ANTAEUS Project for the Regional Vulnerability Assessment of the Current Building Stock in Historical Centers

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This article presents a methodology for the seismic vulnerability assessment of current buildings, suitable for the study of historical centers at the regional scale. The applicability is demonstrated with reference to four case studies: the historical center of the city of Foggia (Italy) and three other small towns of this province, for a total of 4519 housing units. Field data were collected by several teams of technicians by means of a survey form, provided in electronic format. The subsequent data processing and drawing of vulnerability maps was performed using geographical informa-tion system (GIS) technology. The collected data were used also for the validation of the algorithm, by comparing the results with those of the methodology used by the Gruppo Nazionale per la Difesa dai Terremoti (GNDT [Italian National Group for Defense Against Earthquakes]), which is widely adopted in Italy. The results of the research study and the application showed some critical points, related to the poor nature of the information collected and to the reliability of the final results. These issues are analyzed and discussed, proposing a strategy for improving the methodology.

KEYWORDS
Seismic vulnerability assessment; historical centers preservation; vulnerability index method; building inventory; field survey form; geographical information system (GIS) mapping

1. Introduction

The seismic vulnerability assessment at the regional scale is a crucial element of seismic risk prevention and mitigation strategies, which are the challenges of the past decades. Many recent earthquakes have shown that the existing building stock is severely at risk in many countries, and, in many cases, the policies adopted have been inadequate, leaving space to unco-ordinated actions, with ineffective or even detrimental effects (D'Ayala and Benzoni 2012).

In the past 20 years, two different approaches for the seismic vulnerability assessment at the regional scale have been developed, generally known as first-level and second-level approaches:

- First-level procedures are aimed at a preliminary evaluation based on few empirical parameters. Input data are gathered by simple and quick visual inspections (Gruppo Nazionale per la Difesa dai Terremoti [GNDT, Italian National Group for Defense Against Earthquakes] 1994, 2000, 2001; Benedetti and Petrini 1984; Corsanego 1993;Dolce et al. 1994; Goretti and Di Pasquale 2002; Zuccaro 1996;Whitman,Reed,andHong 1973;Braga,Dolce, and Liberatore 1982; Spence, Coburn, and Pomonis 1992; GLABEC 2001; Dolce et al. 2003; Lagomarsino and Giovinazzi 2006; Calvi et al. 2006; Rota, Penna, and Strobbia 2008; Rota et al. 2011).
- second-level procedures include more detailed ele-ments about structural characteristics and damage modes. They always operate at a territorial or urban scale, but are usually devoted to a specific building type (churches, palaces, bridges. . .) and collect more detailed information (Casolo et al. 2000; Petrini, Casolo, and Doglioni 1999; GNDT 1999a, 1999b; GLABEC 2001; Lagomarsino and Podestà 2004a, 2004b; Casolo and Uva 2011; Mezzina, Palmisano, and Raffaele 2012; Lagomarsino 2012; Raffaele et al. 2013b; Casoloetal.2013; Mansour et al. 2013)

Recently, multi-level approaches have been intro-duced (Federal Emergency Management Agency [FEMA] 2012; Mouroux and Le Brun 2006; Cosenza et al. 2005), which provide different levels of analysis. A progressive and rational increase of the amount of information and accuracy of the results is performed, according to strategic priorities and available resources. A well acknowledged method, in this field, is the HAZUS methodology, which is based on a semi-quan-titative approach: the seismic demand (expressed in

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terms of the acceleration displacement response spectrum, or ADRS), is compared with the structural capacity, expressed by an equivalent acceleration-displacement curve obtained from an incremental non-linear pushover analysis. It is organized into multi-ple levels, from the regional scale up to the scale of the individual building. All the results provided at a large scale (both regional and urban) have only a relative validity within the considered set of buildings (which shall be sufficiently homogeneous with regard to the typological, structural and constructive aspects). It is possible to sort the buildings by vulnerability/risk level, in order to budget the different intervention options and support the definition of mid and long-term miti-gation strategies. In contrast, a direct comparison among results relative to very different geographic areas can be misleading. Finally, the actual safety level of an individual building can be obtained by means of a complete structural analysis of the building, that is sometimes referred to as the third-level analysis (Lagomarsino and Giovinazzi 2006; Casolo and Sanjust 2009; Milani et al. 2011; Casolo et al. 2013).

2. The adopted methodology

This article presents the research study ANTAEUS, concerning the regional seismic vulnerability assessment of the building stock in the historical centers of the Province of Foggia (Puglia, Southern Italy, Figure 1). It is a module of a wider research project funded by Regione Puglia and managed by Autorità di Bacino della Puglia (Basin Authority of Puglia), in cooperation with a number of public institutions (Department Dicatech of the University Politecnico di Bari, Municipality of Foggia, Administration of the Province of Foggia). The general regional project involves various types of natural risks: earthquake, floods, geomorphological instabilities, landslides, which have been studied by different research groups, and then integrated within a geographic information system, or GIS (Sextos, Kappos, and Styliandis 2008; Castorani et al. 2011). The seismic module ANTAEUS has the objective of providing the local authorities with methodologies and tools for the quick vulnerability assessment of the historical centers in the territory by means of empirical methods, which in Italy represent the most widely used approach. The idea is that each municipality can gradually plan and implement the procedures for collecting the data and sensitive information required for the risk assessment, before an earthquake occurs. The seismic vulnerability and risk assessment is organized according to a multi-level scheme, of which the first one is here discussed. Details about the other modules of the project can be found in the literature (Raffaele et al. 2013a).

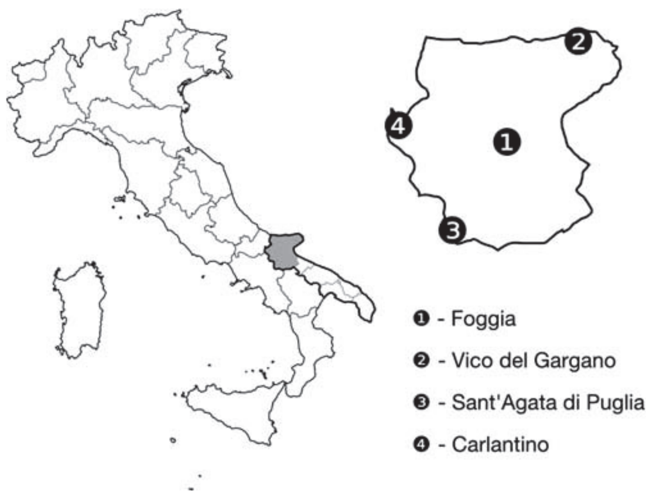

Figure 1. Localization of the historical centers object of this study. The Province of Foggia (Puglia) is shaded in gray.

The research scope has been limited to historical centers, in which there are large sets of buildings with similar structural characteristics (e.g., masonry walls, timber roof and floors), and it seems reasonable to adopt a second-level procedure. Nevertheless, there are some drawbacks:

1. Existing second-level forms are dedicated to specific structural typologies (e.g., the GNDT form is restricted to masonry buildings), whereas in many Italian centers there is also a significant amount of reinforced concrete (RC) buildings.
2. The quantity of data to be collected is extensive and requires the employment of specialized and trained technicians. The survey involves, in general, the inspection of the interior of the building (which is often not accessible, since many Italian historical centers are only inhabited during holiday periods).

First-level procedures are a possible alternative, widely used for the vulnerability assessment at a large scale (Dolce et al. 2003); however, when managing a relatively small sample of buildings, the use of such a basic level of investigation could be poorly significant. Therefore, this research team has decided to propose a specific survey form and an algorithm for the evaluation of the vulnerability index (ANTAEUS) whose results are directly comparable with those of the GNDT methodology (GNDT 1994; Ferrini et al. 2003), which is the Italian reference for the seismic vulnerability assessment. Since GNDT vulnerability index method is aimed at masonry buildings, an extension to RC structures has been suggested. The proposed procedure is described in the first part of the article (in Sections 3, 4, and 5).

The second part of the article is focused on the extensive application on four representative case studies (the historical centers of Foggia, Carlantino, Vico del Gargano and Sant'Agata di Puglia). These towns are different from each other for extension, number of inhabitants, history, constructive and typological characters, and geomorphological condition. Their choice was made in order to provide a representative picture of the 64 municipalities of the Province of Foggia. In general, they might be considered a valid model for many historical centers of Southern Italy. In the selected towns, groups of technicians (architects and engineers) have assessed 4519 buildings by means of rapid visual inspections, filling in the ANTAEUS vulnerability form. The field survey provided a large database for the application and calibration of the approach. In particular, this researcher team performed a critical assessment of the quality, representativeness and reliability of input data, vulnerability parameters and results. The procedure illustrated in Sections 3, 4, and 5 is based on well-established methods of indirect vulnerability assessment, introducing specific variations in the number and type of input data, in the number and definition of vulnerability parameters, and in the final algorithm. Side-by-side with the application of the survey form on the selected case studies, it was necessary to check the performance of the procedure, verifying the results obtained on a reference bench-mark. In particular, in Section 7, a detailed analysis of a significant sample of 140 buildings (73 in the Municipality of Foggia; 67 equally distributed among the other case studies) was made.

Results were systematically compared with two different vulnerability index methods: the version applied in Italy by GNDT (Benedetti and Petrini 1984; GNDT 1994) and the version modified by Tuscany Region (Ferrini et al. 2003). The procedure described in Sections 4 and 5 is the final version, obtained after the verification and calibration process presented in Section 7. Then, the data about the 4519 buildings were implemented in a GIS, plotting different maps representing the spatial distribution of the most significant parameters. In particular, the objective was to analyze in detail the quality of the data and the uncertainty factors related to the phase of data retrieval (quickness and coarseness of rapid visual inspections; possible incompleteness of information; subjectivity of data reading/interpretation; nonhomogeneity in the level of training and experience of the operators). A detailed reliability analysis of the results was performed, in order to identify possible critical points, propose a sanitization of the database, and optimize the performance of the procedure (Section 8). Throughout all this phase, there was a constant interaction between the scientific board and the coordinators of the survey teams, in order to intervene promptly on the survey form and solving operational difficulties.

