JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2022; 9 (3): 447–460

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/jtte

Original Research Paper

Simplified approach to integrate seismic retrofitting prioritization with social cost evaluation: A case study in central Italy

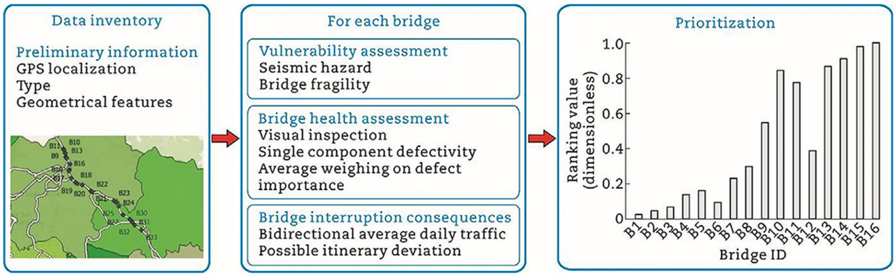
Mauro D'Apuzzo [a], *Azzurra Evangelisti* [a,*], *Alessandro Rasulo* [a], *Vittorio Nicolosi* [b]

[a] *Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Cassino 03043, Italy*
[b] *Department of Enterprise Engineering "Mario Lucertini", University of Rome "Tor Vergata", Rome 00133, Italy*

HIGHLIGHTS

- Introducing an updated review on bridge retrofitting prioritization methods.
- Studying a new approach to evaluate earthquake impact on transportation networks.
- Focusing on costs related to transportation networks earthquake induced disruptions.
- Applying a simplified prioritization method that can be easily implemented.
- Providing a sound and simple prioritization approach in limited budget scenarios.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 January 2020
Received in revised form
18 January 2021
Accepted 25 January 2021
Available online 14 May 2022

ABSTRACT

In the last three decades, bridge stock seismic retrofitting prioritization has become one of the cult topics for scientific discussions in the bridge management strategies. More recent methods are focusing on the evaluation of the generalized failure cost, of a specific bridge derived from direct and indirect costs induced to the users/residents of the area exposed to the seismic hazard as a consequence of bridge collapse. However, when these approaches have to be applied to large transport networks, appear still very complex and computational demanding, and therefore simplified methods to evaluate the impact in terms of

---

* *Corresponding author*. Tel.: +39 0776 2993 893; fax: +39 0776 2993 939.
E-mail addresses: dapuzzo@unicas.it (M. D'Apuzzo), aevangelisti.ing@gmail.com (A. Evangelisti), a.rasulo@unicas.it (A. Rasulo), nicolosi@uniroma2.it (V. Nicolosi).

Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2021.01.002

Keywords:
Bridge engineering
Seismic hazard
Fragility models
Failure cost
Transportation networks
Seismic retrofitting

social cost related to the reduced efficiency of a transportation network due to potential bridge failure, are required.

In this work, a simplified method for seismic retrofitting prioritization on a bridge stock is proposed, which is based on a "blended" approach considering specific fragility curves according to several bridge features and condition state, seismic inputs and generalized failure costs related to the transportation network. The effectiveness of the method has been showed on a case study of a local bridge stock placed in central Italy and the obtained results have been compared with those provided by more refined transport simulation models, on one hand, and by more traditional prioritization approaches, on the other. It is highlighted that this method can be very useful for transportation network managers with in a limited budget scenario, in case of lack of information about possible earthquake-induced impacts on a transportation network efficiency.

1. Introduction

The development of the modern communities' economic and social aspects is based on the efficiency and reliability of transport network system which has to guaranty service continuity also during extreme situations. Due to both economic (as funds deficiency) and environmental (as territory revaluation) aspects, in recent years, the main aim of transportation systems administrations has been the "existing infrastructures' heritage maintenance", including an indispensable and obsessive resources optimization. Therefore, engineering-economic procedures have been developed and implemented into proprietary tools with various purposes as: more efficient management of ordinary and extraordinary maintenance operations; rational support decision-making and road asset risk evaluation. These tools are an integral part of the Asset Management Systems together with the information systems (e.g., GIS) and procedures and systems for performance monitoring. Other management systems, particularly pavement and bridge management, have preceded the current interest in asset management by several decades.

As a matter of fact, Bridge Managements Systems (BMS) have been historically developed since early eighties. Initially, the BMS have been developed as computerized inventories of bridges basic information which should be as accurate and complete as possible (Siddiquee and Alam, 2017); then inspections planning, past scheduling and repair work data have been added. Subsequently, procedures for the prioritization of maintenance and asset valuation have been introduced.

The BMSs generally are based on a two-level approach.

- A project level which is mainly focused on the maintenance planning and design issues related to the single bridge based on a detailed technical assessment of its state.
- A network level which is mainly concerned with the management of a bridge stock and where there is a greater emphasis on economic and political management issues.

In the current state of knowledge modern the network level BMS can be considered as a subset of overall asset management system.

Between these two levels of management there are obviously strong interactions. In recent years, the economic shortcomings and the necessity of maintenance of the bridges have emphasized the need to assess the maintenance in economic terms, comparing costs and benefits of the possible maintenance interventions (Golabi and Shepard, 1997; Hawk and Small, 1998; Thompson et al., 1998). For these reasons management systems, which, at network level, define maintenance intervention priorities within the entire bridges' stock, and at single bridge level, identify the most effective and convenient maintenance planning and design actions (Billah and Alam, 2013, 2014a), have to be promoted.

In seismic areas this need appears even more urgent since:

- despite the fact that they remain strategic as far as the operational aspects of transportation networks are concerned, bridge stocks are often characterized by a few amount of seismic-resistant structures;
- seismic retrofitting interventions often require a huge amount of economic resources that are not consistent with short and long-term budget scenarios of local transportation agencies.

For these reasons, in the past forty years, several studies have been devoted to the development of prioritization or screening methods for bridge seismic retrofitting, of which a brief discussion is given in the followings.

1.1. *Overview on bridge seismic retrofitting prioritization*

Many prioritization methods for bridge seismic retrofitting have been proposed in the past, especially in US. Since the 1983, the Federal Highway Administration (FHWA) published a set of guidelines with the aim to present the state of art at that time. Following research and in-depth analysis have been

