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REGIONAL SAFETY ASSESSMENT OF EXISTING BRIDGE INFRASTRUCTURE EXPOSED TO SEISMIC HAZARD

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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, especially when featuring many bridges that were built prior to the introduction of seismic design guidelines in the 1970s (or later). This paper describes and presents the main outcomes of the two-year EU-funded project INFRA-NAT (Increased Resilience of Critical Infrastructure to Natural and Human-Induced Hazards, www.infra-nat.eu), which focused on the bridge infrastructure networks in the Republic of North Macedonia, Israel and Italy, from both seismic hazard and ageing/deterioration perspectives. An extended database of each country's bridge population was developed through data collection forms, which allowed to put together a detailed exposure model of the bridge network. By considering the general characteristics of the bridge population, representative samples of bridges were chosen to develop fragility functions for classes of bridges exposed to seismic hazard. The connectivity of the network was also modelled and the entire bridge network vulnerability was considered in a more comprehensive and global manner for seismic hazard and infrastructure ageing. In line with the mission of the EU Civil Protection Mechanism, the funding scheme of INFRA-NAT, the ultimate scope of the project was 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 roadway networks and where limited resources should be invested for increased resilience.

Keywords: bridges, seismic risk, ageing, road network, web-based platform

1. Introduction

In recent years, the use of large-scale assessment has become increasingly popular to evaluate the seismic risk of a specific region to an earthquake event by applying the convolution of hazard, exposure and vulnerability. These types of assessments tend to focus on the vulnerability of the building stocks and, even when bridge structures are included, they typically focus on direct losses, based on the physical vulnerability of the assets, lacking to account for the indirect negative impacts that are caused by interruption of the network systems that are essential to the normal activities of a community.

This oversight can severely underestimate the effects of a disaster since, for example, road infrastructure systems represent a critical component in a society's well-being, as they are essential for transportation of people, commercial goods and the development of industrial and cultural activities. Also, following a disruption to a road infrastructure due to a disaster, these systems become fundamental as they facilitate search and rescue efforts, transportation of medical teams and hospitalization of injured individuals, as well as repair, restoration and daily supplies for communities in distress.

The current paper details the work performed in the context of the European funded project INFRA-NAT ((Increased Resilience of Critical Infrastructure to Natural and Human-Induced Hazards, www.infra-nat.eu) that dealt with the development of tools for the large-scale assessment of bridge inventories present in the road networks of Italy, North Macedonia and Israel.

Specifically, a robust methodology was defined to: a) account for the seismic hazard in each of the partner countries, b) create homogenized datasets that make up for detailed exposure models with which characterization and identification of the main bridge typologies can be made and, c) determine the physical vulnerability of the most representative bridge types in each partner country. All these steps were carried out considering the implementation of state-of-the-art practices in each of the previously mentioned components of risk. Furthermore, all the information was included in a web-based platform capable of running calculations to predict road network interruptions, which serves as a tool for stakeholders in bridge management and emergency authorities to prioritize their resources towards the most critical components in their roadway bridge inventories.

2. Methodology

In general, the adopted methodology divided the work in to three tasks representing the main components of a conventional risk model: hazard, exposure and vulnerability. Additionally, it included another task for the development of a web-based platform to serve as the main product of the project. A schematic representation of the adopted methodology can be seen in Fig.1.

The hazard component was mainly characterized by a literature review process to determine the most updated models for the seismic hazard in each of the participating countries, after which they were implemented in an uniform seismic hazard model capable of running scenario simulations and determining the resulting intensity measure fields in any geographic location within the case study areas. This hazard model was also used to select earthquake records compatible with the seismic conditions of specific key sites within each case study region, for later use in the physical vulnerability task.

In terms of exposure, uniform data collection forms were created to be used during a data collection campaign that gathered homogeneous descriptions of the bridge inventories in each of the case study regions. This information was then processed into a georeferenced database and was later used to determine the most representative bridge typologies and their corresponding structural characteristics.

Given the great amount of assets in the combined bridge inventories, as well as the typical limitations of big-data collection campaigns, in which the resulting information is not exhaustive and complete, a taxonomy-based approach was implemented in order to determine the physical vulnerability of the bridge structures.