2.1. Application context

Puglia was traditionally considered a low seismic risk region, even in the northern areas (Province of Foggia) that were affected in the past by seismic events: it is worth remembering the destructive earthquake of 1731, which caused many damages in the city of Foggia (Mezzina 2011). Before 1962, none of the municipalities was classified as seismic. In year 1962, a few municipalities in Gargano and Dauni Mountains were classified, whereas only since June 3, 1981, the seismic hazard in the whole Province of Foggia was acknowledged as medium-high (Figure 2). Therefore, the regional authorities have faced the issue of the seismic risk mitigation at the regional scale much later than other Italian regions. After the earthquake of Molise and Puglia of 31 October 2002 (Regione Molise 2002), the problem of the territorial inventory of the building stock and appraisal of its level of vulnerability became urgent, and a number of projects were initiated, among which the pilot research study ANTAEUS.

2.2. Algorithm for the calculation of the vulnerability index

The vulnerability index (IV) is calculated for each building after the filling of a rapid field survey form that contains a number of vulnerability-sensitive information (e.g., materials, constructive elements and details, plan and elevation configuration, type of foundation). These data are combined into a set of seismic vulnerability parameters, and associated to a vulnerability class (from the lowest [A] to the highest [D]). The class assigned to each parameter is then translated into a numerical score, according to a conventional pre-defined scale. After assigning the vulnerability class, the score can be modified to take into account for special situations or secondary factors (e.g., the presence of seismic retrofitting or improvement can modify the vulnerability class

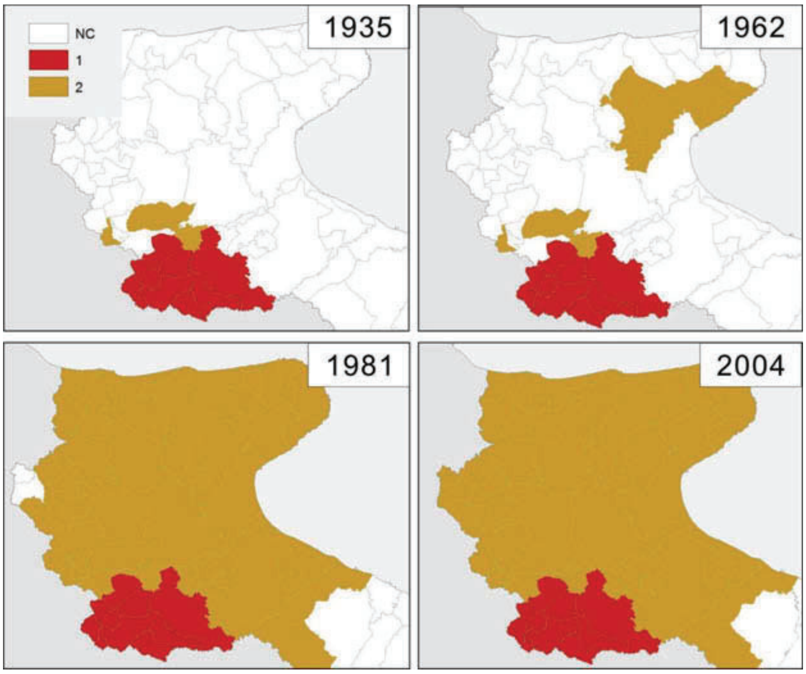

Figure 2. Evolution of seismic classification in the Province of Foggia: 1935, 1962, 1981, 2004.

assigned on the base of the year of construction of the building). The modifiers adopted in the algorithm are listed in the manual (ANTAEUS Project 2011). Finally, the combination of the scores, weighted by proper coefficients, provides the overall vulnerability index

3. Description of the antaeus form

The ANTAEUS form is divided into three parts (Appendix): (a) the first one contains the general data of the building; (b) the second part is the proper vulnerability assessment form (Sections [3.1], [4.1], [4.2]); and (c) the third is devoted to the assessment of the actual damage of the building. For each independent structural unit, one form has to be filled in. In the case of more units with structural continuity, a *structural aggregate* is noted, and the position of the unit within the aggregate will represent a specific vulnerability factor.

3.1. General data

This part of the survey (Sections [1.1][1.2][2.1]) is aimed at clearly identifying the geographical position of the building and defining the general characteristics of the structure by means of pictures and a few sketches in plan.

3.2. Vulnerability data

This part of the survey is divided into three sections: a general one (common data [3.1]), suitable for all types of buildings, and two special sections respectively aimed at masonry buildings (Section 4.1) and reinforced concrete buildings (Section 4.2). The attention is focused on the elements that are useful for evaluating the role of the different structural elements on the global seismic behavior of the building, as briefly described below (a detailed explanation is provided in the form reported in the Appendix and the Manual [ANTAEUS Project 2011]).

3.3. Damage assessment [section 4.3]

Within this section, the possible damage of the structural elements shall be reported, such as, for instance, cracks and deformations that could compromise the structural safety of the unit.

4. Appraisal of the vulnerability for masonry buildings

The following paragraphs describe the procedure adopted for evaluating the vulnerability index in the case of masonry buildings. Instead of the 11 vulnerability parameters provided by the original vulnerability index method (Benedetti and Petrini 1984;GNDT 1994), the number was reduced to 10 (Parameter 8–Distance between bearing walls was eliminated). The reason for this reduction is to allow the filling of the forms based on an external survey only. This is a crucial point, since in many cases it is not possible to visit the building interior, and the vulnerability assessment would be invalidated. In particular, Parameter 8 of the original GNDT form involves the maximum distance between load-bearing walls, and it cannot be easily evaluated without accessing the building or without a plan of the ground floor.

Moreover, many of the vulnerability parameters have been significantly simplified. The numbering of the parameters, anyway, is left unvaried, in order to facilitate the comparison between the two methods. Hereinafter, the notation *URM* will be adopted to indicate *unreinforced masonry* and *RM* for *reinforced masonry*.

4.1. Vulnerability parameters

4.1.1. Parameter 1: type and organization of the resisting system

Parameter 1 takes into account the capacity of the building to withstand horizontal loads. This parameter is related to the in-plan organization of the resisting masonry walls (which should be well distributed along the two main orthogonal directions, and effectively connected to each other) and to the presence of rigid floors efficiently connected to the walls.

The first element considered for the assignment of the class is the box-like behavior of the structure, appraised by considering the following elements: presence and effectiveness of the connections between walls and the presence of ring beams or ties. The assignment of the lowest vulnerability class takes also into account the evolution of national seismic codes. It is supposed that the adoption of a more severe seismic classification determines a greater attention to detail and quality of the construction. Finally, the vulnerability class is assigned according to Table 1. After assigning the vulnerability class, the score can be modified to take into account the presence of later alterations of the building (e.g., enlargements, additional stories), seismic retrofitting or improvement interventions. The modifiers adopted in the algorithm are listed in the manual (ANTAEUS Project 2011).

4.1.2. Parameter 2: quality of the resisting system

This parameter describes the quality of the masonry: materials (e.g., blocks and mortar), and organization (e.g., homogeneity, interlocking). It is mainly based on a qualitative description, as provided in the Section [4.1.1] of the survey form. In the case of masonry walls with rubble infill, the presence or absence of effective headers is considered as an additional parameter. The assignment of the class is done according to Table 2.

4.1.3. Parameter 3: conventional capacity

In the second-level GNDT form for masonry buildings, the third parameter used is the conventional resistance, which requires measuring the in-plan area of the shear walls along two main directions. This measurement must be done by a direct survey of the building, or at least on the basis of existing plan views.

In the case of ANTAEUS form, it was not possible to provide a so detailed level of investigation by the surveyors, who were asked to work quickly. In

Table 2. Masonry buildings: assignment of the vulnerability class for Parameter 2.

Masonry Buildings				
Parameter 2: Quality of the resisting system				
	Age of construction		Rubble infill	
Masonry Type	> 1987	≤ 1987	Presence of headers	No headers
M3.2: Reinforced masonry	A	A	—	—
M1.3: Regular stone masonry	A	B	B	C
M3.1: Brick masonry	A	B	B	C
M2: Tuff masonry	A	B	B	C
M1.2: Irregular stone masonry	C	C	C	D
M1.1: Rubble stone	D	D	D	D

Table 1. Masonry buildings: assignment of the vulnerability class for Parameter 1.

Masonry Buildings					
Parameter 1: Type and organization of the resisting system					
		URM			
		Presence of quoins		No quoins	
Age class	RM	Ring beams or ties	No ring beams nor ties	Ring beams or ties	No ring beams nor ties
Age class $\geq$ 2008	A	A	—	—	—
$Y_c <$ age class $<$ 2008	A	B	—	—	—
Age class $\leq Y_c$	B	B	C	C	D

Yc is the year in which the municipality has been seismically classified for the first time.

addition, information available from land registry plans was lacking: for more than 50% of the buildings, no plan at all was retrieved. Thence, the evaluation of this parameter was deeply revised, introducing a simpler, alternative index conceived in order to roughly represent the seismic capacity of the building. The fundamental approximation is that each structural unit can be considered a *simple masonry building* according to the definition of current seismic codes (Norme Tecniche per le Costruzioni [NTC, Italian Building Code] 2008; European Committee for Standardization [CEN] 2005). For this kind of buildings, no explicit seismic verification is required, and it is admitted that the safety assessment can be performed under the vertical loads alone, with a proper safety factor. According to this approach, we have chosen to express the conventional seismic capacity by means of the following index of resistance to vertical loads (I_{RV}):

$$I_{RV} = \frac{\sigma_M}{f_M/\gamma_M} \qquad \text{(EQ1)}$$

where:

- γ_M is the partial safety factor for masonry ($\gamma_M = 4.2$, as specified by the Italian Building Code—Chapter 4, Par. 4.5.6.4 for simple masonry buildings);
- f_M is the average compressive strength of masonry;
- $\sigma_M = \frac{N}{A}$ is the normal stress at the ground floor; and
- $\mathrm{N} = \mathrm{W_T}$ is the total vertical load at the ground floor, estimated by considering dead and live loads of all stories ($\gamma_G = \gamma_Q = 1$) plus the weight of the load-bearing walls (with no reduction for the openings). The calculation is performed with an approximated automatic procedure, taking into account the geometry of the building and the typology of vertical structures (the complete procedure is explained in detail in the manual [ANTAEUS Project 2011]).

