Community Resilience Analysis for the Formulation of a Seismic Mitigation Strategy at Inter-municipal Level

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Abstract. In recent years, community resilience assessment has also become a central issue in earthquake risk mitigation. However, the application of resilience concepts is extremely complex. In the study of seismic risk, applications are highly multidisciplinary. Consequently, they are often incomplete or partial. Although new rigorous mathematical models have been developed, most applications are extremely complicated and susceptible to the input data and skill of the user. Even more so, applications to real large-scale contexts are much more complex than applications on a local scale or on single structures. New models and procedures are needed to apply resilience principles in the formulation of mitigation strategies at regional or sub-regional scales. In the present study, the impact of a highway on a set of communities is evaluated. The seismic resilience of communities is assessed by integrating the seismic performances of bridges and viaducts with those of the connected housing systems. The latter are estimated by modelling their physical damage with vulnerability curves for buildings. The main results are illustrated and discussed.

Keywords: Seismic Risk Mitigation Strategies · Resilience · Decision-Making

1 Introduction

Medium- and strong-intensity earthquakes continuously demonstrate the considerable vulnerability of existing buildings (private, public and strategic), as well as of other civil structures and infrastructures (e.g., [1–4]). The consequent social and economic losses are becoming too risky and no longer acceptable (e.g., [5–7]). Since the times and costs of reconstruction are exorbitant (e.g., [8, 9]), seismic risk mitigation strategies should be carefully planned and performed defining prioritizations and intervention measures at different territorial scales [10].

Many recent studies in the seismic risk field have detected the key role of resilience in the definition of mitigation strategies [e.g., 11–13]. To mitigate the seismic risk and therefore reduce the direct and indirect losses with a resilient perspective, competent

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authorities should establish financial resources and acceptable performance levels in a clear and transparent way and in accordance with the needs of all stakeholders [14]. However, the operative implementation of resilience concept at different territorial and decisional levels is a hard work, especially in complex and strongly heterogeneous systems (urban sub-systems, cities, city's systems, regions, etc.).

The resilience concept in seismic mitigation strategies is usually understood as the ability of a system to absorb disaster impacts and quickly return to normal socioeconomic activities. To this aim, undamaged facilities (public and private) and lifelines (communication, transportation and utilities networks) are crucial to ensure the recovery phase in the aftermath of a disastrous earthquake. Rigorous theoretical and analytical frameworks on these issues have significantly developed in recent years [e.g., 15–19] but, in many cases, their applications to real case studies focus on a local scale (neighborhood, district, city) and/or single structures [20]. Most of these frameworks are based on the seminal work of Bruneau et al. [21], who developed a general framework to quantitatively evaluate and improve the seismic resilience of communities by analyzing four resilience dimensions: technical, organizational, social, and economic (TOSE).

Basically, the resilience concept is used to offer strongly multidisciplinary solutions capable of capturing the beneficial impact of prioritizations and intervention types on the seismic response of vulnerable communities. In this direction, interesting studies based on the use of Multi-Criteria Decision-Making (MCDM) analysis are recently presented to conciliate resilience assessments in the mitigation strategy definition on a large territorial scale [14, 22, 23]. These studies link the post-earthquake functionality of a system (urban sub-system, city, city's system, region) and therefore its resilience to three main aspects that embody groups of interwoven TOSE dimensions: i) seismic risk, ii) emergency management and recovery, iii) integration and social cohesion.

In the present work, a concrete application of this MCDM analysis to thirty-three municipalities located in Basilicata region is reported. In particular, the work investigates the functional interdependencies of the housing systems of these municipalities with the State Highway 407, namely a road network segment that is crucial for the emergency management of Basilicata region. Census data and seismic risk assessments incorporating stratigraphic amplification effects are used to define a resilience prioritization of the exanimated municipalities. The analysis is carried out on the basis of the data obtained from the individual bridge or viaduct, census section and/or municipality. It is evolving and the multidisciplinary and multidimensional connection between housing systems and the strategic infrastructural network may be seen as the main outcome of this work.

2 Case Study Analysis

Basilicata is a region in southern Italy with 131 municipalities (one hundred belong to the province of Potenza and thirty-one belong to the province of Matera) and a total population slightly under 600,000 people according to the National Institute of Statistics (ISTAT) [24]. Basilicata can be considered as the most mountainous region in the south of Italy. In fact, it covers an area of approximately 10,000 km^2, most of which is covered by mountains (47%) and hills (45%). An extensive part of this region is covered by the southern Apennine Mountains, an area where seismic activity is well known. Among

the most destructive earthquakes to have occurred in this area in the last centuries, the 1694 Irpinia–Basilicata earthquake destroyed many towns in the north-west of the region causing about 6,000 casualties, while the 1857 Basilicata earthquake devastated much of the region causing about 19,000 casualties. More recently, the 1930 and 1980 Irpinia earthquakes widely affected Basilicata, Campania and Puglia region, destroying many towns between Basilicata and Campania and causing 1,404 and 2,914 casualties, respectively.

The 1980 Irpinia earthquake is the most disastrous Italian seismic event in the last hundred years. The main shock (6.8 on the Richter scale) occurred on Sunday 23 November at 7:35pm (local time) and the subsequent aftershocks devastated 687 municipalities (8.7% of current Italian municipalities) in just a few hours. According to a Fire Brigade report [25], a consistent part of the national fire brigade worked continuously for 48 days, when the search and excavation operations were completed and the last victim was found. However, the adverse geomorphological and atmospheric conditions together with the occurrence of landslides (which compromised the existence of some towns and affected the transportation network) and damaged infrastructure had a negative impact on the rescue action during the first 10 crucial days. The delay in relief efforts led to the birth of the modern Italian Civil Protection system. For the first time, civil protection is defined as a primary task of the Italian State following four main directions: prediction, prevention, rescue, restoration of normality.

