Towards Regional Safety Assessment of Bridge Infrastructure

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ABSTRACT: In the aftermath of disasters, it is increasingly recognized that while their occurrence is often inevitable, proactive risk management through adequate prioritization and preventative measures ought to be of utmost importance. Regions with large infrastructure networks (e.g. roadway bridges) exposed to different types of hazards and structural ageing/deteriorating over time are particularly vulnerable. Such vulnerability can become even more relevant in developing countries, which can face higher challenges in coping with extreme events. This paper describes a study on the bridge infrastructure network in the Former Yugoslav Republic of Macedonia (FYROM), Israel and Italy as part of the project INFRA-NAT (www.infra-nat.eu). An extended database of each country's bridge population is developed through a data collection form and allows for a detailed exposure model of the bridge network to be compiled. By considering the general characteristics of the bridge population, a representative sample of bridges is chosen to develop fragility functions for bridges exposed to seismic hazard. The connectivity of the network is modelled and the entire bridge network vulnerability is considered in a more comprehensive and global manner for seismic hazard and infrastructure ageing. The scope of this work is to provide practical web-based tools and databases for each country with which more informed decisions can be made related to the most vulnerable parts of the country and where resources should be invested for increased resilience.

1. INTRODUCTION

A functioning infrastructure network during emergencies is an important aspect for every country. Bridges represent a critical facet as they provide reliable modes of transportation throughout a region (i.e. railway, roads). A major component in determining the vulnerability of bridge infrastructure is associated with seismic events. Ensuring bridges do not collapse and are usable during the aftermath of an earthquake is crucial for relief efforts (e.g. access to hospitals, aid to be dispatched). For instance, within Italy alone, much of the bridge infrastructure was constructed prior to the 1970s, primarily in the construction boom that followed the war in Europe (Calvi et al. 2018). These ageing structures suffer from deterioration and corrosion which represents an additional source of hazard. Over the past 2 years, 4 bridges have collapsed in Italy, killing 50 people and injuring 23 in what is clearly not just an issue of natural hazard such as earthquakes. This confirms that an approach to consider multiple hazards is needed when assessing the vulnerability of bridge infrastructure. As such, the mitigation of risk related to both seismic and ageing/deterioration hazards is the focus of a currently on-going research project entitled INFRA-NAT – Increased Resilience of Critical Infrastructure to Natural and Human-Induced Hazards, which comprises the Former Yugoslav Republic of Macedonia (FYROM), Israel and Italy as project partners.

Many past studies have addressed the vulnerability of single elements of bridge networks but few have considered the entire network itself, an issue recently highlighted by Gidaris *et al.* (2017). Whereas the former is important to estimate the capacity of individual bridges during an earthquake event, the latter is extremely important when it comes to assessment in a broader sense (e.g. indirect economic losses due to disruption and emergency response planning). Gidaris *et al.* (2017) have stressed that, to date, no study comprehensively provides for the multi-hazard assessment and restoration of bridge networks in the regional risk and resilience context. INFRA-NAT aims to address this need in the scientific context by applying a methodology for bridge network vulnerability assessment at regional and/or national level. Furthermore, when the increased resilience of infrastructure is sought, a key aspect is to allocate resources efficiently since there are seldom enough funds to both evaluate and upgrade an entire inventory of an infrastructure. Thus, a progressive and iterative approach is sought to ensure adequate resource allocation to the areas that are most vulnerable. This is particularly important if the purpose of the risk assessment is to carry out preventative measures (e.g. increased maintenance protocols, retrofitting, limiting use or complete closure).

Considering the above, the objectives of the INFRA-NAT project are, for each of the three countries that make up the case-study, to: 1) critically review existing seismic hazard models; 2) collect and harmonize full bridge exposure databases; 3) characterize vulnerability via existing analysis methods stemming from past studies on seismic risk; and 4) integrate the collected information and assessment tools within a web-based platform that will identify critical nodes in an infrastructure network and allow for the optimal resource allocation by the relevant public and private stakeholders. This paper focuses on these aforementioned aspects, presenting the information collected and work developed to date followed by a conceptual overview of the work yet to be developed as part of this project.