The assignment of the vulnerability class is made according to Table 3, on the basis of I_{RV}. In particular, the value $\mathrm{I_{RV}}$=0.45 that separates low vulnerability classes (A and B) from high vulnerability classes (C and D) corresponds to the limit indicated by the Italian Building code (par. 4.5.6.) or the verification of simple buildings under vertical loads ($f_k = 0.70 f_M$):

$$\frac{\sigma}{f_k/\gamma_M} \leq 0.65 \rightarrow \frac{\sigma}{f_m/\gamma_M} \leq 0.700.65 = 0.455 \qquad \text{(EQ2)}$$

4.1.4. *Parameter 4: topographic conditions*

In the original GNDT procedure, detailed information is required about the topographic condition and foundations of the building. ANTAEUS form only includes qualitative information about the topography (Morphology of the site—Section [3.1.3]), which is visually appraised, whereas specific data about the foundation system—which are nearly impossible to obtain at this level—are disregarded. The assignment of the vulnerability class is made according to Table 4.

4.1.5. *Parameter 5: floors*

In agreement with the second-level GNDT form, the assignment of the vulnerability class is based on in-plane stiffness of floors, and on the effectiveness of the connections to the walls. Weighting coefficients are introduced in order to account for the percentage of rigid and well-connected floors with respect to the total amount. The entries involved are those reported in Section [4.1.2] of the survey form, and the assignment of the vulnerability class is made according to Table 5.

4.1.6. *Parameter 6: configuration in-plan*

This vulnerability parameter is evaluated in the Section 3.1.2 of the form. Two different indicators are considered. The first one is the regularity in-plan: it is the same used by the GNDT method, and the surveyor directly assigns the vulnerability class in the form. In addition to the GNDT method, the position of the unit within the aggregate is considered as a specific vulnerability factor, as suggested by many recent research studies (D'Ayala and Paganoni 2011; Giovinazzi et al.

Table 3. Masonry buildings: assignment of the vulnerability class for Parameter 3.

Masonry Buildings		
Parameter 3: Conventional Capacity		
	Class	Score
$I_{RV} < 0.15$	A	0
$0.15 \leq I_{RV} < 0.45$	B	5
$0.45 \leq I_{RV} < 0.70$	C	25
$I_{RV} = 0.70$	D	45

Table 4. Masonry buildings: assignment of the vulnerability class for Parameter 4.

Masonry Buildings		
Parameter 4: Topographic conditions		
	Class	Score
S1: Flat ground	A	0
S4: Hillside	B	5
S3: On ridge	C	25
S2: On a slope	D	45

Table 5. Masonry buildings: assignment of the vulnerability class for Parameter 5.

Masonry Buildings						
Parameter 5: Floors						
	Rigid and well bonded		Well bonded		Poorly bonded	
Floors	Not staggered	Staggered	Not staggered	Staggered	Not staggered	Staggered
O1: Wooden	A	B	C	D	D	D
O3: Brick and steel	A	B	C	D	D	D
O2: Brick and concrete	B	C	—	—	D	D
O4: Vaults with ties	B	C	—	—	—	—
O4: Vaults without ties	D	D	—	—	—	—

2004). To this aim, a proper modifier is applied to the vulnerability score (as described in the manual [ANTAEUS Project 2011]).

4.1.7. *Parameter 7: configuration in elevation*

This parameter takes into account the seismic vulnerability induced by irregularities in elevation (e.g., presence of recessed additional stories, towers). The surveyors directly calculated it in Section 3.1.2 with the same method of the GNDT form.

4.1.8. *Parameter 9: roof*

The vulnerability class associated with this parameter is obtained from Section 4.1.3, assuming that thrusting roofs involve a higher vulnerability level. The presence of ties that can partially eliminate the thrust is also taken into account (Table 6).

4.1.9. *Parameter 10: non-structural elements*

It takes into account the vulnerability and damages induced by non-structural elements (e.g., balconies, cornices, eaves, chimneypots) that are not properly connected to the structure (Section 3.1.6). Table 7 provides the vulnerability class as a function of the number of vulnerable elements.

4.1.10. *Parameter 11: maintenance level*

This parameter takes into account the general maintenance of the building, structures and fixtures. The assignment of the basic vulnerability class is determined by the presence (and extent) of damage to roofs and vertical structures (Table 8). The presence of damage in non-structural elements, together with the general state of preservation of the building, is taken into account by means of score modifiers (which are reported in the manual [ANTAEUS Project 2011]).

Table 7. Masonry buildings: assignment of the vulnerability class for Parameter 10.

Masonry Buildings	
Parameter 10: Non-structural elements	
No vulnerable elements	A
One vulnerable element	B
Two vulnerable elements	C
More than two vulnerable elements	D

Table 8. Masonry buildings: assignment of the vulnerability class for Parameter 11.

Masonry Buildings	
Parameter 11: Maintenance level	
No damage on roofs and on vertical structures	A
Minor damage on roofs or on vertical structures	B
Minor damage on roofs and on vertical structures	C
Severe damage on roofs or on vertical structures	D

4.2. *Calculation of the vulnerability index*

For each of the 10 parameters previously described, a vulnerability class (from A to D) is assigned and, according to Table 9, this is translated into a numerical score p_i, which can vary in the range [0,45]. Then, the possible modifiers are applied (the final

Table 6. Masonry buildings: assignment of the vulnerability class for Parameter 9.

Masonry Buildings						
Parameter 9: Roofs						
	Not thrusting		Partially thrusting		Thrusting	
Type	Ring beams or ties	No ring beams nor ties	Ring beams or ties	No ring beams nor ties	Ring beams or ties	No ring beams nor ties
C1: Wooden	A	B	B	C	C	D
C3: Steel	A	B	B	C	C	D
C2: Brick and concrete	B	C	C	D	C	D
C4: Vaults	—	—	—	—	C	D

Table 9. Masonry buildings: weights and scores of the vulnerability parameters.

Masonry Buildings: Scores and Weighting Coefficients					
	Values of p_i for vulnerability class				Weights
Parameter	A	B	C	D	w_i
1: Type and organization of the resisting system	0	5	20	45	0.75
2: Quality of the resisting system	0	5	25	45	0.25
3: Conventional capacity	0	5	25	45	0.50
4: Topographic conditions	0	5	25	45	0.50
5: Floors	0	5	15	45	0.75
6: In plan configuration	0	5	25	45	0.50
7: Configuration in elevation	0	5	25	45	1.00
9: Roofs	0	5	15	45	1.00
10: Non-structural elements	0	5	25	45	0.25
11: Maintenance level	0	5	25	45	1.00

modified value of p_i cannot exceed the limits of the aforementioned interval).

The vulnerability index I.V. is obtained by a weighted sum of the obtained scores: $p_1 w_1 + p_2 w_2 + \ldots + p_{10} w_{10}$ and can vary within the interval [0, 292.5]. Also, w_i are weighting coefficients (Table 9) introduced in order to calibrate the different influence of each parameter on the overall vulnerability of the structural unit.

Finally, the vulnerability index I.V. is normalized between 0 and 1 according to the following expression:

$$I.V. = \frac{(p_1 w_1 + p_2 w_2 + \ldots + p_{11} w_{11})}{292.5} \quad \text{(EQ3)}$$

Both for scores p_i and weights w_i, the values originally attributed by GNDT were changed in order to balance the different quality of information of the ANTAEUS form. In particular, the importance of parameters 1 and 3 was decreased, since their definition is less accurate. For parameters 5, 7 and 9, instead, weights were not varied.

5. Appraisal of the vulnerability for Rc buildings

The application of the vulnerability index method for RC buildings is much less established than for masonry buildings. In this regard, the ANTAEUS project started from the existing references and experiences (GNDT 1999; Regione Molise 2002; Regione Marche 2004; Regione Toscana 2013) for re-elaborating some elements of the methodology: choice of sensitive data, number and type of vulnerability parameters, assignment of the vulnerability classes, scores, weighting coefficients, and combining algorithm. The calculation of the vulnerability index is similar to the one for masonry buildings except for the different range of variation, which is [-27.5, 247.5]. This difference is related to the general lower vulnerability level of this structural system. Moreover, the number of vulnerability parameters is further reduced to 8.

5.1. Vulnerability parameters

5.1.1. Parameter 1: type and organization of the resisting system

The evaluation of the vulnerability of the resisting system is based on the structural typology and the year of construction (Table 10). Besides, it is supposed that the evolution of seismic classification and national seismic codes over the years has involved a higher quality. If seismic retrofitting interventions have been implemented, the class is assigned by substituting, in Table 10, the year of construction with the year of the intervention. Finally, vulnerability score is modified in order to take into account the percentage *T*% of infill panels with respect to the area of the facade (entry [4.2.2] of ANTAEUS form, as shown in Appendix), according to the criteria shown in the manual (ANTAEUS Project 2011).

5.1.2. Parameter 2: quality of the resisting system

This parameter accounts for the quality of the resisting system with respect to materials and execution. It is related to the construction year, since it is supposed that the evolution of seismic codes involves more stringent requirements about the quality and the performance of materials (e.g.,

Table 10. Reinforced concrete (RC) buildings: assignment of the vulnerability class for Parameter 1.

