Seismic assessment of masonry churches in Matera landscape

Michelangelo Laterza[a], Michele D'Amato[a], Daniela Díaz[a]
[a] *Department of European and Mediterranean Cultures, University of Basilicata, Via Lazzazera, Matera, Italy*

Keywords: Cultural Heritage, hazard, masonry churches, seismic risk assessment, seismic vulnerability.

ABSTRACT
Dramatic human and economic consequences are nowadays still resulting from disasters caused by natural phenomena, as in seismic-prone areas, where comprehensive risk management plans for the conservation of cultural property have not been yet completely developed. In particular, earthquakes have destroyed a large amount of cultural heritage in Italy, country which has currently the largest number of World Heritage sites. Matera landscape, located in Southern Italy into a seismic-prone area with moderate seismicity, is characterized by many and important ancient masonry churches, concentrated in *The Sassi and the Park of the Rupestrian Churches of Matera*, recognized as Cultural World Heritage by UNESCO since 1993.
Some masonry churches are evaluated with two simplified procedures for seismic risk assessment, which are based on qualitative and quantitative parameters. Both procedures are complementary and they allow us to define a numeric priority for planning the preventive conservation of the Cultural Property at territorial scale. The qualitative tools aim to identify the main vulnerabilities and hazards for guiding preventive conservation projects, specific studies and risk mitigation. Whereas, the quantitative procedure allows to identify the most vulnerable macro-elements and to plan the retrofitting interventions depending on the assumed reduced nominal life.

1 INTRODUCTION

In geographic areas with high risk of disasters caused by natural phenomena, comprehensive risk management plans for the conservation of Cultural Property have not been completely developed yet. Disasters prevention, in the field of built heritage conservation, has been addressed by developing principles and manuals for risk management settled for example by UNESCO, ICOMOS, 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, 2009, 2013) in Mexico.

In this context, the paper here presented aims to analyse the seismic risk of historic masonry churches, 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 macro-seismic intensity.

Due to the recent observed earthquake damages (Friuli-1976, Irpinia-1980, Umbria and Marche-1997, Lazio-1999, Toscana-1995, Piamonte-2000, Molise-2002, Aquila-2009), seismic vulnerability assessment of masonry buildings has been significantly improved in Italy. The collected data have allowed to individuate the most vulnerable mechanisms, to define with acceptable uncertainty the modelling criteria, and to predict their response.

The Italian Guidelines on Cultural Heritage (DCCM 2011) define three evaluation levels (indicated as LV1, LV2 and LV3) for seismic assessment of churches, and in general of Cultural Heritage, passing from the territorial to the global and local scale. In each of these approaches an increasing number of information is required, in order to obtain more accurate models capable of simulating adequately the system response. On the other hand, recently a simplified approach (Díaz 2016) has been proposed starting from a comparative analysis among the contributions of the aforementioned manuals (UNESCO, ICOMOS, ICCROM, ISCR).

In this paper two simplified methods with different scopes have been applied in order to estimate the seismic vulnerability and the resulting risk of seven masonry churches located in *Sassi di Matera* UNESCO site: the simplified methodology (Díaz 2016), a qualitative method based on expert judgement which allows to assess the seismic risk and to establish a priority at territorial scale; and the LV1 method proposed by the Italian Guidelines on Cultural Heritage (DCCM 2011), also a qualitative method based on expert judgement which results are given in terms of a vulnerability index and a safety index. The chosen churches are: San Giovanni Battista, San Pietro Caveoso, San Francesco d'Assisi, San Rocco, Sant'Agostino, Santa Maria de Armenis and San Nicola dei Greci. At first the seismic assessment of each single church is presented and discussed. Then the obtained results are compared among them.

2 SIMPLIFIED ASSESSMENT OF SEISMIC RISK

2.1 *LV1 method (DCCM 2011)*

The LV1 method proposed by the Italian Guidelines on Cultural Heritage (DCCM 2011) is based on the evaluation of the vulnerability index, derived from the analysis of 28 collapse mechanisms of individual macro-elements. The vulnerability index is given by Eq. (1),

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

where v_{ki} is the score of the fragility indicator, v_{kp} is the score of the seismic-resistant devices, and ρ_k is the weight of each collapse mechanism.