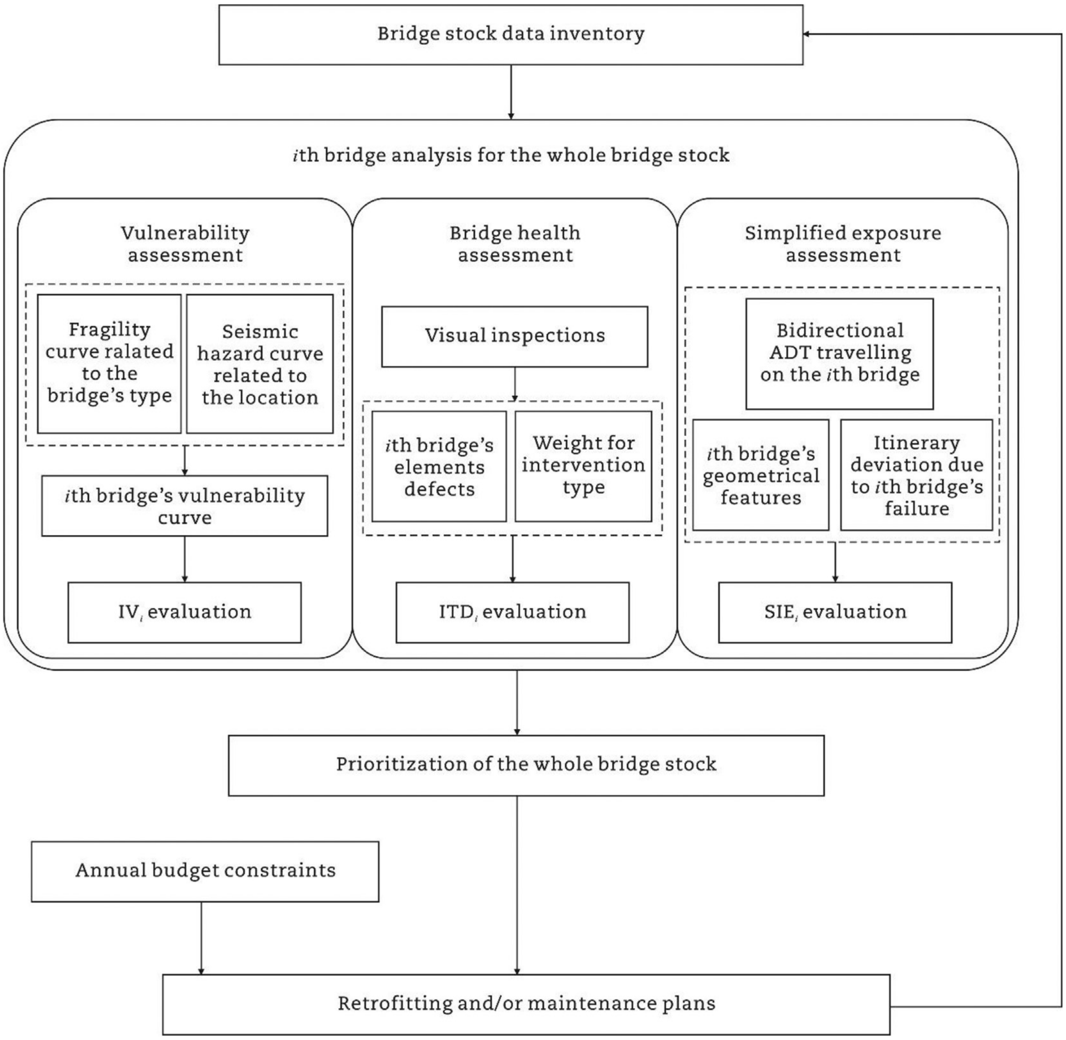


Fig. 1 – Simplified prioritization procedure at network level.

collected and reported into new documents titled "seismic retrofitting manual for highway bridges" (FHWA, 1995, 2006) where preliminary screening process for individuation and prioritization of bridges that need to be assessed for seismic retrofitting, has been proposed. Generally, within the rating phase, different aspects such as structural vulnerabilities, seismic and geotechnical hazards, network redundancy and bridge importance have been considered and usually expressed as synthetic indexes that can have been conveniently combined (FEMA, 2004).

A more comprehensive study has been presented in the mid-nineties (Maffei, 1995). Nearly twenty methods adopted at the time were reviewed and critically analyzed. It was acknowledged that almost all procedures were based on an heuristic approach and showed several flaws concerning with the additive combination formulas, the poor representation of column structural vulnerabilities, and the incorrect evaluation of user costs. It was concluded that prioritization methods based on earthquake loss-estimation techniques could offer a sounder and verifiable means of screening bridges.

A later in-depth analysis has also been presented in (Nuti and Vanzi, 2007) where existing screening methods have been classified according to:

- the method employed to evaluate the condition state and corresponding structural rate of failure of the specific bridge, (that can, in turn, be physically based or dependent on subjective judgment);
- the method to assess the failure cost for each bridge which is related to social cost born by the surrounding communities that can be focused on a specific bridge or on the entire transportation network operating in the area exposed to the seismic hazard.

However, the approach investigating the impact in terms of reduced efficiency of a transportation network can be often extremely complex so that most of recent screening methods still relies on an heuristic approach that remains questionable (Tesfamariam et al., 2018).

More recently, decision support systems like the so-called multi criteria decision making (MCDM) method have been worldwide proposed. The main aim of an MCDM analysis is facilitate the decision making process condensing all the possible features and performances, such as structure inadequacy, role and strategic position into the network, hydraulic vulnerability, seismic risk, vehicular traffic, etc., into a single index. The MCDM methods differ one another for the theories and methodologies used for the aggregation procedures and this aspect determines the choice of a specific MCDM method with respect to the others (FEMA, 2004; Suthanaya and Artamana, 2017). For the bridges prioritization criteria, several methods have been proposed and applied by public and private agencies (Davi et al., 2012; Franchin and Cavalieri, 2013; Giannini et al., 1998; Patidar et al., 2007; Pitilakis et al., 2014; Valenzuela et al., 2010; Viera et al., 2000; Yousefi et al., 2014), on the other hand, several analysis approaches have been developed for the bridge seismic retrofitting issue (Borzi et al., 2015; Nuti et al., 2010; Olmos et al., 2019), however very few of them take into account, on a specific analysis area, socio-economic impacts due to the earthquake event.

Resuming the aforementioned approaches, it is worth to be noticed that research is shifting in providing more sound and community-sensitive prioritization criteria since highway managers are increasingly called to justify and report to the community itself their maintenance plans. In this connection, “social” costs are gaining much more weight in the decision process. Within a limited budget scenario, it becomes therefore crucial to allocate funds in a more effective way in order to minimize costs borne by road user because of earthquake-induced road disruptions. However, the modeling of large area mobility is a prerequisite to tackle this issue and it can be very complex and cumbersome on engineering point of view. On the other hand, a simplistic approach to traffic modeling cannot be pursued since it can provide misleading results.

Basing on these premises, and following the widespread development of management and prioritization approaches employing aggregate and/or synthetic performance indexes, there is the need to develop more direct and simple methods to assess the different aspects involved in the bridge retrofitting process with a particular attention devoted to the social cost related to bridge failure at network level.

This paper intends to offer a contribute to tackle this issue. The methodological approach developed to this purpose is described in the following section and the proposed method is validated on a sample bridge stock in central Italy.

2. Proposed approach

The proposed method for prioritization of seismic retrofitting interventions on an existing bridges stock is founded on the simplified approach for describing the transportation network and corresponding impact due to a specific earthquake event. In detail, the method is based on the concept of Seismic Risk and on the assessment of actual bridge degradation state and social cost related to a seismic scenario. In the following flowchart (Fig. 1) the procedure of the proposed method is summarized and below the detailed description is presented.

2.1. *Theoretical background*

2.1.1. *Seismic risk*

The seismic risk evaluated for a defined bridge can be expressed as follows.

$$\mathrm{SR} = HVE \tag{1}$$

where SR is the seismic risk, H is the seismic hazard, V is the vulnerability, E is the exposure.

The quantitative assessment of Eq. (1) implies separate analysis of each of the aforementioned factors and their subsequent integration (Rasulo et al., 2015, 2016).

2.1.2. *Seismic hazard*

Generally, the seismic hazard defines the expected seismic ground motion at a site (for example the peak ground acceleration, PGA) and the two most worldwide used approaches for its assessment are:

- deterministic seismic hazard analysis (DSHA), which considers the fixed earthquake that expects to produce the strongest level of shaking at the site;
- probabilistic seismic hazard analysis (PSHA), which explicitly takes into account the uncertainty due to site locating, earthquake intensity, PGA, return period, etc. In particular the PSHA approach (Cornell, 1968), evaluates a hazard curve which provides the average annual probability that a ground-motion parameter can be equalized or exceeded.

According to the seismic hazard model used in the PSHA, the distribution of possible ground-motion levels can be expressed either through an hazard curve (which provides the average annual probability that a ground-motion parameter can be equalized or exceeded at a site) or a map (which depicts the expected values of the ground-motion parameter over a wide area for an assigned probability of exceedance). In the case of Italy, the peak ground acceleration, a_g, and the other ordinates of the elastic response spectrum Sa are given by the National Institute of Geophysics and Volcanology (INGV) on a $0.05^\circ \times 0.05^\circ$ (≈ 5 km $\times$ 5 km for Italian latitudes) grid for different average annual probability. Vanzi et al. (2015) found that on all the sites of the national territory the seismic hazard parameters fit extremely well with a linear regression in double logarithmic scale. The proposed approach for a_g (but any other intensity parameter can be used instead, like the ordinates of response spectrum Sa) is Eq. (2).

$$\ln(\upsilon) = a + b\ln(a_g) \tag{2}$$

where $\nu = 1/T_r$ is the mean recurrence rate whilst T_r is the return period of ground motions. In the regression a and b are constants, and vary with the site position on the Italian territory. As explained in the discussion of the case study, in the research the spectral acceleration (Sa) calculated at natural period of vibration of $T = 1$ s, Sa ($T = 1$ s), has been employed as measure of the seismic input.

2.1.3. *Vulnerability*

The seismic vulnerability is the predisposition of a structure to suffer a fixed level of damage, following a seismic event of a given intensity. The task of evaluating the vulnerability of existing structures exposed to a seismic hazard is entrusted to a set of fragility curves. This useful computational tool provide a rational and consistent probabilistic treatment of the possible damage of a class of structures due to seismic action. A fragility curve specifies the probability of exceeding a predefined performance of the bridge in function of the level of earthquake intensity registered at the site. Performance must be defined in terms of discrete or continuous measures that have a realistic design impact, it is usually defined by means of state limits that describe the level of damage reached by the structure (light, moderate, extended or total) (Billah and Alam, 2014b; Pitilakis et al., 2014). Therefore by a mathematical point of view a fragility curve represents the conditional probability of exceeding a prescribed limit state, given a level of earthquake intensity.