RC Buildings				
Parameter 1: Type and organization of the resisting system				
	Year of construction			
Structural type	$B_y \geq 2008$	$1996 \leq B_y < 2008$	$Y_c \leq B_y < 1996$	$B_y < Y_c$
RC2–RC shear walls	A	A	B	C
RC5–Frames and RC shear walls	A	B	C	D
RC4–Frames and strong curtain walls	A	B	C	D
RC1–Frames	A	C	C	D
RC3–Mixed-structure	—	—	D	D

By, year of construction of the building; Yc, year of seismic classification of the municipality.

Table 11. Reinforced concrete (RC) buildings: assignment of the vulnerability class for Parameter 2.

RC Buildings	
Parameter 2: Quality of the resisting system	
$B_y \geq 2008$	A
$1992 < B_y < 2008$	B
$1971 < B_y \leq 1992$	C
$B_y \leq 1971$	D

By, year of construction of the building.

introduction of the use of ribbed rebars in place of smooth ones). The vulnerability score is assigned according to Table 11.

5.1.3. Parameter 3: index of seismic ratingI_{SR}

This parameter expresses the conventional resistance of the building. Under the hypothesis that each examined building was designed by respecting in-force building codes, the research team accepted that the actual seismic capacity coincides with the design seismic capacity, as required by the code. The index is calculated as the ratio between the maximum design base shear V_{des} (provided by the building code in force at the year of construction Y_c) and the current one V_{cur} (i.e. calculated according to the present Italian seismic code, with reference to the maximum seismic demand in the region):

$$I_{SR} = \frac{V_{des}}{V_{cur}} \cdot 100 \qquad \text{(EQ4)}$$

The base shears (both design and current one) are calculated by adopting the method of linear static analysis (the automatic calculation procedure is explained in detail in the manual, ANTAEUS Project, 2011). The final assignment of the vulnerability is given in Table 12.

5.1.4. Parameters 4, 6, 7, 10, and 11: other parameters

For all these parameters, the criteria used to assign the vulnerability class are the same as the case of masonry buildings.

Table 12. Reinforced concrete (RC) buildings: assignment of the vulnerability class for Parameter 3.

RC Buildings	
Parameter 3: Index of Seismic Rating I_{SR}	
$B_y \geq 2008$	A
$1981 < B_y < 2008$ and $I_{SR} \geq 0.3$	B
$1981 < B_y < 2008$ and $I_{SR} < 0.3$	C
$B_y \leq 1981$	D

By, year of construction of the building.

Table 13. Reinforced concrete (RC) buildings: weights and scores of the vulnerability parameters for RC buildings.

RC Buildings: Cores and Weighting Coefficients					
	Values of p_i for vulnerability class				Weights
Parameter	A	B	C	D	w_i
1: Type and organization of the resisting system	−10	5	25	45	1.5
2: Quality of resisting system	−10	5	25	45	1.00
3: Index of Seismic Rating	−5	5	25	45	0.50
4: Topographic conditions	0	5	25	45	0.25
6: In plan configuration	0	5	25	45	0.75
7: Configuration in elevation	0	5	25	45	0.75
10: Non-structural elements	0	5	25	45	0.25
11: Maintenance level	0	5	25	45	0.50

5.2. Calculation of the vulnerability index

For each of the eight parameters, a vulnerability class (from A to D) is assigned, and this is translated into a numerical score p_i, according to Table 13. Then, the possible modifiers affecting the parameter are applied. In any case, the final modified value of p_i cannot exceed the following limits:

- $0 \div 45$ for parameters 4, 6, 7, 10, and 11;
- $-10 \div 45$ for parameters 1 and 2; and
- $-5 \div 45$ for parameter 3.

If these thresholds are exceeded after the application of modifiers, the score p_i is set back to the maximum or minimum value.

The vulnerability index I.V. is obtained by a weighted sum of the scores obtained for each parameter: $p_1w_1 + p_2w_2 + \ldots + p_{11}w_{11}$. It can vary within the interval [−27.5, 247.5] (the weighting coefficients w_i are listed in Table 13).

Finally, the vulnerability index IV is normalized between −0.25 and 1, according to the following expression:

$$I.V. = \frac{\{p_1w_1 + p_2w_2 + p_3w_3 + \ldots + p_{11}w_{11} + 27.5\}}{220} - 0.25 \qquad \text{(EQ4)}$$

6. Case study: four historical centers in the province of Foggia

The ANTAEUS project involved four historical centers in the Province of Foggia (Puglia, Italy): Foggia, Carlantino, Sant'Agata di Puglia and Vico del Gargano (Figure 1), where the survey form previously described was filled for 4,519 residential buildings (96% are masonry buildings).

6.1. Foggia

Foggia is a city of 150,000 inhabitants, administrative center of the homonymous province, located at the center of a vast alluvial plain, and it is built on flat terrain made up of clay. Born as an agricultural center, the city took some importance in the 13th century, under the reign of Frederick II Hohenstaufen, who established there an imperial seat. Over the centuries, the city became important as the center of the surrounding agricultural region and underwent considerable expansion. A remarkable seismic event was the earthquake of 1731 (Mezzina 2011), which severely damaged the city and destroyed about one third of the building stock. The current layout of the historical center is deeply influenced by the reconstruction process that followed: besides the great number of collapsed buildings, unsafe structures were demolished and replaced by one-story masonry shacks, built with tuff stone and coupled to each other to form large blocks. Over the centuries, people have modified these temporary buildings with expansions, fusions and addition of stories (Figure 3), making them a permanent part of the city, as it is clearly visible in the urban fabric (Figure 4). In the other parts of the old city, the common typology is represented by two-story tuff masonry buildings, built before 1919.

Figure 4. The historical center of Foggia, with the surveyed buildings in evidence. The area object of the reconstruction of 1731 is marked in red.

6.2. Vico del Gargano

Vico del Gargano is located in the Northern part of the Gargano Promontory, on a hill made up of limestone of dolomitic type. The historical center grew around the core of the old castle, which is still visible (Figure 5). Over the years, residential buildings have replaced the ancient city walls, whose path still defines the perimeter of the old town. The geometry of the buildings, mostly built of stone, is strongly nonhomogeneous in plan and elevation, also because of alterations made at different times. Masonry is generally very regular, consisting of roughly cut stones, in some cases in weak condition because of the state of abandonment.

6.3. Sant'Agata di Puglia

The town of Sant'Agata di Puglia is located at the foot of Apennine Mountains. The town is built on the eastern side of a hill around the ancient castle, which is on the top. The soil consists of a conglomerate with particles of ruditic size. The buildings—usually, two-story masonry constructions—are built on a steep slope, and characterized by irregularity in elevation (different number of stories towards the valley and towards the mountain, as shown in Figure 6). Moreover, many buildings have an underground artificial cave, with the entrance at the lower level. The walls are mostly made up of roughly squared limestone blocks. The maintenance status of the walls is generally good.

Figure 3. On the left, an example of the original configuration of the houses built after the 1731 earthquake. On the right, the same typology of houses after the addition of a story and an enlargement.

Figure 5. A view of the historical center of Vico del Gargano (left), and an example of the reuse of the city walls (right).

Figure 6. A view of Sant'Agata historical center (left), and an example of the typical structural aggregate, built on a slope with two level elevations (right).

6.4. Carlantino

The town of Carlantino is also located on the Apennine Mountains, at the extreme border of the Province of Foggia. The town has developed since the 16th century as a farming settlement and has no fortification work that influenced its development. The urban fabric looks sparser than other towns (greater distance between houses and wider streets). On average, buildings are two-stories, and in many cases have been recently renovated or enlarged. The soil mainly consists of agglomerate of rocks of variable grain and size.

7. Validation of the methodology for masonry buildings: comparison with GNDT method

After completing the survey in the four municipalities, ANTAEUS procedure was statistically validated by comparing it with other established vulnerability methods (GNDT 1994; Ferrini et al. 2003). For each municipality, a representative sub-sample of masonry buildings was selected, choosing those for which forms were complete and reliable (Table 14). Attention was restricted to masonry building only because the overall number of RC buildings involved in the surveys was small with respect to the total set (less than 4%): the statistical significance of the sample would have been limited, compromising the relevance of the validation.

Table 14. Total number of masonry buildings surveyed with the ANTAEUS form, number of samples for which the GNDT forms were completed.

Municipality	ANTAEUS	GNDT	Sample %
Foggia	2348	75	3.2
Carlantino	650	25	3.8
Sant'Agata di Puglia	725	25	3.4
Vico del Gargano	662	25	3.7

The comparison concerned the GNDT approach for the second-level vulnerability assessment of masonry buildings in its original version (GNDT 1994) and in the modified version adopted by Tuscany Region (Ferrini et al. 2003) and extensively applied in 2003. The survey form used in the two approaches is equivalent, whereas the main differences concern the values of the weighting coefficients attributed to the parameters, as shown in Table 15. When the value of the weighting coefficient is

Table 15. Values of the weights used to calculate the vulnerability index for masonry buildings.