The values of ground acceleration corresponding to the damage limit state (SLD) and the life-safety limit state (SLV) are given by [Eq. (2) and Eq. (3)]:

$$a_{SLD}S = 0.025\cdot 1.8^{2.75-3.44i_v} \qquad (2)$$

$$a_{SLV}S = 0.025\cdot 1.8^{5.1-3.44i_v} \qquad (3)$$

where S is the coefficient of stratigraphic amplification.

By knowing the ground accelerations a_{SLD} and a_{SLV}, two different ratios may be obtained: the seismic safety index (*IS*) and the acceleration factor (F_a). The seismic safety index (*IS*) is estimated by the relation between the return period (T_{SL}) of the seismic action provoking the generic limit state, and the corresponding return period of reference ($T_{R,SL}$), related to the earthquake expected on the site (Eq. 4). While, the acceleration factor (F_a) is calculated by the relation between the acceleration which provokes the generic limit state (a_{SL}) and the acceleration expected on the site ($a_{g,SL}$) (Eq. 5). The building is in a safe condition when *IS* or F_a ratio is greater than or equal to 1.

$$T = \frac{T_{SL}}{T_{R,SL}} \qquad (4)$$

$$F_a = \frac{a_{SL}}{a_{g,SL}} \qquad (5)$$

By knowing the ground acceleration a_g that the structure is able to withstand, the return period T_R corresponding to its resistance is evaluated by (Eq. 6):

$$T_{R,SL} = T_{R1}\cdot 10^{\alpha} \qquad (6)$$

where α corresponds to (Eq. 7):

$$\alpha = \left[\log\left(a_g\right)-\log\left(a_{g,1}\right)\right]\cdot\frac{\log\left(\frac{T_{R2}}{T_{R1}}\right)}{\log\left(\frac{a_{g,2}}{a_{g,1}}\right)} \qquad (7)$$

where the subscript 1 refers to the data of return period and acceleration immediately lower than $T_{R,SL}$ and $a_{g,SL}$, and with the subscript 2, those immediately above, in reference to the table provided by the Annex B of the NTC-2008. Thus, the nominal life of the existing building is calculated by (Eq.8).

Starting from the returning period corresponding to the calculated ag, the nominal life of the structure determine the nominal life referred to the actual conditions or in the design state is given by:

$$V_N = -\frac{T_{R,SL}}{C_U}\ln\left(1-P_{VR}\right) \qquad (8)$$

where the probability of exceeding (P_{VR}) for the life-safety limit state is 10%, for the damage limit state is 50%, and C_U is the importance factor in accordance with the NTC-2008.

2.2 *Qualitative tools for the seismic vulnerability and hazard assessment as causes of decay (Díaz 2016)*

The simplified method proposed in Díaz (2016) evaluates all the generic threats (not only the seismic one) and the resulting risks for historic buildings. In this method, a correlation among the identification of threats and vulnerabilities and the causes of historic buildings deterioration has been derived, based on the document developed by De Angelis (1972) for the ICCROM. To address the seismic risk, two different tools can be consecutively applied:

– Tool 1: seismic vulnerability assessment;
– Tool 2: description, hierarchy and hazard mapping.

The tool 1 takes into account the GNDT form (DGPT 2003), the Chilean Norm N° 3332 (INN 2013) for earthen built heritage, recent research on: the stability of masonry buildings for the presence of diatons (Binda and Saisi 2001), the consolidation with compatible materials in terms of shape, dimension, thick and resistance to facilitate the box-behaviour (Carocci 2001; Modena 2009), among others. It evaluates parameters regarding the position of the building, its geometry, resistant system, condition, alterations and vulnerability to fire. All the parameters are evaluated with a score (v) and each parameter has a weight (p), related with their importance in the seismic behaviour of the building. The vulnerability index (VI) is given by Eq. (9).

$$VI = \sum_{i=1}^{n} v_i p_i \tag{9}$$

In particular, the considered parameters are: the *position of the building and its foundations*, which 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 high, 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 connection between orthogonal walls and between them and floors by the means of horizontal structures executed with compatible materials. Regarding the *horizontal structures* and *roofing* parameters, they assess the deformability, 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 from A to D, where A indicates a very low and D a very high vulnerability, having also a numerical value. The parameters weight are based on the GNDT form (DGPT 2003), where a table for the vulnerability quantification was proposed. In the proposed model the numerical values are modified for adapting the GNDT form to include the adobe and Cultural Property seismic assessment (Table 1).

