Preliminary investigation of multi-hazard resilience analysis for urban transportation networks and data availability for hazard models and vulnerability of physical objects

Dina D'Ayala, Erdal Safak, Ji-Eun Byun, Emin Mentese

TOMORROW'S CITIES WORKING PAPER

April 2022

Tomorrow's Cities is the UKRI GCRF Urban Disaster Risk Hub

About **Tomorrow's Cities**

1.1.1 "Our mission is to reduce disaster risk for the poor in tomorrow's cities."

Tomorrow's Cities is the UK Research and Innovation (UKRI) Global Challenges Research Fund (GCRF) Urban Disaster Risk Hub – a five-year global interdisciplinary research hub.

Our aim is to catalyse a transition from crisis management to multi-hazard risk-informed and inclusive planning and decision-making, for cities in low-and-middle income countries.

Globally, more than two billion people living in cities of low-to-middle income countries are exposed to multiple hazards such as floods, earthquakes, landslides, volcanoes and fires, which threaten the cyclical destruction of their lives and livelihoods. With urban areas expanding at unprecedented rates, this number is expected to reach four billion by 2050.

Failure to integrate multi-hazard disaster risk into urban planning and decision-making presents a major barrier to sustainable development, including the single greatest global challenge of eradicating poverty in all its forms.

But this global challenge is also major opportunity: as ~60% of the area expected to be urban by 2030 remains to be built, we can reduce disaster risk in tomorrow's cities by design.

We are one of 12 UKRI GCRF Hubs funded by a UKRI Collective Fund Award, as part of the UK AID strategy, putting research at the heart of efforts to deliver the United Nation's Sustainable Development Goals (SDGs).

www.tomorrowscities.org
@UrbanRiskHub

The UKRI GCRF Urban Disaster Risk Hub

ECCI High School Yards, Infirmary Street, Edinburgh EH1 1LZ

Summary

HUB-Istanbul work package (WP) 2.6 aims to develop tools to analyse the multi-hazard resilience of urban transportation network in complex and evolving metropolitan environment, and propose a demonstrative application to a case study area: Fikirtepe in Istanbul, Turkey. Research outcomes will be conveyed by five deliverables. This document is the first deliverable, summarising the overall framework of analysis and required data for assessing physical vulnerability. Based on the framework, the second deliverable will deal specifically with another type of data required to evaluate traffic functionality of roadways and network performance. Based on the framework and datasets identified in the first two deliverables, the third deliverable will develop a probabilistic model to incorporate multi-layered analysis and data, which will be demonstrated by pilot examples. The fourth deliverable will present a thorough analysis of real-world transportation networks in the case study area, including mapping, network analysis and network performance evaluation. The evaluation results should be used to support decisions through mathematically formulated decision tasks, which will be illustrated in the fifth deliverable.

This first deliverable summarises and proposes the research objectives, the framework of multi-hazard disaster resilience analysis of urban transportation networks and data requirement for assessing physical vulnerability, which are accompanied with thorough literature review. Based on the development, major hazard threats and distributions of bridges are identified for the case study area, Fikirtepe in Istanbul, Turkey.

Table of Contents

List of Figures

List of Tables

2 Introduction

2.1 RESEARCH OBJECTIVE: MULTI-HAZARD RESILIENCE ANALYSIS OF URBAN TRANSPORTATION NETWORKS

The interdisciplinary research hub, Tomorrow's Cities aims to enhance multi-hazard disaster resilience of cities experiencing rapid development and transformation, whose vision can be summarised into four topics: (1) multi-hazard, (2) urban environment, (3) planning developing cities and (4) social equality. Multi-hazard reflects the interactions among destructive and disruptive events, generated by different natural causes, which may amplify the consequences of individual hazards through cascading occurrences of otherwise uncorrelated events. On the other hand, the urban environment object of this study is characterised by dense development, whereby closely positioned structures can disrupt each other during a hazard occurrence. Planning developing cities indicates that the research hub focuses on cities under rapid development and transformation, instead of established and static ones. While the latter prioritise the optimal maintenance and operation of existing networks and facilities, developing cities rather focus on planning and expanding undersized network and implementing facilities. The project objective is to support such plans by developing awareness and tools which underpin risk-informed decisions, while placing the primary focus on promoting social equality.

In alignment with the vision of the research hub, the work package (WP) 2.6 aims to evaluate the multi-hazard disaster resilience of urban transportation networks and there-by, developing tools for supporting decisions underpinning new road infrastructure de-sign. This task requires a multidisciplinary approach that includes structural analysis, transportation network analysis and probabilistic analysis. In addition, to make the result relevant to practical decision-making and social well-being, the evaluation needs to in-corporate social science so as to interpret engineering quantities in terms of social needs. It is noted that there is no universally correct answer for social norms, whereby the measure that quantifies infrastructures' contributions should be designed through discussions between researchers and local stakeholders.

It is noted that while this study aims to develop a general analysis framework, the de-tails and accuracy of the analysis greatly depend on data availability, i.e. data acquisition is the prerequisite of performing analysis. Therefore, prior to developing theory and models, the first two deliverables are devoted to identifying data needs and availability.

2.2 RESEARCH SCOPE

The framework proposed for the current project is underpinned by two previous FP7 funded European project SYNER-G (SYNER-G 2012) and INFRARISK (INFRARISK 2016). The SYNER-G project compiled a comprehensive repository of fragility curves of civil structures, including buildings, bridges, road surfaces and railways. This is particularly relevant to Istanbul as data were compiled specifically for European structures, including case studies in Turkey.

Conclusions

The INFRARISK project focused on determining a robust approach to determine multi -hazard risks of transportation systems and pioneered disaster resilience analysis. The thorough literature review and demonstration provide critical insights for this study.

The aim of the present study is to establish a framework for multi-hazard analysis of urban transportation networks, which will achieve three major novelties:

- Probabilistic model for thorough system reliability analysis
- Functionality measures for transportation networks, reflecting social equality
- Explicit decision support system

To demonstrate the viability of the developed framework, an application will be implemented for the transportation network of Fikirtepe, Istanbul, Turkey.

2.3 RESEARCH OUTLINE

The workflow to establish the multi-hazard resilience framework requires a systematic approach with five interdisciplinary components, that rely on as many layers of interconnected data: (1) hazard severity, (2) functionality of components, (3) functionality of transportation system, (4) probabilistic analysis and (5) decision support system. The term critical component is used as a counter-term to system, referring to the constituents of a system whose functionality jointly determines the functionality of the system, e.g. bridges, overpasses, road surfaces, buildings and slopes.

Hazard severity can be evaluated probabilistically by quantifying given intensity measures (IMs) for selected disruptive events (e.g. peak ground acceleration (PGA) for earthquakes and water depth for flooding) and associated return periods or yearly occurrence. Then, the IMs can be used to compute the functionality state of critical components, by which the system’s functionality can be determined as well. It is noted that functionality is a multi-dimensional concept that reflects both physical damage (e.g. structural damage of roadways and adjacent buildings) and the capability to fulfil the expected performance (e.g. traffic capacity). The evaluation of hazard severity and functionality losses can be integrated through probability/reliability methods. The results of probabilistic analysis can be utilised to support decision tasks of interest.

The rest of the deliverable is organised as follows. Section 2 discusses multi-hazard analysis of urban transportation networks, for which Section 2.1 summarises challenges and preceding studies of multi-hazard analysis; while Section 2.2 presents the overall analysis framework. The proposed framework requires various types of data, while data required to evaluate physical vulnerability are discussed in Section 3. To apply the framework to the transportation network in the testbed, i.e. Fikirtepe, Istanbul, Turkey, Section 4 analyses historical hazard data of Istanbul to determine the relevant hazard scenarios, while investigating the bridges in the area to estimate their structural vulnerability. The concluding remarks and recommendations for future re-search are presented in Section 5.

3 Multi-hazard vulnerability analysis of transport systems

To evaluate the resilience of transport systems, their vulnerability should be evaluated first, based on which resilience can be evaluated by introducing further dimensions such as recovery time and socio-economic loss. While such additional dimensions are discussed in the second deliverable, this section illustrates the challenges and available methods to perform vulnerability analysis of transport systems.

3.1 CHALLENGES IN HAZARD-INTERACTION MODELLING

The procedure of multi-hazard analysis can be summarised as in Table 2.1 (Kappes et al. 2012). The first step consists of selecting hazard types relevant to the site or scope of the study, for which there are therefore two approaches: space-oriented and motif-oriented. The first approach considers all threats within a selected region and sorts out relevant threats. For such selection, multiple criteria have been proposed, including a cut-off point (i.e. a threshold related to expected damage levels) (Saarinen et al. 1973), a set of norms (e.g. annual probability, the number of affected people, economic and environmental costs, and political and social impact) (European Commission 2010) and locality (i.e. ubiquitous threats such as meteorite impacts are excluded) (Greiving et al. 2006). In contrast, the second approach defines multi-hazard analysis simply as considering more than one hazard. This approach is useful for investigating specific aspects of hazard occurrences, e.g. a hazard triggering a second process (e.g. earthquakes and floods leading to land-slides), an event causing multiple threats (e.g. a volcanic eruption resulting in lava flows, lahars, and ash and lapilli fallout) and hazards sharing certain characteristics (e.g. commonality of snow avalanches, debris flows and rock fall).

Table 3.1 Challenges in multi-hazard analysis and example approaches (Kappes et al. 2012)

Selecting hazards	Reference units	Interactions
Space-oriented Motif-oriented	Qualitative Semiquantitative	Triggering occurrence Changing likelihood Compounding damage
Vulnerability assessment	**Multi-hazard vulnerability**	**Risk evaluation**
Curves (functions) matrices (coefficients) Indicator-/index-based	Exposure to different hazards Simultaneous impact Sequential impact	Qualitative Semiqualitative Quantitative

In contrast to single-hazard analysis, multi-hazard analysis faces two additional challenges: (1) comparing multiple hazards that have different processes and consequences and (2) identifying correlations and interactions between hazards. The first challenge arises from the differences in their nature, intensity, return period and the effects they have on exposed elements. Accordingly, the comparison of hazards requires reference units, which can be defined by two approaches (Kappes et al. 2012): classification of hazard risks and quantification using indices. The first approach defines intensity and frequency thresholds to classify the levels of threat of individual hazards into predefined categories (e.g. high earthquake and high flood hazard). The second approach defines continuous indices by which threat levels of different hazards can be compared quantitatively.