Masonry Buildings			
Parameter	GNDT	GNDT Tuscany	ANTAEUS (first proposal)
1: Type and organization of the resisting system	1.00	1.50	1.50
2: Quality of resisting system	0.25	0.25	0.25
3: Conventional resistance	1.50	1.50	0.50
4: Topographic conditions	0.75	0.75	0.50
5: Floors	0.5 ÷ 1.0 (0.99)	0.5 ÷ 1.25 (0.99)	0.75
6: Configuration in plan	0.50	0.50	0.50
7: Configuration in elevation	0.5 ÷ 1.0 (1.00)	0.5 ÷ 1.0 (1.00)	1.00
8: Maximum distance between the walls	0.25	0.25	—
9: Roofs	0.5 ÷ 1.0 (0.59)	0.5 ÷ 1.5 (0.59)	1.00
10: Non-structural elements	0.25	0.25	0.25
11: Maintenance level	1.00	1.00	1.00

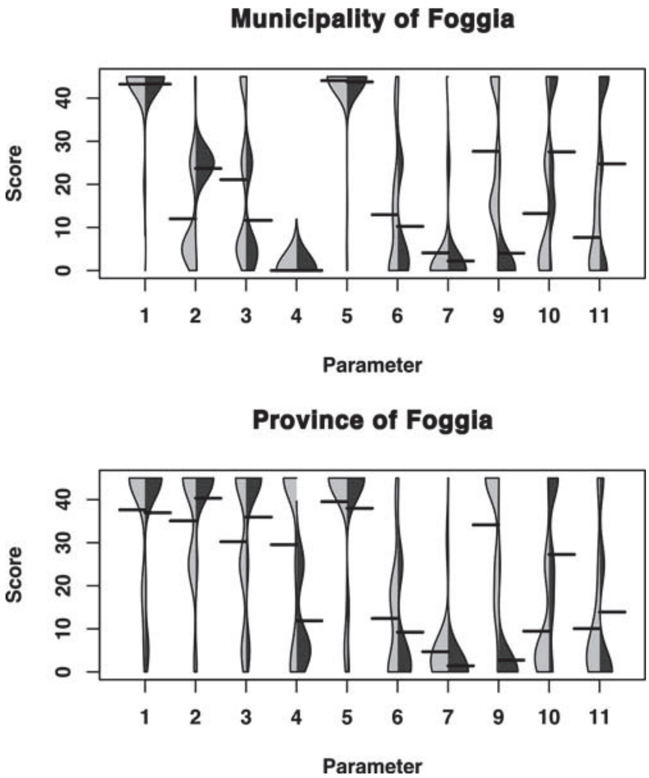

Figure 7. Sample of Foggia (top), Carlantino, Sant'Agata, Vico del Gargano (bottom): distribution curves of the vulnerability parameters for GNDT/GNDT–Tuscany (light gray) and ANTAEUS (dark gray).

not unique but varies within an interval, the table reports the varying range and—in round brackets—the mean value obtained on the sample. For each building of the sample, the GNDT/Tuscany form was filled by deducing the data from the ANTAEUS form and accordingly calculating the vulnerability index. In order to fill the GNDT[1] forms it was necessary a further process1 and—in some cases—an integration by additional surveys.

7.1. Analysis of the results and calibration of the algorithm

In this paragraph, the comparison among the results provided by each of the three methods—GNDT, GNDT–Tuscany, and ANTAEUS—is presented and discussed.

7.1.1. Analysis of the sample of Foggia

In the first instance, the analysis was performed on the sample of buildings of the City of Foggia that is the largest one (75 buildings). Figure 7 reports the average score provided by the three methods for each of the 11 vulnerability parameters in absolute terms, i.e. without normalizing scores and without applying weighting coefficients (the values provided by GNDT and GNDT–Tuscany, in absolute terms, are coincident). The major deviations are encountered for parameter 2 (quality of resisting system), parameter 3 (conventional resistance), and parameter 10 (non-structural elements), which are those for which the ANTAEUS methodology has introduced significant simplifications or variations. After the application of the weights and normalization, however, the situation changes, and the incidence of these discrepancies is much reduced (thanks to the fact that the ANTAEUS algorithm attributes a lower weight to these parameters). By analyzing in detail the individual weighted parameters, the performance of the three methods is different: variations can be noticed among all approaches, for almost all parameters. At this stage, it is difficult to perform a direct comparison, whereas it is more useful to look at the final objective, which consists in guaranteeing that the vulnerability index is substantially consistent among the different approaches. In this sense, the discrepancy between the overall vulnerability index in the ANTAEUS method and in GNDT/GNDT–Tuscany is quite limited, and could be compatible with the purposes of a large regional scale assessment. It is anyway possible to further reduce it, and, to this aim, it is convenient to operate on parameter 1, which contributes for approximately 40% to the final value (19.9 points on a total of 48.9). After some simulations aimed at the optimization of the result, it was decided to reduce the weight of the parameter from 1.50 to 0.75.

[1]In many cases, form data were not sufficient, but the attached material (e.g., pictures, plans, sectional views) was sufficient for deducing the necessary information.

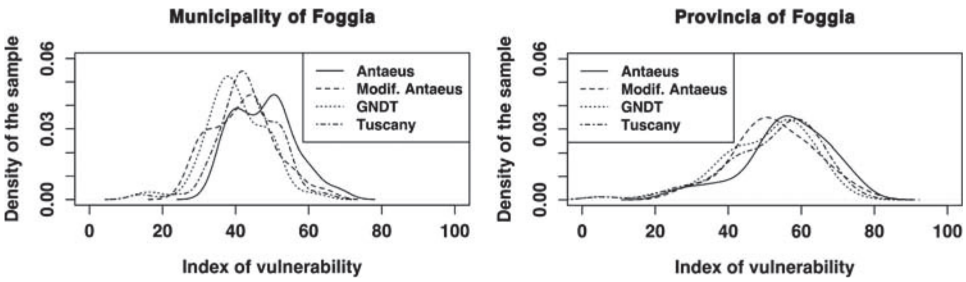

Figure 8. Distribution curves of the vulnerability index for GNDT, GNDT–Tuscany, ANTAEUS and modified ANTAEUS methods. Left: sample of Foggia; sample of Carlantino, Sant'Agata, Vico del Gargano.

In Figure 8–left, the distribution of the vulnerability index is plotted for GNDT, GNDT–Tuscany, ANTAEUS (first proposal), and modified ANTAEUS (after calibration). These diagrams summarize all the observations previously presented, showing, in particular, that the distribution relative to the final calibration of the ANTAEUS method is well consistent with the other methods.

7.1.2. Analysis of the samples of Carlantino, Sant'Agata, Vico del Gargano

The same comparative analysis was performed for the other three municipalities. By applying the calibration proposed for the sample of Foggia (i.e., simply modifying the weight of Parameter 1 from 1.50 to 0.75), the difference between the results of the algorithms is minimized. In particular, Figure 8–right shows the average values and the distribution of the vulnerability index for GNDT, GNDT–Tuscany, ANTAEUS (first proposal), modified ANTAEUS (after calibration).

8. Analysis of the quality of data

The filling of the survey forms is performed by means of an editable PDF module that can be directly interfaced with the database. At the end of field operations, all filled PDF forms are processed by a specific software[2] in order to extract the sensitive data contained in the different fields of the form, and create the database to be used for further elaborations.

8.1. Management of incomplete information: reliability of the forms

A first screening of the vulnerability forms and the extracted database revealed the presence of a large number of incomplete forms (30% of the total), in which missing data were so many as to invalidate the form itself. This number seemed to go beyond the expected physiologic percentage, especially considering that ANTAEUS form was specifically designed for extending the procedure to the largest possible number of buildings. Invalid forms were analyzed in detail, in order to discern occasional errors (related to the specific surveyor teams) from reasons intrinsic to the structure of the form or compelling boundary conditions. It was ascertained that, for most of the invalid forms, the problem was the inability to access the interior of the buildings, and thence the lack of information about the structure and related vulnerability data, which are fundamental for the application of the ANTAEUS algorithm. In the absence of these vulnerability parameters, it is not possible to calculate the vulnerability index and the whole form is unusable. Such a problem can be very common for buildings located in Italian historical centers, because many houses are uninhabited or used only during holidays.

At this point, a question about the management of incomplete information rises, in order to reduce the effects of invalid forms, and the research team introduced some adjustments in the algorithm by providing an automatic a posteriori estimate for missing fields, allowing to proceed in the calculation of the vulnerability index, although approximately. In other words, a limited loss of reliability was accepted in favor of the increase of the valid samples. Within the framework of a regional scale analysis, the interpolation of missing data does not significantly affect the general meaning of results.

After this post-processing, it is necessary to control the reliability level of the results and keep a trace of defective information, by properly differentiating the quality of forms containing revised or integrated data. To this aim, a reliability index I_R was assigned

[2]Data management and processing has been carried out by means of open source software, which ensures maximum compatibility and portability of the code. PDFTK (http://www.pdflabs.com/tools/pdftk-the-pdf-toolkit/) was used for data extraction from PDF files and creation of CSV files. OpenOffice (http://www.openoffice.org/) was used for IV calculation and statistical analysis, and Quantum GIS (http://www.qgis.org/) was used for the plotting of the maps.