2. HAZARD

A principal ingredient of any seismic risk assessment study is a hazard model that can estimate the ground shaking intensity expected at the sites of interest. This section presents a brief review of the models available in each of the three regions involved in the INFRA-NAT project in addition to some of the preliminary results obtained.

2.1. Characterization of seismic hazard

2.1.1. FYROM

FYROM is a seismically active region in the southern Balkan region. Until 1990, seismic design regulations were based on maximum expected intensities maps, which were expressed in terms of different macroseismic intensity scales (Salic et al. 2012). The first seismic hazard maps that were specifically produced for FYROM following a fully probabilistic approach (i.e. PSHA) were the ones generated during the project “Harmonization of Seismic Hazard Maps for the Western Balkan Countries” (BSHAP) in 2010 (Mihaljević et al. 2017). The SHARE model, described in Section 2.1.3 for Italy, also covers FYROM and it represents the more up to date hazard study for the country. Galasso *et al.* (2013) also describe a study that was developed as part of the flood and earthquake risk assessment for Albania, Serbia and FYROM.

2.1.2. Israel

Two hazard studies are available for Israel, the spectral acceleration maps for the Amendment N. 5 (Klar et al. 2011) and the earthquake model of the Middle East region (EMME) (Danciu et al. 2018). The Amendment N. 5 seismic hazard maps have been developed following the standard PSHA approaches to provide design spectra for the Israeli building code. Previous to the Amendment N. 5, the design spectrum in Israel was a fixed shape spectrum anchored to the PGA. Such type of spectrum did not represent a specific probability of exceedance but rather a correspondence to the anchoring value of peak ground acceleration (PGA). The EMME model is a regional study carried out to assess the hazard of a wide area stretching from the Eastern Mediterranean across the Middle East.

2.1.3. Italy

The two most recent probabilistic seismic hazard analysis (PSHA) studies performed in Italy are the MPS04 (Mappa di pericolosità sismica 2004), developed by the Istituto Nazionale Geofisica e Vulcanologia (INGV) in 2004 and adopted by the Italian building code in 2008 (Stucchi et al. 2011), and the ESHM13 (Woessner et al. 2015) which is the result of the project seismic hazard harmonization in Europe (SHARE), funded by the European community and commonly referred to as the SHARE hazard model. This model covers Europe and Turkey and is based on data compiled homogeneously across national borders.

2.2. Hazard analysis results

From each of the seismic hazard models discussed above, a number of sites were examined to characterize the hazard for each of the partner countries. In the case of Italy, which will be discussed further in Section 3.2, the Campania region around Naples was chosen as the case study region. In this region, specific information (Level 2 or 3 as per Figure 4) was available for 47 bridges and hence their locations were examined in more detail. Figure 1 shows the PGA map for a return period of 475 years at the bridge locations, although a total of seven return periods were examined, with return periods ranging from 100 to 10,000 years. A moderate level of hazard is noted around the city of Naples with an increase in expected ground shaking as one moves inland towards Campobasso.

In FYROM, a dataset of bridges with detailed information was not available at the time of the initial hazard characterization but the location of bridges collected from OpenStreetMap (see further details in Section 3) was obtained. Considering both the general distribution of the bridge infrastructure and the seismic hazard characterized at PGA, fives pertinent locations can be tentatively identified also and are shown in Figure 2. Again, a reasonably high of hazard can be noted throughout the country.

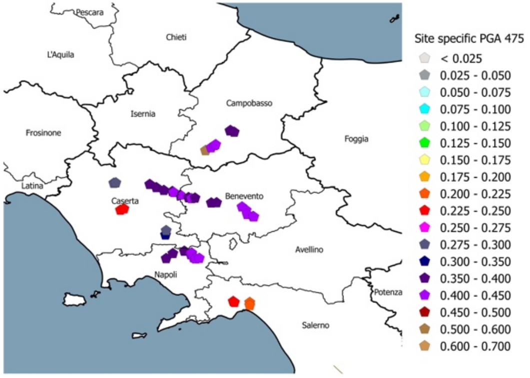


Figure 1: PGA for a return period of 475 years taking into account soil conditions for the locations of 47 bridges in the Campania region of Italy.