Table 1. Rating and weight of parameters to define the seismic vulnerability index (Díaz 2016)

Parameters	Class				p_i
	A	B	C	D	
Position/foundations	0	1,35	6,73	12,12	0,75
Floor plan	0	1,35	6,73	12,12	0,5
Elevation	0	1,35	6,73	12,12	1,0
Dist. between walls	0	1,35	6,73	12,12	0,25
Non-structural elem.	0	0	6,73	12,12	0,25
Type resistant system	0	1,35	6,73	12,12	1,5
Quality resistant system	0	1,35	6,73	12,12	0,25
Horizontal structures	0	1,35	6,73	12,12	1,0
Roofing	0	1,35	6,73	12,12	1,0
Conservation status	0	1,35	6,73	12,12	1,0
Environment alterations	0	1,35	6,73	12,12	0,25
Construction alterations	0	1,35	6,73	12,12	0,25
Vulnerability to fire	0	1,35	6,73	12,12	0,25

The *Tool 2* performs a global analysis of threats affecting the Cultural Property for defining the worst scenario where the greatest magnitude of each threat occurs. It is based on historic information available from the analysis of documents and maps concerning hazards, such as, among others, the *Carta del Rischio* in Italy (ISCR 1992), the Guidelines for the assessment of natural risks for territorial planning in Chile (Subdere 2011), documents developed by the National Centre of Disaster Prevention (Cenapred 2001, 2006) in Mexico. Making the focus on the seismic hazard, some threats have been selected starting from the damage that they might be caused on the structure under the seismic action. Thus, parameters such as the *maximum macro-seismic intensity* and the *landslide or rock fracture* threat are analysed; and also parameters regarding continuous processes such as: *erosion*, *physical stress, air pollution, socio-organizational* threat and *lack of maintenance*, as their main consequence is the material deterioration. Every parameter has a score based on the influence of the threat, as a site effect, in the seismic behaviour of the building (Table 2).

Table 2. Rating and weight of parameters to define the seismic hazard index (Díaz 2016)

Parameters	Severity of damage		
	No damage	Low or gradual	Catastrophic
Max. macro-seismic intensity	0	0,20	0,40
Landslide or rock fracture	0	0,15	0,25
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
Lack maintenance	0	0,01	0,05

The resulting seismic risk, defined as the combination of the probability of an event occurring and its negative consequences (UNISDR 2009), is calculated by multiplying the seismic vulnerability index by the seismic hazard index in according to the expression:
Risk (R) = Vulnerability (V) x [Hazard (H)+1].

3 APPLICATION TO SEVEN CHURCHES IN THE SASSI DI MATERA UNESCO SITE

In order to apply both the considered procedures, seven churches sited in *Sassi di Matera* have been analysed (Figure 1) in order to assess their seismic performance.

Five churches are in calcarenite (limestone) masonry. Of these the churches of Sant'Agostino, San Rocco and San Francesco d'Assisi have an one-nave basilica floor plan configuration, while the churches of San Pietro Caveoso and San Giovanni Battista have a three-naves configuration. Regarding the roof structure, Sant'Agostino, San Rocco and San Giovanni Battista have limestone vault systems, while San Francesco d'Assisi and San Pietro Caveoso have wooden structures and limestone vaults. The church of Santa Maria de Armenis is excavated with a three-leaf masonry façade, while San Nicola dei Greci is completely excavated.

3.1 *Qualitative tools for the seismic vulnerability and hazard assessment as causes of decay (Díaz 2016)*

Regarding the seismic hazard assessment by the tool 2 (Díaz 2016), the maximum macro-seismic intensity observed in Matera has been VII, therefore, historic structures may suffer serious damage and even the collapse of elements inefficiently bounded to the structure.

Moreover, the ravine 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.

