



Large-Scale Seismic Vulnerability and Risk of Masonry Churches in Seismic-Prone Areas: Two Territorial Case Studies

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In this paper, seismic vulnerability and risk assessment of two samples of churches, located in Teramo and Ischia island (Naples gulf), both affected by the most recent earthquakes that occurred in Italy, are presented. To this aim, we applied a simplified method particularly suitable for seismic evaluations at a territorial scale, providing a global resulting score to be compared among the cases analyzed. The data obtained allowed us to provide vulnerability maps and a seismic risk index for all the considered churches. In addition, the calculated indexes permit a preliminary health state evaluation of the inspected churches, for ranking the priorities and planning additional in-depth evaluations.

Keywords: seismic vulnerability, seismic risk, masonry church, L'Aquila earthquake, Ischia earthquake, large-scale analysis method, damage index

INTRODUCTION

The structural analysis of monumental buildings belongs to a multidisciplinary study, where different types information are converging, such as construction history (year of erection, possible transformations, traumatic events), geometrical and structural critical survey, materials features and degradation, and the detection of crack patterns. In this way, it is possible to firstly diagnose the causes that produce instability and/or degradation of structural elements, which are very often multiple and generally act simultaneously. In general, these causes can be classified as intrinsic or extrinsic: the former refers to the origin and nature of the monumental buildings and, therefore, to their vulnerability; the latter is related to the site geographic conditions.

The Italian territory is characterized by a high seismicity level, demonstrated by the last earthquakes that occurred in the recent past such as in Irpinia (1980), San Giuliano of Puglia (2002), L'Aquila (2009), Emilia-Romagna (2012), Central Italy (2016), and Ischia (2017). These events unfortunately gave rise to serious consequences in terms of death and damage to historical buildings. Therefore, from an engineering point of view, appropriate numerical, experimental, and theoretical procedures are required in order to assess the seismic vulnerability of the structures and to design specific interventions useful for repairing the damages or avoiding future ones.

Recently, simplified models useful to preliminarily assess the seismic performance and the related risk at a territorial level have been proposed (Lourenço and Roque, 2006; Directive of the Italian Prime Minister, 2011; Lourenço et al., 2013). These methods are useful for ranking the priorities and for planning further analyses, to be conducted with more refined numerical

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models, which may regard some construction parts or the entire structure. To this aim, the second-level vulnerability forms developed by the Italian National Group for Earthquakes Defense (GNDT) (Benedetti and Petrini, 1984; GNDT, 1994), which are useful for screening the structures through systematic surveys, are worth noting. Among these simplified models, a new and simplified procedure, developed, and validated at the University of Basilicata, has been recently proposed. This procedure may also be applied to ancient masonry churches, and it is useful to evaluate the seismic risk at a territorial scale including natural threats due to the geographical surrounding context. This methodology, described and validated in Díaz Fuentes (2016), D'Amato et al. (2018), and D'Amato et al. (2019), and extended also to Chilean adobe churches in Fuentes et al. (2019a), is being applied in this paper to analyze the seismic vulnerability of two samples of Italian churches. In particular, the considered churches are located in two different geographical areas: in Teramo (Central Italy) and in Ischia island, located in the Naples gulf (Southern Italy). Both areas were affected by recent earthquakes and the considered churches suffered different structural damages. Initially, an international overview is shown on some researches devoted to the preservation of cultural heritage buildings through the proposal of manuals and principles for risk management, not limited to the seismic hazard. Later on, the simplified method considered in Díaz Fuentes (2016) and D'Amato et al. (2018) is described and applied to the two church samples, after collecting all information (structural and related to potential threats in the area) necessary for evaluating seismic vulnerability and the resulting risk indexes. Finally, the achieved results are compared and discussed. The obtained results show that the considered methodology is also useful for comparison of the seismic risk of different geographical areas. Moreover, a new territorial seismic risk score is also proposed.

SEISMIC VULNERABILITY AND RISK OF HISTORICAL CONSTRUCTIONS

Seismic vulnerability influences how damage caused by an earthquake in a given area is assessed from a construction point of view. The causes of high vulnerability even at very low levels of seismic forces may be different due, for instance, to structural irregularities, inadequate design, poor quality of materials, absence of constructive details, and scarce maintenance (Krstevska et al., 2010; Betti and Vignoli, 2011; Milani and Valente, 2015a; Clementi et al., 2017a,b; Fonti et al., 2017; Formisano et al., 2017, 2018; Milani et al., 2017a; Valente et al., 2017; Luchin et al., 2018; Valente and Milani, 2018a,b,c). After the recent seismic events, many efforts of the scientific community have been done in order to develop appropriate procedures for implementing seismic vulnerability analysis (Formisano, 2017; Formisano and Marzo, 2017; Laterza et al., 2017; Lopez et al., 2019) and specific retrofitting interventions (Faggiano et al., 2009; Terracciano et al., 2015; D'Amato et al., 2017; Milani et al., 2017b, 2018). In particular, as previously introduced, recurrent seismic damages were observed in historic masonry buildings characterized by local out-of-plane and

in-plane response mechanisms regarding one or more isolated structure portions (Lagomarsino and Podestà, 2004; Formisano et al., 2010; Leite et al., 2013; Gattulli et al., 2014; Milani and Valente, 2015b; Stockdale, 2016; Valente et al., 2016; Betti et al., 2018; De Matteis et al., 2019; Fuentes et al., 2019b; Penna et al., 2019; Ramirez et al., 2019).

In order to assess the seismic performance of an existing structure, the current Italian Design Code (Ministry of Infrastructures and Transports, 2008a,b; Cecchi and Calvi, 2010; Directive of the Italian Prime Minister, 2011; Ministry of Infrastructures Transports, 2018) defines the design criteria and the performance targets to be satisfied under an earthquake action. These indications are useful for assessing vulnerability combined with the seismic hazard for evaluating the resulting seismic risk as well as all the possible effects in terms of expected damage that an earthquake can produce in a determined time and area.

With regard to cultural heritage conservation in the international scenario, various principles and manuals for risk management, such as those delivered by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Council of Monuments and Sites (ICOMOS, 2008), the International Centre for the Study of Conservation and Restoration of Cultural Heritage (ICCROM), and the Getty Conservation Institute (UNESCO World Heritage Centre, 2002; ICOMOS, 2008), were developed. In addition, innovative prevention programs, such as the Risk Maps of different countries and the Disaster Prevention Program on Cultural Heritage (INAH, 2013), have been set up. However, the principles proposed found rare applications, because they did not take into account the different cultural, social, and economic values among countries. In this context, the ICCROM and the Getty Conservation Institute, with the publication "Between Two Earthquakes" in 1987 (Feilden, 1987), were the first to propose guidelines for prevention of disaster risks. These guidelines focused on two constructive vulnerability aspects, namely, the intrinsic structure, and vulnerability due to building location. In 1998, the first risk management manual for the world cultural heritage was developed (Stovel, 1998), whose most important proposals concerned both threats and the cultural heritage value for the community. This document was updated in 2009, when the United Nations Office for Disaster Reduction (UNISDR) published "Terminology on disaster risk reduction" (UNISDR, 2009). Subsequently, in 2010, UNESCO, ICCROM, ICOMOS, and the World Union for Conservation of Nature (IUCN) developed the Managing Disaster Risks for World Heritage (UNESCO/ICCROM/ICOMOS/IUCN, 2010), a document integrating Stovel's manual and introducing physical nature threats caused by climatic factors and chemical nature hazards.