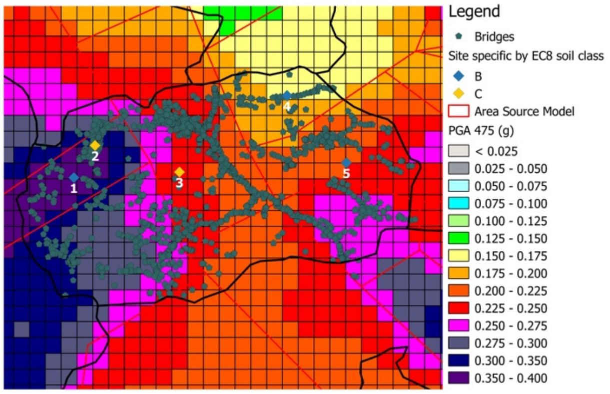


Figure 2: PGA for 475 years return period of the SHARE hazard model (rock conditions) for the entire territory of FYROM.

Similarly, in Israel, a dataset of bridges with a very general information was initially obtained with OpenStreetMap. Here, four locations characterized by different hazard levels and soil conditions were selected and indicated in Figure 3. The general seismicity is quite clear from this diagram, with the expected ground shaking increasing significantly as one moves inland from Tel-Aviv towards the Jordan River.

3. EXPOSURE

The next step following the characterization of suitable hazard models in risk assessment is the development of an exposure model for the structures of interest. To this end, INFRA-NAT has generated a database of bridges for each of the three participant countries via a data collection form. Furthermore, this database should be specific enough to conduct numerical analysis and develop fragility function databases required in later sections.

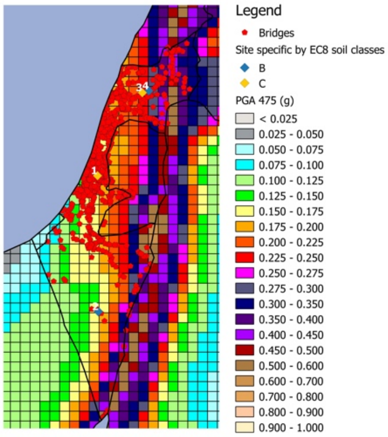


Figure 3: PGA for 475 years return period of the EMME hazard model (rock conditions) for the entire territory of Israel.

3.1. Exposure data collection

In order to collect the information about different bridge typologies, the Eucentre Foundation, which comprises the Italian partner, developed a digital collection form that can be used to document and synthesize bridge data. This collection form is sufficiently generic so that it can be used in each of the participating countries and other countries that will benefit from this project's outputs. This collection form, which is available online here, includes information about the bridge such as location, material type, deck and pier details, information on the supports and bearings in addition to general information on the current condition of the bridge with regards to damage and ageing.

Using this data collection form, users may compile the relevant information in two ways: 1) a desktop study whereby users do not physically visit the bridge but rather make use of information that may be gathered online from sources like Google Street View or OpenStreetMaps; or 2) via a full inspection by visiting the bridge.

3.2. Summary of bridge data inventories

For each of the countries examined in the INFRA-NAT project, this data collection form has been recently implemented. However, in order to somewhat categorize the differing levels of information that may be collected for different sources, this has been divided in levels of knowledge as depicted graphically in Figure 4 and described as follows:

- Level 0: Information of the existence, location and overall length of the bridge. This information is used to determine the total amount of bridges in the inventory.
- Level 1: Basic information of the structural system and material of the bridge is known, as well as incomplete geometrical characteristics of the structural elements. This information can be used to classify the assets according to a taxonomy scheme and in some cases, derive simplified calculations on the structural behavior of the bridge.
- Level 2: Complete information of the bridge geometry is known as well as information regarding the current state of the bridge, visible damage of the structure is known and recorded. This information is usually gathered though a site inspection.
- Level 3: Information on the structural reinforcement configurations, material properties and foundation characteristics are known. This information is gathered by processing and examination of construction blueprints.