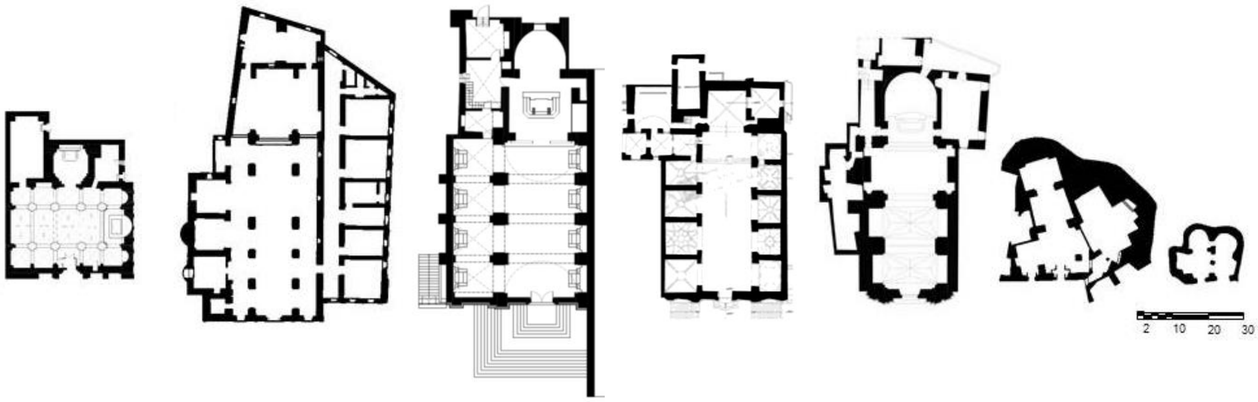

Figure 1. Churches floor plan (from left to right): San Giovanni Battista, San Pietro Caveoso, San Rocco, San Francesco d'Assisi, Sant'Agostino, Santa Maria de Armenis and San Nicola dei Greci. Reference: Superintendence for the Architectural and Landscape Assets in Italy, 2016; La Scaletta (1960); and Marcella Chietera, 2017.

Although the rainfall is not excessive and the chance of a strong earthquake is low, fractures or the rock collapse might take place affecting the churches sited on the ravine border, or the excavated churches, as discontinuities in the rock mass deteriorated by karst erosion, may constitute a vulnerability under the seismic action. In the case of San Nicola dei Greci, there is also a construction above the cave which might be provoking overweight.

Concerning continuous processes threats which might cause material deterioration, there is no threat provoked by physical stress nor serious demographic decline. As regards the erosion threat, although the velocity of the prevalent winds and the rainfall are not as stronger as to cause erosion in the exposed materials, in the cases of Santa Maria de Armenis and San Nicola dei Greci, the infiltration of the rainfall inside the caves has provoked the concentration of humidity without the appropriate ventilation, which has caused karst deterioration. On the other hand, given the strong concentration of touristic activities with likely presence of crowds of people, the socio-organizational threat might produce damage for condensation of vapour inside some churches. Besides, the air pollution acting together with rainfall and scarce maintenance might cause stone decay by rainfall acidulated by carbonic acid. This material deterioration will vary depending of the point of the tuff extraction, which particle size 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 and Carocci 1997). This condition explains the phenomenon of surface degradation which is observed on the façade of the churches of San Francesco d'Assisi, San Pietro Caveoso and Sant'Agostino, having compact and resistant stone blocks along with other degraded and eroded, likely affecting the mechanical characteristics of resistance in the more severe cases.

The built churches present some common vulnerabilities as the asymmetry in the floor plan, the presence of large openings in the façade, openings near the edges of the structure and non-structural elements as gables which are likely to fall with an earthquake. Another vulnerable parameter is the roofing, as all the built churches have stone vaults which cause thrusts, also due to negative interventions, as the alteration of the vault of the church of Sant'Agostino with concrete injection, or due to the scarce connection between the rock cave and the façade in the church of Santa Maria de Armenis. The conservation status is vulnerable specifically in the excavated churches of San Nicola dei Greci and Santa Maria de Armenis, due to the infiltration of rainfall which has deteriorated the limestone by karst. As regards the total seismic risk, the higher scores were obtained by the churches sited in the border of the ravine, Sant'Agostino and San Pietro Caveoso, and by the excavated church of Santa Maria de Armenis, which is deteriorated by weathering, it is sited on a slope, and its façade is not well connected to the rock cave. All the results are shown in Table 3.

