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ResMapper: Matlab tool for seismic resilience mapping of large-scale road networks

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ABSTRACT

A resilience analysis of large-scale road networks is challenging owing to the complexity of analysis and the need for large-scale data. Nonetheless, a development of a general-purpose software to this end is desired to enhance the accessibility to such an advanced analysis and to facilitate interdisciplinary research collaborations. To this end, a Matlab-based toolkit, ResMapper is developed to perform a seismic resilience analysis of road networks. ResMapper innovates on the previous works in two perspectives. First, it performs a probabilistic resilience analysis, being specialised for large-scale networks. Second, it considers various causes of road closures: structural damage of roadways and debris impacts by overpasses and adjacent buildings. The applicability of ResMapper is demonstrated by a benchmark example of the road network of Istanbul, Turkey. In addition, the detailed analyses available in the supplementary document demonstrate the utility of ResMapper for understanding the resilience of a road network and help understand the varying influences of analysis parameters.

Code metadata

Current code version	v1.0.0
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX-D-22-00203
Legal Code License	The MIT License
Code versioning system used	Git
Software code languages, tools, and services used	MATLAB R2021b or newer
Compilation requirements, operating environments & dependencies	MATLAB product
Support email for questions	ji-eun.byun@glasgow.ac.uk

1. Motivation and significance

Transportation networks play a critical role when extreme events such as earthquakes occur. They are critical for enabling emergency actions and expediting recovery to normality. Accordingly, it is crucial to accurately assess the resilience of those networks against hazard risks [1]. Such analysis enables risk-informed decisions that can effectively mitigate disruptions and losses.

However, analysing a road network remains challenging, especially when the scale of a given system is large, i.e. a system consists of a large number of roadways. Such scale issue is often inevitable in order to analyse a network as a unified system rather than a simple aggregation of components (i.e. roadways). Moreover, while it would be preferable to accurately represent network operations than a component-level analysis, a system-level analysis is computationally intensive [2]. Another challenge is that a resilience analysis by definition requires a probabilistic approach since it needs to take into account uncertainties from various sources. Consequently, a disaster resilience analysis of a

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large-scale road network requires complicated analysis models and high computational cost.

Such difficulties make it challenging to develop a general-purpose computational tool to assess large-scale road networks. To address these issues, several software programs have been developed to enable community-level resilience analysis [3]. For example, Ergo-EQ is an open-source platform that features seismic risk assessment [4]. As an extension of the platform, the IN-CORE (Interdependent Networked Community Resilience Modeling Environment) has been developed to take into account interdependence between components in a network system [5]. However, it considers only the interdependence arising from hazard scenarios and not that arising from their joint functionalities (i.e. they do not feature a network analysis). Another example is Retis-Risk, which was developed for seismic risk analysis of road networks [6]. Although it featured a detailed network analysis, i.e. traffic assignment optimisation, the software is no longer available after the completion of the funded project. It is also noted that while there are multiple programs developed for a risk analysis, there are very few programs capable of resilience analysis (i.e. a dynamic analysis of risk analysis to consider recovery process).

In this paper, a computational toolkit is developed to perform the seismic resilience analysis of large-scale road networks, namely *ResMapper*. ResMapper is a Matlab-based toolkit that performs a probabilistic evaluation of network resilience. ResMapper is developed specifically to handle large-scale networks and evaluates a resilience metric of each district. In addition, to improve analysis accuracy, ResMapper takes into account various causes of traffic disruptions: In addition to structural damage, the toolkit evaluates the impact of damaged overpasses and debris generated from adjacent buildings.

ResMapper aims for a sustainable open-source software. Thereby, it can allow for steady collaborations among researchers to develop a resilience analysis model and to compile data. In addition, as an open-source program, it enhances the accessibility to an advanced resilience analysis for both the academic and non-academic. It can also enable local stakeholders to independently assess their road networks.