The second challenge arises from the lack of data and knowledge on the interactions of different hazards. Accordingly, it is often addressed rather subjectively, and it can be summarised into largely three approaches: triggering effect, modifying other hazards' propensity to occur and concurrent occurrences causing compounding damage. Examples of these interaction types are summarised in Table 2.2 (Gill and Malamud 2014).

Table 3.2. Hazard interaction types and examples (Gill and Malamud 2014)

Hazard interaction type		Examples
Triggering effect		Landslide triggered by earthquake, rainfall, snowmelt or flooding Tsunami triggered by submarine landslide Flooding triggered by tsunami Wildfires triggered by lightning during a drought Positive feedback between undercutting of slopes and channel aggradation
Changing propensity to occur	Increased threat	Increased landslide threat after wildfire, earthquake, rainfall or snowmelt Increased flooding threat due to co-seismic regional subsidence
	Decreased threat	Reduced wildfire threat after heavy rainfall Reduced threat of ash fall and pyroclastic debris due to thicker continental ice given global cooling Reduced threat of large wildfire after multiple smaller fires
Spatial and temporal coincidence		Time taken for infrastructure to be repaired or rebuilt Time taken for a population to recover Amplified vulnerability due to triggered hazards or independent hazards occurring within relevant timeframe

After identifying hazard propensity and severity, the next step is assessing vulnerability of the physical components of the network or system being considered, i.e. (1) the propensity of specific structures to suffer different levels of damage when being exposed to different hazards, (2) the alteration of the vulnerability of a structure in case of the simultaneous impact of several hazards and (3) sequential impacts (i.e. the cumulative effect of multiple hazards). Vulnerability can be quantified by either curves (functions), matrices (coefficients) or indicator-/index-based methods. Vulnerability functions offer continuous vulnerability information with regards to IM values. They can provide detailed information, while requiring extensive data in relation to the characterisation of both hazards and structural response. Matrices are discrete approaches often based on observed dam-ages or rough appraisals, historically employed when only empirical data are available and analytical models are not sufficiently developed. While curves and matrices are most commonly used, they share an important constraint that it is not straightforward to adapt them for uncharted parameters, e.g. different structural types (Kappes et al. 2012). This can be overcome by using indicators, whose qualitative evaluation facilitates combining multiple parameters. However, such qualitative and rough estimates made by indicators often lead to loose relations with hazard characteristics and lack general applicability.

The vulnerability of components can be utilised to evaluate the vulnerability of the system, on the basis of which, overall risks and resilience of the systems can be computed. Such risks would reflect expected increase in traffic cost and time, degradation of traffic supply and ensuing socio-economic losses. To this end, three approaches are available: (1) qualitative, (2) semiqualitative and (3) quantitative. The first approach classifies risk levels according to predefined categories, e.g. hazard zone plans. Semiqualitative definitions are distinguished from quantitative ones in that risk indices are computed rather than classified. However, Kappes et al. (2012) point out that both approaches have limitations of being subjective and not transferrable to other applications. On the other hand, quantitative approaches provide specific values of potential damages or losses and thereby, can support decision-making more explicitly.

3.2 MODELS FOR URBAN TRANSPORTATION NETWORKS

The outlined multi-hazard analysis in Section 2.1 can be adopted for the analysis of urban transportation networks as illustrated in Figure 2.1. As indicated in the figure, the evaluation consists of various components and layers, i.e. hazards, physical components, traffic components, network and decision-making, each of which stems from different disciplines and requires different types of analysis and data. Very critically, the models for each of the layers need to be compatible to the others, while maintaining a full probabilistic approach. This means that the variables describing the response of each component layer should be chosen in a way that a direct causal relationship between them can be established. Therefore, the hazard models provide expected IMs based on selected hazard scenarios, which, based on fragility curves, allows for evaluating the damage states of physical components (e.g. bridges, overpasses, road surfaces, buildings and slopes). The damage states are then used to infer the functionality of roadways, i.e. reduced traffic capacity, and thereby, that of the network. The result of network analysis can reveal the in-tensity and spatial distributions of vulnerability (e.g. suggesting the need for investment) or be combined with optimisation to support decisions more directly (e.g. suggesting optimal locations of new roads). There are several challenges to implement the framework, which will be addressed by the present study through multi-disciplinary approach.

The first challenge is establishing a direct correlation between the functionality of traffic components (i.e. the reduced number of lanes and vehicle speeds) and the estimated structural damage of physical components (i.e. structural damage of roadways and col-lapsing buildings and slopes onto or below roadways). While functionality losses of traffic components are often observed during natural destructive events caused by natural hazards, there is no solid estimation available to this end, which should be developed by use of theoretical and observational data (D’Ayala and Gehl 2015). Moreover, such estimation would involve high uncertainties, requiring probabilistic approach. Applying probabilistic analysis to this end is a challenging task, though, as it would involve high-dimensional distributions owing to the large number of roadways in real-world urban networks, which is often the major cause of computational issues.

The second challenge is analysing the functionality of the transportation network. To this end, the first step is to model real-world network as an abstract graph consisting of nodes and edges, i.e. simplifying the network by choosing relevant roads and intersections (Porta et al. 2006). This choice requires a thorough investigation by considering different alternatives and being guided by the hierarchy of the road system, in relation to analysis objectives and decision-making requirements. The functionality of a road net-work needs to satisfy different and possibly conflicting tasks, depending on stakeholders/users requirements and the particular circumstance in which the system needs to de-liver its function, i.e. the immediate aftermath of a destructive event, rapid response phase, short-term recovery phase or medium- to long-term recovery phase. It is therefore not straightforward to represent the ability of the network to satisfy competing demands with a few numerical quantities. Such quantification requires multi-disciplinary investigations including structural engineering and social science so that quantified measures can be relevant to practical decision-making. As road network and community resilience are strictly interrelated, the relationship needs to be investigated and accurately represented so that resilience analysis can become useful.

The final challenge is bridging results of resilience analysis to decision support, as the ultimate goal of disaster resilience analysis is to derive risk-informed decisions to prepare the system in advance. However, transforming complicated real-world decision tasks into abstract mathematical formulations requires thorough and multi-disciplinary studies, re-quiring identification of decision variables, global objectives and constraints of decision-making (Olmsted 1984; Byun and Song 2020). While a decision task can be described by different mathematical problems, the formulations of those problems greatly affect computational efficiency and analysis accuracy.

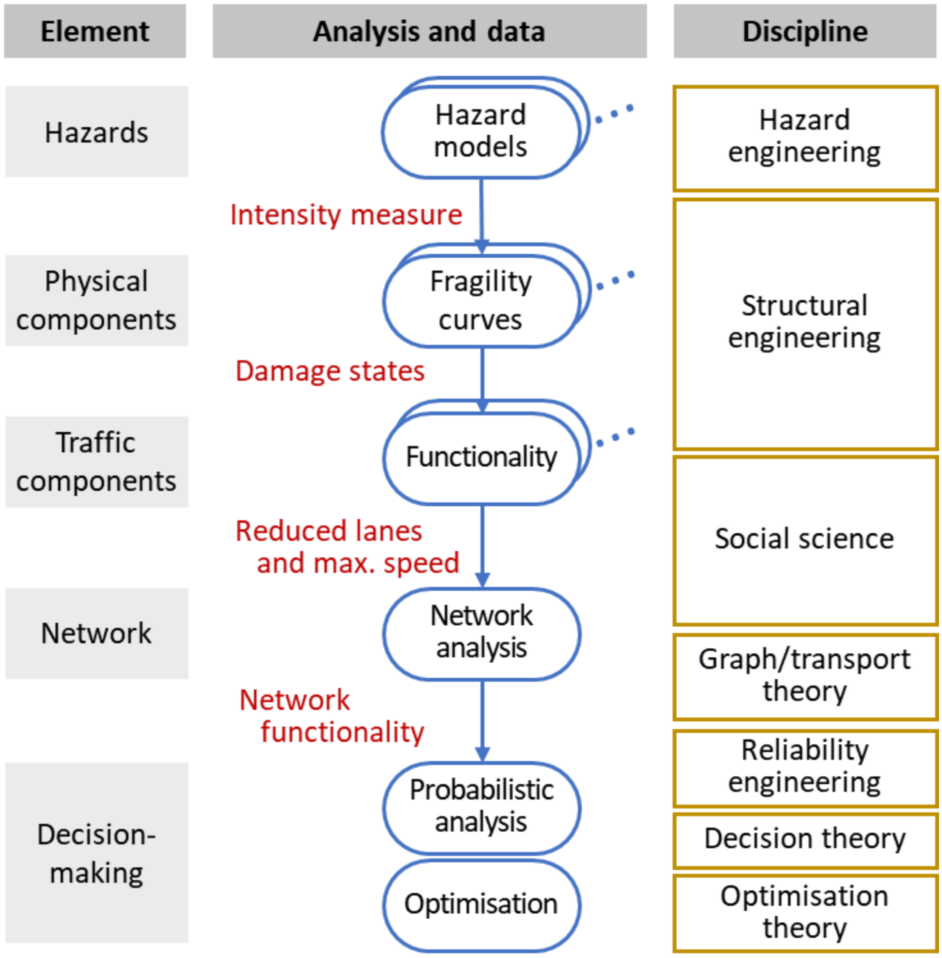


Figure 3.1 Framework of multi-hazard resilience analysis of urban transportation network

4 Required data and availability

Multi-hazard resilience analysis, whose framework is introduced in Figure 2.1, greatly depends on the availability and quality of data. In this section, the available datasets that are relevant to the testbed (i.e. Fikirtepe, Istanbul) are summarised for hazard models, fragility functions, traffic functionality of roadways and recovery of roadways functionality. Data of transportation networks and network functionality are also required, which will be discussed in the second deliverable. In the present study, open source datasets and platforms can be utilised, while for some elements, site-specific models and data will be obtained from local authorities and developed within the HUB. It is noted that there are also some parameters for which reliable data are not available, calling for planning data collection strategy and mining existing data.

Table 3.1 summarises datasets for physical vulnerability to be used in the present study, whose details are illustrated in the following subsections. Among the datasets listed in the table, open source data and models from the literature can be obtained easily, while local datasets and models to be developed within the HUB have not been acquired yet for the present study. In particular, local data are essential for rainfall data and slopes susceptibil-ity data whose wild spatial variability makes global data inapplicable, while local data for cost and duration of structural repair and debris clearance are desirable to improve the accuracy of analysis results. The models to be developed within the HUB and incorpo-rated into the present study afterwards, are denoted in the table with parenthesis indicat-ing the (tentative) work package related to the development.