The current paper describes the Level 0 and Level 1 information that has been made available of the inventories in each of the countries case study, which was gathered from digital resources or from existing local census information for which the team members have obtained access to.

Initially, data was collected using OpenStreetMap to get a general idea of the overall bridge populations of each country. Using this, the quantity and length of bridges could be identified and disaggregated at a provincial level for each case study using GIS software, and constituted the base of the bridge exposure model.

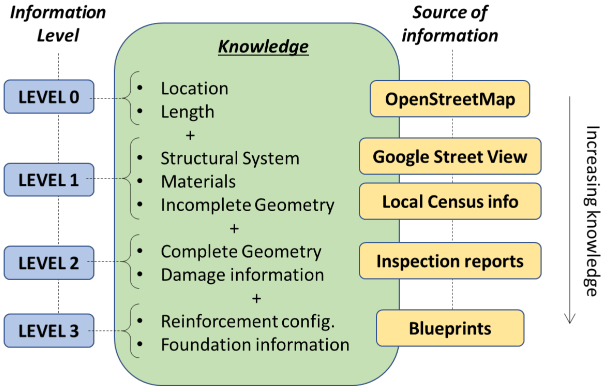


Figure 4: Levels of knowledge of inventory assets.

A preliminary screening of the bridge networks in FYROM and Israel indicates that they both possesses about 2000 bridge, which renders the consideration of the entire country as case study for analysis possible. As for the previous case, the OpenStreetMap metadata regarding bridge location and length was processed for each province and a total amount of 2,034 and 2,089 bridges were identified as shown in Figure 5 and Figure 6 for FYROM and Israel, respectively.

In the case of Italy, the preliminary screening of assets indicated a total of over 100,000 bridges nationally which required the scope to be limited to a specific case-study region that can be thoroughly assessed with the time and resources available in the INFRA-NAT project. This was also done to ensure that the size of the bridge inventories in each country are of a comparable scale. As such, the region of Campania in southern Italy was chosen, as seen in Figure 7. This region was selected since it possesses a high density of infrastructure and is exposed to high seismic hazard with respect to other parts of the country.

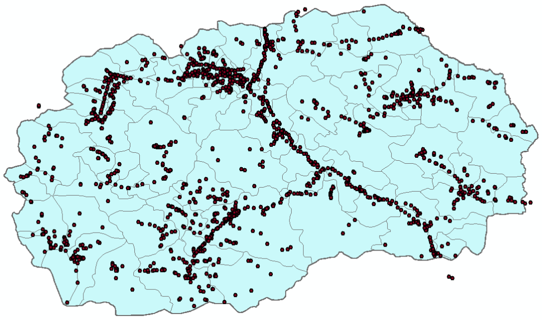


Figure 5: Inventory of bridges in FYROM detected with OpenStreetMap.

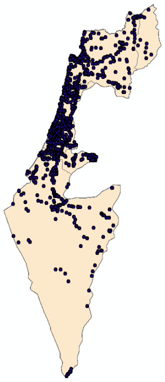


Figure 6: Inventory of bridges in Israel detected with OpenStreetMap.

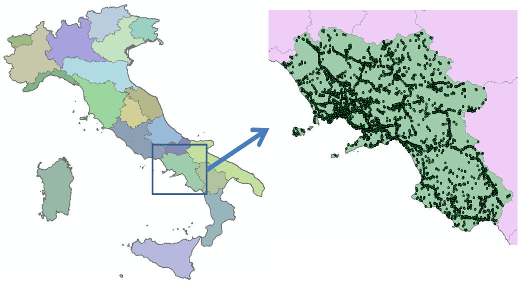


Figure 7: Italian case study region of Campania around Naples.

To give a brief overview of the results collected during the utilization of this bridge data collection form in each of the three case study countries, the following text describes some salient parameters. The distribution of the structural system of the bridges found in FYROM are illustrated in Figure 8, in addition to Figure 9 for Israel. It can be seen how simply supported beams tend to constitute the majority of bridge structural systems in FYROM, whereas Israel tends to have more continuous girder systems.