2. Software description

2.1. Architecture

The architecture of ResMapper is illustrated in Fig. 1. In the figure, grey arrows represent the flow of data and analysis. First, ResMapper requires four types of input data: ground motion (GM) zones, districts, roads and nodes. In addition to the specification of individual datasets, the input data also need to include the joining data across data types, which is represented by dotted lines in the figure. We note that *joining data* refer to pairing related GIS objects (e.g., pairing a roadway to a district in which it is located). Then, the provided input data are used to generate Monte Carlo Simulation (MCS) samples of the closure days of each roadway. Subsequently, these samples are used to evaluate the evolution of the network performance and resilience metrics of districts. Finally, the analysis output is the samples of resilience metric values. For the sake of interpretation and communication, the samples are summarised into the mean and standard deviation as illustrated at the left bottom of Fig. 1.

2.2. Input data

ResMapper is designed by object-oriented programming (OOP), where a community is specified by four classes of objects: ground motion (GM) zones, districts, roads and vertices. The details of the required data are as summarised in Table 1. In addition, the analysis requires joining data between objects to understand their spatial association, which are listed in Table 2. For example, each district is assigned a GM zone where the district lies. In this way, the seismic risk of a district can be determined in order to sample the structural damage of the roadways located in the district. On the other hand, by connecting each road to a pair of nodes at each end, a network topology can be defined. Finally, fragility curves and recovery curves of roadways are required as illustrated in Table 3. For the preparation of input data, users are also referred to the input data of the benchmark example, istanbul_benchmark.mat, available in the shared repository.

To prepare the data listed in Tables 1 and 2, GIS programs (e.g. QGIS and ArcGIS) are useful. Moreover, for most cities, large-scale datasets of districts and roadways are available on OpenStreetMap (OSM), which is also used in the following benchmark example.

Table 1
Input data (1) Objects.

Object	Data
GM zones	GIS ID (in GIS, defined as polygon)
	Moment magnitude (Mw)
	Peak ground acceleration (g) (PGA)
	Spectral acceleration at period 1 s (g) (Sa1)
Districts	GIS ID (in GIS, defined as polygon)
	Area (m^2)
	No. of damaged buildings (a vector representing each damage state)
	Proportions of 10 landslide susceptibility categories [7]
Roads	GIS ID (in GIS, represented by a line)
	Indicator of being a bridge (1 if true, 0 if a paved road)
	Indicator of being a major road (1 if true, 0 if a minor road) [7]
	Length (m)
	Structural type (following indices of fragility curves)
Nodes	GIS ID (in GIS, defined as a point)
	Destination node type (s) (can be none or multiple types)
	Indicator of having a priority for debris clearance (1 if true, 0 otherwise)

Table 2
Input data (2) Joining data.

Pair	Joining data
District – GM	Each district is assigned one GM zone.
Road – District	Each road is assigned one district.
Road – Node	Each road is assigned two nodes.
Road – Overpass	A road can be assigned other road(s) that overpasses it.

Table 3
Input data (3) Others.

Category	Descriptions
Fragility curves	Curves should be provided for all structural types of bridges and paved roads.
	Each curve is specified by a mean and standard deviation.
Recovery curves	The number of days required for repair is given for each damage state of each structural type.
	A curve must be given for each damage state. (i.e. the number of curves must be the same as that of fragility curves).