The resolution and quality of data governs that of analysis results. For hazard models, resolutions need to be finer than the region being analysed as, otherwise, the varying hazard threats across different neighbourhoods or districts cannot be recognised. Struc-tures related to roadways, e.g. bridges, overpasses and road surfaces, need to be identi-fied individually to enable the analysis, while representative fragility functions are desired for accurate analysis. While other structures and objects, e.g. buildings and slopes, do not require the same level of resolution with roadway structures, i.e. one-to-one identifica-tion, higher resolutions and accurate fragility functions are still desirable. Datasets and models illustrating non-structural fragility functions, functionality and recovery mostly do not have solid theoretical models and require qualitative estimations, for which local data play a key role for data calibration.

Table 4.1 Selected datasets in present study

Data		Selected datasets in present study
Hazard models	Earthquake	GEM Models to be developed within HUB (Istanbul WP 2.1)
	Flood	Local rainfall data Local digital elevation data (DEM) Models to be developed within HUB (?)
Fragility functions against earthquakes	Bridges and overpasses	SYNER-G project (SYNER-G, 2012) Models to be developed within HUB (Istanbul WPs 2.5 and 2.6)
	Road surfaces	HAZUS-MH earthquake model (NIBS, 2011)
	Buildings	SYNER-G project (SYNER-G, 2012) Global Earthquake Model (GEM) Models to be developed within HUB (Istanbul WPs 2.5)
Fragility functions against floods	Vehicle movements	Models available in literature
Fragility functions of landslide	Earthquake-induced	HAZUS-MH earthquake model (NIBS, 2011) Local slope susceptibility data
Traffic functionality of critical components	Structural damage	INFRARISK project (INFRARISK, 2016) Reconnaissance reports Data to be estimated by present study
	Road blocked by debris	Reconnaissance reports Models available in literature Data to be estimated by present study

Recovery	Structural repair	HAZUS-MH earthquake model (NIBS, 2011) INFRARISK project (INFRARISK, 2016) Local data (if available)
	Debris clearance	Local data (if available)

4.1 HAZARD MODELS

Given a hazard model and return period of interest, the hazard risk can be described by several IMs, each of which illustrate different aspects of the hazard as summarised in Table 3.2 for selected hazards. The IMs can be evaluated by various models from simple and deterministic ones to sophisticated and probabilistic ones. Simple models are often based on empirical formulations from historical data, while sophisticated models are usually based on detailed simulations of hazard process. D'Ayala and Gehl (2014) summarise a comprehensive set of hazard models for earthquakes and floods as well as landslides induced by earthquakes and floods. While source hazards (i.e. the hazards whose occurrence does not depend on that of other hazards) are evaluated by hazard occurrence models, induced hazards (i.e. the hazards that occur in the aftermath of the occurrence of other hazards) are often evaluated by fragility curves given as functions of source hazards' IM.

For earthquakes, there are open source platforms that provide risk information around the globe such as Global Earthquake Model (GEM). In particular for Turkey, GEM provides a seismic hazard map developed by the 2014 Earthquake Model of the Middle East (EMME) Project, which identified area, fault and background source models based on historical seismic data (Sesetyan et al. 2018; Demircloglu et al. 2018). For floods, there are no global models as the hazard is typically catchment-specific and dependent on local rainfall data. Currently, within the HUB, site-specific models of earthquakes and floods are under development for the targeted cities, which can be adopted afterwards to improve the accuracy of present study.

On the other hand, landslides susceptibility and its representation through fragility functions require geological properties of local ground for which open source data can be utilised, e.g. http://www.mta.gov.tr/eng/maps/geological-500000 for Turkey. In addition to those static parameters, analysing landslides as a consequence of other hazards requires time-variant parameters such as saturation level after flooding or compaction level after ground-shaking.

Table 4.2 Example IMs for earthquake, flood and landslide

Hazard type	Example IMs
Earthquake	Peak ground acceleration (PGA), peak ground velocity (PGV), permanent ground displacement (PGD) and spectral acceleration (Sa)
Flood	Water depth, water velocity and discharge rate
Landslide	Volume and velocity of sliding mass, and PGD

4.2 FRAGILITY FUNCTIOSN FOR CRITICAL COMPONENTS OF THE NETWORK

Physical vulnerability of structures can be evaluated by fragility curves, which provide the probabilities of damage states given an IM value for a given hazard. While there are often multiple IMs for a hazard, the most suitable IM can be selected in terms of various criteria, such as practicality, effectiveness, efficiency, sufficiency, robustness and computability (Pitilakis 2009). On the other hand, the definition of damage states wildly varies across available literature in terms of both their number and descriptions, while causal relationship between damage and specific functionality loss levels are rarely provided (Macabuag et al. 2018; Moya et al. 2020). As a result, damage states should be defined based on the functionality of interest and the consistency between different structures. In this study, this issue is addressed by establishing consistent descriptions of damage states in terms of evaluating the traffic capacity of roadways. It is also noted that the present study utilises the fragility functions for bridges and road surfaces to estimate the structural damage of roadways as well as those for buildings and slopes to account for disrupted traffic owing to foreign materials falling on roadways.

The primary challenge of using fragility curves is the lack of data. In other words, as-signing correct fragility curves to determine physical vulnerability of infrastructure com-ponents, requires the identification of structural parameters and construction details for each structure located in the testbed, which is especially challenging when analysing a large area. Furthermore, since it is unlikely to have exactly corresponding curves from literature for every structure type, the curves need to be chosen based on a reduced number of parameters. Still, for the curves are developed using the most representative parameters, the uncertainties can be effectively controlled with reasonable computational cost. While causing some level of inaccuracy, utilising fragility curves from literature is useful particularly for regional analysis, whose large number of structures makes it infeasible to develop and assign exact functions for every structure. Furthermore, such approach has been proved to provide reasonable accuracy by numerous preceding studies (SYNER-G, 2012).

For fragility curves against earthquakes, the SYNER-G project collected a comprehensive set of curves for structures such as buildings, bridges, road surfaces as well as other types of lifeline structures, while particularly focusing on European structures. The IN-FRARISK project supplements the SYNER-G database especially for bridges, by examining multiple failure modes. The curves provided by the HAZUS-MH earthquake model are also a good database. Although the project focuses on the US environment, some curves can be applied for general settings as confirmed by the SYNER-G project. In addition, the GEM recently collected a comprehensive set of fragility curves for buildings (Yepes-Estrada et al. 2016). More recent works can be found in review papers, including Gidaris et al. (2017), Muntasir Billah and Shahria Alam (2015) for bridges and Maio et al. (2017) for buildings. It is also noted that some site-specific fragility curves will be developed within the HUB although the development will be limited in terms of hazard types and structural parameters. Despite the large number of proposed curves, there is no universal database to this end. Accordingly, it is recommended to refer to database or study that best describes the site-specific characteristics of given structures and hazard. Rossetto et al. (2014) have provided guidelines for rigorous criterion for choosing fragility and vulnerability functions from large repositories and evaluating their suitability.

In contrast to earthquakes, flooding is far less likely to wreak structural damage to buildings and roadways, while the major disruption mechanism is inundation. As a result, the primary disruption mechanism by flooding is the inundation of road surfaces that disrupts vehicles movement (more discussions can be found in Section 3.3). Other failure mechanisms caused by floods worth noting are damages of flood protection structures by hydraulic loading and damages of bridges by scouring (D'Ayala and Gehl 2015), while, in extreme cases, floods can cause the unseating of bridge decks (Gehl and D'Ayala, 2016).

While there are several reports that landslides can damage bridges by pushover loading (Zhiqiang and Lee 2009), the likelihood is still very low, and thus, there are few studies on structural damage following landslides. Similarly, landslides are not very likely to cause the structural instability of buildings. There is still a possibility though, e.g. lateral loading or ground settlement, for which several fragility curves have been developed (Mavrouli et al. 2014; Peduto et al. 2017). On the other hand, landslides have a relatively high likelihood of affecting road pavements through ground displacements or slide mass (Argyroudis et al. 2019; D'Ayala and Gehl 2015; NIBS 2011). For ground displacements, fragility curves have been developed by HAZUS-MH earthquake model, and the SYNER-G project tested and confirmed their applicability to European environments. On the other hand, the vulnerability of roadways in regard to slide mass has not been investigated systematically. This can be measured, in case of slide mass falling onto roadways, by width and volume of the mass on roadways and the expected rate of clearance, while, in case of ground failure below roadways, being measured by the level of ground settlements and repair rate of road surfaces.

4.3 TRAFFIC FUNCTIONALITY OF ROADWAYS

Traffic capacity of roadways can be inferred from their physical damage, by estimating two traffic parameters: closure of lanes and reduction in vehicle speed. Traffic capacity can be reduced either by structural damage of roadways or by foreign materials on roadways, for both of which there are not sufficient theoretical nor observational data. In addition, traffic capacity reduction also depends on administrations, as road facilities can be closed for safety issue or inspection purpose independent from the severity of structural damage (Davies et al. 2017).

While the impact of structural damage of roadways, e.g. cracks on pavements and structural instability, has been investigated by a few studies, empirical models can be developed by use of illustrative descriptions of damage states (NIBS 2011; Pitilakis et al. 2014) and reconnaissance reports (Davies et al. 2017; Mazzoni et al. 2018). D'Ayala and Gehl (2015) pioneered this issue by surveying experts on the expected durations of recovery and the number of lanes being closed, in regard to each damage state of roadway structures. Although they provided a useful insight, D'Ayala and Gehl (2015) points out that the survey results show large variance across expert groups and are not sufficient for practical use. Such lack of data and models highlight the need for further investigations on the relationship between physical and functional damage.

After a hazard occurrence, foreign materials may fall onto roadways and reduce their traffic capacity, e.g. flood water on road surfaces, soil mass from landslides and debris from collapsed buildings. The impact of flooded water to vehicles movement and damage has been discussed by several studies (Martínez-Gomariz et al. 2018; Pregnolato et al. 2017; Teo et al. 2012), although it still requires further investigations. On the other hand, debris from adjacent landslides or collapsed buildings can deter or block vehicles movement as well. In this case, evaluating reduced capacity requires the extent and volume of debris, for which only a few studies are available (Argyroudis et al. 2019; Domaneschi et al. 2019).