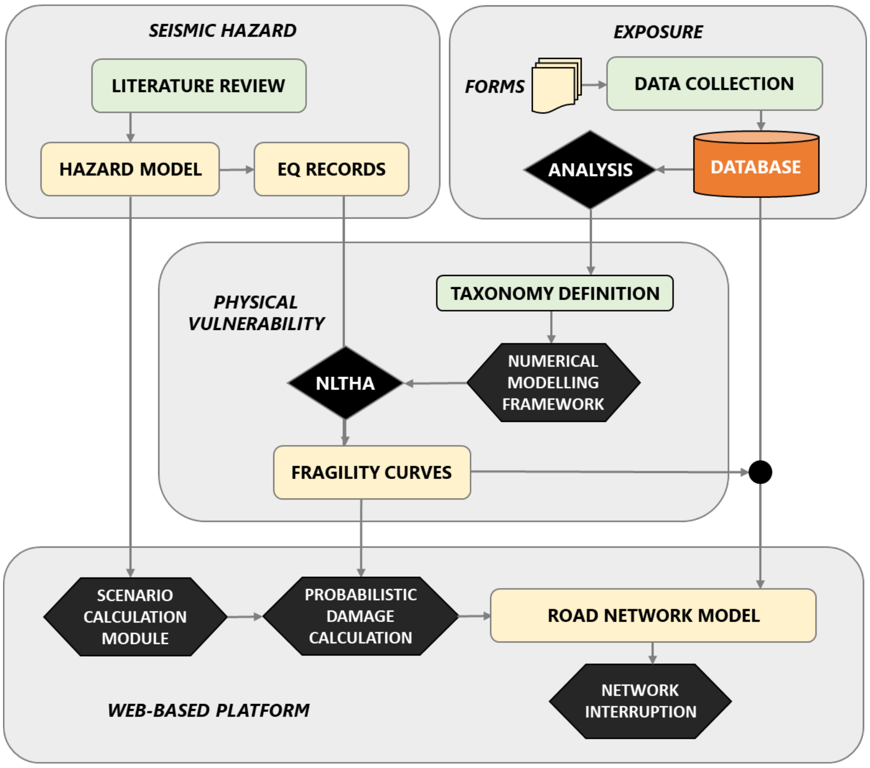


Fig. 1 – Schematic representation of the methodology implemented for the INFRA-NAT Project

For this purpose, once the main structural typologies have been identified and characterized, the information was used to generate synthetic structural models that are assumed to be representative of the behavior of their respective taxonomy branch. These models were used together with specifically-selected earthquake record sets in an evaluation platform that runs nonlinear time-history analysis (NLTHA) to determine fragility curves, representing the probability of exceeding a specific damage state based on the value of intensity of ground-motion at the location of the structure.

Finally, all the information produced in these first three tasks was integrated into an ad-hoc developed web-based platform, which functions as a repository for the data collected and produced, as well as an interface between users and a calculation engine that allows to run probabilistic predictions on the expected damage of bridges due to seismic scenarios and its corresponding network interruption.

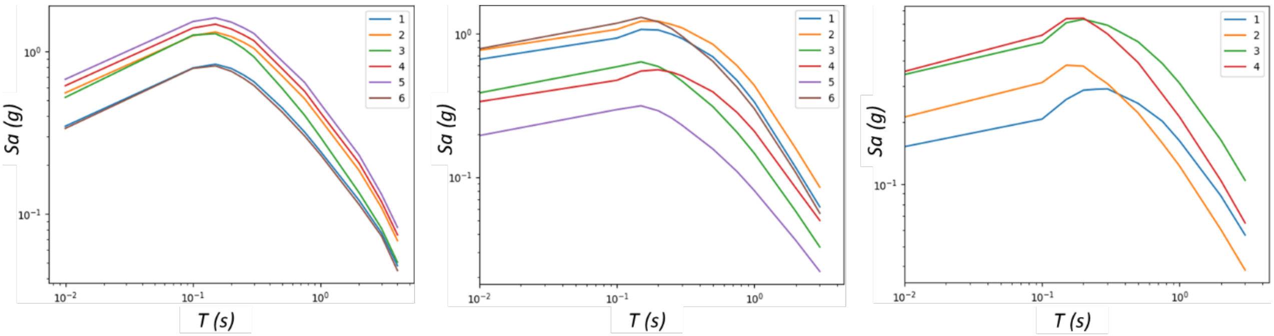
3. Hazard

The hazard component was determined according to the local seismicity of each of the partner countries and the location of the bridges in the case study regions. In each case, a thorough literature review was conducted to determine the most recent account of the seismic sources in each region and then a probabilistic model was implemented, capable of performing site specific analysis at locations of interest. Previous research coming from: a) the 2013 European Seismological Hazard Model [1] for Italy, b) the EC8 National Annex [2] for North Macedonia and, c) a recent study [3] for Israel; was implemented in the OpenQuake Platform [4].

