Ancient masonry cathedrals in Matera landscape: seismic assessment and risk mitigation

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Abstract: Dramatic human and economic consequences are nowadays still resulting from natural and anthropic risks of Cultural Heritage. Matera landscape is characterized by many and important ancient masonry cathedrals, concentrated in its downtown named "*Sassi* of Matera", and recognized as Cultural World Heritage by UNESCO since 1993. The city is located in the southern Italy into a seismic-prone area with moderate seismicity. The structural typology and materials identification of these churches represent a crucial point for their structural safety assessment and risks mitigation.

In this paper some representative examples are illustrated by remarking the main peculiarities of such structures. Then, some chosen study cases are evaluated with simplified procedures for seismic risk assessment. This approach may be also used in a territorial scale for planning the preventive conservation of the Cultural Property, in order to establish priorities lists and to plan preventive mitigation projects based on the specific vulnerabilities of the cases under consideration.

Key-words: Cultural Heritage, hazards; masonry churches, seismic risk assessment, seismic vulnerability.

1. Introduction

In geographic areas with high risk of natural disasters, comprehensive risk management plans for the conservation of Cultural Property have not been completely developed yet. Disaster prevention, in the field of built heritage conservation has been addressed by developing principles and manuals for risk management settled for example by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Council on Monuments and Sites (ICOMOS), the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) and the Getty Conservation Institute, and also by implementing prevention programs as *Carta del Rischio* (ISCR 1992) in Italy and the Disaster Prevention Program on Cultural Heritage (INAH 2002) in Mexico.

In this context, the paper here presented aims to analyze the seismic risk of Cultural Property, which is defined by the seismic vulnerability, measured in terms of the fragility of the constructive system, and the seismic hazard, often measured in terms of ground acceleration or Mercalli Intensity.

Seismic vulnerability assessment of masonry buildings has been largely developed in Italy, due to the recent earthquakes: Umbrian in 1997, Molise in 2002 and Abruzzo in 2009, which have been used as a laboratory by managing the damage collected data from a statistical point of view and linking it with the seismic intensity. On this data set, for example, is based the first assessment level (indicated as LV1) by the Italian Guidelines on Cultural Heritage for the typology of "churches, places of worship and other structures with large spaces, without intermediate horizontal elements". The procedure defines a vulnerability index by considering the vulnerabilities and anti-seismic devices on each macro-element of the church, while the seismic safety index is defined in terms of the ground acceleration corresponding to the achievement of life safety limit state (SLV) or damage limit state (SLD).

Recently an alternative simplified approach by Díaz (2015) has been proposed, addressed to evaluate all the generic threats (not only the seismic one) and the resulting risks for historic buildings. Starting from a comparative analysis among the contributions of the manuals previously mentioned, in this method a correlation among the identification of threats and vulnerabilities and the causes of historic buildings deterioration, based on the document developed by De Angelis (1972) for the ICCROM, has been derived.

In particular, this simplified approach may be applied by the means of the following tools: *Tool 1: seismic vulnerability assessment form*, taking into account the GNDT form (2003), the Chilean Norm N° 3332 (2013) for earthen built heritage, and recent research on assessment and reinforcement of historic masonry buildings; and *Tool 2: description, hierarchy and hazard mapping*, considering existing programs as *Carta del Rischio* (ISCR 1992) in Italy; and documents in the field of territorial planning developed by CENAPRED (2006) in Mexico. The resulting risk, defined as "the combination of the probability of an event occurring and its negative consequences" (UNISDR 2009), is finally calculated by multiplying the seismic vulnerability index (Tool 1 outcome) by the seismic hazard index (tool 2 outcome) in according to the expression:

$$\text{Risk (R)} = \text{Vulnerability (V)} \times [\text{Hazard (H)}+1]$$

The new simplified methodology proposed in Díaz (2015) and the LV1 level provided by the Italian Guidelines on Cultural Heritage (DCCM 2011) are following described and applied to the cathedral typology located in the UNESCO "*Sassi Site*" of Matera for evaluating the seismic vulnerability and the resulting risk. In particular, four churches are considered in this study: *Sant'Agostino, San Pietro Caveoso, San Francesco d'Assisi* and *San Giovanni Battista.*

2. Typical constructive typology in the *Sassi* of Matera

The semantic origin of the name *Matera*, whether it would come from *meta* (rock) or from *materia* (timber) denotes an obvious reference to the morphology and characteristics of the landscape. Moreover, the same name *Sassi* makes reference of the housing system created in geological material, the limestone rock (*tufo*), which is present along the abrupt walls of a deep and imposing ravine, the *Gravina* of Matera. There are chronicles and representations since the middle ages speaking about the spectacular geomorphology and curious landscape of the site, which has been inhabited since Neolithic times (Colonna and Fiore 2014).