The development of fragility curves can be performed through observation of the empirical damage sustained by homogeneous class of bridges. Recent earthquakes have provided a large amount of post-earthquake reconnaissance data (for Italy see, among others: Maffei et al. (2006), Rasulo et al. (2004)). For example, Basöz and Kiremidjian (1997) and Basöz et al. (1999) derived fragility curves from the damages observed over bridges struck in California by the Loma Prieta, 1989 and Northridge, 1994 earthquakes.

In order to overcome the shortcomings of the subjectivity of judgment in reporting the observed damages and the lack of a complete set of empirical sample points for all the class of bridges and all damage states, nowadays analytical fragility curves are preferred. The analytical method is, for the most part, based on the use of computational tools (like finite elements) to reproduce the damage states over fictitious bridges that can be generated also parametrizing the most relevant structural properties (like geometry, materials, loads ⋯) that are deemed to affect the bridge seismic performance (De Felice et al., 2004; Pang et al., 2019; Rasulo et al., 2003, 2020; Zhong et al., 2018, 2019).

For example the fragility curves used in HAZUS (FEMA, 2004) have been produced analytically by Basöz and Kiremidjian (1996) and Basöz and Mander (1999). A rigorous reliability framework was proposed by Gardoni et al. (2002) and Gardoni and Rosowsky (2011). In this case the fragility curves of reinforced concrete bridges were derived by updating traditional deterministic predictions of capacity and demand using a Bayesian approach.

2.1.4. *Exposure*

Historically the concept of exposure has been developed within the building damage context and it has been defined as the quantification, in socio-economic terms, of the adverse consequences that a seismic event produces to a community, whose functions, under normal conditions, are exercised through the operation of a series of tangible assets that are susceptible to reduce or to stop their functioning due to damages suffered during an earthquake. In particular, the presence or absence of assets at risk and, therefore, the consequent possibility of suffering damage defines this parameter. Because of the inherent complexity of this parameter, an in-depth analysis on this issue is needed. A review of the socio-economic impacts induced by an earthquake is reported in the followings.

3. An in-depth analysis of socio-economic costs

Following an earthquake, the assessment of the exposure regarding key infrastructures, such as transportation networks or lifelines, should take into account the evaluation of the socio-economic costs that, can be mainly ascribed to:

- direct losses related to casualties and repair/replacement of the damaged component of the infrastructure;
- indirect losses related to the altered operating condition of the infrastructure in the short, medium and long-term that, in turn, is responsible for the degradation of the level of quality of life perceived by the surrounding communities.

The evaluation of the socio-economic impacts on critical asset induced by an earthquake has been the subject of a wide debate among researchers. It is recognized that a rigorous approach should be based on a complex system analysis able to capture the intimate interactions between the various assets and the related effects at different timeframes (Modaressi et al., 2014). However, as far as the bridges, intended as a critical component in transportation networks, are concerned, different approaches characterized by an increasing complexity can be detected.

Level 0 or base analysis that is based on the fact that major roads are associated to higher traffic flows and therefore the road category can be considered as a simplified exposure index.

Level 1 or volume-based analysis that evaluates on a more rigorous basis the exposure of the specific bridge that is subjected to a defined traffic expressed in terms of annual average daily traffic.

Level 2 or connectivity analysis that is based on a short-term traffic analysis immediately following the seismic event. The aim of this analysis is to identify to what extent the accessibility to all the villages in the study area can be affected by the loss of service of the local road network induced by an earthquake as far as emergency services are concerned. Resulting prioritization is therefore based on the amount of population that is impeded to be reached by first-aid services.

Level 3 or capacity analysis that analyses the impact on the re-distribution of traffic flows in the examined road networks induced by partial or full loss of service of some road links induced by the seismic event by evaluating the resulting delay costs caused by deviation road user will experiment on a long-term basis in the post-earthquake scenario.

Level 4 or serviceability analysis that provides a more detailed analysis of socio-economic impacts induced by the earthquake damages on transportation and economic systems of the study area that, in turns, will imply a decrease of the local gross domestic product.

It has to be reminded that the implementation of the aforementioned analysis' approaches obviously requires a different information level that it is not always available to the managers working for local Road Agencies, especially if the impact on traffic diversion is concerned. On the other hand, more naïve approach (Level 0 or 1) cannot adequately discriminate the real impact on social costs (Small, 2000).

Furthermore, Level 2 implies a complex and mathematical analysis (Sanchez-Silva and Gomez, 2013) that holds true only for short-term post-earthquakes scenarios in developing countries where road network is characterized by a low connectivity level; whereas the Level 4 approach can be implemented only if a deep knowledge of socio-economic layout and intimate connections between the different elements pertaining the economic structure of the study area is known.

Therefore, the Level 3 capacity analysis can provide an effective trade-off between the need to evaluate the socio-economic impacts in the long-term time horizon and the corresponding data collection and computational efforts that is mainly related to the development and calibration of a transportation demand prediction model.

Basically a traffic demand forecasting model allows to evaluate the following quantity, $d_{od}^{z}(s,h,m,k)$, which represents the number of trips performed by a user of the z type (according to his socio-economic role) beginning from origin traffic zone o, and ending in the destination traffic zone d, for a defined purpose s, within the time period h, selecting the transport mode m, and the trip path k (Cascetta, 2009).

On an operating point of view, the study area has to be discretized in several traffic zones emitting and attracting trips basing on their land-use characteristics. Trips are traveling on the main road network that, in turn, is decomposed into road links (arcs) and nodes connected via cordon sections to traffic zones laying in the outside area.

Once that a specific simulation period, h, has been chosen, according to each specific travel purpose, s, trips are emitted and distributed for each traffic zone, the choice of transport mode is evaluated for each origin/destination trip flow and a specific route is subsequently assigned according to several approaches (deterministic or stochastic).

The exposure expressed in terms of overall delay cost (ODC) experienced by transport users in the study area following a seismic event able to damage the transport system to some extent can be evaluated as a good estimate of the social cost borne by the analyzed community in the long-term post-earthquake scenario. Once that the mobility scenario has been evaluated ODC can be evaluated by means of the following relationship (Eq. (3)).

$$\mathrm{ODC} = \mathrm{GTC}_{\mathrm{post}} - \mathrm{GTC}_{\mathrm{pre}} \tag{3}$$

where $\mathrm{GTC}_{\mathrm{post}}$ and $\mathrm{GTC}_{\mathrm{pre}}$ are the generalized transport cost in the post-earthquake and pre-earthquake scenario, respectively. It is worth to be noticed that generalized transport cost represents the sum of the costs borne by the road user and associated to all the trips occurring in the analysis area evaluated on a daily basis.

For each bridge belonging to the examined bridge stock, the travel demand forecasting model can allow to evaluate route deviations and traffic flow re-distribution resulting from the bridge collapse. Embedding the social cost into a prioritization scheme aimed at seismic retrofitting implies the evaluation of the corresponding ODC value that has to be multiplied by the overall amount of days necessary to restore the original conditions.

It has to be highlighted that the same approach can be also employed for a conventional bridge maintenance prioritization insofar that maintenance intervention may affect the specific bridge serviceability and, in turn, traffic traveling on it. In this case ODC value will be computed on the overall period required for the specific maintenance intervention for the selected bridge.

4. Ranking index description

Basing on the aforementioned premises, a ranking index methodology taking into account the exposure expressed in terms of social costs has been proposed. The approach is risk-based and therefore can be expressed as a linear combination of seismic hazard, vulnerability and exposure according to Eq. (1). The ranking index (RI) can be therefore described by means of the following relationship (Eq. (4)).

$$\mathrm{RI}_i = \mathrm{IV}_i \mathrm{IE}_i \tag{4}$$

where RI_i is the ranking index for seismic retrofitting of the ith bridge, IV_i is the index of vulnerability for the ith bridge, IE_i is the index of exposure for the ith bridge.

4.1. *Index of vulnerability*

The IV_i, referred to the ith bridge, is calculated with Eq. (5).

$$\mathrm{IV}_i = (V_{\mathrm{C}i}/V_{\mathrm{Cmax}})\ (\mathrm{ITD}_i/\mathrm{ITD}_{\mathrm{max}}) \tag{5}$$

where $V_{\mathrm{C}i}$ is the index of vulnerability curve of the ith bridge, V_{Cmax} is the maximum index of vulnerability curve evaluated on the entire bridge stock, ITD_i is the index of the total degradation state value for the ith bridge, $\mathrm{ITD}_{\mathrm{max}}$ is the maximum index of the total degradation state value assessed on the whole bridge stock.