The site selection was based on the combination of: a) existence of clusters of existing bridges, b) variability of seismic hazard and, c) variability of soil classes determined by the use of Vs30 information taken from the database of the United States Geological Survey [5]. In total, six sites where chosen for each of the Italian and North Macedonian case studies, while four were selected for the Israeli territory, as shown in Fig. 2. For each site, a detailed seismic hazard study was performed, leading to the Uniform Hazard Spectra (UHS) results shown in Fig.3.

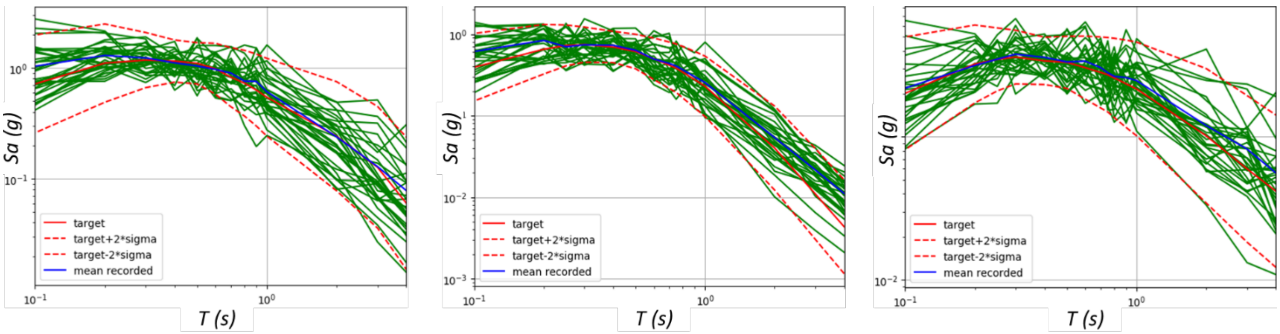
(a) (b) (c)

Fig. 2 – Locations selected for site specific hazard study in: a) Italy, b) North Macedonia and, c) Israel



(a) (b) (c)

Fig. 3 – UHS performed in site specific hazard study: a) Italy for 2475 years return period, b) North Macedonia for 975 years return period, and c) Israel for 975 years return period



(a) (b) (c)

Fig. 4 – Conditional spectrum AvgSa-based record selection performed for: a) Italian site #4 (2475 years return period), b) North Macedonian site #2 (475 years return period) and, c) Israeli site #1 (4975 years return period)

Furthermore, using outputs from these models, a state-of-the-art earthquake record selection was made at each site, with which sets of accelerograms were selected to be later used in the fragility assessment of the individual bridge models. For this purpose, sets of 30 records were selected for seven considered return periods (98, 224, 475, 975, 2475, 4975 and 9975 years) at each site, for a total of 42 sets for Italy and North Macedonia and 28 sets for Israel. The method used involved conditional spectrum-based record selection in terms of AvgSa [6], in the period range of 0.2s to 1.0s, in agreement with disaggregation results from each site taken from the hazard model. The choice of AvgSa as intensity measure was based on a previous study [7] that shows promising results for seismic assessment of bridge inventories using this parameter. Fig. 4 shows examples of the spectral characteristics of the selected records in comparison with the target spectra.

4. Exposure

A data collection campaign [8] was performed to obtain homogenized information about the bridge inventory of each participating country using standardized collection forms, specifically developed for the INFRA-NAT project. The used sources of information included open-source datasets from OpenStreetMap, existing inventories from local authorities, information gathered from Google StreetView platform, site inspection reports and design blueprints.

The collected information was classified into three knowledge levels, depending on the amount of data available for each asset: a) Level 0 (location and length), b) Level 1 (typology and incomplete dimensions) and, c) Level 2 (complete geometry and damage). All the information was used to develop a geo-referenced inventory of assets and their respective role in the road network of each participating country, which was stored in a GIS database and made available through the project website.

Table 1 shows the complete breakdown of assets in the database according to their knowledge level for each participating country, while Fig. 5 shows, for illustrative purposes, the geographical distribution of the bridges for the Italian case study region of Campania.