There is a strong material continuity in Matera due to the use of the same limestone square stone, extracted from the numerous caves along the slopes of the *Sassi*, for building the walls and vaults of the first housing constructions and public buildings like churches. Moreover, the irregular stones of *tufo* were used for the reinforce of the vaults; the stone flakes, together with mortar or mud, constituted the filling material of the walls; and the powder of the *tufo* was used as inert mingled with lime for making mortar (Giuffrè and Carocci 1997). In fact, a possible vulnerability of the construction system in Matera is the variability on the characteristics of the limestone, which particle size range varies depending of the point of extraction, "it goes from a medium to coarse grain size to a medium-fine, from a stone texture material to a kind of coarse cemented sand that may be pulverized with the fingers of the hand" (Giuffrè 1993 in Giuffrè 1997). This condition explains the phenomenon of surface degradation (Cotecchia 1974 in Giuffrè 1997) which may be observed on the same masonry wall damaged by local causes, having compact and resistant segments along with other degraded and eroded, likely affecting the mechanical characteristics of resistance.

The square blocks had a height that varied between 25 and 27 cm; a width between 20 and 25 cm; and a length between 45 and 60 cm, and were settled on the wall in band (the segments are set with their bigger length on facing walls) or head (the segments are arranged with their bigger length transversely to the wall). The masonry was built with thin mortar joints between the stones, made of powder of *tufo* and lime, no more than 0.5 cm thick (Giuffrè and Carocci 1997). The vaults had a wood structure above to sustain the roof or had a filling made with flakes of stone and mortar of lime or poor mud, which was often regularized with a head disposed block, as can be seen on Figure 1.

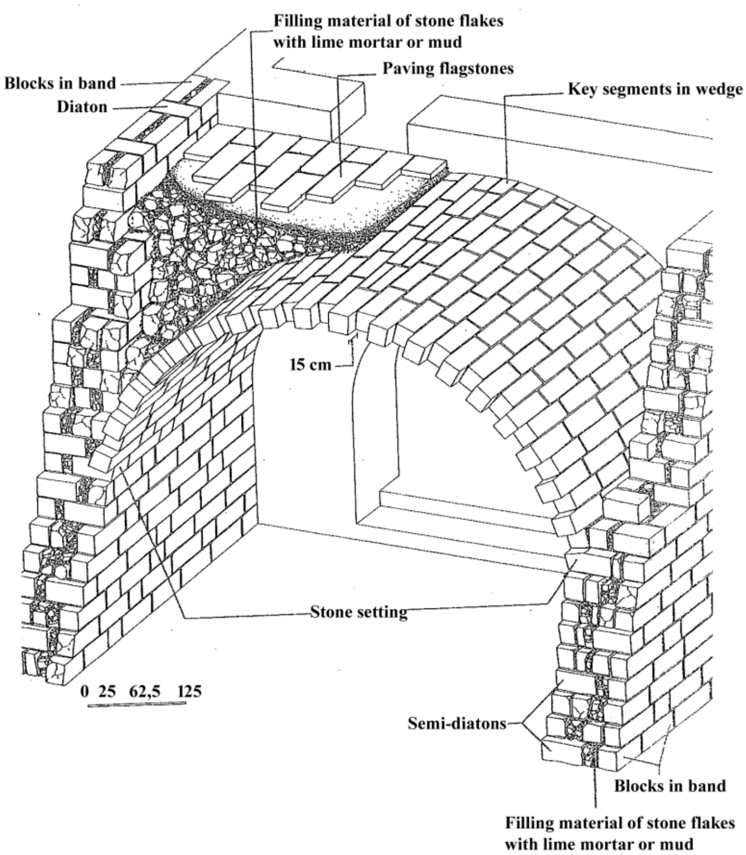

Figure 1 – Constructive system in *Sassi* of Matera (Giuffrè and Carocci 1997)

The thickness of the masonry varied from 50 to 120 cm and was built as a three-leaf wall with a conglomerate of stone flakes and mortar in between; however, usually the filling was made with scarce lime mortar, constituting a static weakening. Regarding the reinforcements, the most used consolidation systems in Matera for neutralizing the thrust of the vaults were: the buttresses that increased the thickness of the wall; and the wooden or metal chains (Giuffrè and Carocci 1997).

3. Simplified assessment of seismic risk

In the following paragraphs the Díaz methodology and the LV1 level of analysis provided by the Italian Guidelines on Cultural Heritage for the typology of “churches, places of worship and other structures with large spaces, without intermediate horizontal elements”, will be synthetized and described, aiming to apply them in the next section to the case studies.

3.1 –Díaz methodology: seismic vulnerability assessment form (tool 1) and description, hierarchy and hazard mapping (tool 2)

The first tool proposed in Díaz (2015) consists on a form to evaluate the structural seismic vulnerability, where the considered parameters were defined from a comparative analysis of documents on structural analysis and post-earthquake damage forms. Figure 2 shows the tool 1 diagram, presenting the parameters for assessing the seismic vulnerability divided into three groups (in green) as follows: position of the building; structure characteristics; and conservation status. In both sides of the main column the parameters related to the main group are shown (in purple), and the source or reference (in white) is shown next to each parameter.