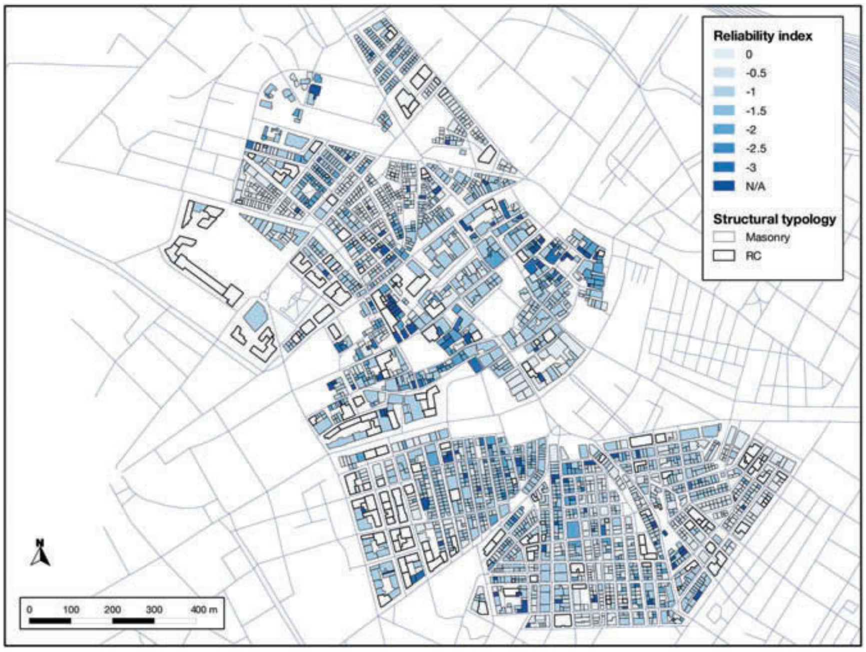

Figure 9. Historical center of Foggia: spatial distribution of the reliability index (2nd survey).

to each form, by taking into account the number of extrapolated parameters: the lower the index, the lower the reliability of the form. Every time that a missing parameter is forced to an extrapolated value, 1 point is subtracted from the reliability index (a value $I_R = 0$ indicates maximum reliability). The minimum accepted value of the reliability index is -3. All forms were classified according to their reliability index, as shown for example in Figure 9 (which is relative to the city of Foggia, after the second survey). In the map, it should be noted that fractional values of the reliability index appear. This appearance is due to the evaluation of the parameter "area of vertical structures", which expresses the percentage of masonry piers in-plan, with respect to the total covered area. (Section [4.1.1] of the form, as shown in the Appendix), which was misinterpreted by some of the survey teams and required a specific evaluation.[3] Statistical analyses on the reliability index are shown in Figure 10, for all the surveyed municipalities.

8.2. Management of operator-dependent errors

With regard to the qualitative analysis of data, an important aspect concerns the verification of the efficiency of survey teams with the consequent detection of systematic errors in the surveyed data (e.g., subjectivity of reading/interpretation of data; nonhomogeneity in the level of training and experience of the operators). In this regard, a check procedure was provided by properly processing and analyzing the database as a function of the reliability index of buildings' forms. In particular, statistical analyses were made in order to classify forms according to the reliability index, assess the average reliability index for each municipality and, more in detail, for individual teams (Table 16, Table 17). The GIS provides an effective and immediate representation that was particularly useful during the operational phase of survey for immediately identifying problems. For example, Table 17 shows that the quality of data collected by the different teams in

[3]Occasionally the values reported were grossly incorrect, since probably some teams reported the absolute value of the vertical structures, expressed in square meters. The parameter was checked and recalculated as follows:

- Values comprised in the range [0.15, 0.30] were considered valid (% of covered area).
- In a first instance, values >1 were interpreted as the area [m^2] of the vertical structures. The % value was numerically calculated. If this was comprised in the interval [0.15, 0.30], it was accepted, but the reliability index was penalized by 0.5 points.
- In all other cases, the value was considered invalid, and the area of the vertical structures was conventionally set to 20% of the covered area in-plan (which was the average value of the parameter on valid forms). The reliability index was penalized by 1 point.

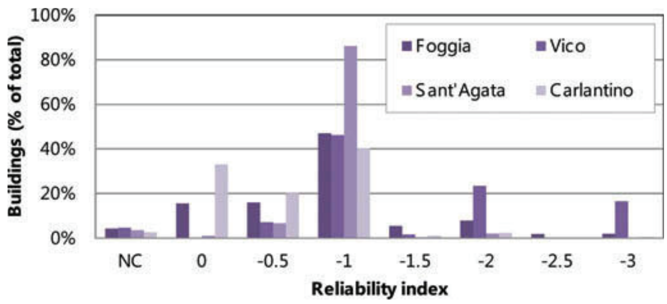

Figure 10. Distribution of the reliability index among the surveyed buildings.

Table 16. Reliability index of the survey forms for the 4 municipalities (4385 total forms, masonry buildings).

Classification of Survey Forms According to the Reliability Index (All Municipalities)								
	Municipality							
Reliability Index	Foggia		Vico del Gargano		Sant'Agata di Puglia		Carlantino	
Invalid forms	100	4.3%	31	4.7%	26	3.6%	17	3%
0 (max. reliability)	367	15.6%	1	0.2%	8	1.1%	215	33%
−0.5	376	16,0%	47	7.1%	48	6.6%	131	20%
−1	1103	47.0%	306	46.2%	625	86.2%	262	40%
−1.5	128	5.5%	11	1.7%	3	0.4%	7	1%
−2	184	7.8%	155	23.4%	15	2.1%	15	2%
−2.5	44	1.9%	1	0.2%	0	0.0%	0	0%
−3	46	2.0%	110	16.6%	0	0.0%	3	
Total (4385)	**2348**		**662**		**725**		**650**	
Average reliability index	**−0.9**		**−1.5**		**−0.9**		**−0.6**	

Table 17. Analysis of the reliability index for the City of Foggia, for masonry buildings.

Reliability class by survey team (City of Foggia)					
Team	Forms	Invalid	Invalid (%)	Average IV	Average Reliability
1	225	12	5.3%	0.40	−1.05
2	229	19	8.3%	0.44	−1.19
3	217	4	1.8%	0.45	−1.18
4	197	4	2.0%	0.38	−0.96
5	231	11	4.8%	0.44	−0.90
6	247	7	2.8%	0.46	−0.42
7	243	10	4.1%	0.54	−1.26
8	248	27	10.9%	0.44	−1.28
9	238	3	1.3%	0.51	−1.04
10	230	3	1.3%	0.44	−0.25
11	43	0	–	0.44	−0.33
Total	**2348**	**100**	**4.3%**	**0.45**	**−0.90**

the city of Foggia is quite heterogeneous. There was no particular evidence of a geographic correlation, that is to say, a same team has a reliability level that is substantially constant over all the different areas of competence (i.e., the reliability cannot be ascribed to an objective difficulty in retrieving data at certain locations). Based on this analysis, the coordinators of the teams were promptly alerted for a rapid intervention and possible sanitization of the problem.

In Vico del Gargano, instead, the map of the vertical structures showed a cluster of buildings with a masonry typology different from the surroundings, whereas it was expected to find uniform masonry fabric. The comparison with the spatial distribution of survey teams revealed that the whole cluster had been assigned to a single team, who made a systematic error in the interpretation of this factor (Figure 11). In this case, coordinators were alerted and the error was promptly corrected.

9. Application of the algorithm and discussion of the results

9.1. Municipality of Foggia

The average value of the IV calculated for masonry buildings (approximately 93% of total) with the modified ANTAEUS algorithm is equal to 0.45. It can be noticed that the average values obtained over the entire population are very similar to the values obtained on the basis of the sub-sample selected for the calibration (Tables 18–19), which confirms the validity of the calibration procedure. Figure 12 shows the map of the index of vulnerability calculated with the modified version of the ANTAEUS algorithm.

9.2. Municipalities of Vico del Gargano, Sant'Agata di Puglia, and Carlantino

The average value of the IV calculated on the entire population of buildings with the modified ANTAEUS

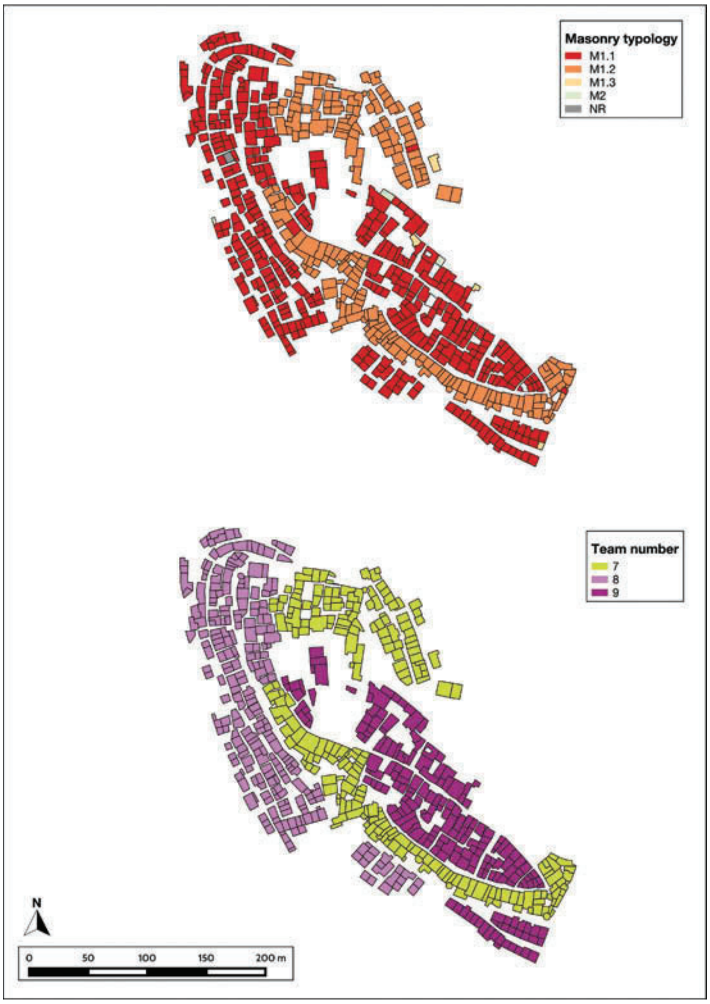

Figure 11. Vico del Gargano: comparison between the spatial distribution of masonry types and survey teams.

Table 18. Comparison among the results of GNDT, GNDT–Tuscany and ANTAEUS for masonry buildings (all parameters are weighted and normalized).