4.4 RECOVERY OF RAODWAYS FUNCTIONALITY

Recovery rates of components and system also affects system resilience, for rapid and effective recovery can reduce total socio-economic loss which should be computed from the disruptive/destructive event occurrence to full recovery. Transportation networks are recovered by two operations: repairing structures and clearing debris. The durations of structural repair for various structural types and damage levels have been compiled by HAZUS-MH earthquake model (NIBS 2011). However, the figures in this model are estimated based on the US data. D’Ayala and Gehl (2015) surveyed several expert groups and network operators/managers to elicit information on the expected times needed to repair bridges in relation to specific damage modes. Although more data is required for practical use, Gehl and D’Ayala (2018) proposed functionality loss and recovery functions for various road network component caused by sequences of different hazards.

It is noted that recovery process depends not only on technical resources, but also on societal and economic situations, such as administrative protocols and authorities’ priorities. For example, the process of clearing debris depends on the amount of resources to be mobilised during a disruptive event, e.g. the number and volume of lorries available per day, and the prioritised areas to be cleared first. Even minor details of such protocols affect the process, as debris of small pieces (e.g. woods, glasses and bricks) and large ones (e.g. reinforcement and concrete elements) require different types of equipment and efforts, i.e. large pieces should be broken into small ones before hauling (NIBS 2009).

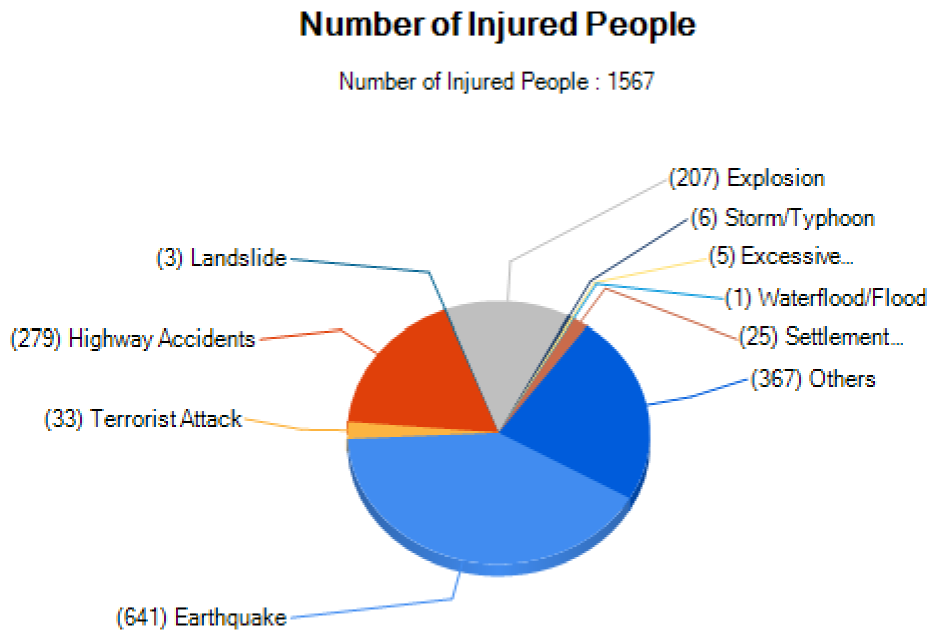
5 Applications: Fikirtepe, Istanbul, Turkey

In the present study, Fikirtepe, Istanbul, Turkey has been selected as case study area. Fikirtepe is one of the 21 neighbourhoods within the border of Kadikoy District on the Anatolian Side of Istanbul. This area is known to have the lowest socio-economic status among other neighbourhoods in Kadikoy and has been experiencing the largest urban transformation far from being completed. Furthermore, the area has potential hazard threats of earthquakes and floods. These characteristics and recent observations of Fikirtepe make the area suitable for case study of multi-hazard resilience of new infrastructure.

5.1 MULTI-HAZARD SCENARIO

The multi-hazard threats of Fikirtepe can be identified by following the procedure out-lined in Section 2. The major hazards for Istanbul are selected based on space-oriented approach to identify all relevant threats. The Turkish Disaster and Emergency Management Authority (AFAD) (2020) provides a comprehensive database of multiple events that have affected Istanbul during the last three decades (from 1 January, 1990 to 30 September, 2020), and their consequences in terms of populations and buildings affected are shown in Figure 4.1. The data suggest the major natural threats in Istanbul are represented by earthquakes, floods and landslides (while settlements and storm/typhoon have also been observed, they can be integrated with landslides and floods, respectively, being included in slope failures and flood related hazards). While the current scope of this study is limited to natural hazards, it is noted that the data also indicates the significance of human-made hazards such as fire, raising the need for future study that incorporates man-made hazards. This source however does not provide indications on the effects of these hazard on road infrastructure components.

(a)



(b)

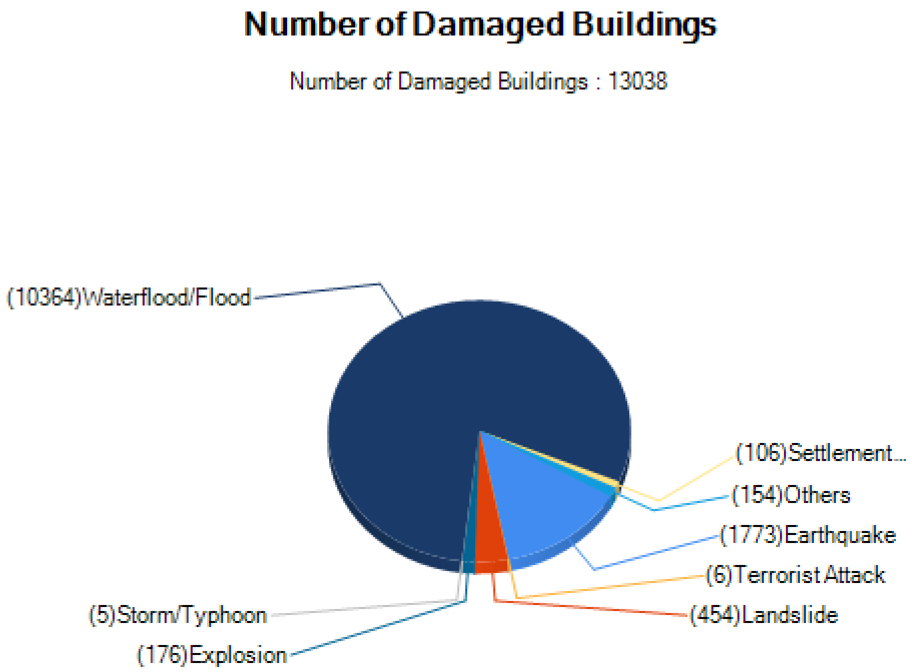
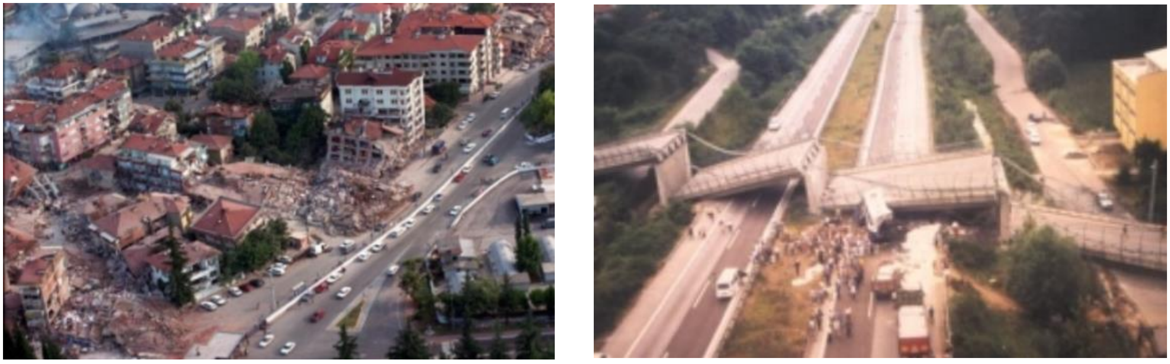


Figure 5.1 of injured people and (b) the number of damaged buildings. To be noted that the two indicators are not correlated for earthquake and flooding

On the other hand, the interactions between the selected hazards are chosen in reflection of the analysis motivation, i.e. performance of urban transportation systems. In this regard, the primary concern is the disconnection or delayed trips between areas within districts and the metropolis or across the metropolis to other regions of Turkey due to degraded roadways. While networks are often designed to ensure reliable trips by having several alternative routes, several routes can experience coincident degradations after concurrent occurrences of multiple hazards. For instance, while a highway was closed after the 2016 Kaikoura earthquake, the other route became the only route between two regions, which increased the impact of its closure. As a result, the speed limit of the high-ways on the route had to be reduced to lower the risk of road closure due to vehicle crashes (Davies et al. 2017), which suggests the importance of securing network redundancy and impact of losing such redundancy. Such degradation can be even worsened in urban environments, in which adjacent objects disrupt each other as illustrated in Figure 4.2, which was observed during 1999 Kocaeli and Duzce earthquakes in Turkey (Erdik 2000).



(a) (b)

Figure 5.2 Traffic disruptions caused by adjacent objects (1999 Kocaeli and Duzce earthquakes): (a) disruptions by collapsed buildings and (2) those by collapsed overpasses

Three observations on the selected hazard are utilised to determine hazard scenario:

(1) Earthquakes have longer impact than flooding.
(2) Flooding has shorter return periods than earthquakes.
(3) Landslides are mostly triggered by earthquakes or flooding (instead of occurring independently).

Accordingly, we analyse the scenario where an earthquake is immediately followed by a flood, which is conservative but possible especially if an earthquake occurs during rainy season, i.e. winter in Istanbul. In such a case, the earthquake would damage roadways, making their repairs take a few days to months; then, the transportation network with less redundancy would be affected much severely if a flood follows soon. Landslides might be triggered by either earthquake or flooding, exacerbating the network functionality. The intensities of hazards are often illustrated by return periods, for which 475 years and 100 years are selected respectively for earthquake and flooding, following the convention of design life span and reference return period for structures and infrastructures. On the other hand, the intensities of landslides, which are considered secondary hazards, can be evaluated by fragility curves (D'Ayala and Gehl 2014).