More recently, after the emergency caused by 2009 L'Aquila earthquake, the Italian government introduced the article 11 of Law No 77 of 24 June 2009 to promote interventions for seismic risk prevention. The government instructed the Italian Civil Protection Department (ICPD) to implement article 11, and ICPD issued eight ordinances, according to which a total of 1.115 billion euros were distributed among the Italian Regions to finance seismic prevention in their territories for the years 2010–2021 [23]. In particular, Ordinance n. 4007/2012 [26] introduced the analysis of the Emergency Limit Condition (ELC) to examine the main physical elements of the emergency management system defined at municipal level in the civil protection plan.

Starting from the ELC analysis, Territorial Contexts (TCs) have recently been defined in Basilicata, Calabria, Campania, Puglia, and Sicily regions, and their fundamental physical elements, i.e. strategic buildings, aggregates and structural units, emergency areas and accessibility/connection infrastructures, are therefore identified. These physical elements define the TC emergency structural system at municipal and inter-municipal level. More specifically, a set of neighboring municipalities is grouped in each TC according to the labor market areas [27] and considering each municipality as a homogeneous unit of reference. In this way, emergency planning and management activities and risk mitigation strategies may be implemented cooperatively among municipalities in a TC [28].

TCs govern the emergency management system of a region and are useful for the territorial resilience assessment and planning. In Basilicata region, fourteen TCs may be found. Examining the accessibility/connection infrastructures of these TCs by means of the ELC information available on the web-GIS platform [29], the State Highway 407 plays a key role in the emergency management of Basilicata region, especially for eight TCs. Consequently, the State Highway 407 and thirty-three municipalities belonging to

these eight TCs are analyzed hereafter. As shown in Fig. 1, the considered municipalities are directly crossed by the State Highway 407 or are close to it.

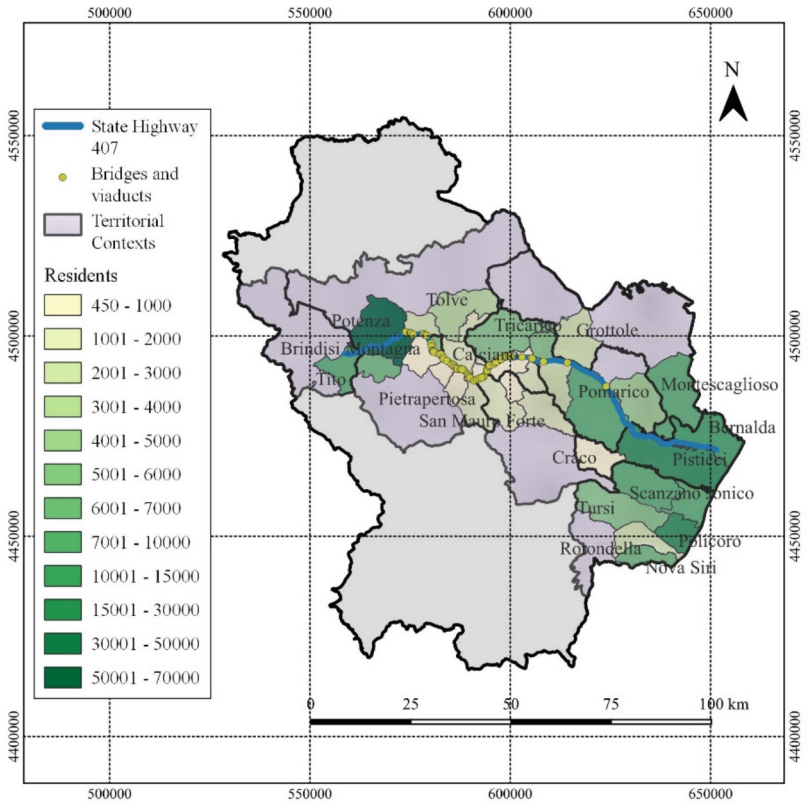


Fig. 1. Bridges and viaducts of State Highway 407 and connected territorial contexts with residents of neighboring housing systems.

The State Highway 407 connects Potenza with Metaponto (a hamlet of the municipality of Bernalda) following the course of the Basento river, entirely in Basilicata. Due to the complexity of the region's orography, the route in the province of Potenza is characterized by numerous bridges and viaducts. Along the route, there are a total of 89 bridges and viaducts considering both directions (Fig. 1). These structures are essential components to ensure the transportation system in the study area, especially for small mountain municipalities. In fact, according to ISTAT census data [30], the percentage of the resident population that moves outside these municipalities for study and work is the highest (Fig. 2).

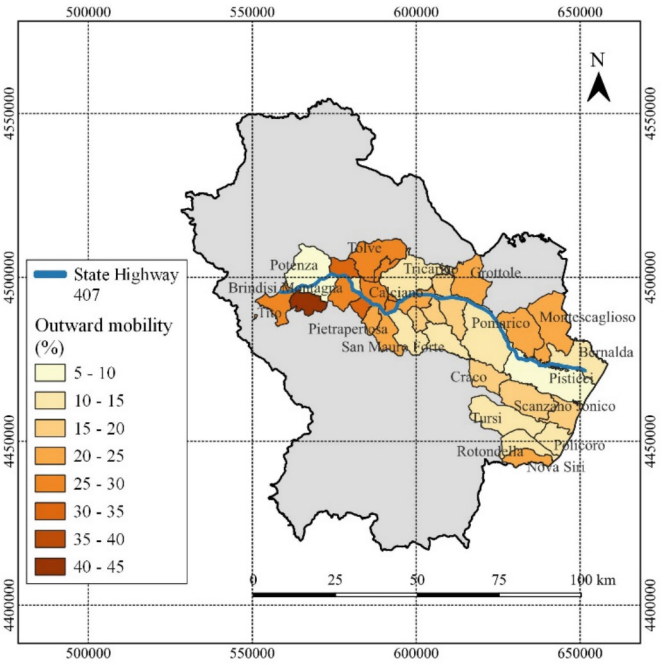


Fig. 2. Mobility outside the municipality for study or work.

