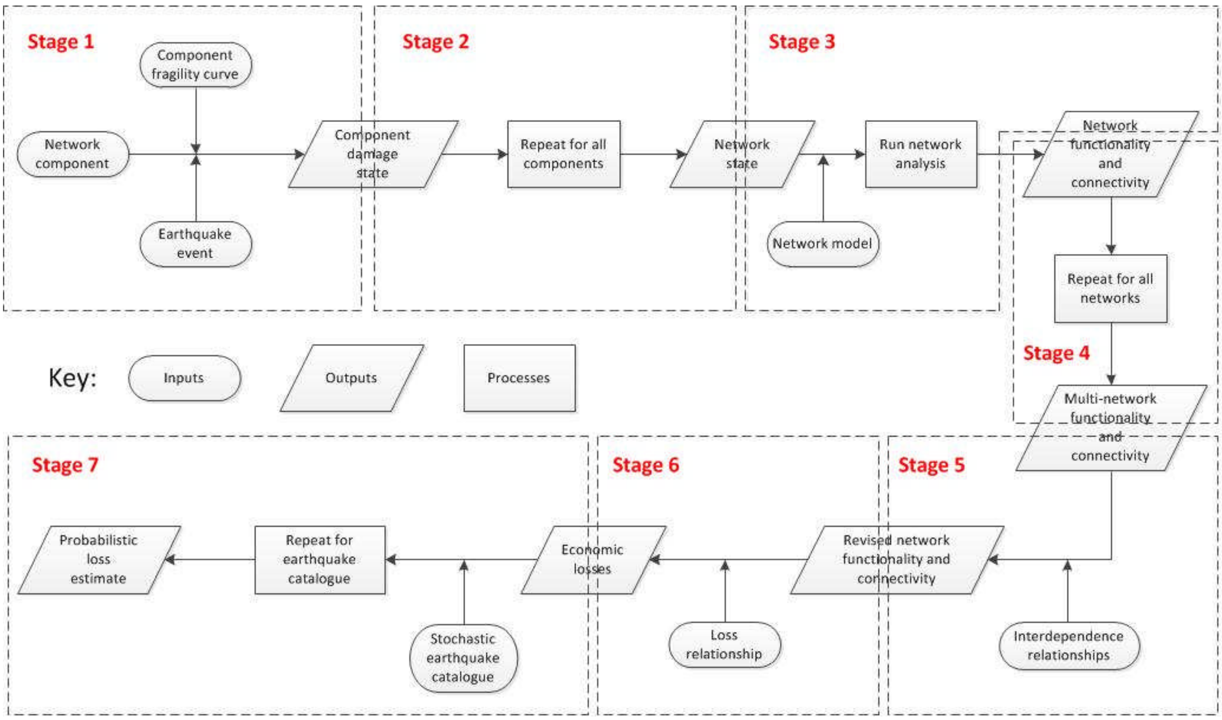

Figure 1 – Process model of methodological framework

There are eleven inputs for the methodology, though not all of these are shown in Figure 1 for clarity. Two of these are outputs from earlier stages but the remaining nine are external and will have to be adopted from other sources or derived anew. These are:

1. Stochastically generated earthquake scenarios
2. Characteristics for each earthquake scenario
3. List of networks under consideration
4. Inventory of each network (components within network)
5. Characteristics of each network component
6. Fragility relationships for each network component
7. Network analysis models
8. Interdependence relationships
9. Economic loss model

4. NEXT STAGES

It is currently intended that the methodology will be tested on two case study locations, Monaco and Istanbul, although it is intended that the methodology will ultimately be applicable globally with the ability to make local adaptations as required. The immediate tasks facing the project are to acquire the relevant background data on hazard and lifeline systems in those locations and to identify fragility curves, network models, interdependence relationships and economic loss models. The main considerations are the choice of resolution for fragility estimation and whether a suite of fragility curves and loss estimation techniques should be provided or just a single option.

Of the interdependency models outlined by SYNER-G (Kakderi et al., 2011), physics-based models are described as 'highly simplified', whilst nodal analysis models only consider components operating at 0% or 100%. One of the key drivers of this project is better understanding of interdependency relationships and so computational effort should be not be sacrificed in this area. Better interdependency models increase complexity but this could be countered by acceptance of more simplified approaches to fragility curves and network flow/connectivity analysis. Many interdependence studies have focused on network models (Kakderi et al., 2011) but agent-based models, despite their significant complexity, are of particular interest because of their ability to account for decision making, which is a crucial in emergency management. It has been noted that human aspects of infrastructure have been neglected in previous studies. Agent-based models present a compelling opportunity to address this and so it is the current intention to progress with this approach to interdependency.

5. CONCLUSIONS

The review of the literature has found that there is still much to be understood in terms of the infrastructure response to earthquakes. Much of the research to date has focused on single systems, assuming binary modes of operation and looking only at direct economic losses. Complex systems requiring the modelling of human behaviour have been neglected and factors such as the spatial correlation of seismic intensities are poorly studied. There have been attempts to overcome this and in particular there are a number of models in production that claim to represent interdependencies, driven primarily by national security concerns in the United States. This has in turn led towards a strong bias towards North America in the research and models that may not be extendable to other regions.

The literature review has been used to develop a methodological framework for the EPICENTRE / WRN project, but the inputs and processes that will realise the framework still need to be determined. There are also a number of important decisions to be made to set the boundaries of the project in terms of infrastructure systems, geographical applicability and outputs. Whilst the primary focus of the project will be on economic impacts there may be scope for outputs to be translated into more social impacts or information to support disaster risk reduction or reconstruction activities. Nevertheless it is hoped that in solving these dilemmas, many of the issues identified from the literature review can be addressed, and a further step will have been taken in providing the financial industry with the requisite tools for infrastructure management.

ACKNOWLEDGEMENTS
This project is being funded jointly by the Engineering and Physical Sciences Research Council in the UK and the Willis Research Network through the Urban Sustainability & Resilience programme at University College London.

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