5.2 FRAGILITY FUNCTIONS OF BRIDGES IN FIKIRTEPE

In regard to the performance of transportation networks, two types of objects are considered: roadways (i.e. bridges, overpasses and road surfaces) and adjacent objects (i.e. slopes and buildings). To assign representative fragility curves to those objects, their structural parameters should be identified, which is a challenging task especially for regional analysis. As a preliminary investigation, fragility curves are assigned to 99 bridges identified in the extended area of Fikirtepe, which are marked by yellow pins in Figure 4.3 (Resvanis 2020). The usage and locations of these bridges are summarised in Table 4.1, where the bridge usage is classified into road bridges, railway bridges, foot bridges and junction bridges.

To assign fragility functions to the bridges, the taxonomy of structural parameters pro-posed by the SYNER-G project were used, which are summarised in Table 4.2 (SYNER-G 2012). Based on this taxonomy, parameters are identified for each bridge as summarised in Tables

4.3 to 4.9. For bridges whose drawings are available, the parameters are identified based on the drawings; otherwise, they are identified based on roadmap view provided by Google Earth street view. Using these parameters, the fragility functions are as-signed as summarised in Table 4.10.

In Tables 4.3 to 4.9, the parameters in brackets indicate that they are assumed based on common engineering practices, while question marks indicate that the parameter's attributes could not be assigned based on the Google Earth image stock because of image quality, position and/or distance. In addition, some overpasses are still under construction, making it challenging to identify relevant fragility functions. Such limitation reveals the high uncertainty in utilising fragility functions, which is common for regional-level analysis. To properly take into account such uncertainty, sensitivity analysis should be per-formed on resilience analysis results with regard to the choice on fragility functions.

Figure 5.3 Bridges identified in extended area of Fikirtepe, which are marked by yellow pins (image provided by Google Earth)

Table 5.1 Locations of identified bridges in Fikirtepe

Bridge type	Bridge location	Bridge ID
Road bridge	Bagdat Cd & & Istanbul Cerve Yolu (O-1 Highway)	R1
	Fahrettin Kerim Gokay Cd & Istanbul Cerve Yolu (O-1 Highway)	R2

	Hizirbey Cd & Istanbul Cerve Yolu (O-1 Highway)	R3
	Mandira Cd & Istanbul Cerve Yolu (O-1 Highway)	R4
	Acibadem Cd & Istanbul Cerve Yolu (O-1 Highway)	R5
	Ord. Prof.Dr. Fahrettin Kerin Gokay & Istanbul Cerve Yolu (O-1 Highway)	R6
	Kosuyolu Cd & D100 Highway	R7
	Alidede Sk. & D100 Highway	R8
	Acibadem Cd & D100 Highway	R9
	Cecen Sokagi & D100 Highway	R10
	Cecen Sokagi & D100 Highway side road	R11
	Uzuncayir & D100 Highway Side access	R12
	Goztepe Kavsagi & Libadiye Cd	R13
	Camlica Cikisi- K13 & Istanbul Cerve Yolu (0-4 and 0-1 Highway junction)	R14-R17
	Sht. Timur Aktemur Cd & Camlica Girisi- K13 (O-4 Highway)	R18
	Libadiye Cd & Camlica Girisi- K13 (O-4 Highway)	R19
	General Tahsin Yasici Cd & Camlica Girisi- K13 (O-4 Highway)	R20
	Esatpasa Cd & Camlica Girisi- K13 (O-4 Highway)	R21
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: (KM: 0 + 110.00 ~ 140.00) ADDITIONAL BRIDGE	R22
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: INTERSECTION-2	R23
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: SOUTH CONNECTION ROAD (KM: 0 + 432.29 ~ 580.41) RAMP	R24
	R24 KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: INTERSECTION-1	R25
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: ETAP-1 VIADUCT	R26
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: ETAP-2 VIADUCT	R27
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: ETAP-3 VIADUCT	R28
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: ETAP-4 VIADUCT	R29

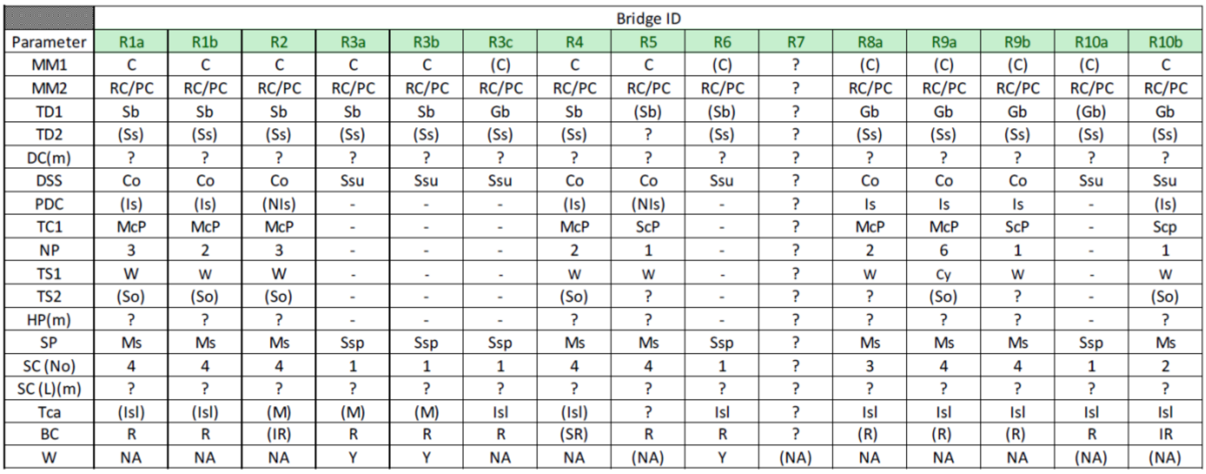
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERSECTION: ETAP-5 VIADUCT	R30
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERCHANGE INTERSECTION	R31
	KADIKÖY DISTRICT, D100 HIGHWAY FIKIRTEPE LOCATION: UZUNÇAYIR INTERCHANGE INTERSECTION	R32
	MEDENİYET UNIVERSITY BRIDGE	R33
Railway bridge	Sogutlucesme station southeast access & & Istanbul Cerve Yolu (O-1 Highway)	L1
Foot bridges	Karayollari 14. Sube Sefligi & D100 Highway	F1
	Park Ici Yolu & D100 Highway	F2
	E-5 Yanyolu & D100 Highway	F3-F4
	Acibadem Cd & Istanbul Cerve Yolu (O-1 Highway)	F5
	Demiray Sokagi & Camlica Girisi- K13 (O-4 Highway)	F6
Junction bridges	Istanbul Cerve Yolu (O-1 Highway) & D100 Highway Junction (Road Bridges)	J1-J8, J13
	Istanbul Cerve Yolu (O-1 Highway) & D100 Highway Junction (Footbridges)	J9-J12, J14
	Goztepe kavsagi & D100 Highway Junction (Road Bridges)	J15-J20
	Goztepe kavsagi & D100 Highway Junction (Footbridges)	J21-J24
	Altunizade kavsagi & Istanbul Cerve Yolu (O-1 Highway) Junction (Road Bridges)	J25-J29
	Altunizade kavsagi & Istanbul Cerve Yolu (O-1 Highway) Junction (Footbridges)	J30-J33

Table 5.2 Structural parameters used to assign fragility functions (SYNER-G 2012)

Abbreviation	Connotation	Categories
MM1	Material 1-C: Concrete, MX: Concrete-steel composites	C: Concrete MX: Concrete-steel composites
MM2	Material 2- RC: Reinforced concrete, PC:Prestressed concrete	RC: Reinforced concrete PC: Prestressed concrete
TD1	Type of superstructure-	Sb: Slab bridge Gb: Girder bridge
TD2	Type of deck	Ss: Solid slab B:Box girder
DC	Width of deck	In metre
DSS	Deck structural system	SSu: Simply supported Co: Continuous
PDC	Pier to deck connection	Nis: Not isolated/monolithic

		Is: Bearings
TC1	Type of superstructure connection	McP: Mutli-Column Pier ScP: Single-Column Pier
NP	Number of piers for column	-
TS1	Type of section of the pier	W:Wall Cy: Cylindrical R: Rectangular Ob: Oblong
TS2	Type of section of the pier 2	Ho: Hollow So: Solid
HP	Height of pier	In metre
SP	Number of spans	Ssp-Single span MS: Multi-span
SC (No)	Span characteristics	Number of spans
SC (L)	Span characteristics	Length of spans in metre
Tca	Type of connection to abutments	F: Free M:Monolithic Isl: Isolated (bearings)
BC	Bridge configuration	R: Regular SR:Semi-regular IR: Irregular
W	Signs of weathering	Y: Yes, apparent NA: Not apparent

Table 5.3 Identified structural parameters of Bridges from R1a to R10b



	Bridge ID														
Parameter	R1a	R1b	R2	R3a	R3b	R3c	R4	R5	R6	R7	R8a	R9a	R9b	R10a	R10b
MM1	C	C	C	C	C	(C)	C	C	(C)	?	(C)	(C)	(C)	(C)	C
MM2	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	?	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC
TD1	Sb	Sb	Sb	Sb	Sb	Gb	Sb	(Sb)	(Sb)	?	Gb	Gb	Gb	(Gb)	Gb
TD2	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	?	(Ss)	?	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)
DC(m)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
DSS	Co	Co	Co	Ssu	Ssu	Ssu	Co	Co	Ssu	?	Co	Co	Co	Ssu	Ssu
PDC	(Is)	(Is)	(NIs)	-	-	-	(Is)	(NIs)	-	?	Is	Is	Is	-	(Is)
TC1	McP	McP	McP	-	-	-	McP	ScP	-	?	McP	McP	ScP	-	Scp
NP	3	2	3	-	-	-	2	1	-	?	2	6	1	-	1
TS1	W	w	W	-	-	-	w	w	-	?	w	Cy	w	-	w
TS2	(So)	(So)	(So)	-	-	-	(So)	?	-	?	?	(So)	?	-	(So)
HP(m)	?	?	?	-	-	-	?	?	-	?	?	?	?	-	?
SP	Ms	Ms	Ms	Ssp	Ssp	Ssp	Ms	Ms	Ssp	?	Ms	Ms	Ms	Ssp	Ms
SC (No)	4	4	4	1	1	1	4	4	1	?	3	4	4	1	2
SC (L)(m)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Tca	(Isl)	(Isl)	(M)	(M)	(M)	Isl	(Isl)	?	Isl	?	Isl	Isl	Isl	Isl	Isl
BC	R	R	(IR)	R	R	R	(SR)	R	R	?	(R)	(R)	(R)	R	IR
W	NA	NA	NA	Y	Y	NA	NA	(NA)	Y	(NA)	NA	NA	NA	(NA)	(NA)