To estimate the performance concerning the fundamental physical elements of a TC, a Territorial Context Structural Operational (TCSO) index and additional indicators are presented in a recent study [31]. In such study, the performance of accessibility/connection infrastructures is quantified by estimating the probabilities of interference due to possible coseismic effects, i.e. landslides and liquefactions, and the collapse probabilities of interfering buildings from fragility curves. For this last purpose, fragility curves for urban road networks are derived from fragility and vulnerability curves of interfering buildings [32].

Fragility and vulnerability curves are essential tools to estimate the seismic risk of exposed assets in terms of damage probabilities and damage factors (or losses), respectively. These curves describe the aforementioned values for a given earthquake intensity measure, usually defined in terms of Peak Ground Acceleration (PGA).

The analyzed bridges and viaducts were built in the years 1960–1970 with isostatic spans. Decks consist of pre-stressed Reinforced Concrete (RC) beams covered with a RC slab. They are simply supported on RC piers by means of isolated pier-to-deck connections. According to a Syner-G report [33], bridges and viaducts are one of the most seismically vulnerable structures in a highway system, and after a literature review on the topic, a set of mean fragility curves was proposed for representative RC bridge types. Depending on this set and the main characteristics of the considered bridges and viaducts, a mean fragility curve for collapse limit state is selected and used in order to estimate their seismic performance in the study area (Fig. 3).

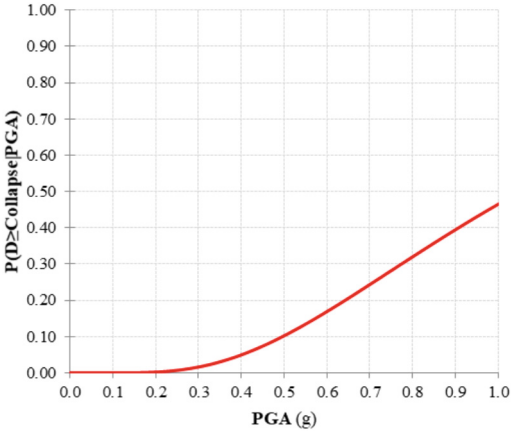


Fig. 3. Mean fragility curve for collapse limit state of regular or semi-regular RC bridges type with isolated pier-to-deck connection [33].

For a return period of 100 and 475 years (39% and 10% probability of exceedance in 50 years, respectively), the corresponding PGA demand of the *i*-th bridge or viaduct is estimated by multiplying the PGA at the outcropping engineering bedrock (deduced from the Italian seismic hazard assessment MPS04 [34, 35]) by the respective average amplification factor recently defined at national level with a regular grid of 50 × 50 m [36]. Then, the collapse probability ($P(D \geq Collapse|PGA)$) of the *i*-th bridge or viaduct is evaluated by entering with the estimated PGA value on the PGA values axis of the mean fragility curve of Fig. 3. Consequently, the seismic robustness of the *i*-th bridge or viaduct can be considered as the probability of non-collapse limit states ($P(D < Collapse|PGA)$). It is calculated as follows (Fig. 4):

$$P(D < Collapse|PGA)_i = 1 - P(D \geq Collapse|PGA)_i \tag{1}$$

The bridges and viaducts belonging to an accessibility infrastructure segment can be assumed to work in series within a TC. Thus, the Accessibility Infrastructure segment Robustness (*AIR*) in the *k*-th TC is based on the product among the probabilities of non-collapse limit states of the concerning bridges and viaducts. Mathematically, this can be expressed as follows:

$$AIR_k = \prod_{i=1}^{n} P(D < Collapse|PGA)_i, \ i \in k \tag{2}$$

where *n* is the number of bridges or viaducts belonging to the accessibility infrastructure segment of the *k*-th TC. Obviously, in addition to the damage to bridges or viaducts, other causes of mobility disruption may be co-present (i.e. landslides, liquefactions and damage to interfering buildings, retain walls, overpasses, underpasses, etc.). Also in these cases, Eq. (2) may be applied because the corresponding fragility curves can be assumed to work in series [32]. Figure 4 summarizes the robustness values of bridges and viaducts together with the *AIR* values of the eight TCs analyzed.