Table 1 – Number of bridges in the exposure model based on knowledge level for each participating country

Knowledge Level	Italy (Campania)	North Macedonia	Israel
Level 0	4622	679	2089
Level 1	526	398	98
Level 2	47	196	17

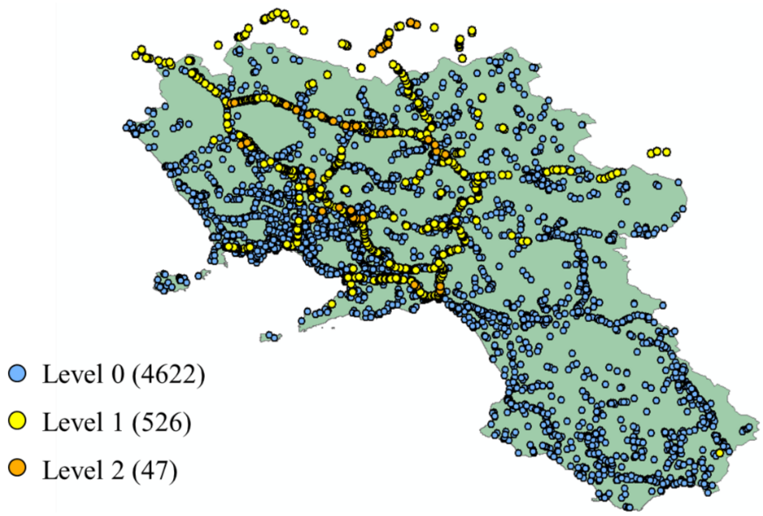


Fig. 5 – Location of bridges in the database for the Italian case study region of Campania, based on knowledge level

4. Vulnerability

Given that the vast majority of bridges in the collected database did not feature sufficient information to allow the production of accurate numerical models to assess their behavior, a methodology was implemented to generate synthetic models that are representative of the most typical bridge types in each participating country.

Initially, the information collected in the database was analyzed to derive the branches of a taxonomy scheme that was representative to the bridge stock of each country. When following this approach, it was assumed that bridges classified under the same taxonomy are to have similar performance under similar seismic excitation intensities.

Based on expert opinion and common practice, as well as being limited to the available information in the assembled database, the taxonomy branches were defined based on possible combinations of: construction material, number of spans, static scheme, deck type and pier type; the possible options within each feature is shown in Table 2. The assets in the database were classified according to these features and all taxonomy branches that included a high percentage of the bridge portfolios were selected for detailed analysis. In total, 21 taxonomy branches were chosen (6 for Italy, 4 for North Macedonia and 11 for Israel).

Table 2 – Bridge taxonomy features

Material	**Number of Spans**	**Static Scheme**	**Deck Type**	**Pier Type**
Reinforced Concrete (RC)	Variable (1, 2, 3, …)	Simply Supported (SS) Continuous (C) Frame (F)	Beam (B) Plate (P) Box (BO)	Wall (W) Single Column (SC) Multiple Column (MC)

Once identified, each taxonomy branch was further studied to determine the variations of characteristic properties in each set that may influence the structural behavior of the group. These distributions were then used as input to an ad-hoc modelling platform to generate synthetic structural models that were assumed to be representative of the behavior of the taxonomy branch group, as illustrated in Fig. 6. A validation process was performed to determine the number of synthetic models required per taxonomy branch, which in all cases led to the need for generation of between 30 and 50 models.