SIMPLIFIED METHODOLOGY FOR SEISMIC RISK ASSESSMENT (Díaz Fuentes, 2016; D'Amato et al., 2018)

Seismic risk is the measurement of the expected damage of buildings placed at a specified site in a given time interval. It is

considered as the combination of three factors, namely, hazard, vulnerability, and exposure. Therefore, in order to assess the seismic risk of a built area, knowledge of only the hazard is not enough, since it is also necessary to carefully estimate the different construction vulnerabilities present during the seismic event and the related economic and social value of their content.

In this paper, the methodology applied refers to a recent work carried out by the University of Basilicata for providing territorial risk maps for planning useful intervention plans also addressed to increase cultural heritage resilience (D'Amato et al., 2018; Fuentes et al., 2019a). This simplified method may be applied, in general, in a multi-risk evaluation procedure, by considering both natural and anthropic threats. In this work, the method is applied only for a seismic risk analysis, involving the application of three distinct tools, each of which assigns a specific score:

1. *Tool 1*: Priority attention on actions related to the buildings according to their exposure value (E);
2. *Tool 2*: Description, classification, and mapping of seismic hazard (H);
3. *Tool 3*: Evaluation and quantification of the seismic vulnerability level (V).

The choice of this simplified method is due to the fact that it allows assessment of seismic risk at a territorial scale before a real seismic event, just supposing different earthquake magnitudes. On the contrary, other methods, such as the ones proposed by the GNDT or Italian civil protection, are based on a post-earthquake survey of damages with visual analyses. Moreover, the method permits a fast appraisal of a large number of ancient churches in a certain area requiring very simple information about dimensional features, environmental characteristics, and site morphology. Once the first seismic risk screening is conducted, it is possible to carry out more in-depth analyses in order to program retrofitting interventions. However, the present simplified model does not take into account the cumulative damage due to repeated shocks (for example, during a typical seismic sequence, or due to a series of events acting on unrepaired buildings) that influences the vulnerability of the buildings investigated and, therefore, may vary seismic risk ranking.

In this study, the simplified method considered is applied, as it will be discussed later on, to two different samples of churches located in two distinct geographical areas: it allows one to perform comparative seismic risk analyses at a territorial scale.

Description

The simplified procedure allows one to separately score exposure value (application of *Tool 1*), seismic hazard (*Tool 2*), and seismic vulnerability (*Tool 3*). Then, the so-obtained scores are multiplied in accordance with the relationship (UNDRRO, 1979; FEMA, 2004):

$$R = E \times H \times V \quad (1)$$

Tool 1 estimates the cultural values, divided into socio-cultural, and economic values. Socio-cultural values include antiquity, historical, symbolic, and aesthetic values. Economic values

concern the value in use, as well as financial and scientific values. In this study, seismic risk assessment has been performed unless the score E is assigned by means of *Tool 1*.

Hazard Scoring (H)

Tool 2 provides the H score. It considers the risk from different points of view, with the aim of conducting a qualitative analysis that leads to the identification of threats conditioning the performances of buildings. Threats are divided into two categories, namely, sporadic events and continuous processes, depending on their occurrence probability. In particular, they can be grouped into three families:

- Natural threats, configured as sporadic events with catastrophic, or serious consequences;
- Physical threats, configured as continuous processes, whose consequences are generally low, even if they gradually increase;
- Anthropogenic, chemical, and electrochemical threats, generally corresponding to continuous processes with low or gradual consequences, except for the cases of sporadic events (i.e., fires caused by industrial activities and forest fires) with catastrophic consequences.

The risk scenarios are divided into the best, the most probable, and the worst. They are determined on the basis of the statistical principle that considers a higher probability of catastrophic events in areas already affected by earthquakes. The main natural threats are earthquakes and tsunami, landslides and floods, hydro-meteorological hazards, and volcanic phenomena. Physical threats are represented by water, terrestrial hazards, thermal risks, and dangers due to atmospheric environment. For these threats, the erosion index and the physical stress ones are defined.

The anthropogenic, chemical, and electrochemical threats are of the following different nature:

- Chemical: fires, explosions, radiation, toxic losses;
- Health-ecological: epidemics or parasites, air, soil, or water pollution;
- Socio-organizational: wars; social hardship manifestations; terrorism; vandalism; tourist pressure; population overload; relative humidity increase; air, marine, or terrestrial accidents; and forest fires;
- Severe demographic decline with consequent building abandonment and consequent lack of maintenance: material deterioration, loss of water (due to broken pipes, drainage problems, water protection, etc.).

Among these threats, those that influence cultural heritage the most are air and water pollution, which cause deterioration of materials and the environment.

All the above parameters are analyzed to determine the worst possible situation, based on historical information. They are subsequently classified according to the severity of the potential damage to monumental buildings. Damage can be absent, low or gradual, and catastrophic. These damage typologies are characterized by a given score assigned to each parameter on the basis of the threat influence on the building seismic behavior (**Table 1**). The resulting seismic hazard index

TABLE 1 | Scenario description and classification of threats according to damage severity.

Parameters		Damage gravity		
		Absence of damage	Middle damage	Catastrophic damage
Sporadic Events	Earthquake and tsunami threat	0	0.2	0.4
	Landslides	0	0.15	0.25
	Volcanic threat	0	0.2	0.4
	Hydro-methodological threat	0	0.15	0.25
	Chemical–technological threat	0	0.15	0.25
	Forest fires	0	0.15	0.25
Continuous Events	Erosion threat	0	0.05	0.1
	Physical stress of threat	0	0.05	0.1
	Air pollution	0	0.01	0.05
	Socio-organizational threat	0	0.01	0.05
	Demographic decline	0	0.01	0.05

(*H*), obtained by summing the singular threats scores, may assume a value ranging from 0 and 1. More details about the *H* scoring may be found in Diaz Fuentes (2016) and D’Amato et al. (2018).

Vulnerability Scoring (V)

The application of *Tool 3* provides the vulnerability score *V*. This tool aims at evaluating the seismic vulnerability of the considered church, and it is based on the assessment of 13 vulnerability parameters related to various construction aspects. Specifically, 10 of these 13 parameters are derived from the Italian second-level GNDT vulnerability datasheet (GNDT, 1994). Each parameter has a different weight *p_i*, and is characterized by four different scores *v_i* associated to four possible classes (A, B, C, and D). The values of *p_i* and *v_i* are reported in **Table 2**.

Finally, according to the considered method, the vulnerability index *V* may be evaluated with the following relationship:

$$V = \sum_{i=1}^{13} v_i p_i \tag{2}$$

where, the sum is extended to all possible parameters considered. In particular, as it is worthy to note, the higher the *V* score, the higher the seismic vulnerability of a structure, which may fall within the following ranges:

- Low vulnerability: $0 < V \leq 10.81$;
- Medium vulnerability: $10.81 < V \leq 55.52$;
- High vulnerability: $55.52 < V \leq 100$.

In the following, each parameter considered is described in detail. More information may be found in Diaz Fuentes (2016) and D’Amato et al. (2018).