3.2 LV1 method (DCCM 2011)

This method was only applied to six churches (Table 3), since it could not be applied to the excavated church of San Nicola dei Greci, due to the continuity of the elements excavated in the rock mass, which inhibits the out-of-plane mechanisms inside the cave and, therefore, they cannot be divided in macro-elements. For the same reason, they present a monolithic behaviour and a low vulnerability to the seismic action.

For calculating the seismic hazard reference period, as the case studies correspond to churches and they have a frequent and sometimes crowded use, the C_U considered was class III (coefficient 1,5). Regarding the nominal life (V_N) two reference periods were considered, 50 years, which is the reference time for the new buildings, and 20 years, which is the minimum possible.

This minimum responds to the criteria of protecting the building for less time but with less invasive interventions, because in a longer reference period, higher magnitude earthquakes might take place. Thus, the data for the life-safety limit state inserted in the software *Spectra Response* considered a reference period (V_R) of 35 and 75 years (V_R=V_N·C_U); the rock subsoil category (A); and the coefficient for the amplification due to topographical condition (1,2 in the church of Sant'Agostino and San Pietro Caveoso, which are sited on a ridge; and 1,0 in the other cases which are sited on a flat surface). Therefore, the reference return period ($T_{R,SLV}$) for the life-safety limit state considered were 285 and 712 years, obtaining two different safety indexes (*IS*): for a period of 285 years, only one church had an unsafe condition, while for a period of 712 years, four churches had an unsafe condition.

As regards the acceleration factor (F_a), which only considers the parameter of acceleration, not the reference period, it allows making an evaluation in terms of capacity and ductility of the construction (DCCM 2011:31). In these terms, the two churches with an unsafe condition are Sant'Agostino and Santa Maria de Armenis, which are also the churches with the higher total risk by the Díaz (2016) tools.

Specifically regarding the vulnerability parameters in terms of collapse mechanisms, and considering that the score equal or over 2 implies a fragility to address, the most vulnerable mechanisms were: the apse overturning in the

Table 3. Score to define the seismic risk by the proposed simplified method and LV1 method (DCCM 2011).