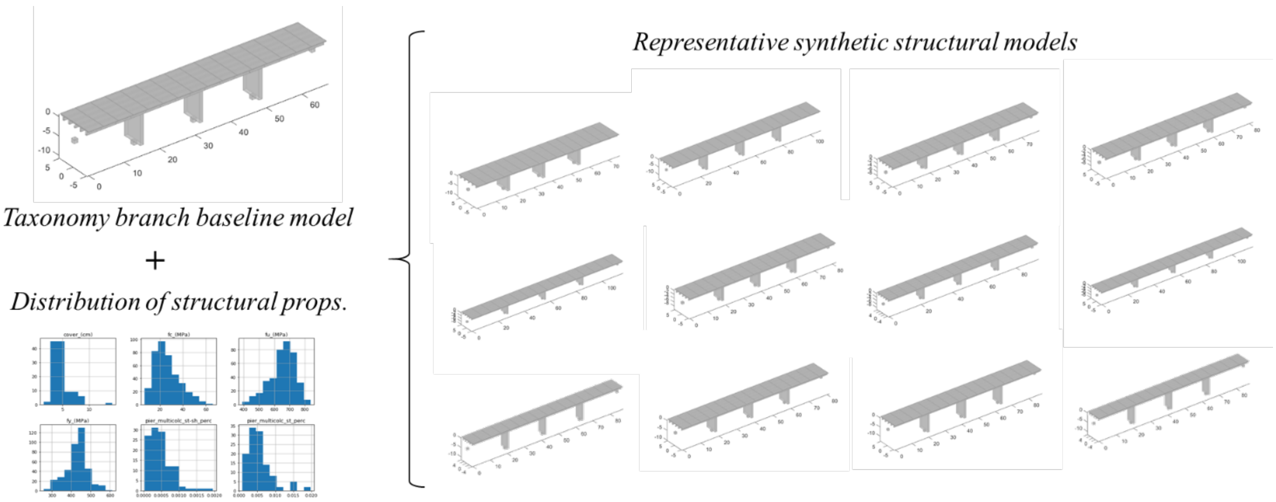


Fig. 6 – Generation of representative synthetic models using baseline and distribution of structural properties information, illustrated for the North Macedonian RC-4-SS-B-W taxonomy branch

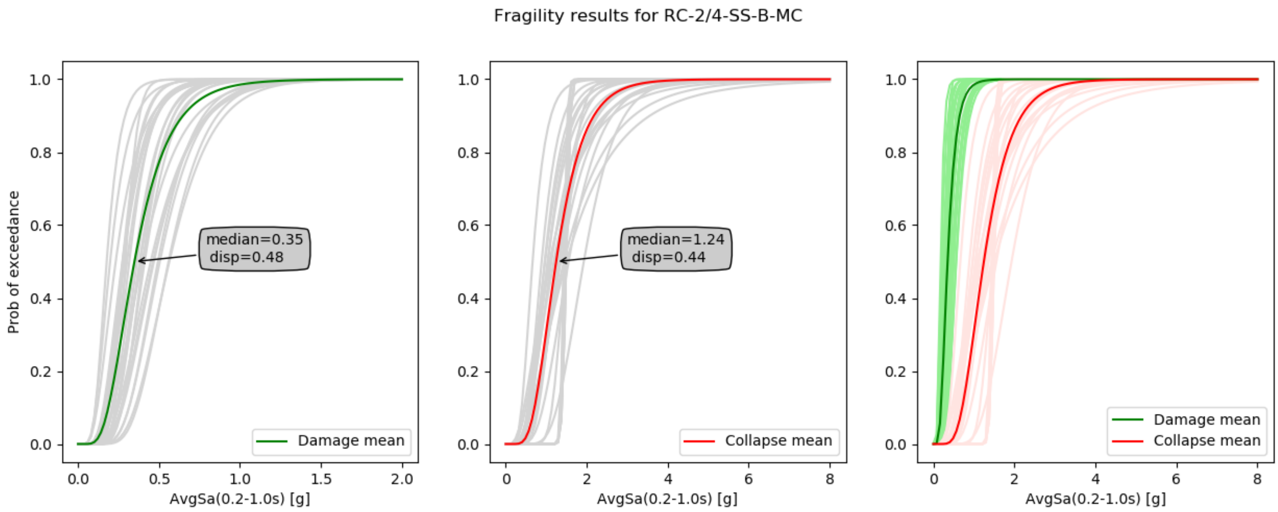
Once each synthetic model was defined, a state-of-the-art tool developed by the Eucentre Foundation called BRI.T.N.E.Y (BRIdge auTomatic Nonlinear analysis based Earthquake fragilitY) [9] was used. The tool creates finite element models for carrying out nonlinear time-history (NLTH) analysis within the OpenSees framework [10], using the bidirectional sets of ground motion records previously described, and processes the results to obtain fragility functions for each bridge.

Two limit states were used for the classification of performance of the assets in the INFRA-NAT project: a) damage limit state and b) collapse limit state. Structural deterioration interactions between elements leading to collapse was not specifically accounted for in the models (i.e. elements will deform beyond the limit response thresholds), but local demand over capacity ratios were calculated for piers and bearings and, depending on the values of these ratios, damage states were later assigned in the post-processing stage.