In particular, the index of the vulnerability curve is calculated integrating the vulnerability curve, which is defined as the convolution between the seismic hazard curve, derived by the seismic hazard maps, and the fragility curve, evaluated for the specific bridge according to its structural layout and type.

It has to be acknowledged that seismic response of a defined bridge is also affected by its deterioration state (Kumar and Gardoni, 2013; Lavorato et al., 2019). Therefore, it could be argued that the index of vulnerability can be somehow “weighted” by means of an index describing its deterioration insofar this latter can aggravate the fragility curve of the specific structure.

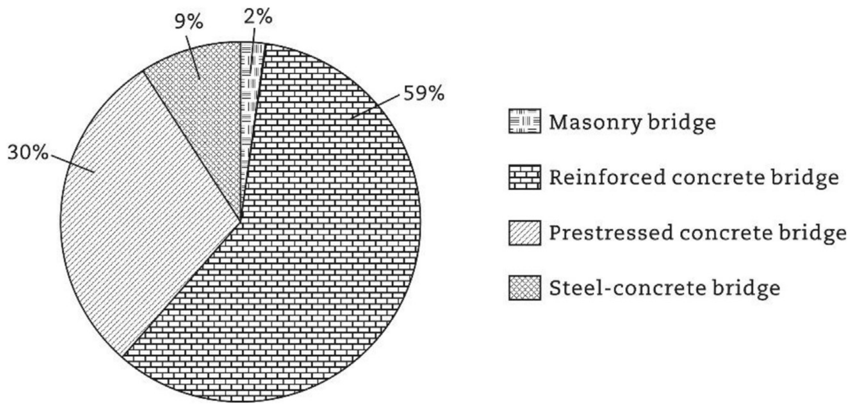


Fig. 2 – Bridge type composition in percentage for the examined case study.

To this purpose, an index of total degradation state related to the conventional bridge health indexes evaluated by bridge visual inspections according several national and international scientific literature (AASHTO, 2013; Chase et al., 2016) has been proposed as weighting factor. This index is mainly defined according to the actual deterioration state of each bridge (and of each of its composing element as abutment, pile, span, etc.) within the examined bridge stock and can be computed by means of Eq. (6).

$$\mathrm{ITD}_i = (\Sigma_j\ W_{ej}\mathrm{ED}_j C_{aj})/n_s \tag{6}$$

where n_s is the number of span composing the ith bridge, ED_j is the degradation state of the jth bridge's element (with j ranging from 1 to m and m is the number of element composing the ith bridge) and this value can be evaluated by expert inspectors crew, C_{aj} is the coefficient depending on the age of the jth bridge's element, W_{ej} is the weight depending on the jth element type (as abutment, pile, span, etc.) and on intervention type.

As far as this latter term is concerned, it is worth to be noticed that the weight value has to be selected with reference to the specific intervention type since different type and degradation levels may affect in a different manner the bridge serviceability whether a conventional maintenance or a seismic retrofitting intervention has to be planned.

4.2. *Index of exposure*

Since the main aim of the paper is to investigate how social cost can affect screening procedure for bridge stock seismic retrofitting compared with a more naïve approach based on traffic volumes, different Exposure Indexes have been proposed that are detailed below.

4.2.1. *Canonical index of exposure (CIE)*

According to this approach, the social cost are evaluated for a specific bridge by computing the overall delay cost due to the traffic re-distribution in the post-earthquake scenario, following the bridge collapse. CIE is expressed by the following relationship (Eq. (7)).

$$\mathrm{CIE}_i = \mathrm{ODC}_i/\mathrm{ODC}_{\max} \tag{7}$$

where CIE_i is the canonical index of exposure for the ith bridge, ODC_i is the overall delay cost of the ith bridge, $\mathrm{ODC}_{\max}$ is the maximum overall delay cost evaluated on the entire bridge stock.

The ranking index embedding the CIE, will be assumed as reference value to be compared with other ranking index employing different approach for evaluating the exposure reported below.

4.2.2. *Traffic naïve index of exposure (NIE)*

This index is based on the simplest traffic oriented approach. Traffic volumes, expressed in terms of annual average daily traffic values, are derived for each road link (by means of simulation but, more realistically, by means of traffic surveys) where a bridge belonging to the examined bridge stock is located, and it can be derived by means of the following relationship (Eq. (8)).

$$\mathrm{NIE}_i = \mathrm{AADT}_i/\mathrm{AADT}_{\max} \tag{8}$$

where NIE_i is the naïve index of exposure for the ith bridge, AADT_i is the bidirectional annual average daily traffic traveling on the ith bridge, $\mathrm{AADT}_{\max}$ is the maximum bidirectional annual average daily traffic evaluated on the entire bridge stock.

4.2.3. *Simplified index of exposure (SIE)*

It has to be acknowledged that the evaluation the ODC for each bridge requires the development and calibration of a travel demand forecasting model. This task could be cumbersome and unbearable for local highway agencies and therefore a simplified approach requiring raw data that can be easily collected by highway managers is needed. In this connection, a simplified approach to assess social costs related to bridge collapse can be sought. The SIE can be conceptually expressed as Eq. (9).

$$\mathrm{SIE}_i = F(T,\mathrm{RN},\mathrm{BC})_i/F(T,\mathrm{RN},\mathrm{BC})_{\max} \tag{9}$$

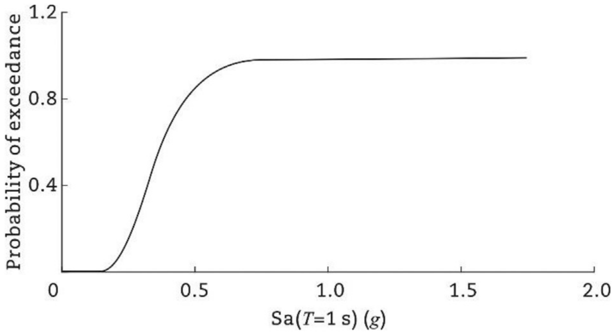


Fig. 3 – Fragility curve for ith bridge (Azevedo et al., 2010).

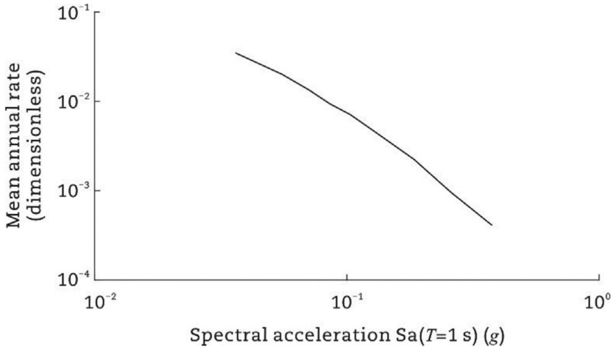


Fig. 4 – Example of seismic hazard curve for ith bridge.

where SIE_i is the simplified index of exposure for the ith bridge, $F(T, RN, BC)_i$ is the simplified analytical expression as a function of traffic value (T), road network layout (RN), bridge characteristics (BC) for the ith bridge, $F(T, RN, BC)_{max}$ is the maximum value of the simplified analytical expression as a function of T, RN, and BC, evaluated on the entire bridge stock.

The different indexes of the exposure previously described can be easily implemented into the ranking index obtaining the following expressions (Eqs. (10)–(12)).

$$CR_i = IV_i CIE_i \tag{10}$$

$$NR_i = IV_i NIE_i \tag{11}$$

$$SR_i = IV_i SIE_i \tag{12}$$

where CR_i is the canonical ranking index for seismic retrofitting of the ith bridge, NR_i is the naïve ranking index for seismic retrofitting of the ith bridge, SR_i is the simplified ranking index for seismic retrofitting of the ith bridge.

The effectiveness of the proposed simplified index expressed by Eq. (12) will be checked against the naïve index of exposure approach (Eq. (11)), by comparing the relative ranking with that obtained by the canonical approach (Eq. (10)).

5. Case study

A local bridge stock placed in central Italy, has been selected for the application of the method previously introduced. In detail the stock is composed by 44 bridges managed by a Public Road Agency and subjected to visual inspections. The examined bridge stock is characterized by a composition depicted in the following Fig. 2.

In order to foster the application of the method, different indexes have to be evaluated for each bridge.