Position of the Building and Foundations

By indicating as Δh the foundation difference altitude, the four considered classes are as follows:

TABLE 2 | Parameter evaluation and quantification in order to calculate the vulnerability index.

Parameters	Class (<i>v_i</i>)				Weight (<i>p_i</i>)
	A	B	C	D	
1 Position of the building and foundations	0	1.35	6.73	12.12	0.75
2 In-plane configuration	0	1.35	6.73	12.12	0.50
3 In-elevation configuration	0	1.35	6.73	12.12	1.00
4 Distance among walls	0	1.35	6.73	12.12	0.25
5 Non-structural elements	0	1.35	6.73	12.12	0.25
6 Resistant system type and organization	0	1.35	6.73	12.12	1.50
7 Resistant system quality	0	1.35	6.73	12.12	0.25
8 Floors	0	1.35	6.73	12.12	1.00
9 Roofs	0	1.35	6.73	12.12	1.00
10 Conservation state	0	1.35	6.73	12.12	1.00
11 Environmental alterations	0	1.35	6.73	12.12	0.25
12 Construction system negative alterations	0	1.35	6.73	12.12	0.25
13 Fire vulnerability	0	1.35	6.73	12.12	0.25

Class A:

- Buildings placed on rocky terrain with slopes equal to or lower than 10% and any Δh ;
- Buildings placed on loose ground with slopes lower than or equal to 10% and $\Delta h = 0$.

Class B:

- Buildings placed on rocky terrain with a slope of 10–30% and any Δh ;
- Buildings placed on loose ground with $\Delta h \leq 1$ m and in the absence of unbalanced pressures due to embankments also verifying one of the following conditions:
 1. A ground slope lower than 10% and $0 < \Delta h \leq 1$;
 2. A ground slope of 10–30% and $\Delta h \leq 1$;
 3. Building without foundations, a ground slope of 10–30% and $\Delta h \leq 1$.

Class C:

- Buildings placed on rocky terrain with a slope of 30–50% and any Δh ;
- Buildings on loose ground and $\Delta h \leq 1$, which verifies one of the following conditions:
 1. Absence of unbalanced thrusts due to embankments, the building has foundations, a ground slope of 30–50%, and $\Delta h \leq 1$;
 2. Absence of unbalanced thrusts due to embankments, the building has no foundations, the ground has a slope of 20–30%, and $\Delta h \leq 1$;
 3. Presence of unbalanced thrusts due to embankments, the building has foundations, the ground has a slope <50%, and $\Delta h \leq 1$;
 4. Presence of unbalanced thrusts due to embankments, the building has no foundations, the ground has a slope <30%, and $\Delta h \leq 1$.

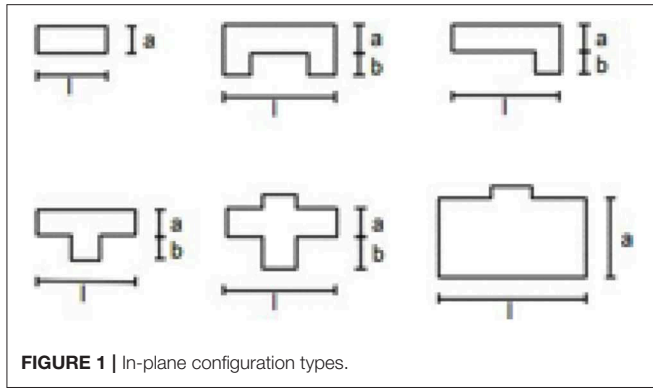


FIGURE 1 | In-plane configuration types.

Class D:

All the other cases that do not fall into the previous classes.

In-plane Configuration

In the case of a rectangular building, a significant parameter is the ratio between the dimensions of minor and major sides $\beta_1 = a/l \times 100$ (Figure 1). In case of plan layouts with different shapes, in addition to the β_1 parameter, it is necessary to take into account another parameter $\beta_2 = b/l \times 100$, which is the ratio between the deviation size and the larger dimension (Figure 1).

The assignment to a given class is made on the basis of the most unfavorable conditions set by the β_1 and β_2 parameters as follows:

Class A:

$$\beta_1 \geq 80 \text{ and } \beta_2 \leq 10$$

Class B:

$$60 \leq \beta_1 < 80 \text{ and } 10 < \beta_2 \leq 20$$

Class C:

$$40 \leq \beta_1 < 60 \text{ and } 20 < \beta_2 \leq 30$$

Class D:

$$\beta_1 < 40 \text{ and } \beta_2 > 30$$

In-elevation Configuration

It is necessary to take into account the presence of porticoes having a significant surface compared to that of the building, as well as towers of significant height and mass compared to the remaining part of the building. For the mass variation evaluation, the $\pm \Delta M/M$ ratio is considered, where:

- ΔM is the mass variation between two successive levels;
- M is the mass of the lower floor.

Percentage variations $<10\%$ can be considered negligible. As a rule, the $\Delta M/M$ ratio can be replaced by the $\pm \Delta A/A$ ratio, where A and ΔA are the plan covered surface and its variation, respectively. The four classes to be considered are as follows:

Class A:

- Buildings with uniform mass distribution over the whole height;
- Buildings with mass continually decreasing.

Class B:

- Buildings with porticoes and loggias of modest size;
- Buildings that present backwardness resulting in a decrease of the floor area >10 and $<20\%$;
- Buildings with towers with a height $<10\%$ of the total building.

Class C:

- Buildings with porticoes or loggias having surface $>10\%$ and equal to or $<20\%$ of the total covering floor area;
- Buildings with retractions involving a reduction of the floor area more than 20% ;
- Buildings with towers with a height more than 10 and $<40\%$ of the total building.

Class D:

All the other cases that do not fall into the previous classes.

Distance Among Walls

The aim of this parameter is to evaluate the presence of walls (without considering partition walls) intersected by transverse ones that are able to constitute an efficient constraint to prevent the development of out-of-plane overturning mechanisms. The vulnerability classes are the following.

Class A:

Buildings having the following geometrical features:

- Slenderness (height/thickness) <8 ;
- The internal room width should not be more than 2.5 times the wall thickness;
- Door and window must be located at a distance from the nearest free edge almost three times the wall thickness;
- The distance between the wall bracing axes must be <6 times the wall thickness;
- The wall relative verticality must not be $>10\%$ of its height.

Class B:

- Buildings with only three of the Class A geometric features.

Class C:

- Buildings with only two of the Class A geometric features.

Class D:

- Buildings that do not have the geometrical features described in class A.

Non-structural Elements

In this parameter, all the non-structural elements, such as fixtures, appendices, and projections that can cause damage to people or things, are considered. The classes are defined as follows:

Class A and Class B:

- Buildings without windows, appendices, overhangs, or false ceilings;
- Buildings with windows and fixtures well-connected to the walls;
- Buildings with balconies that are an integral part of the horizontal structures.

Class C:

- Buildings with external fixtures poorly bounded to the walls and with small false ceilings not well-connected.

Class D:

All the other cases that do not fall into the previous classes.

Resistant System Type and Organization

The organization of the vertical elements is evaluated regardless of the material characteristics of walls. The significant element is the presence and effectiveness of the connections among orthogonal walls in order to ensure box structure behavior efficiency. The four classes are as follows:

Class A:

- Existing buildings consolidated or repaired according to the actual seismic rules.