Table 5.4 Identified structural parameters of Bridges from R10c to R21b

	Bridge ID														
Parameter	R10c	R10d	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20a	R20b	R21a	R21b
MM1	C	C	C	C	C	(C)	?	C	?	C	C	C	C	C	C
MM2	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	?	RC/PC	?	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC
TD1	Gb	Gb	Sb	Sb	Gb	(Gb)	?	Gb	?	Gb	Gb	Gb	Gb	Gb	Gb
TD2	(Ss)	(B)	(Ss)	(Ss)	(Ss)	(Ss)	?	(B)	?	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)
DC	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
DSS	Ssu	Co	Ssu	Ssu	Co	Ssu	?	Co	?	Ssu	Co	Co	Ssu	Co	Ssu
PDC	-	NIs	-	-	Is	Is	?	NIs	?	Is	Is	Is	-	Is	-
TC1	-	ScP	-	-	ScP	ScP	?	ScP	?	ScP	ScP	ScP	-	ScP	-
NP	-	1	-	-	1	1	?	1	?	1	1	1	-	1	-
TS1	-	Cy	-	-	W	Cy	?	Cy	?	W	W	W	-	W	-
TS2	-	(Ho)	-	-	?	(So)	?	(Ho)	?	?	?	?	-	?	-
HP	-	?	-	-	?	?	?	?	?	?	?	?	-	?	-
SP	Ssp	Ms	Ssp	Ssp	Ms	Ms	?	Ms	?	Ms	Ms	Ms	Ssp	Ms	Ssp
SC (No)	1	3	1	1	(3)	(4)	?	3	?	4	2	2	1	2	1
SC (L)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Tca	Isl	M	M	M	?	Isl	?	Isl	?	Isl	Isl	Isl	Isl	Isl	Isl
BC	R	IR	R	R	?	?	?	R	?	SR	IR	IR	R	IR	R
W	Y	(NA)	NA	NA	NA	NA	(NA)	NA	(NA)	NA	NA	NA	NA	NA	NA

Table 5.5 Identified structural parameters of Bridges from R22a to J4

	Bridge ID														
Parameter	R22a	R22b	L1	F1	F2	F3	F4	F5	F6	J1	J2a	J2b	J2c	J3	J4
MM1	C	C	?	C	MX	C	MX	C	C	?	(MX)	C	C	?	(MX)
MM2	RC/PC	RC/PC	?	RC/PC	?	RC/PC	?	RC/PC	RC/PC	?	RC/PC	RC/PC	RC/PC	?	RC/PC
TD1	Gb	Gb	?	Gb	Gb	Gb	Gb	Gb	Gb	?	(Gb)	Sb	Sb	?	Gb
TD2	(Ss)	(B)	?	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	(B)	?	(Ss)	(Ss)	(Ss)	?	(Ss)
DC	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
DSS	Co	Co	?	Co	Co	Co	(Co)	Co	Ssu	?	Ssu	Ssu	Ssu	?	(Co)
PDC	Is	NIs	?	NIs	(Nis)	Is	Nis	Nis	Is	?	-	-	-	?	Is
TC1	McP	ScP	?	ScP	ScP	ScP	ScP	ScP	ScP	?	-	-	-	?	ScP
NP	5	1	?	1	1	1	1	1	1	?	-	-	-	?	1
TS1	Ob	W	?	W	R(Fluted)	W	V shaped*	W	W	?	-	-	-	?	W
TS2	(So)	(So)	?	?	(Ho)	?	?	(So)	(So)	?	-	-	-	?	?
HP	?	?	?	?	?	?	?	?	?	?	-	-	-	?	?
SP	Ms	Ms	?	Ms	Ms	Ms	Ms	Ms	Ms	?	Ssp	Ssp	Ssp	?	Ms
SC (No)	(4)	2	?	3	2	4	3	5	2	?	1	1	1	?	4
SC (L)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Tca	?	M	?	M	-	Isl	(F)	?	Isl	?	(Isl)	M	M	?	(Isl)
BC	?	?	?	R	R	R	(R)	(IR)**	R	?	R	R	R	?	R
W	NA	NA	NA	NA	NA	NA	NA	NA	NA	?	NA	NA	NA	?	NA

Table 5.6 Identified structural parameters of Bridges from J5a to J15c

	Bridge ID														
Parameter	J5a	J5b	J6	J7	J8	J9	J10a	J10b	J11	J12	J13	J14	J15a	J15b	J15c
MM1	C	C	C	C	?	MX	MX	?	?	?	?	MX	(MX)	(MX)	(MX)
MM2	RC/PC	RC/PC	RC/PC	RC/PC	?	?	?	?	?	?	?	?	RC/PC	RC/PC	RC/PC
TD1	Gb	Gb	(Gb)	Sb	?	Gb	Gb	?	?	?	?	Gb	(Gb)	(Gb)	(Gb)
TD2	(B)	(B)	(B)	(Ss)	?	(Ss)	(Ss)	?	?	?	?	(Ss)	(Ss)	(Ss)	(Ss)
DC	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
DSS	Co	Co	Co	Ssu	?	(Co)	?	?	?	?	?	Ssu	Ssu	(Co)	Ssu
PDC	Nis	Nis	Nis	-	?	(Nis)	Nis	?	?	?	?	(Nis)	Is	NIs/Is	Is
TC1	ScP	ScP	ScP	-	?	ScP	McP	?	?	?	?	McP	McP	ScP	ScP
NP	1	1	1	-	?	1	2	?	?	?	?	2	2	1	1
TS1	W	W	W	-	?	W	Cy	?	?	?	?	Cy	W	W	W
TS2	(So)	(So)	(So)	-	?	(So)	(Ho)	?	?	?	?	(Ho)	?	?	?
HP	?	?	?	-	?	?	?	?	?	?	?	?	?	?	?
SP	Ms	Ms	Ms	SsP	?	Ms	Ms	?	?	?	?	Ms	Ms	Ms	Ms
SC(No)	4	4	4	1	?	4	(4)	?	?	?	?	(7)	4	4	4
SC(L)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Tca	(F)	(F)	(F)	M	?	(F)	?	?	?	?	?	?	(Isl)	?	(Isl)
BC	R	R	R	R	?	(SR)	?	?	?	?	?	IR	R	R	R
W	Y	Y	NA	NA	(NA)	NA	NA	NA	NA	?	(NA)	NA	NA	NA	NA

Table 5.7 Identified structural parameters of Bridges from J16 to J29a

	Bridge ID														
Parameter	J16	J17	J18	J19	J20	J21	J22	J23	J24	J25	J26	J27	J28a	J28b	J29a
MM1	(C)	(C)	(C)	?	(MX)	(C)	(C)	?	(C)	(C)	(C)	(C)	(MX)	(C)	(C)
MM2	RC/PC	RC/PC	RC/PC	?	RC/PC	RC/PC	RC/PC	?	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC	RC/PC
TD1	(Gb)	(Gb)	(Gb)	?	Gb	Gb	Gb	?	Gb	Sb	Sb	Sb	Gb	Gb	Gb
TD2	(Ss)	(Ss)	(Ss)	?	(Ss)	(Ss)	(Ss)	?	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	(B)	(B)
DC	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
DSS	Co	Co	Co	?	(Ssu)	(Ssu)	Co	?	Co	Ssu	Ssu	Ssu	(Ssu)	Co	Co
PDC	?	?	?	?	Is	Is	Is	?	Is	-	-	-	Is	Nis	Nis
TC1	ScP	ScP	ScP	?	ScP	ScP	ScP	?	ScP	-	-	-	McP	McP	McP
NP	1	1	1	?	1	1	1	?	1	-	-	-	2	2	2
TS1	Cy/Ob	Cy/Ob	Cy/Ob	?	W	W	W	?	W	-	-	-	W	W	W
TS2	(So)	(So)	(So)	?	?	?	(So)	?	(So)	-	-	-	?	?	?
HP	?	?	?	?	?	?	?	?	?	-	-	-	?	?	?
SP	Ms	Ms	Ms	?	Ms	Ms	Ms	?	Ms	Ssp	Ssp	Ssp	Ms	Ms	Ms
SC (No)	2	2	2	?	3	4	2	?	2	1	1	1	4	4	4
SC (L)	?	?	?	?	?	?	?	?	?	?	?	?	?	?	?
Tca	?	?	?	?	Isl	Isl	Isl	?	Isl	?	?	?	?	?	?
BC	(R)	(R)	(R)	?	SR	R	R	?	R	R	R	R	R	R	R
W	(NA)	(NA)	(NA)	?	NA	NA	NA	?	NA	NA	NA	NA	NA	NA	NA

Table 5.8 Identified structural parameters of Bridges from J29b to R27b

	Bridge ID														
Parameter	J29b	J30	J31	J32	J33	R8b	R23	R24	R25	R26a	R26b	R26c	R26d	R27a	R27b
MM1	(MX)	C	C	C	MX	C	C	C	C	C	C	C	C	MX	MX
MM2	RC/PC	RC/PC	RC/PC	RC/PC	?	PC	RC	PC	RC	RC	RC	RC	RC	RC	RC
TD1	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb
TD2	(Ss)	(Ss)	(Ss)	(Ss)	(Ss)	Ss	B	Ss	B	B	B	B	Ss	Ss	Ss
DC(m)	?	?	?	?	?	9.5	10.4-11.4	7	13-14	10.5-16.6	9	9	9	9	16
DSS	(Ssu)	?	?	?	Co	Ssu	Co	Ssu	Ssu	Co	Ssu	Ssu	Ssu	Ssu	Ssu
PDC	Is	(Nis)	(Nis)	(Nis)	Nis	-	Is/Nis	Is	Is	Nis	Is	Is	Is	Is	Is
TC1	McP	ScP	ScP	ScP	ScP	-	McP	ScP	ScP	ScP/McP	ScP	ScP	ScP	ScP	ScP
NP	2	1	1	1	1	-	2	1	1	1/2	1	1	1	1	1
TS1	W	W	W	W	R	-	Cy	Ob	Ob	W/Cy	Ob	Ob	Ob	Ob	Ob
TS2	?	(So)	(So)	(So)	?	-	So	So	So	Ho/So	So	So	So	So	So
HP(m)	?	?	?	?	?	6.5	5.72-12.57	3.5-6.5	4.15-8	5.5-10.2	9.5-14	9.5-14	7.5-9.9	8-10	8-10
SP	Ms	Ms	Ms	Ms	Ms	Ssp	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms	Ms
SC (No)	4	(4)	4	4	4	1	11	6	7	4	2	2	4	4	2
SC (L)(m)	?	?	?	?	?	31	17.1-34.83	24-25	20-30	18-25	20.9-23.9	20.9-23.9	26-34.8	25-44	32-48.3
Tca	?	?	?	?	-	Isl	Isl	Isl	Isl	Isl	-	-	Isl	Isl	Isl
BC	R	IR	R	R	SR	R	IR	IR	IR	IR	IR	IR	IR	IR	IR
W	NA	NA	NA	NA	NA	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