		Parameters	San Giovanni	S. Pietro Caveoso	San Rocco	San Francesco	Sant' Agostino	S. Maria Armenis	S. Nicola dei Greci
SIMPLIFIED METHOD	1	Position and foundations	A	A	B	A	B	C	A
	2	Floor plan configuration	C	D	C	D	C	D	C
	3	Elevation configuration	A	D	A	A	A	A	C
	4	Distance between walls	D	D	D	D	C	A	A
	5	Non-structural elements	D	A	D	D	C	A	A
	6	Type-organization of R.S.	B	A	B	B	C	C	A
	7	Quality of the R.S.	A	A	A	A	A	A	A
	8	Horizontal structures	A	A	A	A	A	A	A
	9	Roofing	C	C	C	C	D	D	A
	10	Conservation status	A	A	A	B	A	C	D
	11	Environmental alterations	A	B	A	A	B	B	B
	12	Construction system alterations	A	A	A	A	D	B	B
	13	Vulnerability to fire	B	B	B	B	B	A	A
		Seismic vulnerability index (V)	18,53	28,62	19,53	22,56	33.66	40,73	22,89
	1	Maximum macro-seismic intensity	0,20	0,20	0,20	0,20	0,20	0,20	0,20
	2	Landslides / rock fracture	0	0,15	0	0	0,15	0,25	0,25
	3	Erosion	0	0,05	0	0,05	0,05	0,1	0,1
	4	Physical stress	0	0	0	0	0	0	0
	5	Pollution	0,05	0,05	0,05	0,05	0,05	0,05	0,05
	6	Socio-organizational	0,05	0,05	0,05	0,05	0,05	0,05	0,05
	7	Demographic decline	0	0	0	0	0	0	0
		Seismic hazard index (H+1)	1,3	1,50	1,30	1,35	1,50	1,65	1,65
		TOTAL SEISMIC RISK [V x (H+1)]	24,09	42,93	25,39	30,46	50,49	67,20	37,77
LV1	1	Overturning of the façade	0	0	0	0	2	3	0
	2	Damage at the top of the façade	5	2	0	3	2	0	0
	3	Shear mechanisms in the façade	1	2	3	6	3	0	0
	4	Narthex	0	0	0	0	0	0	0
	5	Transversal vibration of the nave	1	3	-3	0	1	0	0
	6	Shear mechanisms in side walls	-5	-3	3	0	-3	0	0
	7	Longitudinal response of colonnade	3	0	3	0	0	0	0
	8	Vaults of the central aisle	3	0	0	0	3	0	0
	9	Vaults of the lateral aisles	3	3	3	0	0	0	0
	10	Overturning of the transept's end wall	0	0	0	0	0	0	0
	11	Shear mechanisms in the transept walls	0	0	0	0	0	0	0
	12	Vaults of the transept	0	0	0	0	0	0	0
	13	Triumphal arches	0	-3	-6	-3	0	0	0
	14	Dome and drum	-3	0	0	0	-3	0	0
	15	Lantern	0	0	0	0	-2	0	0
	16	Overturning of apse	0	0	3	4	9	0	0
	17	Shear mechanisms in presbytery/ apse	0	0	3	0	3	0	0
	18	Vaults in presbytery and apse	0	0	-3	3	3	0	0
	19	Part of roof: side walls nave and aisles	0	-3	-3	-3	0	0	0
	20	Part of roof: transept	0	0	0	0	0	0	0
	21	Part of roof: apse and presbytery	0	0	-3	3	0	0	0
	22	Overturning of the chapels	-6	-1	2	-3	3	0	0
	23	Shear mechanisms in walls of chapels	-4	-4	3	-1	-1	0	0
	24	Vaults of chapels	0	0	3	3	0	0	0
	25	Interactions next to irregularities	-3	3	0	2	0	0	0
	26	Projections (pinnacles, statues, etc.)	-1	0	0	0	-3	0	0
	27	Bell tower	0	0	0	0	3	0	0
	28	Bell cell	0	0	0	0	-1	0	0
		i_V	0,44	0,49	0,57	0,65	0.71	1	?
		$a_{SLV}S$	0,210 g	0,186 g	0,158	0,134 g	0,119 g	0,066 g	?
		$a_{g\,SLV}$	0,121 g	0,136 g	0,121 g	0,097 g	0,168 g	0,123 g	?
		T_{SLV}	1538	1028,3	635,7	405,1	301	5,82	?
		V_N (years)	108,03	72,23	44,65	28,45	21,14	5,82	?
		IS (T_{SLV} / $T_{R,SLV}$) (V_N=50; $T_{R,SLV}$=712)	2,16	1,44	0,89	0,57	0,42	0,01	?
		IS (T_{SLV} / $T_{R,SLV}$) (V_N=20; $T_{R,SLV}$=285)	5,40	3,61	2,23	1,42	1,06	0,02	?
		Fa (a_{SLV} S / $a_{g\,SLV}$)	1,74	1,37	1,31	1,38	0.71	0.68	?

church of Sant'Agostino due to the vault thrust, followed by the shear mechanisms in the façade of the church of San Francesco d'Assisi due to the high slenderness, and the damage at the top of the façade in the church of San Giovanni Battista due to the irregularities of the façade wall.

The most recurrent fragile macro-elements are: the damage at the top of the façade due to the presence of gables; the shear mechanisms in the façade due to the high slenderness; the vaults mechanisms of the lateral aisles due to their irregular shapes and lack of steel tensors; and the apse overturning due to the vaults thrust and the lack of contrast elements as buttresses. As Santa Maria de Armenis is an excavated church, only the façade overturning collapse mechanism might be activated, and as it has a high vulnerability, the calculated vulnerability index is the highest. The narthex, transept, dome and drum mechanisms, on the other hand, are not present in the churches typology in Matera.

In Matera, a moderate seismic-prone area, making a link between the vulnerability index (i_v) and the safety index (IS) of the churches, it is observed that vulnerability scores over than 0,50 are related with an unsafe condition on a hazard reference period of 712 years, and vulnerability scores higher than 0,71 are related with an unsafe condition on a hazard reference period of 285 years. In terms of acceleration or in terms of the building capacity, two churches will not be capable to withstand an expected ground acceleration, reaching a life-safety limit state: Sant'Agostino and Santa Maria de Armenis.