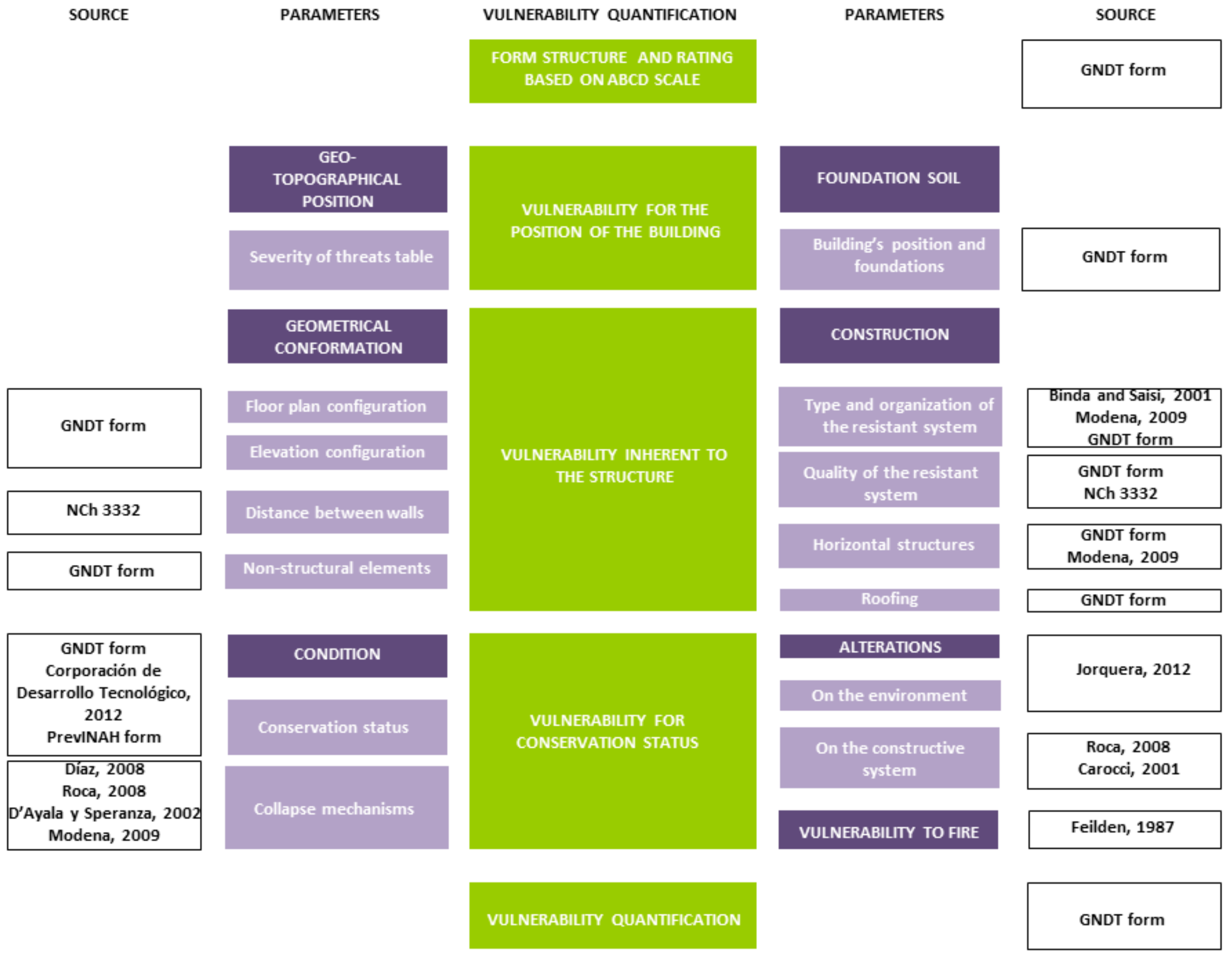

Figure 2 – Parameters of the tool 1: seismic vulnerability assessment (Díaz 2015)

In particular: the *position of building and its foundations* assesses the soil type and slope (if any); the *floor plan configuration or geometry* measures the asymmetry of the building that increases its vulnerability to an earthquake; the *elevation configuration* evaluates the building stories, mass distributions and continuity of resistant elements throughout the height; the *distance between the walls* assesses the slenderness of the walls, the out of plumb, the openings location, the excessive length in plan between two transversal walls, among others; and the *non-structural elements* parameter evaluates the accessories, projections or overhangs that could fall in an earthquake. On the other hand, the parameters assessing the *type, organization and quality of the resistant system* evaluate the constructive system, the material, the lock between orthogonal walls and the connection between walls and floors by the means of horizontal structures executed with compatible materials. Regarding the *horizontal structures* and *roofing* parameters, they assess the deformability in the plane, the material compatibility, the thrusts on the walls and suitable connections between walls and roof. Finally, the *conservation status* evaluates the building visible condition in terms of damage; the *alterations in the construction system* and in the *environment* evaluate the negative interventions that have increased the vulnerability; and the *vulnerability to fire* evaluates the presence of flammable ornaments and furniture, lack of compartmentalization and internal divisions, dangerous activities, etc.