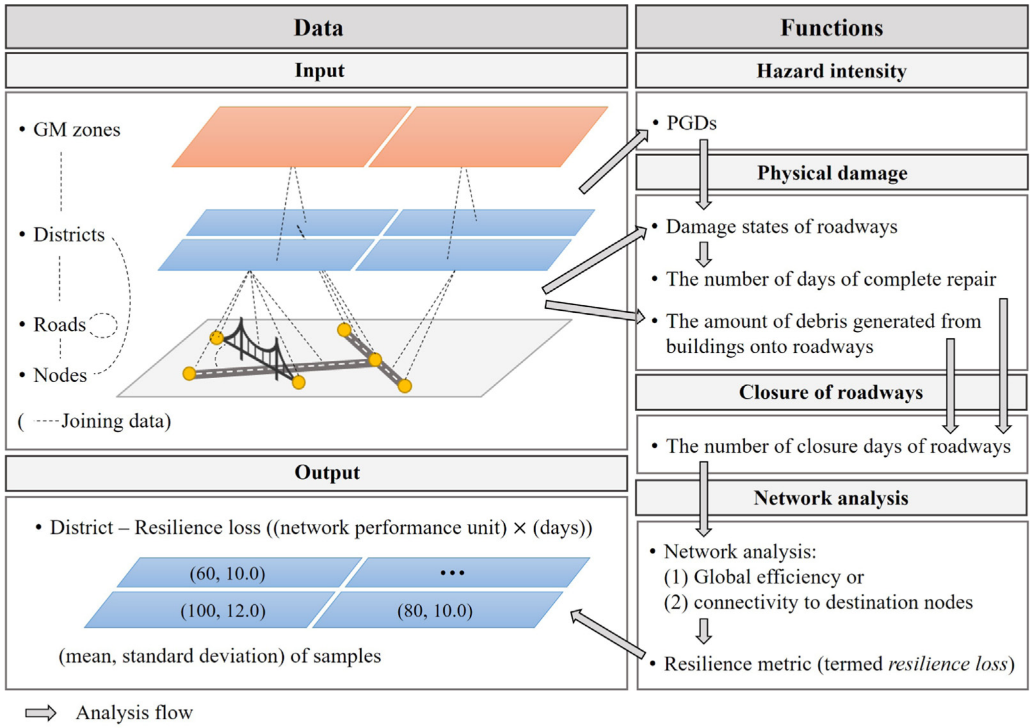


Fig. 1. Architecture of ResMapper.

2.3. Functionalities

The analysis procedure can be found in the script resMapper.m. It is intentionally designed as a script rather than a function so that the process remains accessible to users and readily modifiable to fit local conditions and data availability. While this section provides general descriptions, details of the functions and models are available in the first supplementary document.

The script resMapper.m consists of three parts: creating objects from input data, evaluating closure days of individual roadways and performing network analyses. The first step converts the input data into objects of four classes defined in the toolkit (cf. Table 1). While the current version assumes that the data are provided as a Matlab's data type 'table', any modification can be made depending on the format of input data so long as objects are created to start an analysis with.

The second step is to evaluate the closure days of individual roadways. Specifically, MCS samples are generated on structural damage of roadways and buildings by referring to fragility curves and building damage data. Then, they are used to simulate recovery process, i.e. structural repair and debris clearance. The repair of roadways and overpasses is assessed by using recovery curves. On the other hand, to simulate the clearance process of building debris, it is assumed that the closer a road is to the nodes having clearance priority, the earlier it is cleared (cf. Table 1). Such prioritisation is considered to reflect reality more accurately. That is, clearance work starts locally and propagates to adjacent areas rather than taking place all over a region simultaneously.

In the analysis model, there are three parameters that play a major role:

- the amount of debris that can be cleared a day;
- the ratio of road closure days to the repair days; and
- the ratio of closure days of an underpass to the repair days of an overpass.

Users can modify the parameter values from those used in the benchmark example to fit local conditions.

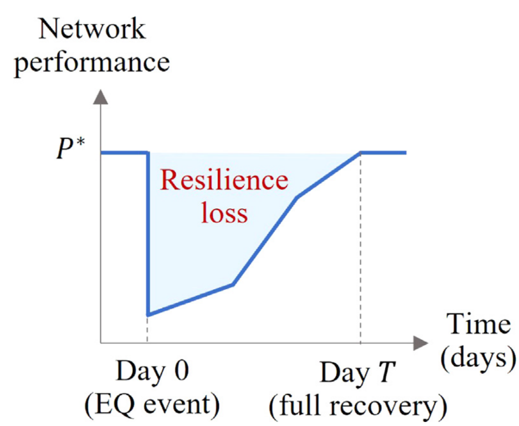
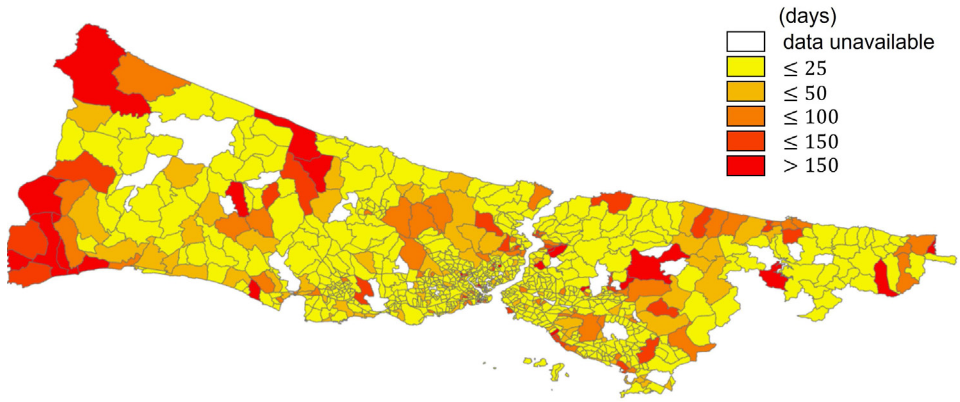


Fig. 2. Illustrative definition of utilised resilience metric termed *resilience loss*.