Class B:

- Buildings with good connections among orthogonal walls.

Class C:

- Buildings that do not have adequate connections between walls and upper floors;
- Buildings with orthogonal walls having a good connection at all levels and floors built up with materials different from the original ones;
- One-story buildings composed of orthogonal walls not adequately connected, which instead have a good connection between the walls and the roofing system thanks to continuous horizontal structures made of original materials or materials compatible to the existing ones in terms of strength and stiffness.

Class D:

All the other cases that do not fall into the previous classes.

Resistant System Quality

It depends on the material and masonry type. The four classes are as follows:

Class A:

- Square stone masonry having a good-quality mortar;
- Tuff masonry with low porosity and a good-quality mortar;
- Masonry composed of solid bricks having a good-quality mortar;
- Retrofitted masonry according to the current seismic rules.

Class B:

- Stone masonry composed of non-homogeneous elements having a good-quality mortar;
- Masonry composed of solid bricks having a medium-quality mortar.

Class C:

- Squared masonry stones with irregularities having plaster and medium-quality mortar;

- Non-squared masonry stones having plaster and medium-quality mortar
- Sack masonry stones having plaster and medium-quality mortar;
- Squared masonry stones having plaster and medium-quality mortar;
- Masonry bricks having low-quality mortar.

Class D:

Masonry types that do not fall within the previous classes.

Floors

This parameter expresses the type and properties of horizontal structures. The four classes are defined as follows:

Class A:

Rigid slabs having:

- Negligible in-plane deformability;
- Effective floor-wall connections;
- Absence of staggered floors.

Class B:

- Buildings that do not satisfy the third requirement of the previous class.

Class C:

- Deformable floor having good connections among walls.

Class D:

- Buildings that do not fall within the previous classes.

Roof

The roof elements influencing the building's seismic behavior are as follows: thrusts on the perimeter walls, connections between roof and walls, seismic mass, stiffness, and strength difference with respect to the masonry building. The four classes are as follows:

Class A:

- Buildings with non-thrusting roofs having edge beams and/or metal tie rods.

Class B:

- Buildings with non-thrusting roofs without edge beams and/or metal tie rods;
- Buildings with non-thrusting roofs having edge beams and/or metal tie rods with the absence of efficient connections between the roof and walls.

Class C:

- Buildings with thrusting roofs made of the original building materials or materials compatible to the original ones in terms of strength and stiffness and without edge beams and/or metal tie rods;
- Buildings with non-thrusting roofs made of the original building materials or materials compatible to the original ones in terms of strength and stiffness and without edge beams and/or metal tie rods.

Class D:

- Buildings that do not fall within the previous classes.

Conservation State

This parameter considers the actual building status. The four classes are as follows:

Class A:

- Walls in good condition without visible cracks.

Class B:

- Buildings with no diffused cracks, but with possible lesions generated by earthquakes.

Class C:

- Buildings with medium-size cracks (width of the lesion: 2–3 mm);
- Buildings without cracks, but with walls having a conservation status leading toward a significant resistance decrease.

Class D:

Buildings that do not fall within the previous classes.

Cracks and deformations can derive from different causes, such as construction defects, humidity presence, earthquakes, etc. The analyzed damage allows the interpretation of possible collapse mechanisms. In the vulnerability general form, it is necessary to identify in the appropriate section the type of existing damage (structural, non-structural, or humidity) and to express the percentage extension on the structural elements. The possible collapse mechanisms are illustrated in **Figure 2**.

Environmental Alterations

The parameters useful for the vulnerability evaluation are as follows:

- Accessibility: in case of a catastrophic event, buildings have no accessibility to roads and/or infrastructures;
- Abandonment: the building is in an abandoned context;
- Population density: the building is located in a densely populated area;
- Isolation: the building is located at a considerable distance from the city center;
- Relationship with the geographical context: the building is in a situation of conflict with the site;
- Relationship with the built context: the building is in a situation of conflict with the adjacent constructions;
- Community relationship: the building is in a situation of conflict with the social context;
- Disinterest: the physical and social environments have no relationship with the building.

The classification is as follows:

Class A:

- Buildings that do not have any of the above conditions.

Class B:

- Buildings that have almost three of the above conditions.

Class C:

- Buildings that have almost six of the above conditions.

Class D:

- Buildings that have more than six of the above conditions.

Constructive System Negative Alterations

Some interventions on buildings are useful for improving the response toward seismic events. However, following recent earthquakes, it was observed that invasive interventions with materials different from building original ones cause high vulnerabilities, leading to collapse in some cases. The classification is as follows:

Class A:

- Structures without interventions to the building system;
- Structures with modifications to the building system by reversible interventions made of materials compatible to the original ones in terms of strength and stiffness.

Class B:

- Structures with modifications to the building system by non-reversible interventions made of materials compatible to the original ones in terms of strength and stiffness.

Class C:

- Structures with interventions made of materials compatible to the existing ones that have modified the building mass.

Class D:

- Structures with interventions made of materials incompatible to the existing ones in terms of strength and stiffness.

Fire Vulnerability

The parameters affecting fire resistance are as follows:

- Presence of ornaments and flammable materials;
- Roofs or cellars dust accumulation;
- Walls, floors, and doors with low fire resistance;
- Lack of compartmentation;
- Inadequate exits through doors, corridors, or stairs;
- Faulty electrical systems;
- Faulty fireplaces with soot and grease accumulation;
- Low standard in organization of fire drills;
- Fire danger due to smoking or kitchen operations.

Seismic Risk Scoring (*R*)

The resulting seismic risk score (*R*) may be calculated, in accordance with the simplified method considered, as follows (D'Amato et al., 2018):

$$R = V \times (H + 1) \quad (3)$$

where the *H* score is increased to unity for having a resulting score higher than 1. As it is easy to understand, the seismic risk