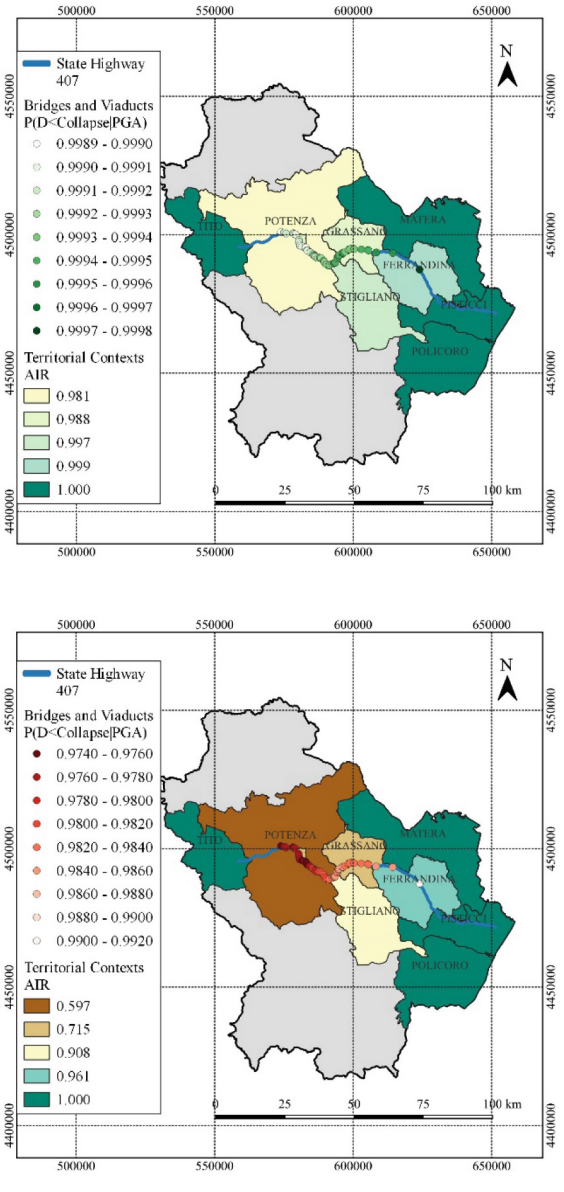


Fig. 4. Accessibility infrastructure robustness for a return period of 100 (a) and 475 years (b).

The robustness of housing systems in the study area (Fig. 5) is estimated by using the procedure of Anelli et al. [37] and data of a probabilistic seismic risk assessment (PSRA). The latter is carried out through the convolution of seismic hazard, vulnerability and exposure models.

The seismic hazard model was determined by integrating the Italian seismic hazard assessment framework [34, 35] with the stratigraphic amplification effects. These effects are evaluated by merging the national map of shear-wave velocity to 30 m depth [38] with a new generation of Ground Motion Prediction Equation (GMPE) [39]. An event based analysis with OpenQuake-engine software [40] was performed to assess the total hazard at the exposure site model.

Two set of vulnerability curves [37, 41] are used as vulnerability model to take in account the uncertainties concerning the structural response of residential buildings. Both sets of vulnerability curves are valid for masonry and RC buildings. More in detail, they categorize the Italian residential building stock in fourteen building types defined in terms of vulnerability and height classes: i) seven macroseismic vulnerability classes (A, B, C1, D1 for masonry buildings and C2, D2, E for RC buildings), ii) two height classes, i.e. low-rise buildings (L = 1-2 storeys) and medium/high-rise buildings (MH $\geq$ 3 storeys).

ISTAT census data on population and buildings [24] and the criteria provided by the National Risk Assessment [42] are used to determine the exposure model. For each municipality, buildings and their occupants are grouped into fourteen taxonomies according to the building types considered in the vulnerability model.

Seismic losses are calculated for both set of vulnerability curves by using the OpenQuake-engine software with a probabilistic event-based risk calculator. In such manner, loss exceedance curves and probabilistic loss maps are developed for a return period of 50, 100, 250, 500, 750, 1000 and 2000 years. Then, the procedure suggested by Anelli et al. [37] is used to estimate the seismic robustness of each municipality according to the calculated seismic losses. Figure 5 summarizes the seismic robustness of the considered housing systems for a return period of 100 and 500 years by averaging the housing robustness associated with the two sets of vulnerability curves.

Depending on the calculated robustness values of housing systems, the maximum restoration time is assessed for each return period by using the formulation proposed in recent studies [20, 23]. Figure 6 condenses the average results for a return period of 100, 250 and 500 years.

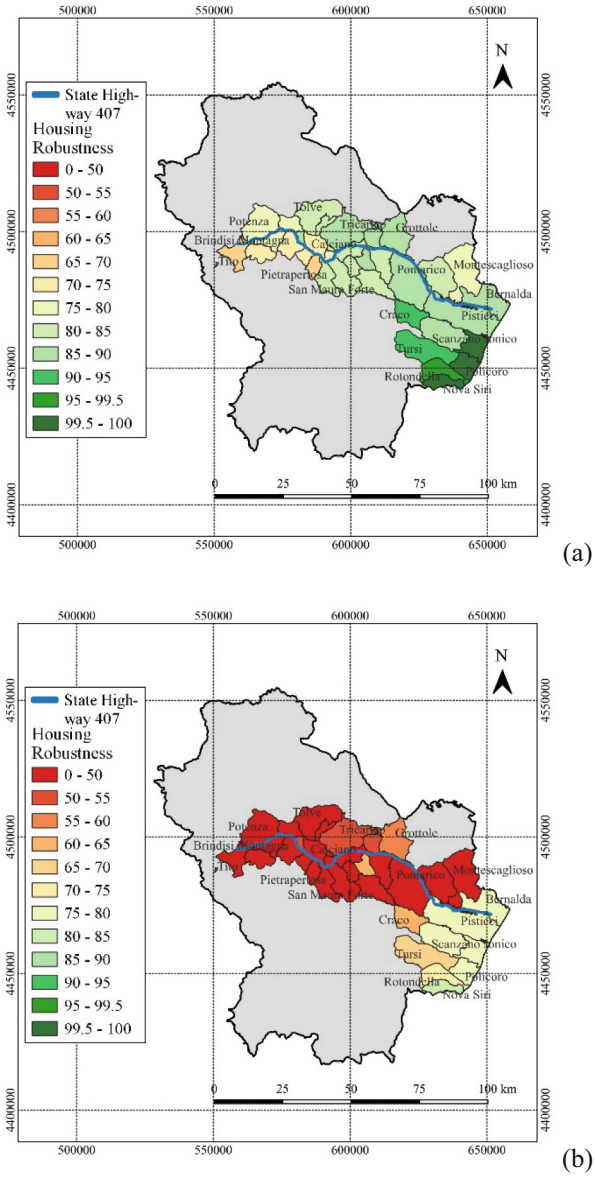


Fig. 5. Seismic robustness of housing systems for a return period of 100 (a) and 500 years (b).