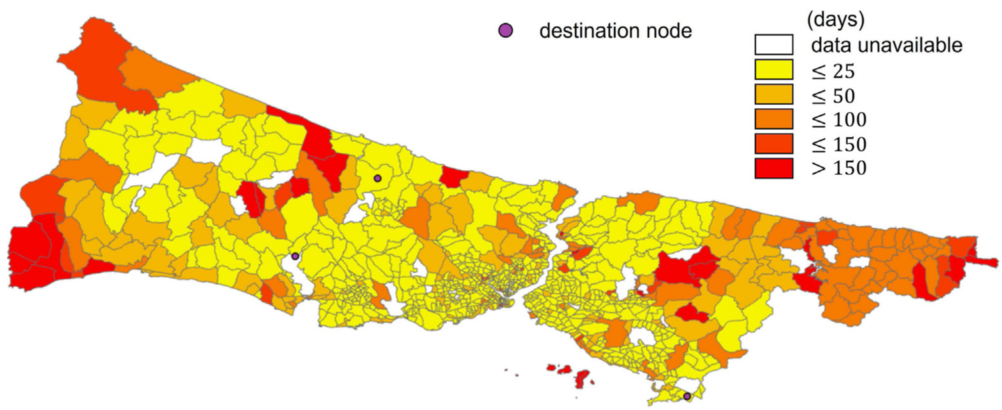
For the third part, the samples of road closure days are used to evaluate the evolution of a network performance until the performance is fully restored, as illustrated in Fig. 2. To this end, a network performance metric needs to be defined, of which ResMapper features two types: the global efficiency [8] and the proportion of nodes that are connected to destination nodes (cf. Table 1). Both metrics are evaluated by network connectivity analysis. Then, as illustrated in Fig. 2, network resilience is evaluated by a metric that corresponds to the area of functionality lost from the occurrence of a seismic event to the full recovery. The metric is termed *resilience loss* to denote that the higher the metric is, the more undesirable it is. By definition, the metric has a unit as (network performance unit)×(days). Relevant theoretical details can also be found in Byun and D'Ayala (2022) [9].

2.4. Output

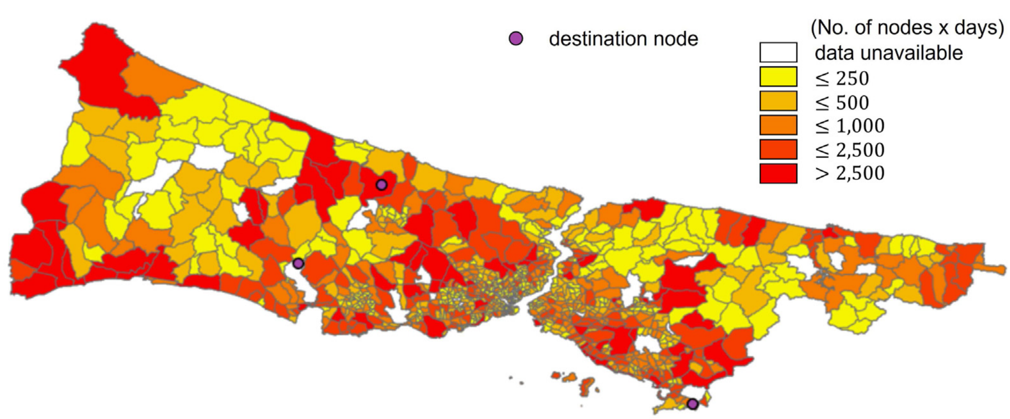
The output of ResMapper is sampled values of a resilience metric (i.e. resilience loss in the toolkit) of districts. The samples



(a) Global efficiency (unit: days)



(b) Connectivity to airports (unit: days)



(c) Connectivity to airports (unit: (number of nodes) × (days))

Fig. 3. Resilience loss map with respect to a given network performance metric.

can be examined directly as themselves, which provides understandings of their distribution, e.g. the shape of a distribution or the thickness of a tail. On the other hand, they can be summarised by a mean and a standard deviation. Calculating such summary statistics is also available by the toolkit.