Finally, sets of fragility curves that account for the probability of exceedance of the defined limit states were defined for each taxonomy branch, represented by a cumulative lognormal distribution characterized by the mean value μ_{lnY} and logarithmic standard deviation σ_{lnY} parameters that describe the fragility curve, as per Eq. (1). As an example, the resulting fragility curves for the RC-2/4-SS-B-MC taxonomy branch of the Italian case-study are shown in Fig. 7.

$$p(LS \mid IM{:}\,x) = \Phi\left(\frac{\ln\left(\frac{x}{\mu_{lnY}}\right)}{\sigma_{lnY}}\right) \qquad \text{Eq.1}$$

The resulting fragility curves were then assigned to each asset in the database depending on their taxonomy branch and stored as a new data feature for each bridge in the web-based platform to be later associated with bridge interruption estimation during seismic scenario calculations.



(a) (b) (c)

Fig. 7 – Fragility functions for the RC-2/4-SS-B-MC taxonomy branch of the Italian case study: a) Damage limit state, b) Collapse limit state, c) Summary

5. Web-based Platform

A web-based platform (*http://egeos-test.eucentre.it/infranat/web/infranat*) was developed to serve as a repository for the information collected, as well as to allow users to run seismic risk calculations and provide metrics on the effects of road network interruption that can be useful for decision-making stakeholders in management and emergency institutions.

Several calculation routines written in Fortran, C and MATLAB programming languages are integrated within the platform and accessible to the users through HTTP calls, according to the paradigm of web services based on the JSON Remote Procedure Call protocol. These routines allow the connection and processing of information between the elements of the database and the hazard models to provide users the ability to make risk calculations. In the front-end, the web-based platform consists of two main sections: a tools section and a map section. The first one includes all the functionalities of calculation, research and selection; while the map section is where data such as raster or vector files are shown. This last data is stored as tables in a dedicated database, specifically PostgreSQL, with PostGIS extension, which can handle geographical information.

A general view of the home screen of the web-based platform can be seen in Fig. 8 and its main functionalities are described in the following sub-sections.

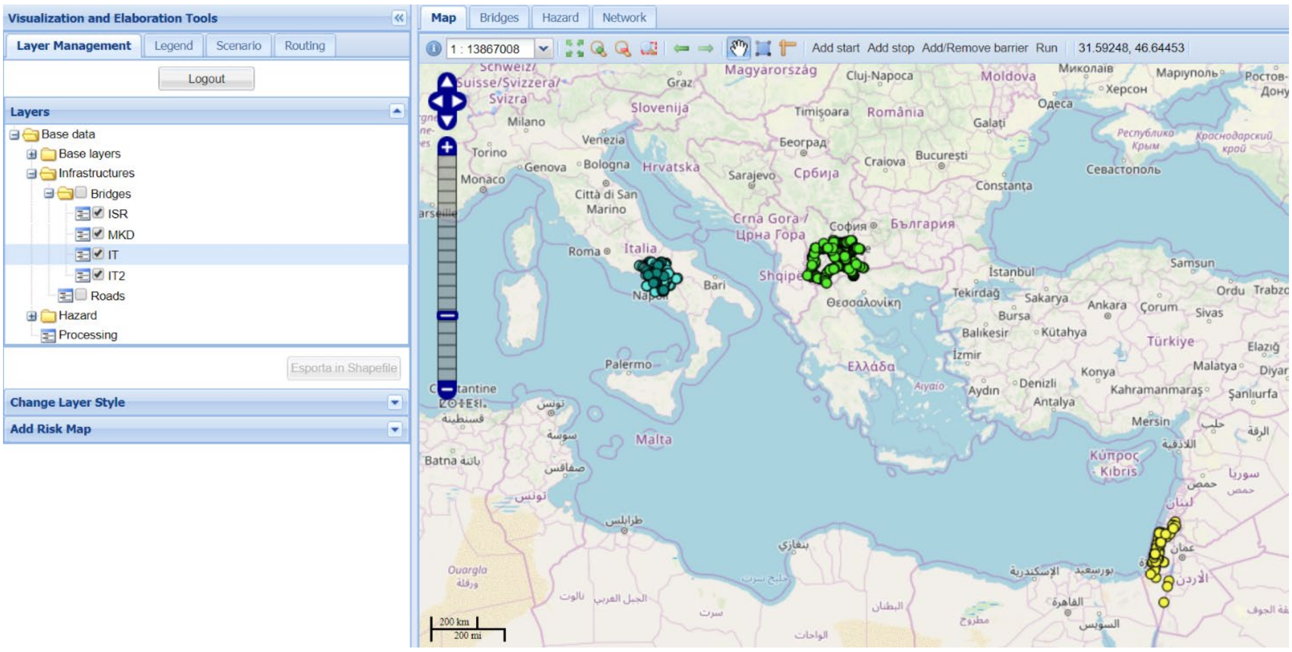


Fig. 8 – Home page of INFRA-NAT web-based platform (available at *http://egeos-test.eucentre.it/infranat/web/infranat*)