The vulnerability index has been evaluated by means of Eq. (5). In particular the index, V_{Ci}, which measures the influence of the vulnerability curve of the ith bridge, has been evaluated through the convolution integral of the fragility curve with the seismic hazard curve. Since the bridge structural data collected have not permitted to develop an “ad hoc” vulnerability study, in this research the fragility curves originally derived by Azevedo et al. (2010), for the bridges

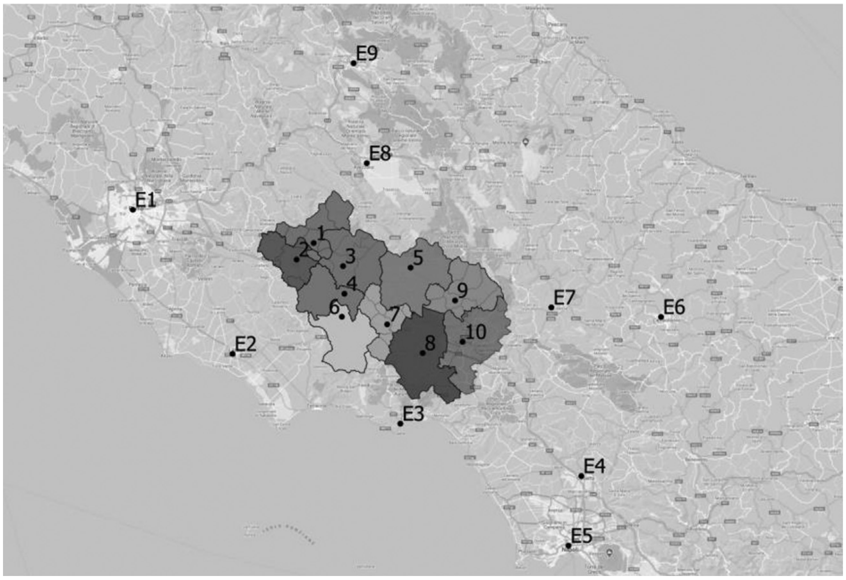


Fig. 5 – Traffic zones and internal and external centroids in the analysis area.

Table 1 — Features of the internal TAZs.

TAZ ID	Population	Emitted daily trips
1	22,142	8733
2	34,117	14,669
3	55,703	25,445
4	85,426	37,604
5	81,414	33,648
6	42,499	18,554
7	33,589	14,006
8	58,119	24,225
9	14,879	6013
10	61,386	27,936

serving the Greater Lisbon region have been used, see for example Fig. 3.

Those curves have been judged to represent well the vulnerability of the bridge population actually present in the central Italy investigated area (Fig. 2), on the basis of the similar typologies of bridges present in both areas. The seismic hazard curve has been evaluated adopting as main variable the same level of earthquake intensity of the fragility curves, i.e., the spectral acceleration ordinate at natural period of vibration of $T = 1$ s, Sa($T = 1$ s), see for example Fig. 4. Those curves have been calculated for each bridge on the basis of the bridge location and soil type, adopting the Vanzi et al. (2015), approach.

The second part is due to the index of the total degradation state which summarizes the degradation conditions, related to the seismic retrofitting and collected during the visual inspections performed for each bridge.

As previously introduced, three different approaches have been presented for the exposure index definition. In order to apply the canonical approach, 10 traffic analysis zones (TAZs) have been identified within the project area comparing socio-economic characteristics and land use percentage. For each TAZ 10 internal centroids (fictitious representation of main and middle centers which count together at least 70% of the TAZ population) and 9 centroids external to the project area have been identified and reported in Fig. 5. The population and the emitted daily trips of each internal TAZ have been summarized in Table 1.

The traffic supply model has been developed for the road network of the project area, considering, for each couple of internal centroids, at least three realistic alternative itineraries and, when possible, including local roads with bridges (Fig. 6). The relative traffic demand forecasting model has been performed: demographic and socio-economic data have been deduced from the Italian National Statistics Database (ISTAT) for the implementation of the generation sub-model and the others sub-models (distribution, mode-choice and path-choice) have been calibrated and experimentally validated comparing, for each traffic zone, modeled traffic volumes with data derived by traffic surveys and traffic counts.

For the evaluation of the naïve index of exposure, by means of Eq. (8) the bidirectional annual average daily traffic traveling on the bridge has been collected for each bridge.

Instead the simplified index of exposure (SIE) generically expressed by means of Eq. (9), for the specific stock analyzed for this case study, can be evaluated as Eq. (13).

$$\mathrm{SIE_i} = (\mathrm{ADT_i}/\mathrm{ADT_{max}})^{k_1} (L_{\mathrm{Bi}}/L_{\mathrm{Bmax}})^{k_2} (\Delta L_{\mathrm{di}}/\Delta L_{\mathrm{dmax}})^{k_3} \tag{13}$$

where $\mathrm{ADT_i}$ is the bidirectional average daily traffic traveling on the ith bridge, $\mathrm{ADT_{max}}$ is the maximum bidirectional average daily traffic evaluated on the entire bridge stock, L_{Bi} is the length of the collapsed ith bridge, L_{Bmax} is the maximum value of the bridge length derived from the entire bridge stock, ΔL_{di} is the difference in length between the itinerary with the

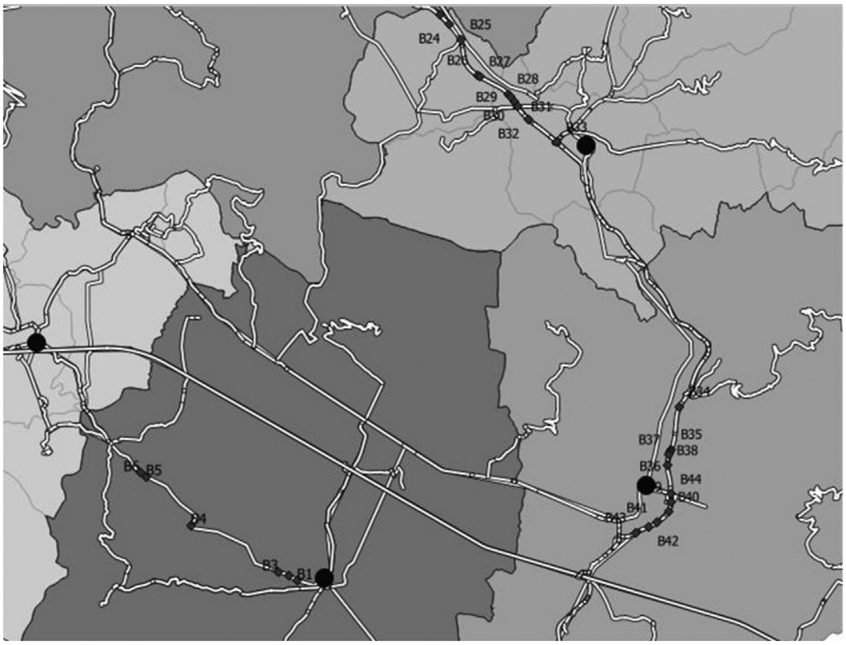


Fig. 6 — Detail of a part of the analysis area with road network.

Table 2 – Summary of the main features of the stock bridge.