3. Applications

3.1. Benchmark example: Istanbul, Turkey

As a benchmark example, Istanbul (in Turkey) is analysed with its 974 districts. GIS data have been collected from an open data source, OSM (c.f. Table 1). Then, their joining data are obtained by using ArcGIS Pro 2.8.0. For all districts, a single GM zone is assumed that has Mw 7.5, PGA 0.4 g and Sa1 0.5 g. The numbers of damaged buildings are provided by the Istanbul Metropolitan Municipality (IMM). The data are given as the number of damaged buildings in each damage state and in each district. The input data can be found in the shared repository, while an analysis can be simulated by running the script `main.m` available in the toolkit.

The resilience loss of both performance metrics, i.e. the global efficiency and connectivity to destination nodes, are evaluated and mapped respectively in Figs. 3(a) and 3(b); in Fig. 3(b), destination nodes are set as the three airports of the city. In Fig. 3, network performance is measured as the ratio to the original functionality. On the other hand, for a performance metric as connectivity to destination nodes, it can be also evaluated in terms of the absolute number of connected nodes, as shown in Fig. 3(c). For further discussions on analysis results and parameter studies, users are referred to the second supplementary document.

3.2. Comments on computational capability

There are two elements that decide size of an analysis: the number of districts and the number of roadways. For the benchmark network, the computation takes around 2 h by a personal computer with Intel® Core™ i7-1165G7 and RAM 16 GB. However, ResMapper's capability is most affected by, rather than computational time, a memory issue. Matlab's ordinary storage mode limits each variable's memory size (not the whole workspace's) to 2 GB. Output data would meet this requirement for problems with roughly up to 1,000 districts and 40,000 roadways. Matlab can save variables with memory higher than 2 GB, but this needs a special storage mode and incurs high RAM space and lengthy time for saving and loading data.

4. Impact

- As an open-source program, ResMapper features the most advanced resilience analysis for road networks: handling large-scale systems and considering impacts of overpasses and adjacent buildings.
- ResMapper pioneers the potential of general software for system-level analysis of infrastructures (which overcomes the limitations of component-level analyses).
- ResMapper can be used to perform various inference tasks such as performing parametric study and comparing decision scenarios. Such systematic investigation enables scientific understandings of seismic resilience of complex networks.
- One of the arch-hindrances of a large-scale resilience analysis is computational complexity that can make an analysis intractable, i.e., complicated methods and large-scale data. ResMapper addresses this issue by making them accessible to users. Thereby, it promotes communication among researchers and stakeholders for drawing consensus on decision-making.
- ResMapper can be used as a platform for research collaborations to develop and expand models and datasets.

5. Conclusions

This paper develops a Matlab-based toolkit, *ResMapper* that performs a seismic resilience analysis of large-scale road networks. The toolkit executes a probabilistic analysis to evaluate resilience of a network, where network performance is degenerated by structural damage and subsequent debris generation. The toolkit is distinguished from previous works in two perspectives. First, it performs a system-level resilience analysis, being specialised for large-scale road networks. Second, as causes of traffic disruptions, it takes into account not only structural damage but also impacts of overpasses and building debris.

For a system-level analysis of large-scale infrastructures, developing a general software program remains greatly challenging owing to the complexity of data and analysis. ResMapper pioneers such possibility and potential of a general-purpose software. Furthermore, by making complicated network analysis and datasets accessible, it is expected to promote interdisciplinary communication and continuous collaborations for probabilistic analysis and decision-making against hazard risks.

The implementation of the toolkit is demonstrated by a benchmark network, which represents Istanbul, Turkey, consisting of 974 districts and 35,502 roadways. To facilitate applications, computational capacity of the toolkit is also discussed. Further details of data and analysis are available in the repository of the toolkit and the supplementary documents. Such detailed investigation reveals distinctive capabilities of the developed toolkit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.softx.2022.101249.

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