3 Resilience Prioritization

To establish a resilience prioritization among the investigated municipalities, sixteen quantitative criteria (Table 1) and thirty-seven political scenarios or criteria weight vectors (Table 2) are considered herein. They are defined based on three main resilience

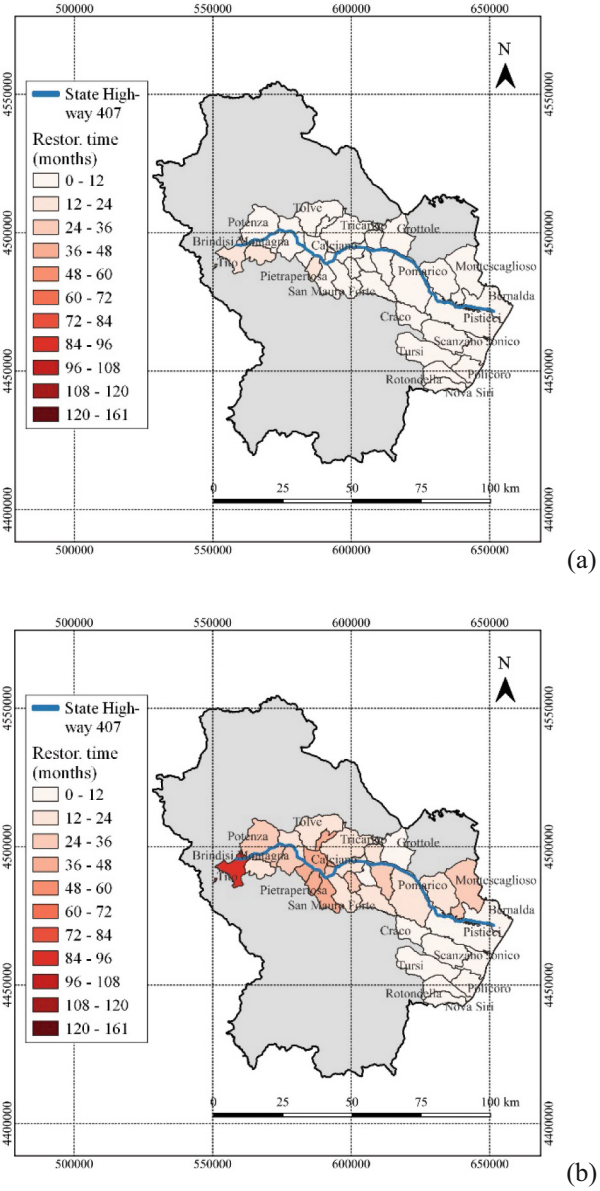
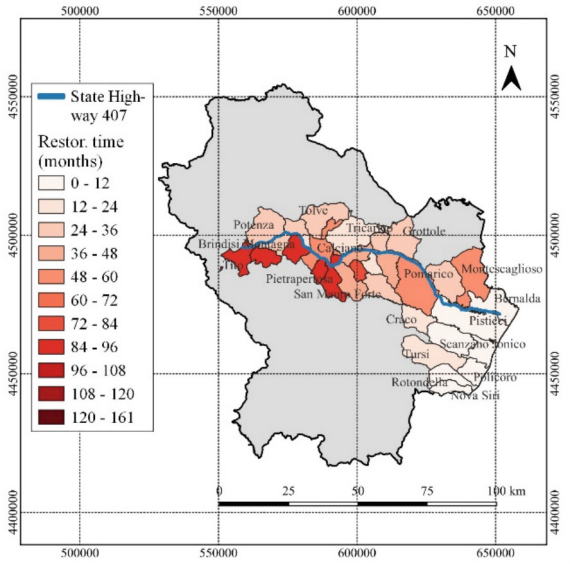


Fig. 6. Restoration time of housing systems for a return period of 100 (a), 250 (b), and 500 years (c).

aspects [14, 22, 23, 37]: i) seismic risk, ii) emergency management and recovery, iii) integration and social cohesion.

The thirty-three municipalities are assessed according to the judgement criteria reported in Table 1, from which the connection between the main resilience aspects



(c)

Fig. 6. (*continued*)

and the considered criteria can also be deduced. In particular, the seismic risk criteria – C_1, C_2, C_3, C_4 – and the emergency management and recovery criteria – C_6, C_7, C_8, C_9 – are described and evaluated in the previous Section (Figs. 2, 4, 5, 6).

When analyzing the municipalities with respect to the C_1 and C_2 criteria, the *AIR* values of the eight TCs (Fig. 4) are extended to all municipalities of the same TC because, as discussed in Sect. 1, emergency planning and management activities and risk mitigation strategies can be implemented cooperatively and uniformly across all municipalities in a TC.

Criterion C_5 aims to evaluate the specific exposure conditions in the compared municipalities. To this aim, ISTAT census data on population and buildings [24] are used. In criterion C_{10}, each municipality is analyzed by using a Geographic Information System (GIS) to identify its organizational relationships with the closest accessibility infrastructure.