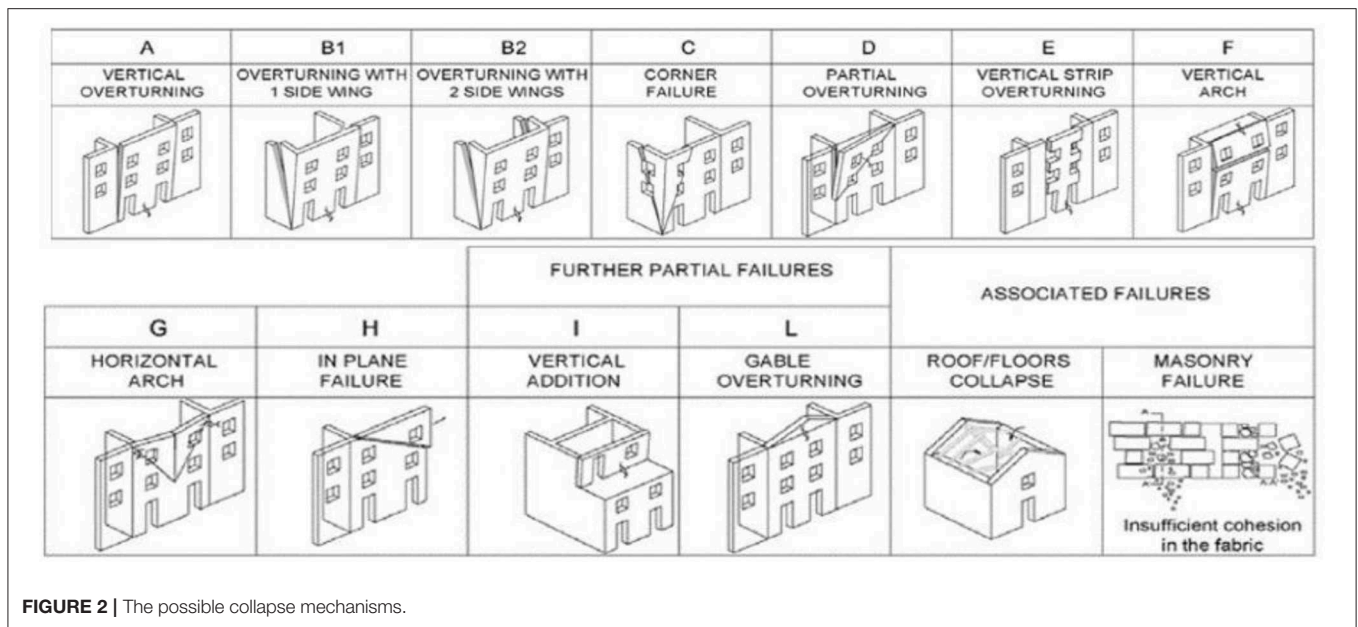


FIGURE 2 | The possible collapse mechanisms.

score R increases as the vulnerability V and/or the hazard scoring H increases.

CASE STUDIES

As previously introduced, in this paper, the vulnerability and the risk assessment of two samples of churches are presented. In particular, the chosen churches are located in two different geographical areas, both struck by recent Italian earthquakes. The first group of churches is located in Teramo, in central Italy, hit by the L'Aquila earthquake in 2009. The second group of churches falls within the Ischia island, in the province of Naples, which was hit by an earthquake in 2017.

Teramo Churches

Teramo is the provincial capital of the homonymous province, located in the northern area of Abruzzo. It is placed within the Tordinone Valley, a hilly area near the Gran Sasso Mountain, which extends toward the coast with a rich vegetation of vineyards and olive groves. It is the third most populous town of the Abruzzo region and has an area of about 10 km². The churches investigated, distributed within the Teramo area as reported in **Figure 3**, are 12 in total and listed as follows, indicating also the city hamlets where they are located:

1. Saint John church (Teramo);
2. Saint Anastasio church (Poggio Cono, hamlet of Teramo);
3. Holy Mary of Carmine church (Cavuccio, hamlet of Teramo);
4. Saint Nicola church (Cavuccio, hamlet of Teramo);
5. Saint Catherine of Alexandria church (Teramo);
6. Saint Luca church (Teramo);

7. Saint Mary de Praediis church (Pantaneto, hamlet of Teramo);
8. Saint Michael Archangel church (Magnanella, hamlet of Teramo);
9. Saint Francis of Assisi church (Villa Romano, hamlet of Teramo);
10. Saint John in Pergulis church (Valle San Giovanni, hamlet of Teramo);
11. Most Holy Salvatore church (Frondarola, hamlet of Teramo);
12. Saint Stephen church (Rapino, hamlet of Teramo).

Some images of the considered churches are reported in **Table 3**. For sake of completeness, the main geometric features of each church are reported in **Table 4**. In this table, the major and minor dimensions and the height of the hall and of the apse (if present) are reported. In addition, information about the presence of the bell tower and its estimated height are given as well.

Ischia Churches

Ischia is an Italian island belonging to the *Flegree* islands archipelago in the Naples province. The island, which is the largest of the *Flegree* islands, is located in the northern area of the Gulf of Naples and not far from the Procida island in the Tyrrhenian Sea. Ischia is about 18 nautical miles from Naples; it extends 10 and 7 km from east to west and from north to south, respectively, and has a coastline of 34 km and a surface area of about 46.3 km². The island has a volcanic character, formed by several eruptions since about 150,000 years ago. The oldest parts of the island, which dates back to between 147,000 and 100,000 years ago, are recognizable along the southern coastlines. The following 10 churches are considered,

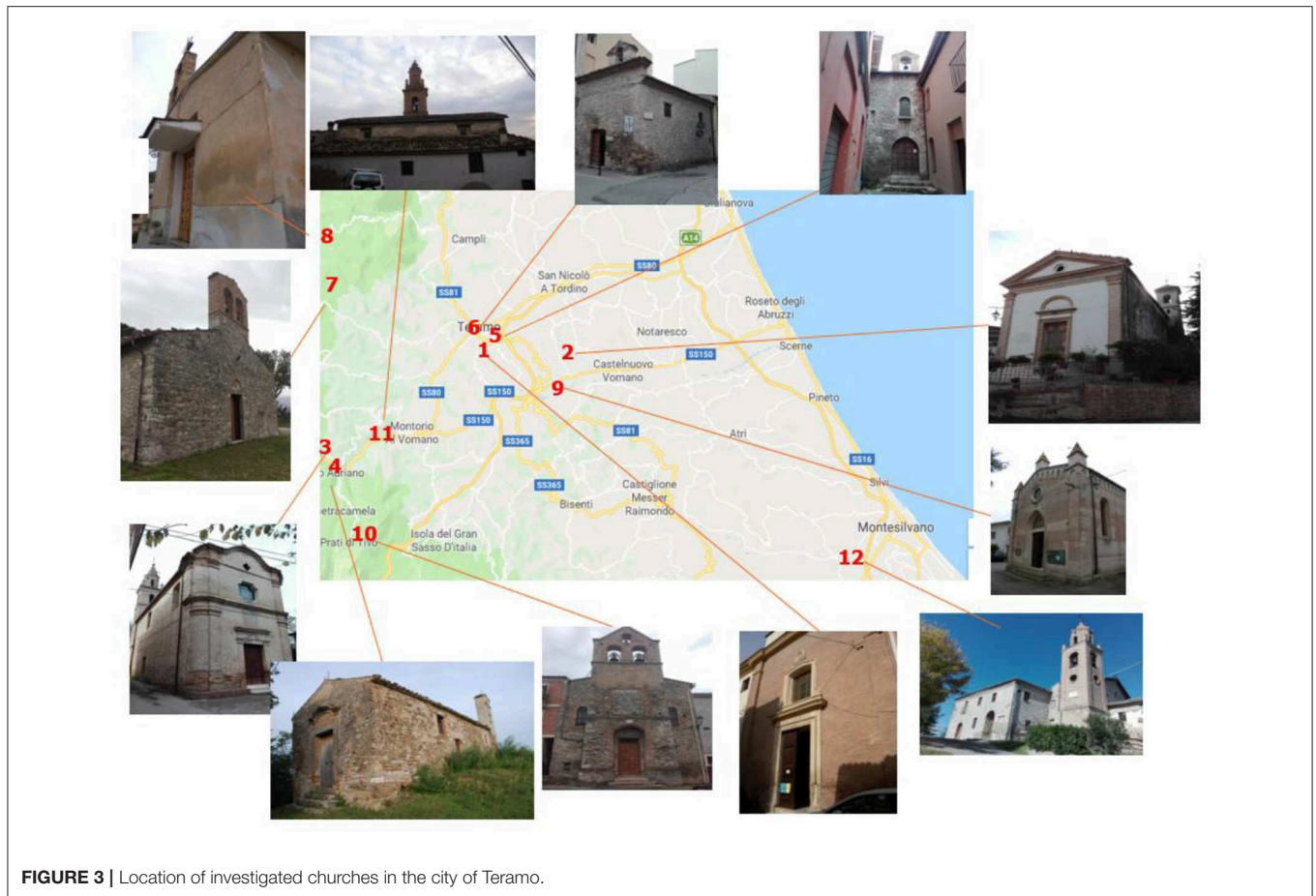


FIGURE 3 | Location of investigated churches in the city of Teramo.