Each parameter is classified on the scale A, B, C and D, where A indicates a very low vulnerability and D a very high vulnerability of the building by a numerical value. The values and weight of each parameter were based on the GNDT form (2003), which proposed a table for vulnerability quantification, taking into account the varying importance of each parameter for the purposes of seismic behavior of the structure. Since in the Díaz (2015) procedure the parameters were modified and increased with the aim of adapting the form for assessing the Cultural Property, the values of the table were changed but keeping the proportions of those proposed by the GNDT (Table 1).

Table 1 –Rating and weight of parameters to define vulnerability index (Díaz 2015)

Parameters		Class				Weight
		A	B	C	D	
1	Position of the building and foundations	0	1,35	6,73	12,12	0,75
2	Floor plan configuration or geometry	0	1,35	6,73	12,12	0,5
3	Elevation configuration	0	1,35	6,73	12,12	1,0
4	Distance between walls	0	1,35	6,73	12,12	0,25
5	Non-structural elements	0	0	6,73	12,12	0,25
6	Type and organization of the resistant system	0	1,35	6,73	12,12	1,5
7	Quality of the resistant system	0	1,35	6,73	12,12	0,25
8	Horizontal structures	0	1,35	6,73	12,12	1,0
9	Roofing	0	1,35	6,73	12,12	1,0
10	Conservation status	0	1,35	6,73	12,12	1,0
11	Environmental alterations	0	1,35	6,73	12,12	0,25
12	Construction system alterations	0	1,35	6,73	12,12	0,25
13	Vulnerability to fire	0	1,35	6,73	12,12	0,25

Thus, the vulnerability index is defined with the relationship given by Eq. (1),

$$VI_j = \sum_{i=1}^{n} v_{j,i}\, p_i \qquad (1)$$

where $v_{j,i}$ is the value of the parameter that takes into account its characteristics and its influence on the seismic behavior of the building; and p_i is the weight that takes into account the relative importance of the parameter in the general evaluation of the building. The seismic vulnerability index is then classified in a range proposed by Díaz (2015): low vulnerability: $0 < V \leq 10.81$; medium vulnerability: $10.81 < V \leq 55.52$; and high vulnerability: $55.52 < V \leq 100$. Finally, the seismic vulnerability index is multiplied by the seismic hazard index to calculate the seismic risk.

The second tool developed in Díaz (2015) is addressed to the hazard mapping and it is based on the analysis of documents in the field of territorial planning and heritage conservation. It performs a global analysis of threats that may affect the Cultural Property aiming to evaluate the worst scenario, where each of the threats is considered with the greatest magnitudes based on historical information. The threats are then prioritized based on the severity of damage that they might cause on the building. The diagram in Figure 3 shows the classification of the threats into three main groups (in green): natural hazards of occasional action; threats of physical nature; and man-made and chemical hazards. In both sides of the main column the parameters related to the main group are shown (in purple), and the source or reference (in white) is shown next to each parameter.