5.1 Seismic Scenario Calculations

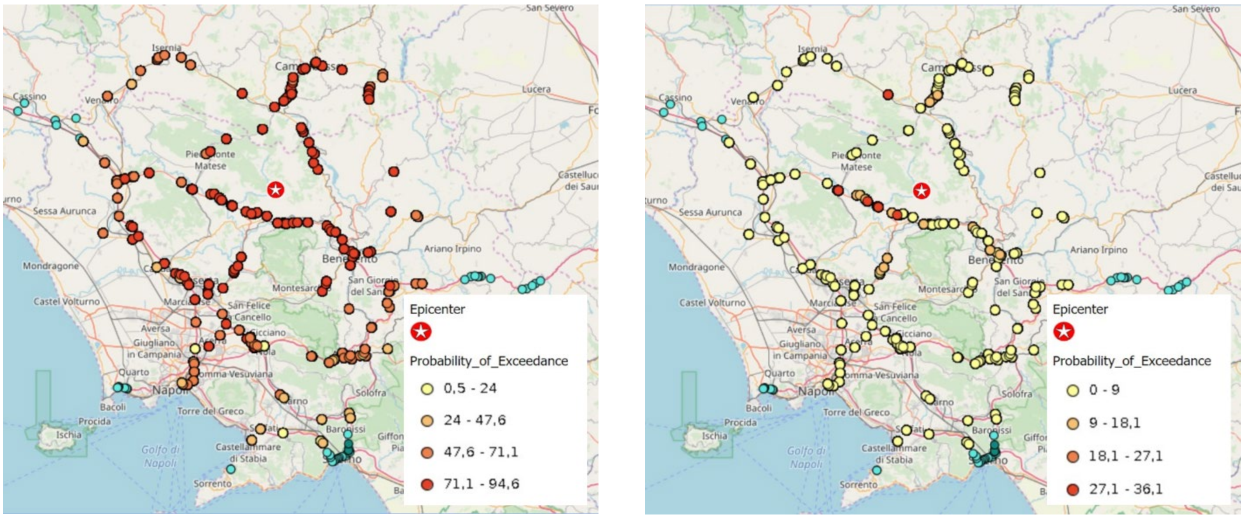
The platform is equipped with a calculation engine that connects with the seismic hazard model in order to determine the geographic distribution of intensity of ground shaking based on an earthquake event defined by the user.

Using these results, the earthquake intensity in terms of AvgSa is calculated at the location of each bridge within a user defined radius around the epicenter. This is in turn correlated with the fragility curves assigned to each asset in order to determine the probability of exceedance of each limit state, leading to a probabilistic account of vulnerability associated with the evaluated seismic scenario. Fig. 9 shows an example of the results obtained for a simulation of the 1688 Sannio earthquake (7.06 Mw) [11], used to test the functionality of the platform [12].

5.2 Network Interruption Calculations

In order to account for the impact of flow interruption in locations where a bridge might be damaged or collapsed, the platform includes a routing module that allows to implement, in a simplified fashion, a network analysis [13]. To perform this, an extension of the Postgres database, called *pgRouting*, uses the Dijkstra algorithm for shortest path definition [14] between specific points in the road network, taking into account the road lengths and speed limit in order to determine optimal travel times.

Using this algorithm, the platform evaluates the travel times that a single user would incur driving between the locations identified as points of interest (POI) in the uncongested state of the road network before the seismic event. With this information, a baseline travel time matrix (BTT) was created, including the time in minutes to travel between the POIs. An example of such calculation is shown in Fig. 10 for the Italian case-study, where the cities of Napoli, Casserta, Benevento and Campobasso where chosen as POIs.