Bridge ID	Type	n° span	Tot *L* (m)	IV	NIE	SIE
B1	RC	1	15.0	0.0006	0.124	0.308
B2	RC	1	28.0	0.0007	0.124	0.351
B3	RC	1	12.0	0.0022	0.124	0.294
B4	RC	1	10.0	0.0045	0.124	0.284
B5	RC	11	174.9	0.0058	0.124	0.513
B6	RC	1	12.0	0.0031	0.124	0.294
B7	M	1	26.0	0.0202	0.278	0.643
B8	RC	1	20.0	0.0432	0.257	0.685
B9	RC	1	20.0	0.4086	0.250	0.127
B10	PRC	8	352.0	0.7001	0.250	0.229
B11	PRC	3	132.0	0.5720	0.250	0.187
B12	RC	1	6.0	0.3556	0.250	0.099
B13	PRC	21	924.0	0.6239	0.250	0.280
B14	PRC	20	880.0	0.8227	0.250	0.270
B15	PRC	4	176.0	0.7277	1.000	0.750
B16	PRC	16	704.0	0.9541	1.000	1.000
B17	PRC	6	264.0	0.6367	1.000	0.816
B18	RC	1	9.0	0.2330	0.856	0.192
B19	S-C	3	105.0	0.1076	0.856	0.320
B20	RC	1	12.0	0.1728	0.856	0.204
B21	RC	1	9.2	0.3827	0.659	0.164
B22	S-C	1	36.0	0.6765	0.659	0.217
B23	S-C	1	36.0	0.0792	0.319	0.103
B24	RC	1	7.0	0.3405	0.319	0.073
B25	PRC	1	7.0	0.4639	0.319	0.073
B26	RC	1	6.0	0.2207	0.313	0.179
B27	S-C	1	40.0	0.2631	0.313	0.265
B28	RC	1	6.0	0.1627	0.313	0.179
B29	RC	1	36.0	0.0042	0.313	0.260
B30	RC	1	5.0	0.0636	0.313	0.172
B31	PRC	1	18.0	0.3649	0.313	0.225
B32	PRC	3	105.0	1.0000	0.313	0.324
B33	RC	1	10.0	0.3168	0.313	0.199
B34	RC	1	7.0	0.4073	0.447	0.191
B35	RC	2	18.0	0.5385	0.447	0.175
B36	RC	1	21.0	0.2156	0.447	0.181
B37	RC	1	21.0	0.2118	0.447	0.181
B38	RC	1	18.0	0.2375	0.447	0.175
B39	RC	9	324.0	0.3532	0.983	0.523
B40	RC	5	175.0	0.3381	0.983	0.460
B41	RC	0	245.0	0.3714	0.983	0.181
B42	PRC	1	22.0	0.3101	0.983	0.110
B43	PRC	3	132.0	0.4115	0.983	0.159
B44	PRC	4	176.0	0.4561	0.983	0.169

Note: M is masonry bridge; RC is reinforced concrete bridge; PRC is prestressed reinforced concrete bridge; S-C is steel-concrete bridge.

Table 3 – Hourly travel cost of different vehicle types.

Vehicle type	Light vehicle (€/h)	Heavy vehicle (€/h)
Hourly travel cost	12	45

*i*th bridge and the deviation due to the loss of functionality of the *i*th bridge, ΔL_{dmax} is the maximum value obtained on the entire bridge stock, of the difference in length between the itinerary with the *i*th bridge and the deviation due to the loss of functionality of the *i*th bridge, $k_1 = 0.626$, $k_2 = 0.208$, $k_3 = 0.858$ are calibration constants derived from the comparison between the canonical exposure based and the simplified exposure based prioritizations. In Table 2 have been summarized the main features of the stock bridge.

For the ranking phase, 44 scenarios generated hypothesizing one collapsed bridge at a time, have been analyzed and the traffic hourly volume, previously estimated, have been reassigned according to the conventional rule called "all-or-nothing". For each collapse scenario the hourly travel cost, reported in Table 3, have been multiplied with the generalized travel costs (GTC) in the pre-earthquake and post-earthquake scenarios (provided by the application of the transport demand forecasting model previously defined).

Finally, in order to the evaluation of the ranking index (CRI, NRI, SRI), for each collapse scenario, the overall delay cost (ODC) calculated according to Eq. (3) as the difference between GTC in the pre- and post-scenarios, have been multiplied by the number of days needed to restore initial bridge conditions.

6. Results and discussion

In order to highlight the benchmarking of the approaches previously presented, the synthetic ranking accordance index (RAI) which can be evaluated as a mathematical norm, has been used.

In detail, once that all the indexes have been calculated according to the aforementioned approaches, it is possible to obtain different prioritization results. By assuming the ranking provided by the CRI, as the reference for prioritization, it is interesting to evaluate how close naïve and simplified ranking are to the canonical one.

To this purpose, for each bridge, a score based on the ranking position can be defined and attributed according to a specific prioritization criterion. On a general basis, if *N* is the overall number of bridges belonging to the examined bridge stock, a score equal to *N* can be set for the bridge at the first position in the selected prioritization criterion, whereas a score equal to 1 can be pointed to the bridge at last position.

Therefore, it is possible to define an RAI for the naïve and the simplified approach by evaluating the following expressions, Eqs. (14) and (15) respectively.

$$\mathrm{RAI_N} = \Sigma_i\ \mathrm{SN_i SC_i} / \Sigma_i (\mathrm{SC_i})^2 \tag{14}$$

$$\mathrm{RAI_S} = \Sigma_i\ \mathrm{SS_i SC_i} / \Sigma_i (\mathrm{SC_i})^2 \tag{15}$$

where $\mathrm{RAI_N}$ is the ranking accordance index, according to the naïve exposure approach, $\mathrm{RAI_S}$ is the ranking accordance index, according to the simplified exposure approach, $\mathrm{SC_i}$ is the score attributed to the *i*th bridge (with *i* ranging from 1 to *N*, and *N* is the number of bridges belonging to the examined bridge stock) according to the prioritization derived by the canonical approach (i.e., by assessing the corresponding CRI value and by ordering from the higher to the lower), $\mathrm{SN_i}$ is the score attributed to the *i*th bridge according to the prioritization derived by the naïve approach (i.e., by assessing the corresponding NRI value and by ordering from the higher to the lower), $\mathrm{SS_i}$ is the score attributed to the *i*th bridge according to the prioritization derived by the simplified approach (i.e., by

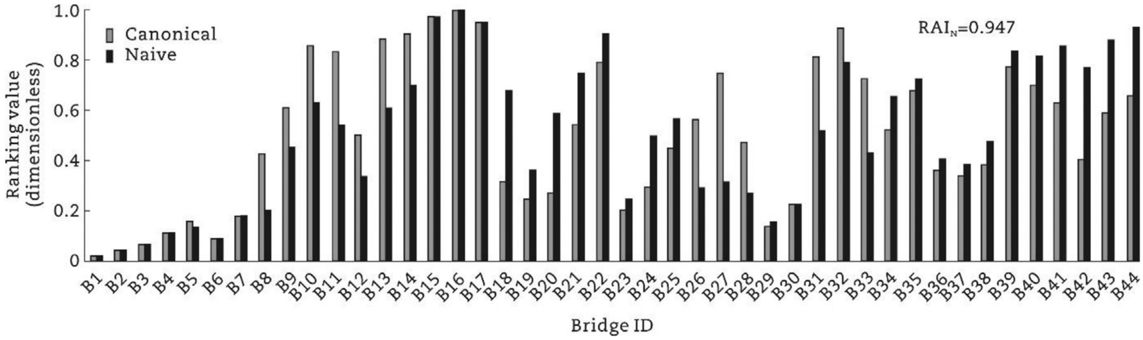


Fig. 7 – **Comparison of prioritization results provided by the canonical and naïve ranking methods for seismic retrofitting.**

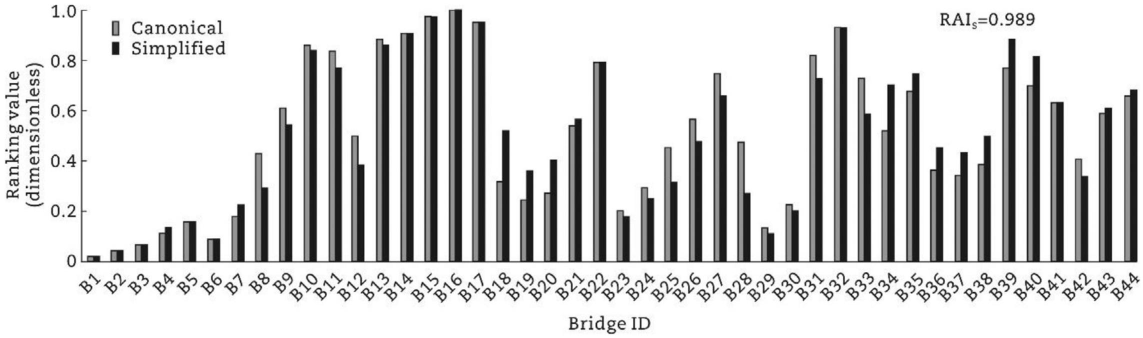


Fig. 8 – **Comparison of prioritization results provided by the canonical and simplified ranking methods for seismic retrofitting.**

assessing the corresponding SRI value and by ordering from the higher to the lower).

In this way, values close to 1 represent a sufficient agreement between the results obtained by the specific approach and the canonical (or reference) one.

The results of the application of the three approaches previously calculated, have been summarized in the following figures. Details in Figs. 7 and 8 are depicted the comparison of the results obtained with the canonical approach (considered as reference) and the naïve approach and the comparison of the results obtained with the canonical approach and the simplified approach, respectively.

Although the value is fairly satisfactory, the simplified exposure index does not seem to “surrogate” the entire prioritization pattern provided by the canonical approach.