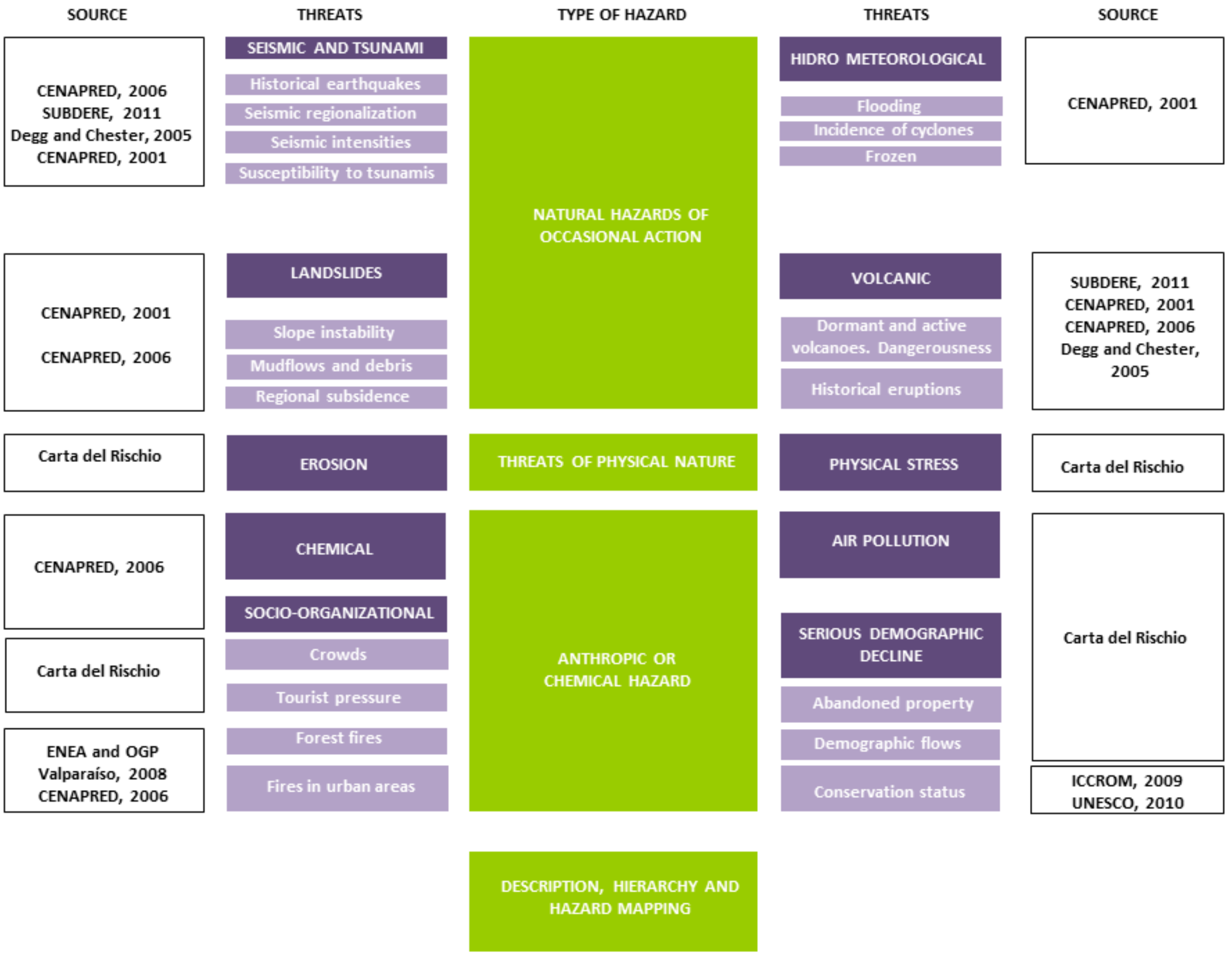

Figure 3 – Parameters of the tool 2: description, hierarchy and hazard mapping (Díaz 2015)

Based on this methodology the current analysis aims to assess the *seismic risk*; therefore*, the volcanic, hydro meteorological* and *chemical* threats will not be evaluated. The seismic threat will be assessed in terms of maximum Mercalli Intensity, and the *landslide or rock fracture threat* will be analyzed because is a likely consequence of a strong earthquake. The continuous processes threats will be assessed as well: *erosion, physical stress, air pollution, socio-organizational threat* and *serious demographic decline* (linked to lack of maintenance), since their main consequence is the material damage.

The first step to assess *seismic threat* includes the research of historic earthquakes, their intensity, maximum acceleration of the ground and distance from the epicenter, and also the danger of tsunami according to the study of affected areas. The *landslide or rock fracture threat* is analyzed considering: topography and geometry of the slopes; geological stratification distribution and stress status; mechanical properties of the soil; ordinary and extraordinary rainfall; surface and underground hydrology; and identification of anthropogenic interventions which may have caused: changes in the pressure system of underground water, in the geometry of the slope or in the rise of overload, and deforestation without technical evaluation.

Regarding the continuous processes threats, they occur at least one time a year and are mainly related with the geographical position, the weather and the social context. The *erosion threat* parameter assesses the average and maximum rainfall, the distance to the coast, the relative humidity and the direction and speed of prevailing winds that may provoke material deterioration. The *physical stress threat* assesses: the average and maximum rainfall, maximum and minimum temperatures, thermal oscillation and solar lighting, aiming to assess the likely damage in the materials by a strong oscillation of temperature, and the confluence of raining and temperatures below 0° that may provoke the icing of water particles and the consequent disintegration or cracking of materials. On the other hand, *air pollution threat* assesses: vehicular congestion zones; location of airports and seaports; highways and daily circulation of cars, in order to evaluate the concentration of air pollution and the likely blackening of materials or its dissolution by acid rainfall. *Socio-organizational threat* parameter analyzes the overload or damage on the monuments for the presence of crowds of people by analyzing touristic pressure, and it also analyses the likeliness of fire. On the other hand, the likely lack of maintenance in monuments is analyzed by studying the *serious demographic decline* and by identifying the location of abandoned buildings and general conservation status.

All these parameters are analyzed for establishing the worst scenario based on historical information and is then classified depending of the severity of damage that the scenario might cause in the monuments which may be: no damage, low or gradual or catastrophic. Every parameter has a score based on the influence of the threat, as a site effect, in the seismic behavior of the building (Table 2).