	Foggia					Vico del Gargano				
Parameter	ANTAEUS average	GNDT average	GNDT diff. %	Tuscany average	Tuscany diff %	ANTAEUS average	GNDT average	GNDT diff. %	Tuscany average	Tuscany diff %
1	0.199	0.119	167.3%	0.168	118.4%	0.087	0.094	92.1%	0.133	65.4%
2	0.005	0.016	28.8%	0.015	30.6%	0.038	0.031	123.0%	0.029	131.0%
3	0.032	0.048	67.4%	0.045	71.6%	0.070	0.182	38.4%	0.172	40.7%
4	0.000	0.000	–	0.000	–	0.026	0.015	170.5%	0.014	185.7%
5	0.101	0.120	84.3%	0.113	89.5%	0.084	0.091	92.7%	0.085	98.8%
6	0.020	0.014	141.1%	0.013	149.8%	0.025	0.018	142.2%	0.017	147.1%
7	0.013	0.006	206.2%	0.006	219.0%	0.010	0.003	364.1%	0.003	333.3%
8	–	0.003	0.00%	0.003	0.00%	0.000	0.000	–	0.000	–
9	0.085	0.045	187.9%	0.042	199.5%	0.120	0.038	316.6%	0.036	333.3%
10	0.010	0.017	59.7%	0.016	63.4%	0.010	0.003	303.4%	0.003	333.3%
11	0.024	0.013	183.2%	0.012	194.5%	0.038	0.019	197.6%	0.018	211.1%
Average I.V.	**0.49**	**0.40**	**121.6%**	**0.43**	**112.5%**	**0.51**	**0.49**	**102.8%**	**0.51**	**99.6%**

	Sant'Agata di Puglia					Carlantino				
Parameter	ANTAEUS average	GNDT average	GNDT diff. %	Tuscany average	Tuscany diff %	ANTAEUS average	GNDT average	GNDT diff. %	Tuscany average	Tuscany diff %
1	0.109	0.112	97.5%	0.158	69.2%	0.095	0.112	84.8%	0.158	60.0%
2	0.030	0.029	101.7%	0.027	109.3%	0.019	0.029	64.7%	0.027	68.7%
3	0.051	0.178	28.6%	0.168	30.3%	0.027	0.178	15.2%	0.168	16.1%
4	0.067	0.030	222.6%	0.028	238.4%	0.066	0.030	218.5%	0.028	232.0%
5	0.115	0.118	97.8%	0.111	104.0%	0.110	0.118	93.0%	0.111	98.7%
6	0.014	0.008	181.1%	0.007	203.5%	0.025	0.008	313.9%	0.007	333.3%
7	0.024	0.007	338.7%	0.007	348.9%	0.014	0.007	197.6%	0.007	209.8%
8	0.000	0.000	–	0.000	–	0.000	0.000	–	0.000	–
9	0.136	0.062	220.6%	0.058	234.4%	0.090	0.062	146.4%	0.058	155.5%
10	0.008	0.014	56.4%	0.014	58.1%	0.005	0.014	36.2%	0.014	38.5%
11	0.029	0.020	148.2%	0.019	153.4%	0.035	0.020	177.7%	0.019	188.7%
Average IV	**0.58**	**0.58**	**101.0%**	**0.60**	**97.8%**	**0.49**	**0.58**	**84.0%**	**0.60**	**81.3%**

Table 19. Statistics for masonry buildings: comparison between weighted averages obtained by ANTAEUS algorithm.

	Original		Modified	
Municipality	IV	SD	IV	SD
Foggia	0.49	0.09	0.45	0.10
Vico del Gargano	0.53	0.12	0.51	0.11
Sant'Agata	0.59	0.09	0.56	0.08
Carlantino	0.50	0.10	0.46	0.09

algorithm is equal to 0.51 for Vico del Gargano, 0.56 for Sant'Agata di Puglia and 0.46 for Carlantino (Table 19). These data are consistent with the prediction provided by the preliminary analysis carried out on the samples (Table 18). The resulting vulnerability maps are shown in Figure 13–15.

10. Final remarks

The main objective of the research study was to develop and validate a procedure that can be applied at a large, regional scale by local authorities, in order to obtain a pre-event vulnerability assessment and establish a rational basis for the risk mitigation strategies and territorial development policies. In this sense, this regional project represents, in Puglia, a pilot experience that could be extended to other areas of Southern Italy presenting a building stock with similar characteristics.

The proposed survey procedure is quite simple, excluding data that were too unreliable and difficult to retrieve, in order to rationalize the fieldwork and limit as

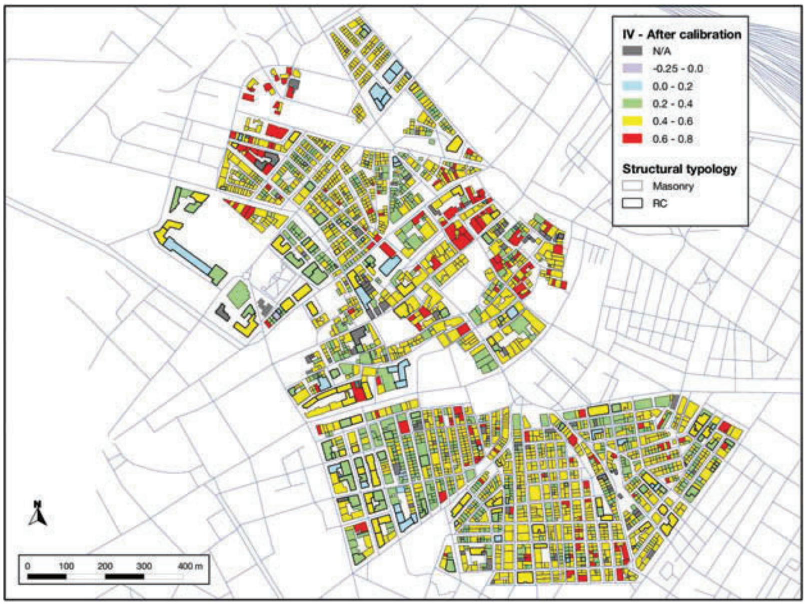

Figure 12. Vulnerability map of Foggia historical center (modified ANTAEUS algorithm).

Figure 13. Vulnerability map of Vico del Gargano historical center (modified ANTAEUS algorithm).

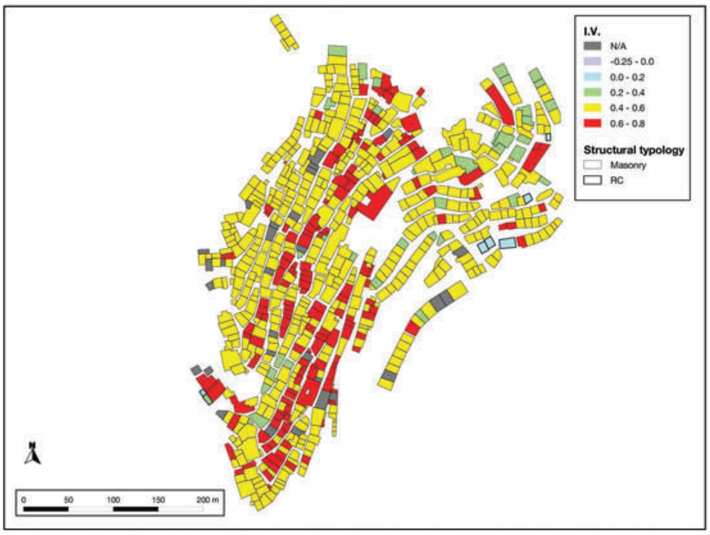

Figure 14. Vulnerability map of Sant'Agata di Puglia historical center (modified ANTAEUS algorithm).

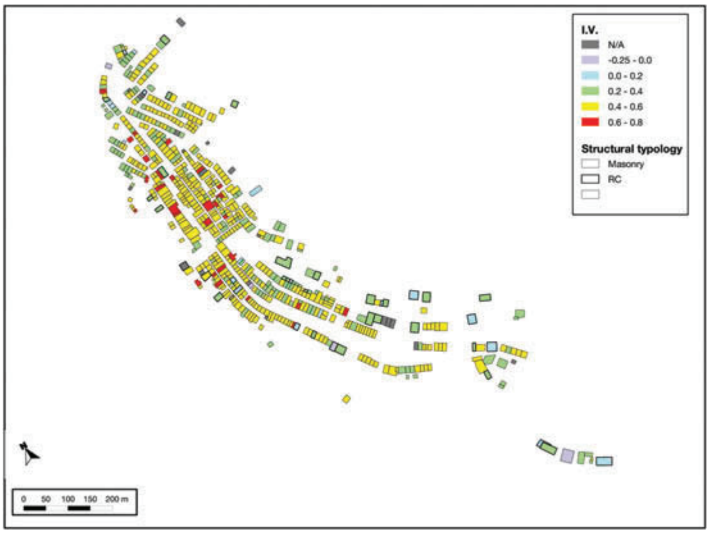

Figure 15. Vulnerability map of Carlantino historical center (modified ANTAEUS algorithm).

much as possible uncertainty and errors. A specific survey form is provided, which is an editable PDF module directly connected with a database, together with an algorithm for the appraisal of the index of vulnerability. The procedure is derived by the classical GNDT method, even if some significant modifications of the survey form and the vulnerability algorithm were introduced, with the idea of obtaining a simplification and a better accounting for the regional features.

Since Puglia is a low-medium hazard region, few observational data about post-earthquake events are available, which it makes impossible to perform a statistical validation. The validation of the ANTAEUS procedure, thence, was made with an indirect approach, by performing a detailed comparison, on a sample of buildings, with the results provided by GNDT and GNDT-Tuscany methods. The results were critically evaluated, introducing the necessary calibrations, which consisted in the adjustment of the weighting coefficient for one parameter (see Section 0). Overall, the three compared methods exhibit discrepancies with regard to individual parameters, but the correspondence in terms of the final vulnerability index is good.