Table 5.9 Identified structural parameters of Bridges from R27c to R33

	Bridge ID									
Parameter	R27c	R27d	R28	R29a	R29b	R29c	R30	R31	R32	R33
MM1	MX	MX	MX	MX	MX	MX	C	C	C	C
MM2	RC	RC	RC	RC	RC	RC	RC	PC	PC	PC
TD1	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb	Gb
TD2	Ss	Ss	Ss	Ss	Ss	Ss	B	Ss	Ss	Ss
DC(m)	11.5	9	16.6	11	11	12.5	14.5	18	24.5	12
DSS	Ssu	Ssu	Co	Ssu	Ssu	Co	Co	Ssu	Ssu	Ssu
PDC	Is	Is	Is	Is	Is	Is	Nis	Is	-	-
TC1	ScP	ScP	ScP	ScP	ScP	ScP	ScP	ScP	-	-
NP	1	1	1	1	1	1	1	1	-	-
TS1	Ob	Ob	W	Ob	Ob	W	W	Ob	-	-
TS2	So	So	So	So	So	So	Ho	So	-	-
HP(m)	8-10	8.2	11	7-11	3-7	3-7	5-12	6.17	6.75	6
SP	Ms	Ssp	Ms	Ms	Ms	Ms	Ms	Ssp	Ssp	Ssp
SC (No)	2	1	7	8	3	4	5	1	1	1
SC (L)(m)	33	20.54	33.8-53.5	31-49	35-41.3	38-49	18-25	28.15	35.37	26
Tca	Isl	Isl	Isl	Isl	Isl	Isl	Isl	Isl	Isl	Isl
BC	IR	R	IR	IR	IR	IR	IR	R	IR	R
W	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)	(NA)

Table 5.10 Selected fragility curves for bridges in extended area of Fikirtepe

Bridge ID	Selected fragility curve	Curve specification
R1A	SYNER-G deliverable D3.06.(2011)	ISR
R9A	SYNER-G deliverable D3.06.(2011)	ISR
J16	SYNER-G deliverable D3.06.(2011)	ISR
J17	SYNER-G deliverable D3.06.(2011)	ISR
J18	SYNER-G deliverable D3.06.(2011)	ISR
R22A	SYNER-G deliverable D3.06.(2011)	ISR
R10D	SYNER-G deliverable D3.06.(2011)	ISR
J15A	SYNER-G deliverable D3.06.(2011)	ISR
J28A	SYNER-G deliverable D3.06.(2011)	ISR
J29B	SYNER-G deliverable D3.06.(2011)	ISR
F5	SYNER-G deliverable D3.06.(2011)	ISR
J30	SYNER-G deliverable D3.06.(2011)	ISR
J10A	SYNER-G deliverable D3.06.(2011)	ISR
J14	SYNER-G deliverable D3.06.(2011)	ISR
ISR	SYNER-G deliverable D3.06.(2011)	ISR
R23	SYNER-G deliverable D3.06.(2011)	ISR
R25	SYNER-G deliverable D3.06.(2011)	ISR
R26a	SYNER-G deliverable D3.06.(2011)	ISR
R26b	SYNER-G deliverable D3.06.(2011)	ISR
R26c	SYNER-G deliverable D3.06.(2011)	ISR
R26d	SYNER-G deliverable D3.06.(2011)	ISR
R28	SYNER-G deliverable D3.06.(2011)	ISR
R29a	SYNER-G deliverable D3.06.(2011)	ISR
R14	Avsar *et al*. (2011)	MS_SC_SL
R10B	Avsar *et al*. (2011)	MS_SC_SL
R18	Avsar *et al*. (2011)	MS_SC_SL
J21	Avsar *et al*. (2011)	MS_SC_SL
F6	Avsar *et al*. (2011)	MS_SC_SL
R24	Avsar *et al*. (2011)	MS_SC_SL
R29b	Avsar *et al*. (2011)	MS_SC_SL
F2	Avsar *et al*. (2011)	MS_SC_SL
F4	Avsar *et al*. (2011)	MS_SC_SL

J9	Avsar *et al.* (2011)	MS_SC_SL
J33	Avsar *et al.* (2011)	MS_SC_SL
R30	Jeong and Elnashai (2007)	SM
J28B	Karakostas *et al.* (2006)	EAK_2003_Spectrum Y direction
J29A	Karakostas *et al.* (2006)	EAK_2003_Spectrum Y direction
R3A	Mander (1999)	Single span Seismic Design
R3B	Mander (1999)	Single span Seismic Design
R5	Mander (1999)	Single span Seismic Design
R6	Mander (1999)	Single span Seismic Design
R11	Mander (1999)	Single span Seismic Design
R12	Mander (1999)	Single span Seismic Design
J2B	Mander (1999)	Single span Seismic Design
J2C	Mander (1999)	Single span Seismic Design
J7	Mander (1999)	Single span Seismic Design
J25	Mander (1999)	Single span Seismic Design
J26	Mander (1999)	Single span Seismic Design
J27	Mander (1999)	Single span Seismic Design
R3C	Mander (1999)	Single span Seismic Design
R10A	Mander (1999)	Single span Seismic Design
R20B	Mander (1999)	Single span Seismic Design
R21B	Mander (1999)	Single span Seismic Design
R10C	Mander (1999)	Single span Seismic Design
J2A	Mander (1999)	Single span Seismic Design
R2	Moschonas *et al.* (2009)	311-Longitudinal with gap closure
R9B	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
R13	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
R19	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
R20A	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
R21A	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
R16	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
R22B	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J5A	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J5B	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J6	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
F1	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
F3	Moschonas *et al.* (2009)	221-Longitudinal with gap closure

J31	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J32	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J22	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
J24	Moschonas *et al.* (2009)	221-Longitudinal with gap closure
J15C	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
J20	Moschonas *et al.* (2009)	121-Longitudinal with gap closure
R8a	Nielson (2005)	MSC Concrete
R8B	Nielson (2005)	SS Concrete
R27d	Nielson (2005)	SS Concrete
R31	Nielson (2005)	SS Concrete
R32	Nielson (2005)	SS Concrete
R33	Nielson (2005)	SS Concrete
R1B	Shinozuka *et al.* (2000)	Analytical approach, Bridge 2
J15B	Ramanathan *et al.* (2010)	MSC Steel Bridge
J4	Ramanathan *et al.* (2010)	MSC Steel Bridge
R27a	Ramanathan *et al.* (2010)	MSC Steel Bridge
R27b	Ramanathan *et al.* (2010)	MSC Steel Bridge
R27c	Ramanathan *et al.* (2010)	MSC Steel Bridge
R29c	Ramanathan *et al.* (2010)	MSC Steel Bridge
R7	Not able to be classified	N/A
R15	Not able to be classified	N/A
R17	Not able to be classified	N/A
J8	Not able to be classified	N/A
J13	Not able to be classified	N/A
J1	Not able to be classified	N/A
J3	Not able to be classified	N/A
J19	Not able to be classified	N/A
J10B	Not able to be classified	N/A
J11	Not able to be classified	N/A
J12	Not able to be classified	N/A
J23	Not able to be classified	N/A

6 Conclusions

HUB-Istanbul work package (WP) 2.6 aims to analyse multi-hazard disaster resilience of urban transportation networks, especially for emerging cities and to enhance social equality. To this end, this deliverable summarises the general objectives and scope of the research, while investigating relevant challenges, solutions and data as a groundwork for the prospective research of WP 2.6. Based on the reflections, the analysis of the testbed, Fikirtepe, Istanbul, Turkey is discussed by identifying the hazard scenario and assigning fragility curves to the bridges located around the region. This discussion will be suppl-mented by the second deliverable, which discusses another type of data required for the present study to evaluate traffic functionality of roadways and network performance. The comprehensive discussions on data requirement and availability will lead to the subsequent deliverables that undertake the full-scale analysis, i.e. developing probabilistic models, performing resilience analysis, deriving optimal decision scenarios and applying to the case study area.

It is noted that the illustrated multi-layered data and models are geographically related, all being located in the analysed area. Therefore, they should be obtained as georeferenced data so that they can be mapped for visualisation and computation. Such data can be obtained from open source data, e.g. seismic hazard maps from GEM and road maps from OpenStreetMap (https://www.openstreetmap.org/). Digital elevation model (DEM), which presents ground elevation information, is also a crucial georeferenced data particularly for evaluating flood risks. While various types of DEM are available from complimentary data to commercial ones with varying resolutions and information, high-resolution data are often commercial and costly. On the other hand, in case there is no existing map data, e.g. buildings distribution, new maps can be created using satellite imagery, e.g. im-ages provided by Google Earth. Once all map data are obtained, they can be handled through Geographic Information Systems (GIS) software such as QGIS and ArcGIS, which can be combined with other applications, e.g. Python, to compute the data.

This preliminary investigation highlights several topics for future research, which can be addressed either during this project or by another projects afterwards. Hazard analysis can become more comprehensive by an expanded scope, such as aftershocks of earthquakes, human-made hazards (e.g. urban fire and terrorist attack) and climate change. While resilience analysis requires various types of data, those data need a continuous update to reflect local characteristics (e.g. hazard models, fragility curves, traffic capacity of damaged roadways and recovery rates of damaged structures). In addition, the definition of social equality is not constant nor absolute, which requires constant review and modification to serve contemporary needs.