Table 2 –Rating and weight of parameters to define seismic hazard index

Parameters		**Severity of damage**		
		No damage / No hazard	**Low or gradual**	**Catastrophic**
Sporadic events	Max. Mercalli Intensity	0	0.20	0.40
	Landslide or rock fracture	0	0.15	0.25
Continuous processes	Erosion	0	0.05	0.10
	Physical stress	0	0.05	0.10
	Air pollution	0	0.01	0.05
	Socio - organizational	0	0.01	0.05
	Demographic decline	0	0.01	0.05

Afterwards, the seismic hazard index is obtained by adding the 7 parameters, ranging from 0 to 1, and then it is multiplied by the seismic vulnerability index to calculate the seismic risk, according to Eq. (2).

$$SR = VI_j \cdot (H + 1) \qquad (2)$$

3.2 – Italian Guidelines on Cultural Heritage procedure: LV1 level for seismic risk assessment

The Italian Guidelines for the seismic risk evaluation and reduction for the Cultural Heritage, aligned with the NTC 2008 give indications for three seismic analysis levels to assess the seismic safety: 1) LV1 level, used to provide the assessment at territorial scale; 2) LV2 level, used for evaluating local interventions on limited parts of buildings; 3) LV3 level, used to design interventions that influence the whole structural behavior. Regarding LV1 level, the systematic analysis of the damage in churches after the main Italian seismic events of the last decades, has shown that the seismic behavior of this type of building can be interpreted through their decomposition into architectural portions (called macro-elements), characterized by a structural response substantially independent of the church as a whole (façade, nave, apse, bell tower, dome, triumphal arch, etc.) (DCCM 2011). The methodology considers 28 collapse mechanisms associated with different macro-elements that may be present in a church.

Based on the survey of damage and vulnerability of about 4000 churches, the maximum ground acceleration corresponding to the different limit states was related to a number indicator, the vulnerability index, obtained through a suitable combination of a score given to the different elements of vulnerability and anti-seismic features. Therefore, the seismic behavior of the entire building is represented, on a statistical basis, by a vulnerability index, variable between 0 and 1, which is defined as a weighted average from the behavior of the different macro-elements of the church (DCCM 2011).

The collapse mechanisms analyzed in terms of the presence of vulnerability elements or anti-seismic features are: regarding the façade: overturning and in plane mechanisms, mechanisms in the top of the façade and in the narthex; in the nave: transversal and longitudinal response, columns longitudinal response in churches with more than one nave, and the vault response in the central and lateral naves; regarding the transept, chapels, presbytery and the apse: overturning and shear mechanisms in walls, and vault response; and related to roof components: mechanisms in the lateral walls of the nave, in the transept, apse or presbytery. Other mechanisms analyzed are related to: interactions in proximity of irregularities in plan or elevation; projections (gable, pinnacles, statues, etc.); the presence of a bell tower, dome – drum and lantern.

In order to define the vulnerability index according to the LV1 level of the Italian Code, each church is assessed considering fragility indicators and possible anti-seismic devices for each potential mechanism, assigning a score ranging from 0 to 3, and then, the vulnerability index is given by Eq. (3), where v_{ki} is the score of the fragility indicator, v_{kp} is the score of the anti-seismic devices, and ρ_k is the weight of each collapse mechanism. The weights are equal to 1 for the most important macro-elements, while for the secondary ones (relative to prothyrum - narthex, transept and chapels) there is a range between 0.5 and 1.

$$i_v = \frac{1}{6}\frac{\sum_{k=1}^{28}\rho_k\left(v_{ki}-v_{kp}\right)}{\sum_{k=1}^{28}\rho_k}+\frac{1}{2} \tag{3}$$

From the statistical analysis of the damage on churches after the seismic events, the probabilistic distributions associated to different seismic intensities were evaluated by damage probability matrixes, when varying the vulnerability index. That allowed calculating for each church, the values of ground acceleration corresponding to the damage limit state (SLD) and the life-safety limit state (SLV) by applying Eq. (4) and Eq. (5).

$$a_{SLD}S = 0.025\cdot 1.8^{2.75-3.44 i_v} \tag{4}$$

$$a_{SLV}S = 0.025\cdot 1.8^{5.1-3.44 i_v} \tag{5}$$

Afterwards, a security index (IS) is calculated by the acceleration corresponding to the limit state divided on the maximum ground acceleration. If the value of the security index is greater than or equal to one, means that the building is in a safe condition; and when the value is less than one, highlights situations that deserve attention. The relation between the vulnerability index and the ground acceleration regarding both limit states is shown in Figure 4.

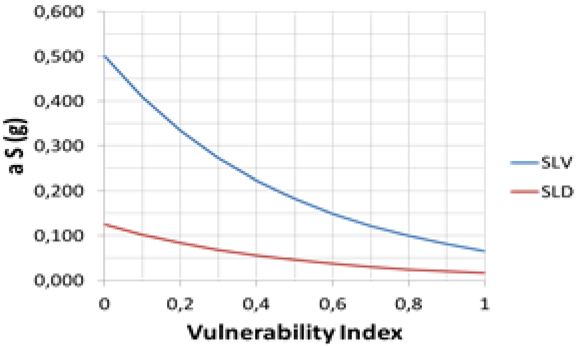

Figure 4 – Graphic of vulnerability index and ground acceleration regarding limit states.