ISTAT census data are also employed to analyze the municipalities with respect to the criteria of integration and social cohesion. More in detail, for the C_{11} criterion, the Average Population Growth Rate (*APGR*) of the *m*-th municipality is calculated as follows:

$$APGR_m = \frac{P(t + \Delta t)_m - P(t)_m}{P(t)_m \cdot \Delta t} \tag{3}$$

where Δt is assumed to be equal to ten years, while $P(t)$ and $P(t + \Delta t)$ is the number of inhabitants obtained from the ISTAT population census data for the years 2001 and 2011, respectively. This criterion aims to consider the risk of depopulation of a municipality. It is a significant and very worrying risk for Basilicata region.

Table 1. Resilience prioritization criteria.

Seismic Risk	C_1	Accessibility infrastructure robustness for a return period of 100 years
	C_2	Accessibility infrastructure robustness for a return period of 475 years
	C_3	Housing robustness for a return period of 100 years
	C_4	Housing robustness for a return period of 500 years
	C_5	Inhabitant per built area
Emergency Management & Recovery	C_6	Mobility outside the municipality for study or work
	C_7	Restoration time for a return period of 100 years
	C_8	Restoration time for a return period of 250 years
	C_9	Restoration time for a return period of 500 years
	C_{10}	Travel time from the nearest main accessibility infrastructure
Integration & Social Cohesion	C_{11}	Average population growth rate
	C_{12}	Incidence of foreign residents
	C_{13}	Incidence of young couples with children
	C_{14}	Participation in the job market
	C_{15}	Social and material vulnerability
	C_{16}	Unemployment rate

Municipal data concerning the remaining criteria – C_{12}, C_{13}, C_{14}, C_{15}, C_{16} – are directly taken from ISTAT database [30]. These criteria are able to take into account the social and economic dimensions of the communities involved. Among these, criterion C_{15} deserves particular attention because it is able to examine the overall socio-economic vulnerability of each municipality according to seven socio-economic indicators (for more details, see [43]).

A decision matrix (33x16) is used to capture the relationships between the thirty-tree municipalities and sixteen criteria considered.

To take into account the possible uncertainties involved in the decision-making process, thirty-seven political scenarios are defined based on the consistent comparisons of the three main resilience aspects (for more details, see [14, 22]). Then, the same relative importance is assigned to the criteria of each resilience aspect in order to simplify the procedure [23].

As shown in Table 2, the first twelve political scenarios emphasize the importance of seismic risk criteria, the second twelve place more emphasis on the emergency management and recovery criteria, the third twelve give greater importance to the criteria of integration and social cohesion, and, finally, the last political scenario attributes the same importance to the different resilience aspects.

Once the decision matrix and the political scenarios have been defined, the MCDM procedure suggested by Anelli et al. [23] is applied to calculate a Relative Resilience

Table 2. Political scenarios or criteria weight vectors.