located within the municipality indicated within parentheses, as illustrated in **Figure 4**:

1. Saint Francis of Paola church (Forio municipality);
2. Saint Vito church (Forio municipality);
3. Most Holy Annunciation church (Lacco Ameno municipality);
4. Saint Sebastiano church (Barano d'Ischia municipality);
5. Saint Michael Archangel church (Forio municipality);
6. Saint Mary of Loreto church (Forio municipality);
7. Saint Francis of Assisi church (Forio municipality);
8. Most Holy Annunciation coven (Forio municipality);
9. Saint Mary of Soccorso church (Forio municipality);
10. Saint Gaetano church (Forio municipality).

Table 5 depicts some images of the considered church samples, while the main geometric features of each church are reported in **Table 6**.

APPLICATION OF THE METHODOLOGY

Application of *Tool 2*

From the analysis of all the collected information related to sporadic and continuous events [described in the section *Hazard Scoring (H)*], it has been possible to qualitatively evaluate

the potential damage severity that could affect the examined churches. The evaluations are numerically reported in **Table 7**, where the damage assigned for each event is in bold and underlined. One can easily note that the investigated area of Ischia has a hazard score H greater than that of Teramo. This is due to the fact that, in the island, the potential threats that could produce damages are greater than those in the Teramo area.

Application of *Tool 3*

In order to apply the analysis with *Tool 3*, it has been necessary to carry out physical observations and detailed historical researches for each considered church, with the aim of acquiring as much information as possible. **Table 8** and **Figure 5** summarize the evaluation of the seismic risk score for the churches studied. In particular, in **Table 8**, the R score is evaluated in accordance with the proposed (Equation 3), while in the **Figure 5**, a comparison between vulnerability and seismic risk score for each church is represented in the form of a histogram.

Table 9 shows, for the Teramo and Ischia samples, the number of churches falling into each class (from A to D) for a given vulnerability parameter. In this way, the distribution of the classes may be observed.

In the Teramo churches, there is a prevailing class for some of the vulnerability parameters, such as *position of the building*

TABLE 3 | Geometrical features of churches investigated in Teramo.

Church name	External view	Internal view	Plan
1. Saint Giovanni			
2. Saint Anastasio			
3. Holy Mary of Carmine			
4. Saint Nicola			
5. Saint Catherine of Alexandria			
6. Saint Luca			

(Continued)

TABLE 3 | Continued



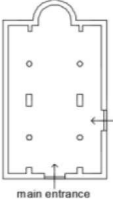


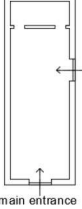


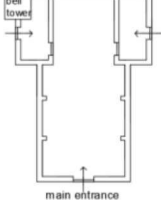





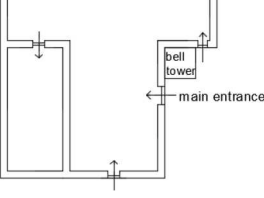


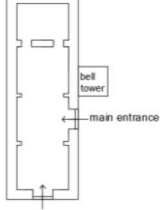
Church name	External view	Internal view	Plan
7. Saint Mary de Praediis			 main entrance
8. Saint Michael Archangel			 main entrance
9. Saint Francis of Assisi			 main entrance
10. Saint John in Pergulis			 entrance staircase
11. Most Holy Salvatore			 bell tower main entrance
12. Saint Stephen			 bell tower main entrance

TABLE 4 | Geometrical features of churches investigated in Teramo.

Church	Hall			Apse			Bell Tower	
	Major side [m]	Minor side [m]	Average height [m]	Major side [m]	Minor side [m]	Average height [m]	Yes/no	Estimated height [m]
1. Saint John	16.50	14.30	10.00		–		No	–
2. Saint Anastasio	14.70	7.20	6.70	7.50	3.50	7.15	Yes	10.00
3. Holy Mary of Carmine	11.30	6.20	7.20	6.45	5.00	7.00	Yes	15.00
4. Saint Nicola	11.00	4.60	3.50		–		No	–
5. Saint Catherine	13.40	6.50	7.50		–		No	–
6. Saint Luca	8.00	4.00	6.00		–		No	–
7. Saint Mary de Praediis	14.50	9.00	5.00	3.00	1.50	5.00	No	–
8. Saint Michael Archangel	16.20	5.30	5.00		–		No	–
9. Saint Francis of Assisi	11.40	7.00	7.80	5.85	5.80	6.00	Yes	13.00
10. Saint John in Pergulis	14.90	9.30	8.00		–		Yes	12.90
11. Most Holy Salvatore	10.70	7.20	8.00		–		Yes	18.00
12. Saint Stephen	14.40	5.25	5.85	3.40	5.25	3.50	Yes	15.00