4. Application to four churches in *Sassi* of Matera

In order to apply both methodologies, four churches sited in *Sassi* of Matera will be analyzed: the church of *Sant'Agostino* and the church of *San Francesco d'Assisi* which have a basilica floor plan with an only nave, and the church of *San Pietro Caveoso* and *San Giovanni Battista* which have a three naves configuration. They are all built with limestone masonry, but *Sant'Agostino* and *San Giovanni Battista* have vault systems built with the same stone, while *San Francesco d'Assisi* and *San Pietro Caveoso* have wooden structures and vaults in the roof system. As above mentioned, there is an intrinsic vulnerability of the construction system in Matera due to the variability on the characteristics of the limestone, condition that explains the phenomenon of surface degradation, which may be observed in *Sant'Agostino* and *San Francesco's façade*, having compact segments along with eroded ones. On the other hand, *San Pietro* and *Sant'Agostino* have been recently consolidated, having the first one a comprehensive project including soil consolidation and general anchor between the macro-elements of the building, and between the building and the foundation rock; while the second had a negative intervention above the vault due to concrete injection, adding weight with an incompatible material.

Regarding seismic hazard (tool 2), the maximum macro-seismic intensity observed in Matera is equal to VII, therefore, historic structures may suffer serious damage and even the collapse of elements inefficiently bounded to the structure. Moreover, the gorge of Matera has the higher hydrogeological risk of the region because it is formed by a hard dolomitic calcareous, but fractured in layers and benches and often with karst, and it is surrounded by geological faults which may increase the possibility of rock fracture in case of a strong earthquake. Although the rainfall is not excessive and the chance of a strong earthquake is low, fractures or the rock collapse might take place on the ravine border affecting the Cultural Heritage (Figure 5).

On the other hand, concerning continuous processes threats which might cause material deterioration, there is no threat provoked by erosion, physical stress nor serious demographic decline. However, there are low hazards due to: air pollution, since the limestone blocks without coating or scarce maintenance are vulnerable to the action of rainfall acidulated by carbonic acid; and socio-organizational threat, due to the strong concentration of touristic activities with likely presence of crowds of people, which might produce damage for condensation of vapor inside the churches.

The results of the application of the tool 1, the tool 2 and LV1 to the study cases are shown in Table 3.

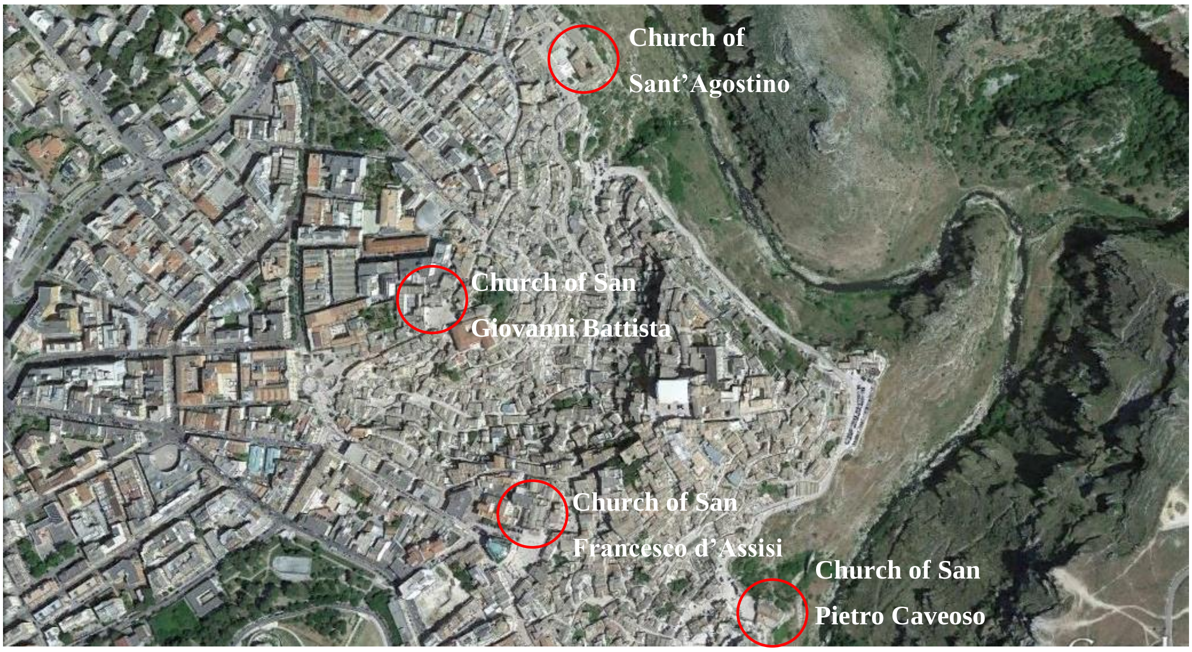

Figure 5 – Location of the churches in the "*Sassi* of Matera"