$\mathbf{W}_1{}^{\mathrm{T}} =$	{0.108,0.108,0.108,0.108,0.108,0.059,0.059,0.059,0.059,0.059,0.027,0.027,0.027,0.027,0.027,0.027}$^{\mathrm{T}}$
$\mathbf{W}_2{}^{\mathrm{T}} =$	{0.108,0.108,0.108,0.108,0.108,0.033,0.033,0.033,0.033,0.033,0.049,0.049,0.049,0.049,0.049,0.049}$^{\mathrm{T}}$
$\mathbf{W}_3{}^{\mathrm{T}} =$	{0.127,0.127,0.127,0.127,0.127,0.052,0.052,0.052,0.052,0.052,0.017,0.017,0.017,0.017,0.017,0.017}$^{\mathrm{T}}$
$\mathbf{W}_4{}^{\mathrm{T}} =$	{0.127,0.127,0.127,0.127,0.127,0.021,0.021,0.021,0.021,0.021,0.043,0.043,0.043,0.043,0.043,0.043}$^{\mathrm{T}}$
$\mathbf{W}_5{}^{\mathrm{T}} =$	{0.132,0.132,0.132,0.132,0.132,0.053,0.053,0.053,0.053,0.053,0.013,0.013,0.013,0.013,0.013,0.013}$^{\mathrm{T}}$
$\mathbf{W}_6{}^{\mathrm{T}} =$	{0.132,0.132,0.132,0.132,0.132,0.016,0.016,0.016,0.016,0.016,0.044,0.044,0.044,0.044,0.044,0.044}$^{\mathrm{T}}$
$\mathbf{W}_7{}^{\mathrm{T}} =$	{0.143,0.143,0.143,0.143,0.143,0.043,0.043,0.043,0.043,0.043,0.011,0.011,0.011,0.011,0.011,0.011}$^{\mathrm{T}}$
$\mathbf{W}_8{}^{\mathrm{T}} =$	{0.143,0.143,0.143,0.143,0.143,0.013,0.013,0.013,0.013,0.013,0.036,0.036,0.036,0.036,0.036,0.036}$^{\mathrm{T}}$
$\mathbf{W}_9{}^{\mathrm{T}} =$	{0.150,0.150,0.150,0.150,0.150,0.036,0.036,0.036,0.036,0.036,0.012,0.012,0.012,0.012,0.012,0.012}$^{\mathrm{T}}$
$\mathbf{W}_{10}{}^{\mathrm{T}} =$	{0.150,0.150,0.150,0.150,0.150,0.014,0.014,0.014,0.014,0.014,0.030,0.030,0.030,0.030,0.030,0.030}$^{\mathrm{T}}$
$\mathbf{W}_{11}{}^{\mathrm{T}} =$	{0.164,0.164,0.164,0.164,0.164,0.018,0.018,0.018,0.018,0.018,0.015,0.015,0.015,0.015,0.015,0.015}$^{\mathrm{T}}$
$\mathbf{W}_{12}{}^{\mathrm{T}} =$	{0.200,0.200,0.200,0.200,0.200,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000}$^{\mathrm{T}}$
$\mathbf{W}_{13}{}^{\mathrm{T}} =$	{0.059,0.059,0.059,0.059,0.059,0.108,0.108,0.108,0.108,0.108,0.027,0.027,0.027,0.027,0.027,0.027}$^{\mathrm{T}}$
$\mathbf{W}_{14}{}^{\mathrm{T}} =$	{0.033,0.033,0.033,0.033,0.033,0.108,0.108,0.108,0.108,0.108,0.049,0.049,0.049,0.049,0.049,0.049}$^{\mathrm{T}}$
$\mathbf{W}_{15}{}^{\mathrm{T}} =$	{0.052,0.052,0.052,0.052,0.052,0.127,0.127,0.127,0.127,0.127,0.017,0.017,0.017,0.017,0.017,0.017}$^{\mathrm{T}}$
$\mathbf{W}_{16}{}^{\mathrm{T}} =$	{0.021,0.021,0.021,0.021,0.021,0.127,0.127,0.127,0.127,0.127,0.043,0.043,0.043,0.043,0.043,0.043}$^{\mathrm{T}}$
$\mathbf{W}_{17}{}^{\mathrm{T}} =$	{0.053,0.053,0.053,0.053,0.053,0.132,0.132,0.132,0.132,0.132,0.013,0.013,0.013,0.013,0.013,0.013}$^{\mathrm{T}}$
$\mathbf{W}_{18}{}^{\mathrm{T}} =$	{0.016,0.016,0.016,0.016,0.016,0.132,0.132,0.132,0.132,0.132,0.044,0.044,0.044,0.044,0.044,0.044}$^{\mathrm{T}}$
$\mathbf{W}_{19}{}^{\mathrm{T}} =$	{0.043,0.043,0.043,0.043,0.043,0.143,0.143,0.143,0.143,0.143,0.011,0.011,0.011,0.011,0.011,0.011}$^{\mathrm{T}}$
$\mathbf{W}_{20}{}^{\mathrm{T}} =$	{0.013,0.013,0.013,0.013,0.013,0.143,0.143,0.143,0.143,0.143,0.036,0.036,0.036,0.036,0.036,0.036}$^{\mathrm{T}}$
$\mathbf{W}_{21}{}^{\mathrm{T}} =$	{0.036,0.036,0.036,0.036,0.036,0.150,0.150,0.150,0.150,0.150,0.012,0.012,0.012,0.012,0.012,0.012}$^{\mathrm{T}}$
$\mathbf{W}_{22}{}^{\mathrm{T}} =$	{0.014,0.014,0.014,0.014,0.014,0.150,0.150,0.150,0.150,0.150,0.030,0.030,0.030,0.030,0.030,0.030}$^{\mathrm{T}}$
$\mathbf{W}_{23}{}^{\mathrm{T}} =$	{0.018,0.018,0.018,0.018,0.018,0.164,0.164,0.164,0.164,0.164,0.015,0.015,0.015,0.015,0.015,0.015}$^{\mathrm{T}}$
$\mathbf{W}_{24}{}^{\mathrm{T}} =$	{0.000,0.000,0.000,0.000,0.000,0.200,0.200,0.200,0.200,0.200,0.000,0.000,0.000,0.000,0.000,0.000}$^{\mathrm{T}}$
$\mathbf{W}_{25}{}^{\mathrm{T}} =$	{0.059,0.059,0.059,0.059,0.059,0.033,0.033,0.033,0.033,0.033,0.090,0.090,0.090,0.090,0.090,0.090}$^{\mathrm{T}}$
$\mathbf{W}_{26}{}^{\mathrm{T}} =$	{0.059,0.059,0.059,0.059,0.059,0.033,0.033,0.033,0.033,0.033,0.090,0.090,0.090,0.090,0.090,0.090}$^{\mathrm{T}}$
$\mathbf{W}_{27}{}^{\mathrm{T}} =$	{0.052,0.052,0.052,0.052,0.052,0.021,0.021,0.021,0.021,0.021,0.106,0.106,0.106,0.106,0.106,0.106}$^{\mathrm{T}}$
$\mathbf{W}_{28}{}^{\mathrm{T}} =$	{0.021,0.021,0.021,0.021,0.021,0.052,0.052,0.052,0.052,0.052,0.106,0.106,0.106,0.106,0.106,0.106}$^{\mathrm{T}}$
$\mathbf{W}_{29}{}^{\mathrm{T}} =$	{0.053,0.053,0.053,0.053,0.053,0.016,0.016,0.016,0.016,0.016,0.110,0.110,0.110,0.110,0.110,0.110}$^{\mathrm{T}}$
$\mathbf{W}_{30}{}^{\mathrm{T}} =$	{0.016,0.016,0.016,0.016,0.016,0.053,0.053,0.053,0.053,0.053,0.110,0.110,0.110,0.110,0.110,0.110}$^{\mathrm{T}}$
$\mathbf{W}_{31}{}^{\mathrm{T}} =$	{0.043,0.043,0.043,0.043,0.043,0.013,0.013,0.013,0.013,0.013,0.120,0.120,0.120,0.120,0.120,0.120}$^{\mathrm{T}}$
$\mathbf{W}_{32}{}^{\mathrm{T}} =$	{0.013,0.013,0.013,0.013,0.013,0.043,0.043,0.043,0.043,0.043,0.120,0.120,0.120,0.120,0.120,0.120}$^{\mathrm{T}}$
$\mathbf{W}_{33}{}^{\mathrm{T}} =$	{0.036,0.036,0.036,0.036,0.036,0.014,0.014,0.014,0.014,0.014,0.125,0.125,0.125,0.125,0.125,0.125}$^{\mathrm{T}}$
$\mathbf{W}_{34}{}^{\mathrm{T}} =$	{0.014,0.014,0.014,0.014,0.014,0.036,0.036,0.036,0.036,0.036,0.125,0.125,0.125,0.125,0.125,0.125}$^{\mathrm{T}}$
$\mathbf{W}_{35}{}^{\mathrm{T}} =$	{0.018,0.018,0.018,0.018,0.018,0.018,0.018,0.018,0.018,0.018,0.136,0.136,0.136,0.136,0.136,0.136}$^{\mathrm{T}}$
$\mathbf{W}_{36}{}^{\mathrm{T}} =$	{0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.000,0.167,0.167,0.167,0.167,0.167,0.167}$^{\mathrm{T}}$
$\mathbf{W}_{37}{}^{\mathrm{T}} =$	{0.067,0.067,0.067,0.067,0.067,0.067,0.067,0.067,0.067,0.067,0.056,0.056,0.056,0.056,0.056,0.056}$^{\mathrm{T}}$