4 CONCLUSIONS

The seismic safety assessment of existing masonry churches is a very relevant issue, as they are vulnerable already from low intensity seismic events, which are more frequent even in moderate seismic-prone areas. Two different approaches have been evaluated in this work for seismic assessment of ancient churches, the LV1 method and the tools developed by Díaz (2016). Both methods are not directly comparable in terms of vulnerability score, because the first one provides a vulnerability index based on the acceleration which activates the church limit state while the simplified procedure evaluates constructive and geometric parameters based on the better performance of the box-behavior. However, after comparing the outcomes of both methods, aiming to verify the correspondence between them, it was observed that the results are coherent in terms of establishing a relative scale of risk, therefore, for a high seismic vulnerability index by the LV1 method, there is a corresponding high seismic risk by the simplified procedure by Díaz (2016).

The applied procedures represent a first approach for evaluating the seismic risk at territorial scale aiming to establish intervention priorities and to guide risk mitigation projects by understanding the vulnerabilities and hazards in terms of intrinsic and extrinsic causes of decay, and by analysing the vulnerability of the macro-elements that have an autonomous behaviour under the seismic action. In particular, this work was aimed at the study of the seismic behavior of seven churches in the *Sassi di Matera* UNESCO site, five of them with a basilica floor plan, one excavated in the rock with a masonry façade, and one completely excavated in the rock.

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 tools proposed by Díaz (2016), the correlated hazards increasing the seismic risk are considered as well. For instance, even if the seismic risk is low, the cumulative damage of the foundation rock by hydrogeological threat, increased by geological faults, might provoke a rock fracture in case of a strong earthquake, affecting the churches of San Pietro Caveoso and Sant'Agostino, sited in the border of the ravine Gravina. 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 churches shall be addressed as well, by means of a constant maintenance and monitoring (Laterza et al. 2016b).

Regarding the seismic vulnerability assessed by means of the tool 1 (Díaz 2016) and the LV1 method (DCCM 2011), the results of both methods were consistent with the definition of the most vulnerable cases: Sant'Agostino and Santa Maria de Armenis, which have an insecure condition assessed by the acceleration factor (F_a), even in the moderate seismicity zone of Matera. However, the outcomes do not agree on the definition of the vulnerability of San Pietro Caveoso. The tool 1 ponders a high importance to the symmetry in plan and elevation, thus, the high tower of the church arose the general vulnerability, whereas the LV1 procedure gives more importance to the constructive solutions, therefore, the vulnerability of the high bell tower was decreased for the presence of seismic-resistant devices.

Regarding the application of the LV1 procedure, it was only possible to apply in six churches, five of them corresponding to completely built churches, which result was a safe condition on a hazard reference period of 285 years. In the built-excavated church of Santa Maria de Armenis, however, the result was a vulnerable condition due to the façade overturning mechanism, having a nominal life of 5 years in terms of capacity. This result might be highlighting a general vulnerability of this typology of churches in Matera, of which there are 22 examples just in the *Sassi di Matera* UNESCO site core area. However, the not-visible thickness of the vaults and walls carved into the rock, as well as the difficulties in the determination of the loads and stresses acting on the elements, makes problematic the application of the LV1 method even in the built-excavated churches, nevertheless it would be possible to recognize, in certain cases, macro-elements susceptible of kinematic mechanisms known in the literature (Laterza et al. 2016a). Concerning the fully excavated churches, the continuity of all the structural elements excavated in the rock mass, tends to inhibit the out-of-plane mechanisms inside the cave and, therefore, they present a low vulnerability to the seismic action.