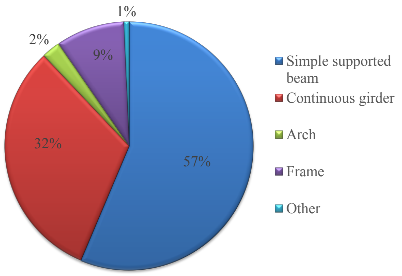


Figure 8: Distribution of the structural systems used for bridge structures in FYROM.

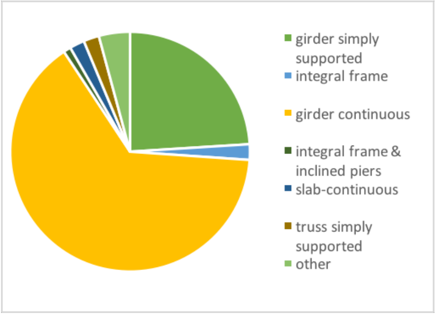


Figure 9: Illustration of the structural systems used for the bridge structures in Israel.

Regarding the main structural material used for the Italian inventory, these are depicted in Figure 10 showing that the majority of bridge structures in this region of Italy are built with reinforced concrete.

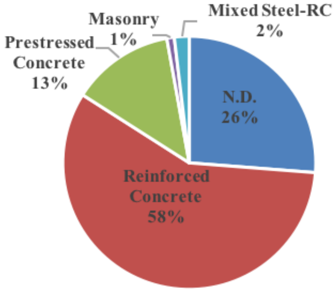
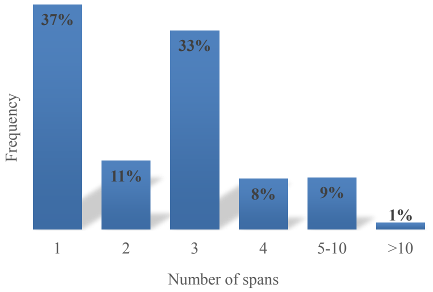


Figure 10: Distribution of the main construction material for the Italian case study of Campania.

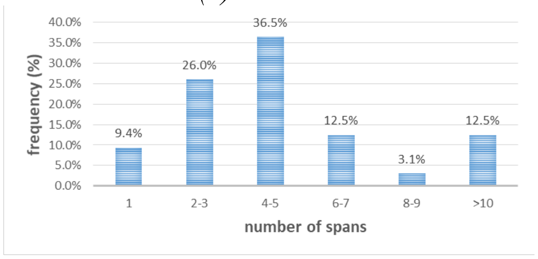
Finally, the distribution of the number of spans typically found in the bridge structures in each of the case study countries is shown in Figure 11. In Italy, it can be noted that the vast majority of bridges are single span whereas FYROM tends to have more bridge two and three span bridges. Israel, on the other hand, typically tends to have bridges with multiple spans.

4. VULNERABILITY

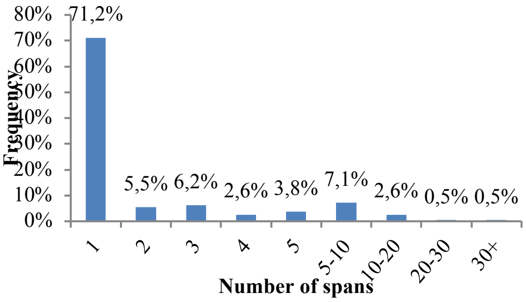
Following the identification of a suitable hazard model and the development of an exposure database, the next step will be to develop vulnerability models for the various bridge structures. The INFRA-NAT project has not yet reached this stage so just the process to be followed is described herein. To this end, a number of numerical models will be developed for the most representative bridge taxonomies in the regions examined.



(a) FYROM



(b) Israel

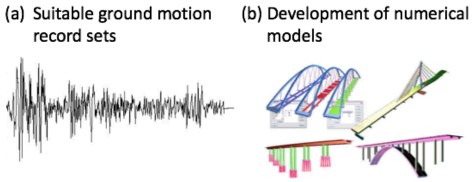


(c) Italy

Figure 11: Distribution of the typical number of spans found for bridges in (a) FYROM, (b) Israel and (c) Campania, Italy.