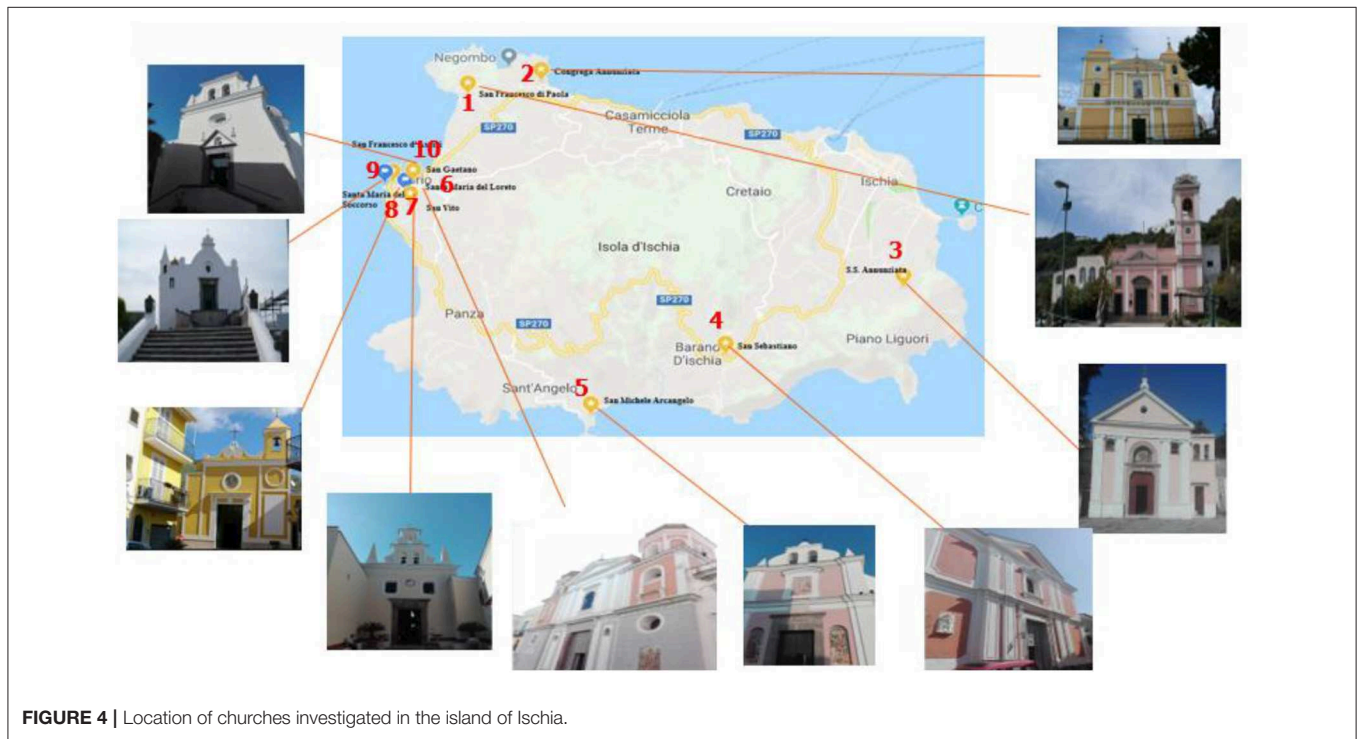


FIGURE 4 | Location of churches investigated in the island of Ischia.

and foundation (no. 1), non-structural elements (no. 5), resistant system type and organization (no. 6), floors (no. 8), and fire vulnerability (no. 12).

On the other hand, in the Ischia church samples, a prevailing class for each parameter is observed in almost all cases, with the exception of the parameter *distance among walls* (no. 4), where classes A and B have been assigned to the same number of churches.

Finally, by observing the obtained results, the following considerations can be remarked:






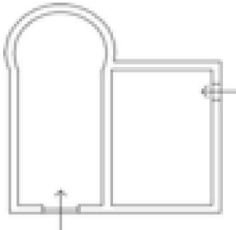


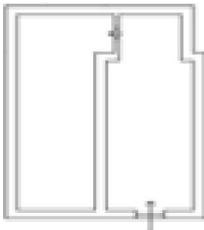


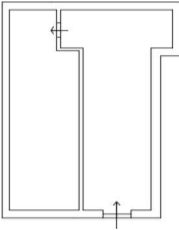
1. Class A of the parameter *position of the building and foundations* (no. 1) has been assigned to almost all the churches, since they are located on loose ground with a slope not higher than 10% and with discrete geotechnical properties. However, it has not been possible to detect the in-elevation differences of the foundations due to the absence of appropriate geological analyses;
2. Class D of the parameter *floors* (no. 8) has been attributed to all churches since rigid floors have never been observed;

TABLE 5 | Geometrical features of churches investigated in Ischia.

Church name	External view	Internal view	Plan
1. Saint Francis of Paola			
2. Saint Vito			
3. Most Holy Annunciation			
4. Saint Sebastiano			
5. Saint Michael Archangel			
6. Saint Mary of Lorero			

(Continued)

TABLE 5 | Continued

Church name	External view	Internal view	Plan
7. Saint Francis of Assisi			
8. Most Holy Annunciation			
9. Saint Mary of Soccorso			
10. Saint Gaetano			

- It has not been possible to give objective judgments on the connection quality among orthogonal walls and between walls and horizontal structures because of the presence of frescos and decorations. However, the experience suggests neglecting a good level of connection among walls because, in the past, orthogonal walls were generally simply juxtaposed to each other, showing in most of the cases overturning mechanisms, especially in the façade elements;
- Almost all roofs are made of timber elements that have, depending on the case, pushing or no-pushing structures. In general, it is rare to find edge beams with the exception of those where the roof was built in recent times. Even the presence of metal tie rods is quite rare: they are absent in the majority of cases;
- The churches located in Teramo have a vulnerability index ranging from 21.22 to 66.32, with an average value of 45.68;
- The churches located in Ischia have a vulnerability index ranging from 25.93 to 46.46, with an average value of 30.13;

- The Ischia island hazard index ($H = 1.31$) is greater than that of Teramo ($H = 0.78$).

In order to determine the church sample and, consequently, the geographical area that are subjected to the highest seismic risk, in this paper, a new territorial seismic risk index ρ is proposed as follows:

$$\rho = \frac{\sum S_j R_j}{\sum S_j} \quad (4)$$

where S_j is the j th church area, R_j is the j th church seismic risk index, and $\sum S_j$ is the total area of investigated churches. Precisely, in the two geographical areas analyzed, the ρ index is equal to 63.13 for Teramo churches and to 67.47 in the case of Ischia churches. The higher ρ value in the case of Ischia churches is probably due to their higher vulnerability with respect to Teramo churches.

TABLE 6 | Geometrical features of churches investigated in Ischia.

Church	Hall			Apse			Bell tower	
	Major side [m]	Minor side [m]	Average height [m]	Major side [m]	Minor side [m]	Average height [m]	Yes/no	Estimated height [m]
1. Saint Francis of Paola	19.50	3.30	7.00	3.40	3.30	8.50	Yes	18.00
2. Saint Vito	22.00	4.80	7.10	4.80	2.80	10.00	Yes	27.00
3. Most Holy Annunciation	6.50	3.90	6.55	4.80	4.00	6.55	No	–
4. Saint Sebastiano	17.30	6.30	12.30	6.30	4.60	8.00	Yes	17.00
5. Saint Michael Archangel	8.60	5.20	8.00	5.20	4.70	8.00	No	–
6. Saint Mary of Loreto	30.00	5.80	11.00	8.15	5.80	10.00	Yes	17.00
7. Saint Francis of Assisi	21.00	8.40	10.00	9.00	6.80	12.00	No	–
8. Most Holy Annunciation coven	11.00	5.60	7.00	6.00	5.50	7.40	Yes	15.00
9. Saint Mary of Soccorso	14.80	6.80	7.50	4.60	4.10	8.50	Yes	12.00
10. Saint Gaetano	17.00	5.80	13.70	4.70	1.70	7.15	No	–

TABLE 7 | Scenarios description and classification of threats for church samples.

	Parameters	Damage gravity				
		Absence of damage	Middle damage	Catastrophic damage		
Churches located in the Teramo area	Sporadic Events	Earthquake and tsunami threat	0	0.2	0.4	
		Landslides	0	0.15	0.25	
		Volcanic threat	0	0.2	0.4	
		Hydro-methodological threat	0	0.15	0.25	
		Chemical–technological threat	0	0.15	0.25	
		Forest fires	0	0.15	0.25	
	Continuous Events	Erosion threat	0	0.05	0.1	
		Physical stress of threat	0	0.05	0.1	
		Air pollution	0	0.01	0.05	
		Socio-organizational threat	0	0.01	0.05	
		Demographic decline	0	0.01	0.05	
		Resulting Hazard score		H = 0.78		
		Churches located in the Ischia area	Sporadic Events	Earthquake and tsunami threat	0	0.2
Landslides	0			0.15	0.25	
Volcanic threat	0			0.2	0.4	
Hydro-methodological threat	0			0.15	0.25	
Chemical–technological threat	0			0.15	0.25	
Forest fires	0			0.15	0.25	
Continuous Events	Erosion threat		0	0.05	0.1	
	Physical stress of threat		0	0.05	0.1	
	Air pollution		0	0.01	0.05	
	Socio-organizational threat		0	0.01	0.05	
	Demographic decline		0	0.01	0.05	
	Resulting Hazard score		H = 1.31			