Index (RRI). This procedure was implemented to define a ranking of all TCs of Basilicata, Calabria, Campania, Puglia, and Sicily regions according to a wide range of political scenarios. Depending on the RRI values, funds among TCs and regions can also be distributed. For more details on the RRI calculation, please see the reference document above.

In the case study, the same procedure is applied to establish a resilience prioritization among the analyzed municipalities (Fig. 7). More specifically, in the RRI calculation, criteria – C_1, C_2, C_3, C_4, C_{11}, C_{13} – are considered as cost criteria (their minimization is the objective), while the remaining criteria are processed as benefit criteria (their maximization is the goal). Consequently, a maximization of RRI values is sought to obtain a ranking of the municipalities from the least resilient to the most resilient. As can be deduced from Fig. 7, the municipality of Castelmezzano (depicted in dark blue, RRI = 0.0428) is the least resilient among the municipalities investigated. It is followed by the municipalities of Pietrapertosa (RRI = 0.0415) and Albano di Lucania (RRI = 0.0400). On the contrary, the municipality of Policoro (depicted in light yellow, RRI = 0.0138) is the most resilient. It is preceded by the municipalities of Scanzano Jonico (RRI = 0.0167), Nuova Siri (RRI = 0.0171) and Bernalda (RRI = 0.0195), all located along the Ionian coast of the Basilicata region.

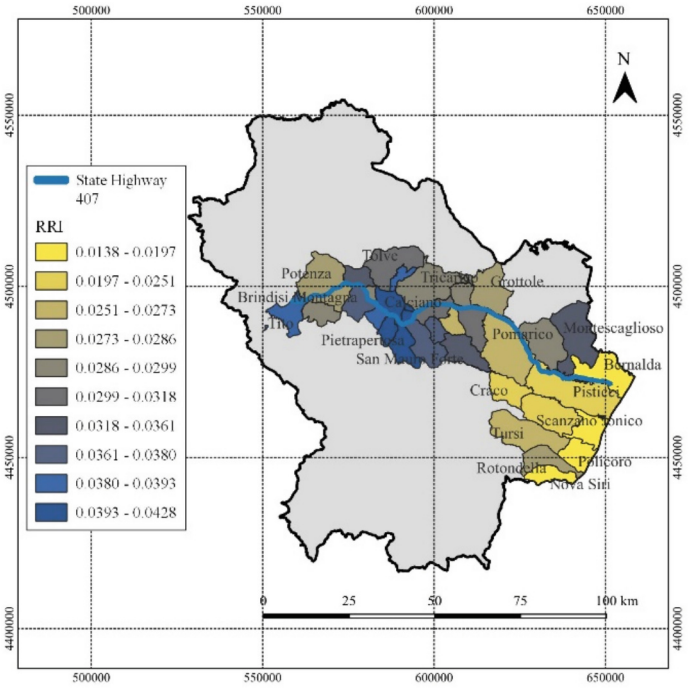


Fig. 7. Resilience prioritization of the municipalities according to their RRI value.

4 Conclusions

In this paper, a resilience prioritization among thirty-three municipalities in Basilicata region is proposed to show how resilience principles can be applied in the formulation of mitigation strategies on an inter-municipal level. At this territorial scale, the main

contribution to the field is the analysis of the functional interdependencies between housing systems and the main infrastructure system, especially in terms of emergency response.

Census data and seismic risk assessments incorporating stratigraphic amplification effects are used to analyze, with a transparent and multidisciplinary approach, the different resilience dimensions of the investigated systems. These data are integrated in the decision-making process by using a multi-criteria procedure that is able to rank the compared municipalities in relation to a large number of criteria and political scenarios.

Sixteen resilience prioritization criteria and thirty-seven political scenarios are considered, and then relative resilience measurements (RRI values) among the municipalities are determined with the procedure used. In this way, a resilience assessment of the municipalities is obtained in relative terms and a final ranking is defined according to their resilience values. The latter take into account the possible uncertainties involved in the decision-making process thanks to the ability of the procedure to find solutions based on multiple criteria and political scenarios.

The used procedure could become a main tool to define priorities and allocate funds among regions, TCs and municipalities for emergency planning and prevention purposes. By using this procedure at different territorial scales, a new and rational seismic risk mitigation policy can be developed to build resilience communities. Moreover, the procedure can be further enriched by analyzing the different urban systems. This last aspect can be considered the main limitation of the present work, but it can be further improved in future studies using the present methodological approach.

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