The results can be considered satisfactory within the scope and objectives of the project: the assessment procedure was performed by using a very simplified data-sheet and in a short time by providing an estimate of the vulnerability level compatible with more detailed approaches. An important issue considered in the study was the analysis of the quality of the data with respect to the issue of the uncertainty factors related to the phase of data retrieval (e.g., quickness and roughness of rapid visual inspections, possible incompleteness of collectable information, subjectivity of data reading/interpretation). A detailed reliability analysis of the results was performed, in order to identify critical points and propose a sanitization of the database. The management of incomplete/erroneous data was made by activating a fruitful interaction between the scientific board and the coordinators of the survey teams, and allowing a prompt intervention both on theoretical aspects (by means of proper a-posteriori re-elaboration of data) and operational issues (by performing ad hoc controls and integrations on site).

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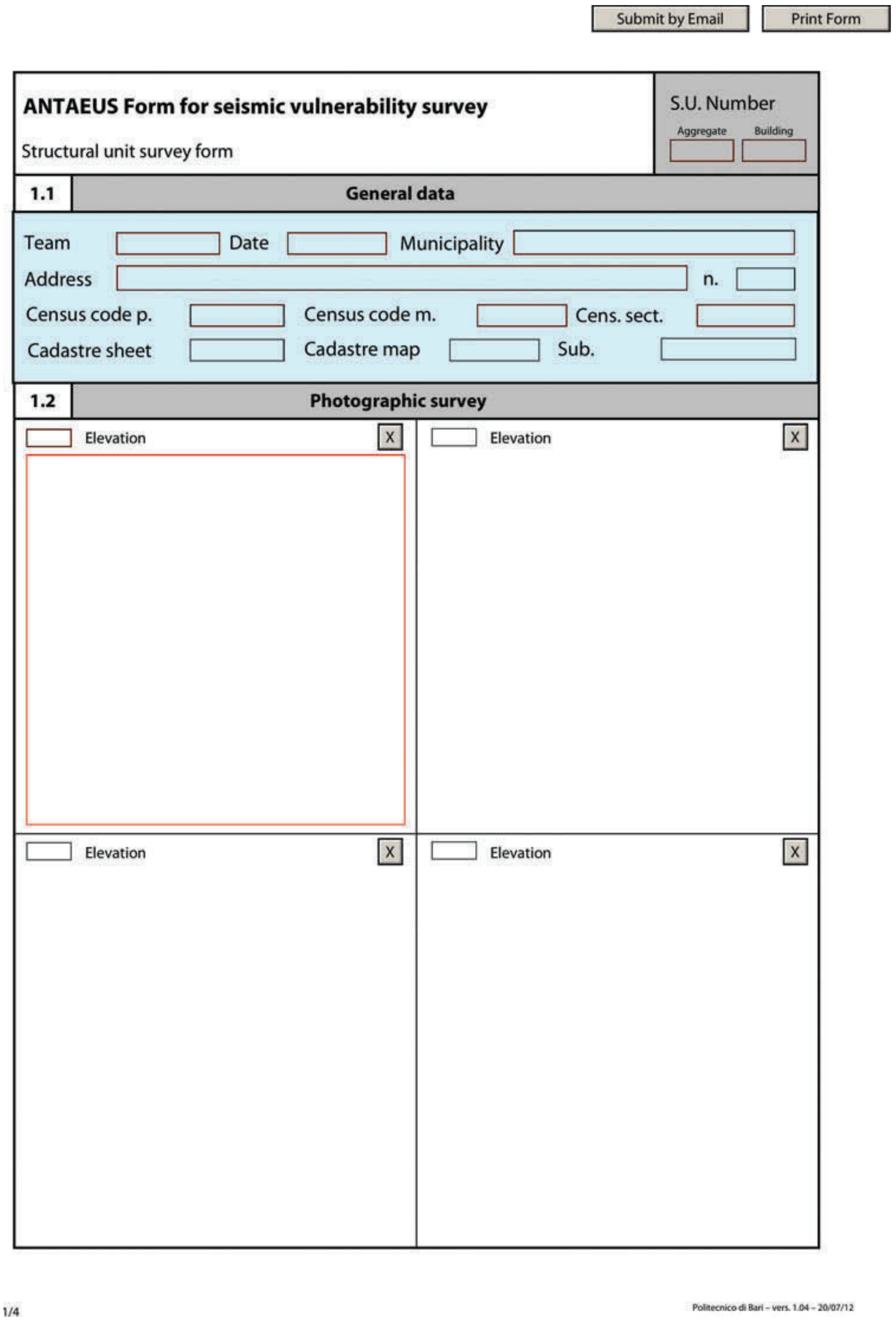
Appendix

The ANTAEUS Vulnerability form is an editable PDF file, which is intended for the surveyor to complete directly on site by means of portable devices (e.g., a tablet). After a final phase of deskwork, when data are checked and additional information is uploaded (e.g., land registry plans, pictures, sketches), the file is closed and sent to the remote system, which automatically extract numerical data and store them in the database. In this Appendix, a print of the PDF module is reported, showing the different sections and entries to be filled, which are recalled and described in the article text.



Submit by Email   Print Form

ANTAEUS Form for seismic vulnerability survey

Structural unit survey form

S.U. Number
Aggregate   Building

1.1 General data

Team   Date   Municipality
Address   n.
Census code p.   Census code m.   Cens. sect.
Cadastre sheet   Cadastre map   Sub.

1.2 Photographic survey

Elevation   X
Elevation   X
Elevation   X
Elevation   X

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2.1	**Graphic survey**

X

Location (1:500 aggregate plan, aerial view)

X

Ground floor plan

3.1	COMMON DATA	
	Vulnerability indicators	**Instructions**
1	*Geometric data* Lx: [ ] Ly: [ ] Min. height: [ ] Max. height: [ ] Storeys: [ ] Basements: [ ] Covered area: [ ] ☐ underground cavities	**All measurements in meters [m] or squared meters [m²].** **Lx**: max. length in x direction **Ly**: max length in y direction
2	*Morphology of the structural unit* Pos. into the aggregate: [ ] Irregularities in plan* [ ] ☐ staggered floors ☐ weak floor Irregularities in elevation* [ ] ☐ loggias or porches	**Typology of building:** **A1** Head **A4** Isolated **A2** Internal **NR** Not surveyed **A3** Corner
3	*Morphology of the site* Morphology of the site: [ ]	**Morphology of the site** **S1** Flat **S4** Hillside **S2** On ridge **S3** On a slope **NR** Not surveyed
4	*Maintenance* General ○B ○C — Fixtures ○B ○C ○A Plaster / cladding ○B ○C — Wiring system ○B ○C ○A Roof ○B ○C ○A — Plumbing sys. ○B ○C ○A	**Maintenance status** **B** Good **C** Bad **A** Lacking
5	*Modifications after construction* Raising ☐ in masonry ☐ in r.c. Extension ☐ in masonry ☐ in r.c. ☐ seismic upgrading year [ ] ☐ alteration of load-bearing walls ☐ seismic retrofitting year [ ] ☐ alteration of original internal partition ☐ local repairs	In the case of upgrading or retrofitting, you should report the year of execution of the works.
6	*Non-structural elements* Vulnerable — Vulnerable ☐ chimney-pot ○Yes ○No — ☐ balcony ○Yes ○No ☐ cornice ○Yes ○No — ☐ shelters / cantilever roofs ○Yes ○No ☐ parapet ○Yes ○No — ☐ suspended ceiling Yes ○No	
7	*Exposure* Prevalent use: [ ] Avg. number of occupiers [ ] Percentage of occ. [ ] ☐ cultural heritage D. Lgs. 42/2004 ☐ uninhabited/abandoned	**Prevalent use** **U1** Housing **U5** Workshop **U2** Commercial **U6** Public use **U3** Office **U4** Industry **NR** Not surveyed

* See manual

4.1 ☐ MASONRY

Vulnerability indicators		Instructions
1	*Vertical structures* Typology: ☐ grouted masonry Piers* [% on façade]: Area of vertical struct. ☐ headers — Effective ○ Yes ○ No; ☐ tie rods — Effective ○ Yes ○ No ☐ quoins — Effective ○ Yes ○ No; ☐ ring beams — Effective ○ Yes ○ No	**Typology of vertical structures** **M1.1** Rubble stone **M1.2** Irregular stone masonry **M1.3** Regular stone masonry **M2** Tuff blocks **M3.1** Unreinforced brick masonry **M3.2** Reinforced brick masonry **NR** Not surveyed
2	*Floors* Typology: ☐ stiff ☐ well connected	**Typology of floors:** **O1** Wooden structure **O2** Brick and concrete **O3** Brick and steel **O4** Masonry vaults **NR** Not surveyed
3	*Roof* Typology: Pitch: ☐ ties or ring beams ○ Pushing ○ Partially pushing ○ Non-pushing	**Typology of roof:** **C1** Wooden structure **C2** Brick and concrete **C3** Steel **C4** Masonry vaults **NR** Not surveyed
4	*Age of the building* Age class: ☐ Estimated	**Age class:** **1** Before 1919 **2** From 1919 to 1930 **3** From 1931 to 1945 **4** From 1946 to 1961 **5** From 1962 to 1971 **6** From 1972 to 1981 **7** From 1982 to 1987 **8** After 1987

4.2 ☐ REINFORCED CONCRETE

Vulnerability indicators		Instructions
1	*Structural system* Typology:	**Typology of structural system** **RC1** RC frames **RC2** Internal frames and perimeter load-bearing walls **RC3** RC frames with strong infill walls **RC4** Frames and RC walls **RC5** Frames and RC shear walls **NR** Not surveyed
2	*Infill* Infill on façade [%]:	
3	*Age of the building* Year of construction: ☐ Estimated	**Infill on façade:** you should report the percentage of infill compared to the lateral surface of the building.

4.3 DAMAGE ASSESSMENT

			Instructions
Vertical struct.:	○ G ○ L ○ A	Roof: ○ G ○ L ○ A	**Damage level:**
Floors:	○ G ○ L ○ A	Infill: ○ G ○ L ○ A	**G** Serious **L** Slight **A** None
Stairs:	○ G ○ L ○ A		

4.4 NOTES

SIGNATURE

* See manual