CONCLUSIONS

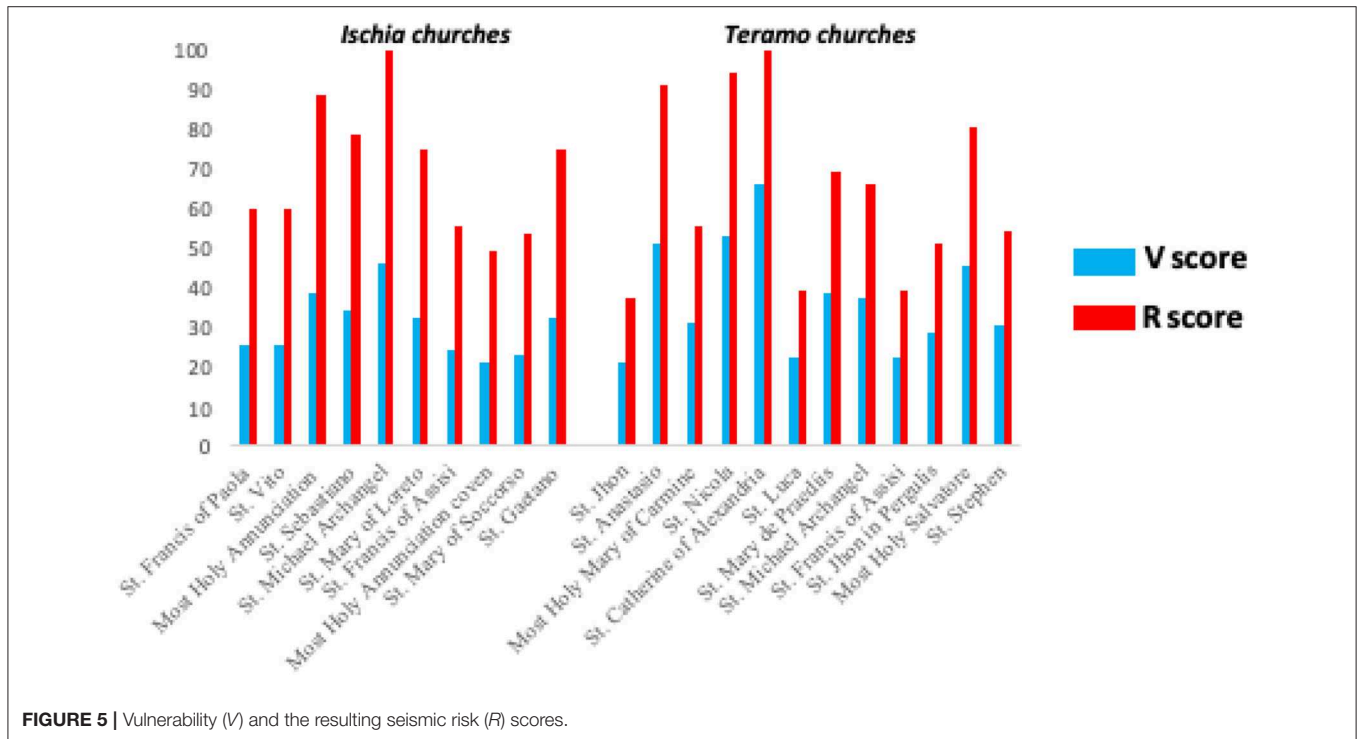
In this paper, a simplified method recently developed and validated for ancient masonry churches has been applied to case studies. The proposed method separately evaluates hazard (H) and vulnerability (V) in order to assess the seismic risk at a territorial scale. The method is a very useful tool

because it quickly provides a territorial preliminary ranking for screening the intervention priorities and for considering different earthquake scenarios as well. The method is also versatile for comparing seismic risk evaluations performed in different geographical areas.

The case studies examined involved two samples of churches located in Teramo and in the Ischia island in the gulf

TABLE 8 | Seismic risk evaluation.

	Churches	Hazard, <i>H</i>	Vulnerability, <i>V</i>	Seismic risk, <i>R</i>
Churches located in the Teramo area	1. St. John	0.78	21.22	37.78
	2. St. Anastasio		51.52	91.70
	3. Holy Mary of Carmine		31.32	55.74
	4. St. Nicola		53.18	94.67
	5. St. Catherine of Alexandria		66.32	118.05
	6. St. Luca		22.23	39.57
	7. St. Mary de Praediis		39.06	69.53
	8. St. Michael Archangel		37.37	66.53
	9. St. Francis of Assisi		22.23	39.58
	10. St. John in Pergulis		28.96	51.55
	11. Most Holy Salvatore		45.44	80.89
	12. St. Stephen		30.64	54.54
Churches located in the Ischia area	1. St. Francis of Paola	1.31	25.93	59.90
	2. St. Vito		25.93	59.90
	3. Most Holy Annunciation		38.64	89.26
	4. St. Sebastiano		34.33	79.30
	5. St. Michael Archangel		46.46	107.32
	6. St. Mary of Loreto		32.66	75.44
	7. St. Francis of Assisi		24.25	56.02
	8. Most Holy Annunciation coven		21.56	49.80
	9. St. Mary of Soccorso		23.24	53.68
	10. St. Gaetano		32.33	74.68



of Naples, both affected by recent seismic events. The territories of churches have many features in common, but there are some differences modifying the vulnerability index calculations. In particular, the analysis of results shows that

all the churches of Teramo have a medium vulnerability index. The most vulnerable church is the Saint Catherine of Alexandria, which is, in fact, actually unusable. Even the Ischia churches have a medium vulnerability index, with

TABLE 9 | Distribution of parameter classes for Teramo churches.

Parameters	Teramo churches				Ischia churches				
	Classes				Classes				
	A	D	C	D	A	D	C	D	
1	Position of the building and foundations	11	–	1	–	10	–	–	–
2	In-plane configuration	–	2	6	4	1	2	5	2
3	In-elevation configuration	5	4	3	–	9	1	–	–
4	Distance among walls	5	6	1	–	5	5	–	–
5	Non-structural elements	7	1	1	3	1	2	6	2
6	Resistant system type and organization	–	8	2	2	–	9	1	–
7	Resistant system quality	–	6	5	1	–	9	1	–
8	Floors	–	–	–	12	–	–	–	10
9	Roofs	1	6	–	5	–	7	2	1
10	Conservation state	–	7	3	2	–	3	6	1
11	Environmental alterations	5	7	–	–	–	10	–	–
12	Construction system	6	1	5	–	7	–	2	1
13	Fire vulnerability	–	12	–	–	–	10	–	–

the highest value found in the case of the Saint Michael Archangel church.

Finally, it has been possible to estimate the vulnerability of inspected church areas by means of a new territorial seismic risk index ρ , which depends on the territory area covered by the churches and on their seismic risk index R . This new introduced index, useful for territorial comparisons, may be applied for globally evaluating the seismic risk of a certain area, representing a unique parameter taking into account all the constructions built and the related seismic risk scores.

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DATA AVAILABILITY

All datasets generated or analyzed for this study are included in the manuscript.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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The reviewer MV declared a past co-authorship with one of the authors AF to the handling editor.

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