Conclusions

References

AFAD. (2020). Turkey Disaster Database (TABB). Accessed on 19 October 2020. https://tabb-analiz.afad.gov.tr/

Argyroudis, S. A., Mitoulis, S., Winter, M. G., and Kaynia, A. M. (2019). Fragility of transport assets exposed to multiple hazards: State-of-the-art review toward infrastructural resilience. *Reliability Engineering & System Safety*, 191, 106567.

Avsar O., Yakut A., Caner A. (2011). Analytical fragiltiy curves for ordinary highway bridges in Turkey, *Earthquake Spectra*, 27(4), 971-996.

Byun, J.-E. and Song, J. (2020). Efficient probabilistic multi-objective optimization of complex systems using matrix-based Bayesian network. *Reliability Engineering & System Safety*, 200, 106899.

D'Ayala, D., and Gehl, P. (2014). *INFRARISK Deliverable 3.1 Hazard Distribution Matrix*. INFRARISK CONSORITUM.

D'Ayala, D., and Gehl, P. (2015). *INFRARISK Deliverable 3.2 Fragility Functions Matrix*. INFRARISK CONSORITUM.

Davies, A. J., Sadashiva, V., Aghababaei, M., Barnhill, D., Costello, S. B., Fanslow, B., Headifen, D., Hughes, M., Kotze, R., Mackie, J., Ranjitkar, P., Thompson, J., Troitino, D. R., Wilson, T., Woods, S., and Wotherspoon, L. M. (2017). Transport infrastructure performance and management in the South Island of New Zealand, during the first 100 days following the 2016 Mw 7.8 'Kaikōura' earthquake. *Bulletin of the New Zealand Society for Earthquake Engineering*, 50(2), 271–299.

Demircioğlu, M. B., Şeşetyan, K., Duman, T. Y., Can, T., Tekin, S., and Ergintav, S. (2018). A probabilistic seismic hazard assessment for the Turkish territory: part II—fault source and background seismicity model. *Bulletin of Earthquake Engineering*, 16(8), 3399-3438.

Domaneschi, M., Cimellaro, G. P., and Scutiero, G. (2019). A simplified method to assess generation of seismic debris for masonry structures. *Engineering Structures*, 186, 306–320.

European Commission. (2010). Risk Assessment and Mapping Guidelines for Disaster Management. *Commission Staff Working Paper SEC (2010) 1626 final, European Commission*, 1–43.

Erdik, M. (2000). *Report on 1999 Kocaeli and Düzce (Turkey) earthquakes*. Boğaziçi Üniversitesi, Kandilli Rasathanesi ve Deprem Araştirma Enstitüsü.

Gehl, P. and D'Ayala, D. (2016). Development of Bayesian networks for the multi-hazard fragility assessment of bridge systems. *Structural Safety*, 60, 37–46.

Gehl, P. and D'Ayala, D. (2018). System loss assessment of bridge networks accounting for multi-hazard interactions. *Structure and Infrastructure Engineering*, 14(10), 1355-1371.

Gidaris, I., Padgett, J. E., Barbosa, A. R., Chen, S., Cox, D., Webb, B., and Cerato, A. (2017). Multiple-hazard fragility and restoration models of highway bridges for regional risk and resilience assessment in the United States: State-of-the-art review. *Journal of Structural Engineering*, 143(3), 04016188.

Gill, J. C., and Malamud, B. D. (2014). Reviewing and visualizing the interactions of natural hazards. *Reviews of Geophysics*, 52(4), 680-722.

Greiving, S., Fleischhauer, M., and Lückenkötter, J. (2006). A Methodology for an integrated risk assessment of spatially relevant hazards. *Journal of Environmental Planning and Management*, 49(1), 1–19.

INFRARISK. (2016). *Novel Indicators for identifying critical INFRAstructure at RISK from natural hazards – INFRARISK*. Accessed on 19 October 2020. http://www.infrarisk-fp7.eu/

Jeong, S.H. and Elnashai, A.S. (2007). Probabilistic fragility analysis parameterized by fundamental response quatities. *Engineering Structures*, 29(6), 1238-1251.

Kappes, M. S., Keiler, M., von Elverfeldt, K., and Glade, T. (2012). Challenges of analyzing multi-hazard risk: A review. *Natural Hazards*, 64(2), 1925-1958.

Karakostas, C., Makarios, T., Lekidis, V., and Kappos, A. (2006). Evaluation of vulnerability curves for bridges – a case study. *First European Conference on Earthquake Engineering and Seismology*, 3-8 September, Geneva, Switzerland.

Macabuag, J., Rossetto, T., Ioannou, I., and Eames, I. (2018). Investigation of the effect of debris-induced damage for constructing tsunami fragility curves for buildings. *Geosciences*, 8(4), 117.

Maio, R., Tsionis, G., Sousa, M. L., and Dimova, S. L. (2017). Review of fragility curves for seismic risk assessment of buildings in Europe. *Proceedings of the 16th World Conference on Earthquake*, 9-13.

Mander, J.B. (1999). Fragility curve development for assessing the seismic vulnerability of highway bridges. University at Buffalo, State University of New York.

Martínez-Gomariz, E., Gómez, M., Russo, B., and Djordjević, S. (2018). Stability criteria for flooded vehicles: a state-of-the-art review. *Journal of Flood Risk Management*, 11, S817–S826.

Mavrouli, O., Fotopoulou, S., Pitilakis, K., Zuccaro, G., Corominas, J., Santo, A., Cacace, F., De Gregorio, D., Di Crescenzo, G., Foerster, E., and Ulrich, T. (2014). Vulnerability assessment for reinforced concrete buildings exposed to landslides. *Bulletin of Engineering Geology and the Environment*, 73(2), 265-289.

Mazzoni, S., Castori, G., Galasso, C., Calvi, P., Dreyer, R., Fischer, E., Fulco, A., Sorrentino, L., Wilson, J., Penna, A., and Magenes, G. (2018). 2016–2017 Central Italy Earthquake Sequence: Seismic Retrofit Policy and Effectiveness. *Earthquake Spectra*, 34(4), 1671–1691.

Moschonas, I.F., Kappos, A.J., Panetsos, P., Papadopoulos, V., Makarios, T. and Thanopoulos, P. (2009). Seismic fragilitycurves for greek bridges: methodology and case studies. *Bulletin of Earthquake Engineering*. 7(2), 439-468.

Moya, L., Mas, E., Yamazaki, F., Liu, W., and Koshimura, S. (2020). Statistical analysis of earthquake debris extent from wood-frame buildings and its use in road networks in Japan. *Earthquake Spectra*, 36(1), 209-231.

Muntasir Billah, A. H. M., and Shahria Alam, M. (2015). Seismic fragility assessment of highway bridges: a state-of-the-art review. *Structure and Infrastructure Engineering*, 11(6), 804–832.

NIBS. (2009). HAZUS-MH 2.1: Technical Manual, Flood Model, Federal Emergency Management Agency, Washington DC.

NIBS. (2011). HAZUS-MH 2.1: Technical Manual, Earthquake Model, Federal Emergency Management Agency, Washington DC.

Nielson, B.G. (2005). Analytical fragility curves for highway bridges in moderate seismic zones. Ph.D. Thesis. Georgia Institute of Technology, US.

Olmsted, S.M. (1984). On representing and solving decision problems. Stanford University.

Peduto, D., Ferlisi, S., Nicodemo, G., Reale, D., Pisciotta, G., and Gullà, G. (2017). Empirical fragility and vulnerability curves for buildings exposed to slow-moving landslides at medium and large scales. *Landslides*, 14(6), 1993-2007.

Pitilakis, K. (2009). *SYNER-G Deliverable 3.12 Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain*. SYNER-G CONSORTIUM.

Pitilakis, K., Crowley, H., and Kaynia, A. (2014). *SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk*. Springer, Berlin.

Porta, S., Crucitti, P., and Latora, V. (2006). The network analysis of urban streets: A primal approach. *Environment and Planning B: Planning and Design*, 33(5), 705–725.

Pregnolato, M., Ford, A., Wilkinson, S. M., and Dawson, R. J. (2017). The impact of flooding on road transport: A depth-disruption function. *Transportation Research Part D: Transport and Environment,* 55, 67–81.

Ramanathan, K., Desroches, R., and Padgett, J. (2010). Analytical Fragility Curves for Multispan Continuous Steel Girder Bridges in Moderate Seismic Zones. *Transportation Research Record: Journal of the Transportation Research Board*, 2202(1), 173-182.

Resvanis, S. (2020). Seismic fragility assessment of critical bridges for transport network resilience analysis, with limited knowledge. MSc thesis. University College London, UK.

Rossetto, T., D'Ayala, D., Ioannou, I., and Meslem, A. (2014). Evaluation of Existing Fragility Curves. In SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. pp 47-93. Springer Netherlands

Saarinen, T. F., Hewitt, K., and Burton, I. (1973). The Hazardousness of a Place: A Regional Ecology of Damaging Events. Geographical Review, 63(1), 134.

Sesetyan, K., Demircioglu, M. B., Duman, T. Y., Can, T., Tekin, S., Azak, T. E., and Fercan, Ö. Z. (2018). A probabilistic seismic hazard assessment for the Turkish territory—part I: the area source model. *Bulletin of Earthquake Engineering*, 16(8), 3367-3397.

Shinozuka, M., Feng, M.Q., Lee, j., and Naganuma, T. (2000). Statistical analysis of fragility curves. *ASCE Journal of Engineering Mechanics*, 126(12), 1224-1231.

SYNER-G. (2012). *SYNER-G: Systemic Seismic Vulnerability and Risk Analysis for Buildings, Lifeline Networks and Infrastructures Safety Gain*. Accessed on 19 October 2020. http://www.vce.at/SYNER-G/files/project/proj-overview.html

Teo, F. Y., Xia, J., Falconer, R. A., and Lin, B. (2012). Experimental studies on the interaction between vehicles and floodplain flows. *International Journal of River Basin Management*, 10(2), 149–160.

Yepes-Estrada, C., Silva, V., Rossetto, T., D'Ayala, D., Ioannou, I., Meslem, A., and Crowley, H. (2016). The Global Earthquake Model Physical Vulnerability Database. *Earthquake Spectra*, 32(4), 2567–2585.

Zhiqiang, W., and Lee, G. C. (2009). A comparative study of bridge damage due to the Wenchuan, Northridge, Loma Prieta and San Fernando earthquakes. *Earthquake Engineering and Engineering Vibration*, 8(2), 251-261.