(a) (b)

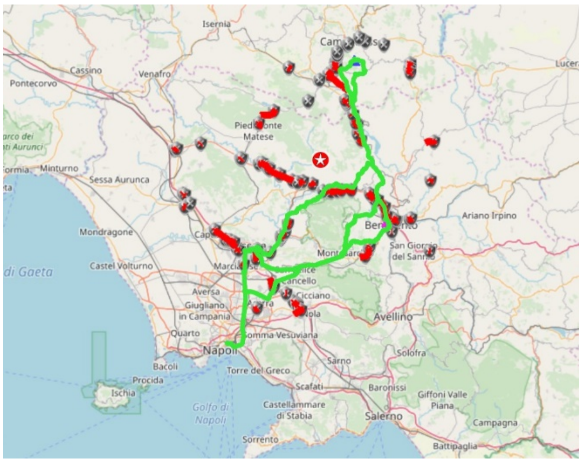
Fig. 9 – Probability of exceedance results for the Italian case study after running the 1688 Sannio Earthquake scenario in the web-based platform: a) Damage limit state, b) Collapse limit state

Baseline Travel Time BTT (min)	Caserta	Benevento	Campobasso	Napoli
Caserta	0	46	95	22
Benevento	46	0	51	60
Campobasso	95	51	0	109
Napoli	22	60	109	0

Fig. 10 – Baseline travel time (in minutes) between POIs defined in for the Italian case study without network disruption calculated with the routing module of the web-based platform

After the seismic scenario analysis has been performed, the platform allows the user to select the bridges that are considered as interrupted by defining a threshold of the limit states over which a barrier is placed at the bridge location The system does not impose or recommend the threshold values, but for the case of the Italian case study scenario shown in Fig.11, unusable bridges after an earthquake with the characteristics of the 1688

Sannio event were defined by a probability of occurrence higher than 70% for the Damage limit state, or higher than 30% for the Collapse limit state. Once the road network has been modified by the definition of barriers, the travel time between POIs is recalculated, this time avoiding the roads that have been interrupted. With this information, an interrupted travel time matrix (ITT) is created as shown in Fig. 11.



Interrupted Travel Time ITT (min)	Caserta	Benevento	Campobasso	Napoli
Caserta	0	53	106	23
Benevento	53	0	63	66
Campobasso	106	63	0	121
Napoli	23	66	121	0

Fig. 11 – Baseline travel time (in minutes) between POIs defined in for the Italian case study without network disruption calculated with the routing module of the web-based platform

When both analyses are completed, an interruption coefficient matrix is created by performing an element-based division of the BTT over the ITT, each coefficient representing the level of interruption that was caused in the connection between any two POIs by the missing bridges in the network.

Furthermore, a city-based coefficient is calculated by averaging all non-diagonal terms in each row in the matrix, leading to a new set of values deemed interruption indexes that represent the overall level of disruption of each POI analyzed. Also, an overall index is created by averaging all interruption indexes previously calculated, which is indicative of the overall disruption proneness of the entire road network after the seismic event. Results for the Italian case study after the 1688 Sannio earthquake are shown in Fig. 12 as an example.

Interruption Coefficients (BTT/ITT)	Caserta	Benevento	Campobasso	Napoli
Caserta	1	0.868	0.896	0.957
Benevento	0.868	1	0.810	0.909
Campobasso	0.896	0.810	1	0.901
Napoli	0.957	0.909	0.901	1

P.O.I. Interruption Index	
Caserta	0.907
Benevento	0.862
Campobasso	0.869
Napoli	0.922

Event Interruption Index	**0.890**

Fig. 11 – Interruption coefficients calculated for the Italian case study after the 1688 Sannio earthquake calculated with the routing module of the web-based platform

It is important to note that while these values have no specific meaning by themselves, they are meant to be analyzed in relative terms to provide insight of which locations of the network suffer more impact from disruption after a seismic event.

6. Conclusions

The current research lays the foundation of a framework for risk assessment of bridge inventories that was successfully implemented in the regions of Campania (Italy), North Macedonia and Israel, by the development of a complete and state-of-the-art characterization of each of the seismic risk components: hazard, exposure and vulnerability; and their implementation in a user-friendly web-based platform capable of evaluating seismic scenarios and predicting their effects in road network interruptions.
This work is replicable to other countries and expandable to the inclusion of different types of hazards. It is indeed intended that the European scientific community builds upon this work, to increase resilience of the road networks in the region by generating tools to allow the successful implementation of disaster risk reduction practices.

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- European Centre for Training and Research in Earthquake Engineering EUCENTRE (Italy)
- Institute of Earthquake Engineering and Engineering Seismology IZIIS (North Macedonia)
- Yaron Offir Engineers Ltd. YOE (Israel)

6. Copyrights

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