However, by observing the results in terms of ranking and of RAI, it is possible to deduce that the SIE-based approach can be able to provide a more reliable prioritization for seismic retrofitting compared with naïve one.

In order to better highlight the economic impact of the proposed simplified approach, a numerical simulation has been carried out for the examined case study.

Different seismic retrofitting scenarios have been considered (namely the 10%, the 20% and the 30% of the overall examined bridge stock) according to the prioritization criteria following the aforementioned canonical, naïve and simplified approach, respectively.

For each of the aforementioned retrofitting scenario, the overall social cost (OSC), provided for the entire bridge stock by the aforementioned transportation network model, has been evaluated by means of the following relationship (Eq. (16)).

$$OSC = \Sigma_i ODC_i OAD_i \tag{16}$$

where ODC_i is the overall delay cost for the ith bridge, OAD_i is the overall amount of days necessary to restore the original conditions for the ith bridge.

By assuming the OSC evaluated following the retrofitting prioritization according to the canonical approach as a reference basis, the increase of the OSC has been evaluated for the naïve and the simplified approach and conveniently reported in the following Table 4.

As it can be observed by the results reported in Table 4, the retrofitting prioritization according to the proposed simplified approach is able to provide a dramatically lower increase of post-earthquake overall social cost with respect to the prioritization provided by the naïve approach.

Table 4 – **Increase of overall social cost for the naïve and simplified prioritization approach compared with canonical one, according to different retrofitting scenarios.**

Retrofitting scenario (percent of retrofitted bridges) (%)	OSC (€)	
	Naïve	Simplified
10	7,859,298	0
20	7,585,691	0
30	16,494,304	6,563,805

7. Conclusions

In this paper, following an overview on existing bridge management systems, the issue related to the prioritization for seismic retrofitting of a bridge stock is tackled. It is acknowledged that a sound criterion for screening of bridge seismic retrofitting can be based on a risk approach where seismic hazard, structure vulnerability and exposure are separately evaluated and embedded into a global ranking index.

The novel feature of the proposed framework is to consider as a descriptor of the exposure the long-term impact induced by the disruption of a specific bridge belonging to a defined bridge stock, as far as the social costs borne by a community are concerned.

It is believed that social costs can be estimated by evaluating the overall delay cost, related to the seismic induced failure of a specific bridge, that, in turn, can be expressed as the generalized transport cost difference between the post and the pre-earthquake scenario, according to scientific literature.

However, the evaluation of the ODC requires the development and the calibration of a complex travel demand prediction model that cannot be always pursued by a local highway agency due to the huge amount of data collection and the cumbersome computational effort and engineering judgment.

Therefore, a simplified approach has been proposed in order to overcome this issue. The proposed simplified method requires few information on transport and bridge stock characteristics and it can be easily implemented in a local road network.

In order to demonstrate the effectiveness of the proposed simplified method a case study on a bridge stock located in the central Italy has been examined. A travel demand model has been implemented and calibrated in case study area in order to assess generalized transport cost in pre- and post-earthquake scenario and the resulting ODC has been evaluated for each bridge belonging to the examined bridge stock.

A dimensionless exposure index based on the social cost associated to the ODC, namely a canonical index of exposure has been derived and implemented into a canonical ranking index, where bridge vulnerability (derived by local seismic hazard, fragility curve and degradation state of the specific bridge) is also taken into account. The resulting CRI has been compared to that obtained by a naïve approach based on a simple traffic volume ranking criterion, namely a naïve ranking index, NRI by means of an original ranking criterion. Results of the comparison were fairly unsatisfactory for the naïve approach.

An improved simplified index of exposure has therefore been proposed and implemented in the bridge ranking index comprehending the bridge vulnerability (namely the simplified ranking index) and has compared with canonical one, CIE, according to the same original ranking criterion. Results of comparison, (expressed also in terms of relative economic impacts compared with the canonical approach), greatly improved thus providing a promising evidence that the proposed approach may be effective in correctly describing the prioritization of seismic retrofitting of a bridge stock based on social cost evaluation even if information on mobility pattern in the study area are missing or poor.

Conflict of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Acknowledgments

The authors acknowledge the precious help the support of Eng. Mirco Zullo and of the students of the course “Construction of highways, railways and airports”, of the University of Cassino and Southern Lazio, in collecting data.

REFERENCES

AASHTO, 2013. Manual for Bridge Evaluation. American Association of State Highway and Transportation Officials (AASHTO), Washington DC.

Azevedo, J., Guerreiro, L., Bento, R., et al., 2010. Seismic vulnerability of lifelines in the greater Lisbon area. Bulletin of Earthquake Engineering 8 (1), 157–180.

Basöz, N.I., Kiremidjian, A.S., 1996. Risk Assessment for Highway Transportation Systems. Technical Report No. 118. The John A. Blume Earthquake Engineering Center, Stanford University, Stanford.

Basöz, N.I., Kiremidjian, A.S., 1997. Evaluation of Bridge Damage Data from the Loma Prieta and Northridge, CA Earthquakes. Technical Report No. 127. The John A. Blume Earthquake Engineering Center, Stanford University, Stanford.

Basöz, N.I., Kiremidjian, A.S., King, S.A., 1999. Statistical analysis of bridge damage data from the 1994 Northridge, CA, earthquake. Earthquake Spectra 15 (1), 25–54.

Basöz, N.I., Mander, J., 1999. Enhancement of the highway transportation lifeline module in HAZUS. National Institute of Building Sciences 16 (1), 31–40.

Billah, M., Alam, M.S., 2013. Statistical distribution of seismic performance criteria of retrofitted multi-column bridge bents using incremental dynamic analysis: a case study. Bulletin of Earthquake Engineering 11 (6), 2333–2362.

Billah, M., Alam, M.S., 2014a. Performance-based prioritisation for seismic retrofitting of reinforced concrete bridge bent. Structure and Infrastructure Engineering 10 (8), 929–949.

Billah, A., Alam, M.S., 2014b. Seismic fragility assessment of highway bridges: a state-of-the-art review. Structure and Infrastructure Engineering 11 (6), 804–832.

Borzi, B., Ceresa, P., Franchin, P., et al., 2015. Seismic vulnerability of the Italian roadway bridge stock. Earthquake Spectra 31 (4), 2137–2161.

Cascetta, E., 2009. Transportation Systems Analysis: Models and Applications, second ed. Springer, New York.

Chase, S.B., Adu-Gyamfi, Y., Aktan, A.E., et al., 2016. Synthesis of National and International Methodologies Used for Bridge Health Indices. FHWA-HRT-15-081. Federal Highway Administration (FHWA), Washington DC.

Cornell, C.A., 1968. Engineering seismic risk analysis. Bulletin of the Seismological Society of America 58 (5), 1583–1606.

Davi, D., Criado, D., Thibault, C., et al., 2012. A global methodology for seismic vulnerability assessment and retrofit of existing bridges adapted to the French context. In: The 15th World Conference on Earthquake Engineering, Lisbon, 2012.

De Felice, G., Giannini, R., Rasulo, A., 2004. A probabilistic approach for seismic assessment of R.C. structures: application to highway bridges. In: The 13th World Conference on Earthquake Engineering, Vancouver, 2004.

Federal Emergency Administration of the United States (FEMA), 2004. Multi-hazard Loss Estimation Methodology Earthquake Model HAZUS®MH MR4 Technical Manual. FEMA, Washington DC.

FHWA, 1995. Seismic Retrofitting Manual for Highway Bridges. FHWA RD-94-052. Federal Highway Administration, US Department of Transportation, McLean.

FHWA, 2006. Seismic Retrofitting Manual for Highway Structures: Part 1–Bridges. FHWA-HRT-06-032. Federal Highway Administration, US Department of Transportation, McLean.

Franchin, P., Cavalieri, F., 2013. Seismic vulnerability analysis of a complex interconnected civil infrastructure. In: Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Woodhead Publishing Limited, Cambridge, pp. 456–513.

Gardoni, P., Der Kiureghian, A., Mosalam, K.M., 2002. Probabilistic Models and Fragility Estimates for Bridge Components and Systems. PEER Report 2002/13. Pacific Earthquake Engineering Research Center, University of California Berkeley, Berkeley.

Gardoni, P., Rosowsky, D., 2011. Seismic fragility increment functions for deteriorating reinforced concrete bridges. Structure and Infrastructure Engineering 7 (11), 869–879.

Giannini, R., Donferri, M., Nuti, C., et al., 1998. Seismic Risk Analysis of the Network Bridges of the Autostrade Company. AUTOSTRADE, Roma.