These numerical models, developed using the BRITNEY platform outlined in Borzi et al. (2015), will be subjected to earthquake records consistent to quantify the exceedance of various limit states in each bridge, as illustrated in Figure

12. The effects of ageing will be accounted for in the numerical modelling by considering their impact on material properties and reinforcement content over time and the subsequent impact on the fragility analysis results. Repeating this process, fragility function sets for the bridge infrastructure classes will be derived. Fragility function uncertainty, including aleatory earthquake ground motion variability and epistemic numerical modelling uncertainty, will be incorporated to maintain in a fully probabilistic workflow.


(a) Suitable ground motion record sets
(b) Development of numerical models

(c) Development of fragility functions describing various states of bridge damage

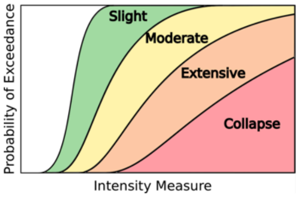


Figure 12: Illustration of the use of the numerical models developed from collected bridge data in tandem with the characterized seismic hazard to develop sets of fragility functions for each bridge typology.

5. BRIDGE NETWORK ASSESSMENT

At this point, a bridge network risk model in each participant country will be developed. The hazard and exposure have already been characterized and the vulnerability for these bridge structures is currently underway and will be carried out as described in the previous section. What remains is how this information collected and developed can be used to assess bridge networks as a whole. This section will briefly describe what this entails.

By considering locations in a region as nodes connected by the different road networks and inevitably the bridges, a conceptual illustration is shown in Figure 13. For each bridge structure at a certain location within in a given bridge network, an expected level of ground shaking may be estimated for a scenario earthquake. The spatial correlations between the ground shaking at the different bridge locations is account for to generate what may be referred to as a shake map. For each bridge structure, the probability of different damage states (e.g. collapse) may be estimated and the various tags of performance assigned, as shown Figure 13. This may be repeated for different scenarios or also using a time-dependent approach.

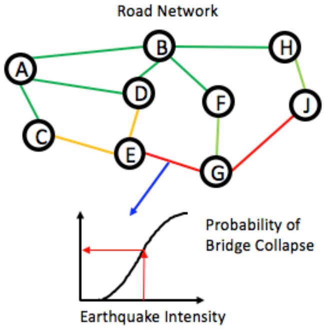


Figure 13: Illustration of a hypothetical bridge network and the use of fragility functions to estimate the probability of different levels of damage for a give shake map distribution.

Using this information, a methodology with which to establish the consequences due to the disruption bridge infrastructure network will be established. This involves the potential impacts that the loss of a particular bridge would have on the local and regional community. This will be examined in the context of both direct economic loss to repair the bridge and indirect economic loss to the disruption to the surrounding community. In addition, the availability of alternative routes and redundancy of the bridge network in different regions will be investigated so as to ensure the maintenance of access for essential services.

As a result, a more informed decision-making process will be developed for the allocation of resources to improve the overall resiliency of bridge infrastructure networks. This is because it will target the more critical parts of the infrastructure network that have the most significant impact on the functionality and resilience of the overall bridge infrastructure network.

6. CONCLUSIONS

This paper has described a study on bridge infrastructure networks in the Former Yugoslav Republic of Macedonia (FYROM), Israel and Italy, as part of the EU-funded INFRA-NAT project. It first reviewed the relevant seismic hazard models in each region followed by how an exposure model may be then collected via a data collection form also developed as part of the project. An extended database of each country's bridge population was developed using this data collection form and some of the salient bridge population characteristics in each country were outlined. It was then described how by considering the general characteristics of the bridge population, a representative sample of bridges will be used as part of future project work to develop fragility functions for bridges exposed to seismic hazard. The main aim of this work will be therefore to provide practical web-based tools with which more informed decisions can be made related to where resources should be invested for increased resilience. At the same time, the results may also enable a better understanding of the relevance of the vulnerability level of critical infrastructure in the different analyzed countries, correlating it to the corresponding levels of development, as well as other socio-economic variables.

7. ACKNOWLEDGEMENTS

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