A framework for modelling the impact of spatial hazards on critical infrastructure networks

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Summary

Spatial hazards such as floods, windstorms and ash clouds can cause widespread disruption to critical spatial infrastructure networks, such as those which deliver electricity and provide transport. Understanding the spatial vulnerability and robustness of these is important to design appropriate adaption and mitigation strategies. Here we present an open source toolbox that has been developed for the modelling and simulation of spatial infrastructure network robustness which can be used to investigate their response to perturbations from spatial hazards. This is demonstrated via an analysis of the electricity network for England and Wales to different spatial configurations of spatial hazard footprints.

KEYWORDS: critical spatial infrastructure networks, spatial hazards, robustness modelling

1. Introduction

Critical infrastructure networks underpin the economic well-being of nations and the quality of life of those who utilise the services they provide. Natural hazards can cause significant disruption to services provided by these essential infrastructures; for example, an ice storm in Canada in 1998 is estimated to have caused \$3billion worth of damage leaving people without power for a week (Kerry *et al.*, 1999), while the ash cloud caused by the eruption of the Eyjafjallojokull volcano (Iceland) in 2010 led to widespread disruption to flights across Europe, with an estimated impact on the airline industry of \$1.7billion (Mazzocchi *et al.*, 2010). With the number and magnitude of many natural hazards expected to increase with climate change (Met Office, 2011), it is essential that we develop an improved understanding of the spatial vulnerability and robustness of our critical infrastructure networks to spatially distributed hazards. This paper introduces a database modelling framework and associated analytical functionality for the simulation of failures on critical infrastructure networks when perturbed by spatial hazards. A case study investigating the robustness of the electricity transmission and distribution network for England and Wales to different spatial configurations and size of spatial hazards is used to demonstrate this new spatial simulation capability.

2. Software modelling framework

An open source modelling and simulation framework has been developed within a PostgreSQL database environment employing the PostGIS spatial extension (Figure 1). Both spatial infrastructure network models and the associated spatial hazards are encoded and managed using a database schema developed within PostgreSQL/PostGIS, while associated modelling/simulation modules have been developed via a python-binding that employs NetworkX; a 'Python language package for the creation, manipulation, and study of the structure, dynamics, and functions of complex networks' (NetworkX, 2014) (Figure 1).



Figure 1: Components of the modelling and simulation framework for spatial infrastructure network robustness assessment.

Spatial infrastructure networks are represented using a recently developed extension of the Infrastructure Transitions Research Consortium (ITRC) interdependent network database schema (Barr *et al.*, 2013). The extension now allows not only multiple networks and the interdependences between them but also allows the dynamic modelling and simulation of flows, resource buffering, dynamic cues, response latency and flow resistance to be explicitly represented and modelled via response and transfer functions (Figure 2).

A suite of network failure models have also been developed for the analysis of the vulnerability of spatial infrastructure networks, ranging from relatively simple random or targeted attack iterative failure models, through to complex capacity constrained cascading failure models (Figure 3). In all cases a unique aspect of the modeling functionality is that an 'analysis' schema, developed within this work, is used to record fully the model parametrisation, model progression and final results (Figure 4); thus, providing useful diagnostic information on the dynamic progression of any model and failure analysis, as well as a persistent record for provenance tracking of the modelling.



Figure 2: The extended ITRC interdependent spatial infrastructure network database schema.

3. Modelling the spatial vulnerability of the national electricity network

To demonstrate the functionality of the developed framework the impacts of different spatial configuration and size of spatial hazards upon an infrastructure network representation of the electricity transmission and distribution network for England and Wales was undertaken. The network model was constructed as part of the ITRC project (ITRC, 2013), using National Grid transmission network data (National Grid, 2014) and a heuristic distribution network generated from Ordnance Survey Points of Interest Data. The network consists of 170,669 nodes and 173,039 edges representing electricity generation sites through to 11Kv substations and their associated transmission and distribution cables.

The modeling and subsequent analysis compares the impact of different sized and spatially arranged hazards on the number of second-order spatial failures that propagate outside the direct initial footprint of a hazard. In this particular modelling exercise, assets are assumed to have no fragility function and hence if they fall within a footprint they are deemed to completely fail (first-order failures). All assets which then become disconnected from the higher level transmission network, and thus are not supplied with electricity, are then regarded as second-order failures.



Figure 3: Stages of a capacity constrained cascading failure model.



Figure 4: The 'analysis' schema used to represent parametrisation, run-time dynamics and results.

Figures 5, 6 and 7 show the results of three of the scenarios investigated (A, B and C) in the modelling and analysis. In each the number and size of the spatial hazards were varied but the number of electricity nodes perturbed remained approximately 2% of total node assets. The hazard areas were randomly located and in each case 5 different runs were undertaken. Figures 5, 6 and 7 show visually that the number of second-order failures increase as the number of spatial hazard areas increase, despite the number of first-order failures remaining similar (Table 1); for scenario A an average of 3306.0 first-order failures resulted in an average of 361.2 second-order failures, where as for scenario B and C the ratio between first and second-order failures was 3169.2:5457.8 and 3229.6:6366.8 respectively. There is also an observed increase in the distance of failure propagation from the original hazard footprints, with the mean distance increasing by more than 100% from scenario A, 4.33Km, to 12.64 and 9.96Km for scenarios B and C (Table 1). Similarly, the maximum distance of substation failures increases by over 300% where multiple hazards have been simulated in scenarios B and C compared to the single hazard simulations in scenario A.

Scenario (number of hazard areas)	Mean number of node asset failures		Distance for second-order node asset failures (Km)		Mean number of edge asset failures	
	first-order	second-order	mean	maximum	first-order	second-order
Scenario A (1)	3306.0	361.2	4.33	20.45	3446.4	272.2
Scenario B (4)	3169.2	5457.8	12.64	85.74	3546.6	3553.4
Scenario C (8)	3229.6	6366.8	9.96	87.79	3729.8	3893.8

Table 1: Node and edge asset failure statistics for the three failure scenarios.

4. Conclusion

A framework coupling a spatial database schema and spatial failure modelling tools has been presented and demonstrated through the application to a statistically generated electricity transmission and distribution network for England and Wales. The results show that while the number of directly affected components remains approximately 2% of those in the network, there is an increase in the number of second-order failures as the number of hazard areas increase as well as a greater propagation of failure from the initial hazard areas, suggesting a vulnerability to simultaneous multiple hazards. The developed framework in the future will be applied to a wider assortment of both critical infrastructure networks and spatial hazard scenarios, with simulated hazard areas replaced with observed hazard data and modelling outputs e.g. from hydrological flood models.

5. Biographies

Craig Robson received a B.Sc. (Hons) degree in Geographic Information Science from Newcastle University in 2011. He has recently submitted his Ph.D. in spatial infrastructure network modelling at Newcastle University and now works as a research assistant on the ITRC project MISTRAL (Multiscale Infrastructure Systems Analytics).

Stuart Barr is a senior lecturer in Geographic Information Science at Newcastle University.

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transmission/distribution lines



Figure 5: Spatial hazard areas and second-order failure patterns for the five simulations in scenario A. Contains OS data © Crown copyright and database right 2017.

(i)

(iii)

- second-order failed substations
 - hazard area
 - hazard location
- functioning substations
 - transmission/distribution lines



Figure 6: Spatial hazard locations and second-order failure patterns for scenario B simulations. Contains OS data © Crown copyright and database right 2017.

(i)



hazard area



Figure 7: Spatial hazard locations and second-order failure patterns for scenario C simulations. Contains OS data © Crown copyright and database right 2017.

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