Golabi, K., Shepard, R., 1997. Pontis: a system for maintenance optimization and improvement of US bridge networks. Interfaces 27 (1), 71–88.

Hawk, H., Small, E.P., 1998. The BRIDGIT bridge management system. Structural Engineering International 8 (4), 309–314.

Kumar, R., Gardoni, P., 2013. Stochastic modelling of deterioration in buildings and civil infrastructure. In: Tesfamariam, S., Goda, K. (Eds.), Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Woodhead Publishing Limited, Cambridge, pp. 410–434.

Lavorato, D., Fiorentino, G., Pelle, A., et al., 2019. A corrosion model for the interpretation of cyclic behavior of reinforced concrete sections. Structural Concrete 21 (5), 1732–1746.

Maffei, J.R., 1995. Management and prioritization of bridge seismic evaluations and upgrading. In: National Seismic Conference on Bridges and Highways: Progress in Research and Practice, San Diego, 1995.

Maffei, J.R., Bazzurro, P., Marrow, J., et al., 2006. Recent Italian Earthquakes: Examination of Structural Vulnerability, Damage, and Post-earthquake Practices. Earthquake Engineering Research Institute, Oakland.

Modaressi, H., Desramaut, N., Gehl, P., 2014. Specification of the vulnerability of physical systems. In: Pitilakis, K., Franchin, P., Khazai, B., et al. (Eds.), SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities. Geotechnical, Geological and Earthquake Engineering. Springer, Dordrecht, pp. 131–184.

Nuti, C., Vanzi, I., 2007. Screening of Bridges for Assessment and Retrofit. Fédération Internationale du Béton, Lausanne.

Nuti, C., Rasulo, A., Vanzi, I., 2010. Seismic safety of network structures and infrastructures. Structure & Infrastructure Engineering: Maintenance, Management, Life-Cycle 6 (1–2), 95–110.

Olmos, B., Jara, J.M., Gómez, G., et al., 2019. Influence of steel jacket thickness on the RC bridges' seismic vulnerability. Journal of Traffic and Transportation Engineering (English Edition) 6 (1), 15–34.

Pang, Y., Cai, L., Ouyang, H., et al., 2019. Seismic performance assessment of different fibers reinforced concrete columns using incremental dynamic analysis. Construction and Building Materials 203, 241–257.

Patidar, V., Labi, S., Sinha, K.C., et al., 2007. Multi-objective Optimization for Bridge Management Systems. NCHRP Report 590. Transportation Research Board, Washington DC.

Pitilakis, K., Franchin, P., Khazai, B., et al., 2014. SYNER-G: Systemic Seismic Vulnerability and Risk Assessment of Complex Urban, Utility, Lifeline Systems and Critical Facilities. Methodology and Applications. Springer, Dordrecht.

Rasulo, A., Di Donna, M., Giannini, R., 2003. Seismic fragility of existing RC bridges. In: The FIB Symposium 2003: Concrete Structures in Seismic Regions, Athens, 2003.

Rasulo, A., Goretti, A., Nuti, C., 2004. Performance of lifelines during the 2002 Molise, Italy, earthquake. Earthquake Spectra 20 (S1), 301–314.

Rasulo, A., Testa, C., Borzi, B., 2015. Seismic risk analysis at urban scale in Italy. In: Computational Science and Its Applications-ICCSA 2015. Springer, Cham, pp. 403–414.

Rasulo, A., Fortuna, M.A., Borzi, B., 2016. A seismic risk model for Italy. In: Computational Science and Its Applications-ICCSA 2016. Springer, Cham, pp. 198–213.

Rasulo, A., Pelle, A., Lavorato, D., et al., 2020. Finite element analysis of reinforced concrete bridge piers including a flexure-shear interaction model. Applied Sciences 10 (7), 10072209.

Sanchez-Silva, M., Gomez, C., 2013. Risk assessment and management of civil infrastructure networks: a system approach. In: Handbook of Seismic Risk Analysis and Management of Civil Infrastructure Systems. Woodhead Publishing Limited, Combridge, pp. 437–464.

Siddiquee, K., Alam, M.S., 2017. Highway bridge infrastructure in the province of British Columbia (BC), Canada. Infrastructures 2 (2), 2020007.

Small, E.P., 2000. Examination of Alternative Strategies for Integration of Seismic Risk Considerations in Bridge Management Systems. TRB, Washington DC.

Suthanaya, P.A., Artamana, I.B., 2017. Multi-criteria approach for prioritizing bridge maintenance in developing country (case study of Bali Province, Indonesia). Asian Journal of Applied Sciences 5 (2), 410–418.

Tesfamariam, S., Bastidas-Arteaga, E., Lounis, Z., 2018. Seismic retrofit screening of existing highway bridges with consideration of chloride-induced deterioration: a Bayesian belief network model. Frontiers in Built Environment 4, 00067.

Thompson, P.D., Small, E.P., Johnson, M., et al., 1998. The Pontis bridge management system. Structural Engineering International 8 (4), 303–308.

Valenzuela, S., Solminihac, H.D., Echaveguren, T., 2010. Proposal of an integrated index for prioritization of bridge maintenance. Journal of Bridge Engineering 15 (3), 337–343.

Vanzi, I., Marano, G.C., Monti, G., et al., 2015. A synthetic formulation for the Italian seismic hazard and code implications for the seismic risk. Soil Dynamics and Earthquake Engineering 77, 111–122.

Viera, V., Oliveira, C.S., Costa, C.B., et al., 2000. A methodology to evaluate strategic importance of bridges and tunnels considering seismic vulnerability: application to Lisbon. In: 2nd Euro Conference on Global Change and Catastrophe Risk Management: Earthquake Risks in Europe, Laxenburg, 2000.

Yousefi, A., Ahamad, M.S.S., Majid, T.A., 2014. Application of TOPSIS method in prioritization of highway bridges for seismic retrofitting. Engineering Structures and Technologies 6 (3), 114–123.

Zhong, J., Jeon, J.S., Ren, W.X., 2018. Risk assessment for a long-span cable-stayed bridge subjected to multiple support excitations. Engineering Structures 176, 220–230.

Zhong, J., Jeon, J.S., Shao, Y., et al., 2019. Optimal intensity measures in probabilistic seismic demand models of cable-stayed bridges subjected to pulse-like ground motions. Journal of Bridge Engineering 24 (2), 04018118.

Mauro D'Apuzzo graduated with full marks in civil engineering at the University “Federico II” of Naples in 1994 and appointed PhD in transportation engineering at the University of Rome “La Sapienza” with a thesis on road traffic induced vibrations on February 2000. At the moment he is an associate professor of road, railway and airport construction (ICAR-04) at the Department of Civil and Mechanical Engineering of the University of Cassino and Southern Lazio. His research interests regard, mainly, environmental, design and management issues of transport infrastructures and road safety, where he authored and co-authored more than 80 national and international scientific papers.

Azzurra Evangelisti graduated in civil engineering at the University of Rome “Tor Vergata” in 2011 and she has been visiting scholar at the Virginia Polytechnic Institute and State University, VA (USA). She received the PhD degree in civil engineering, presenting the thesis “evaluation of road surface macrotexture: variability and prediction methods” on March 2015, from the University of Cassino and Southern Lazio where currently she is a temporary research fellow at the Department of Civil and Mechanical Engineering. Her research interests and scientific publications include mainly, design and asset management of transport infrastructures, risk assessment of critical infrastructures and networks, road safety and environmental issues.

Prof. Alessandro Rasulo got his PhD in earthquake engineering from the Politecnico di Milano (2001). He has been a visiting scholar at the University of California, Berkeley (academic year 2000–2001). Since 2005 he is an assistant professor in structural engineering at the University of Cassino and Southern Lazio. He is the author of more than fifty papers published in peer reviewed journals and conference proceedings on design criteria for the construction of new earthquake-resistant structures, the assessment/retrofit methodologies for the seismic protection of existing structures, the seismic reliability of critical infrastructures and networks.

Vittorio Nicolosi received the civil engineer degree as well the PhD degree in transportation engineering from University of Naples “Federico II”. He is a professor in the Department of Enterprise Engineering “Mario Lucertini” at University of Rome “Tor Vergata” and is involved as investigator in several international research projects. Prof. Nicolosi's specialty areas include several pavement engineering and asset management of transport infrastructures sectors with a particular focus on performance indicators and optimization of management processes. He has been a member of numerous technical committees and working group and leader of WG who develop the asset management manual of world road association.