Table 3 –Score of the parameters to define the seismic risk

Parameters			**Churches in Sassi of Matera**			
			San Pietro Caveoso	**Sant'Agostino**	**San Giovanni Battista**	**San Francesco d'Assisi**
VULNERABILITY	1	Position and foundations	A	B	A	A
	2	Floor plan configuration	D	C	C	D
	3	Elevation configuration	D	A	A	A
	4	Distance between walls	D	C	D	D
	5	Non-structural elements	A	C	C	D
	6	Type/organization of the R.S.	A	C	B	B
	7	Quality of resistant system	A	A	A	A
	8	Horizontal structures	A	A	A	A
	9	Roofing	B	D	C	A
	10	Conservation status	A	A	A	B
	11	Environmental alterations	B	B	A	A
	12	Construction alterations	A	D	A	A
	13	Vulnerability to fire	B	B	B	B
		Seismic vulnerability index (V)	**23.24**	**33.58**	**17.18**	**15.83**
HAZARDS	1	Maximum Mercalli Intensity	0.20	0.20	0.20	0.20
	2	Landslides / rock fracture	0.15	0.15	-	-
	3	Erosion	-	-	-	-
	4	Physical stress	-	-	-	-
	5	Air pollution	0.05	0.05	0.05	0.05
	6	Socio-organizational	0.05	0.05	0.05	0.05
	7	Serious demographic decline	-	-	-	-
		Seismic hazard index (H)	**0.45**	**0.45**	**0.30**	**0.30**
		TOTAL RISK [V x (H+1)]	**33.70**	**48.69**	**22.33**	**20.58**
LV1		**Iv**	**0.217**	**0.687**	**0.453**	**0.616**
		$a_{SLV}S$	0.323 g	0.124 g	0.200g	0.144g
		$a_{SLD}S$	0.081 g	0.031 g	0.062g	0.036g
		$a\ g_{SLV}$	0.143 g	0.143 g	0.143 g	0.143 g
		IS ($a_{SLV}S / a\ g_{SLV}$)	**2.26**	**0.87**	**1.39**	**1.01**

5. Conclusions

In this work the seismic risk of four historical masonry churches located in the Sassi of Matera has been assessed by means of the new simplified methodology proposed in Díaz (2015) and by the LV1 first level of assessment (DCCM 2011) provided by the Italian Guidelines on Cultural Heritage. The procedures proposed a first approach for evaluating the seismic risk at a territorial scale aiming to guide risk mitigation procedures, according to a priority and the identification of the main vulnerabilities and threats.

As the seismic hazard and the ground acceleration is the same in all the considered churches, the seismic vulnerability is the main comparative factor. Nevertheless, it is worth to note that in the simplified method proposed in Díaz (2015) are also considered other factors increasing the relative risk. For instance, considering the location of the churches of *San Pietro Caveoso* and *Sant'Agostino* in the border of the ravine *Gravina*, even if the seismic risk is low, the cumulative damage of the foundation rock by hydrogeological threat, increased by near geological faults, may provoke a rock fracture in case of a strong earthquake. Therefore, thorough mechanic soil studies shall be addressed. On the other hand, considering the intrinsic vulnerability of the limestone blocks, the action of acid rainfall and the condensation of vapor inside the four churches shall be addressed as well, by means of a constant maintenance and monitoring.

Regarding the vulnerability assessment, although both procedures highlighted *Sant'Agostino* as the most vulnerable church, there were differences regarding the less vulnerable due to the parameters analyzed. The less vulnerable church in the Díaz procedure was *San Francesco*, because the roofing cause moderate thrusts in the walls and the resistant elements are practically uniform in the total high of the building; in the LV1 procedure instead, the less vulnerable church was *San Pietro Caveoso*, since the vulnerable geometry is not considered, neither in plan nor elevation, being more important the constructive solutions. For instance, the vulnerability of the high bell tower was decreased for the presence of anti-seismic devices.

Both procedures from a qualitative point of view, allow identifying the main vulnerabilities that may guide the mitigation projects. For example, some vulnerable conditions and elements that shall be addressed in all the cases are: the openings near the connection between the walls; the scarce thickness of the masonry in specific points; the vault roofing provoking thrusts without metal chains to avoid the overturning; the large gables; and specifically in *Sant'Agostino*, the negative alterations in the constructive system with incompatible materials.

In terms of the seismic risk assessment, both procedures allow making a numerical priority, but are complementary. The safety index (IS) of LV1 highlighted that only the church of *Sant'Agostino* is unsafe, or requires some interventions, while the tool 2 of the simplified approach suggests that, due to soil conditions where a rock fracture may occur with an earthquake, also *San Pietro Caveoso* is in risk and requires thorough mechanic soil studies.

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