The Italian Guidelines for the assessment and mitigation of the seismic risk of the cultural heritage (DCCM 2011) established an acceptance criteria by tolerating a low security level for the Cultural Heritage, through the notion of a reduced nominal life, even less than 50 years, “values of the nominal life over 20 years can however be considered acceptable for cultural property” (DCCM 2011:31). This acceptance criteria protects the construction in probabilistic terms for a lesser number of years, but enables less invasive interventions. Concluded the nominal life period, the use of the building might be extended as a result of a condition update or an improvement intervention. Regarding the nominal life calculated through the buildings capacity, only the church of Santa Maria de Armenis, with a calculated nominal life of 5 years, does not reach the minimum of 20 years established by the Italian Guidelines. This result meets with the safety condition calculated by the means of the safety index (IS) with a hazard reference period of 285 years. Moreover, only two churches reached a nominal life over 50 years, having San Rocco, San Francesco and Sant’Agostino a nominal life between 20 and 50 years.

Both procedures, from a qualitative and quantitative approach, allow identifying the main vulnerabilities that may guide 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 some walls as the façade; the vault roofing provoking thrusts without steel tensors or buttresses to avoid the overturning; the large gables or irregularities in thickness and geometry of the facades; and specifically in Sant’Agostino, the negative alterations in the constructive system with incompatible materials.

REFERENCES

Angelis, G. De, 1972. *Guida allo studio metodico dei monumenti e delle loro cause di deterioramento*, Roma, ICCROM/Università di Roma.

Binda, L. and Saisi, A., 2001. State of the Art of Research on Historic Structures in Italy. *Advanced Research Centre for Cultural Heritage Interdisciplinary Projects*, available in [http://www.arcchip.cz/w11/w11_binda.pdf], May 2015.

Carocci, C., 2001. Guidelines for the safety and preservation of historical Centres in Seismic Areas, *Historical Constructions*, available in [http://www.hms.civil.uminho.pt], May 2015.

Cenapred, 2001. *Diagnóstico de peligros e identificación de riesgos de desastres en México*, México, Secretaría de Gobernación/Cenapred (Centro Nacional de Prevención de Desastres).

Cenapred, 2006. *Guía básica para la elaboración de atlas estatales y municipales de peligros y riesgos. Conceptos básicos sobre peligros, riesgos y su representación geográfica,* México, Secretaría de Gobernación/Cenapred (Centro Nacional de Prevención de Desastres).

DCCM, 2011. *Guidelines for the evaluation and reduction of the seismic risk of Cultural Property, in alignment with the Technical Norms for Constructions*, Official Gazette of the Italian Republic n. 47, February 26th (in Italian), DCCM (Directive of the Chairman of the Council of Ministers).

DGPT, 2003. *Rilevamento della vulnerabilità sismica degli edifici in muratura. Manuale per la compilazione della Scheda GNDT/CNR di II livello*, Rome, Direzione Generale delle Politiche Territoriale e Ambientali (DGPT), available in [http://www.regione.toscana.it/documents], november 2016.

Díaz, D., 2016. *Diseño de herramientas de evaluación del riesgo para la conservación del patrimonio cultural inmueble. Aplicación en dos casos de estudio del norte andino chileno*, México, Publicaciones ENCRYM/INAH.

Giuffrè, A. and Carocci, C., 1997. *Codice di pratica per la sicurezza e la conservazione dei Sassi di Matera*. Edizioni La Bautta.

INAH, 2002, 2009 y 2013. *Programa de prevención de Desastres en Materia de Patrimonio Cultural*, México, INAH (Instituto Nacional de Antropología e Historia).

INN, 2003. *Norma chilena núm. 3332 oficializada el año 2013: Estructuras- Intervención de construcciones patrimoniales de tierra cruda. Requisitos del Proyecto Estructural*, Santiago, INN (Instituto Nacional de Normalización).

ISCR, 1992. *Carta del Rischio*, Roma, ISCR (Istituto Superiore per la Conservazione ed il Restauro), available in [http://www.cartadelrischio.it/index.asp], november 2016.

La Scaletta, 1960. *Le chiese rupestri di Matera*. De Luca Editori.

Laterza, M., Guida, A., D'Amato, M., Pagliuca, A., Díaz, D., Chietera, M. 2016a. Technical and technological qualification of ancient buildings. The case of churches in "Sassi di Matera". *XII International Conference on Structural Repair and Rehabilitation CINPAR*. October 26-29, Porto, Portugal.

Laterza, M., D'Amato, M., Díaz, D., 2016b. Ancient masonry cathedrals in Matera landscape: seismic assessment and risk mitigation. *XII International Conference on Structural Repair and Rehabilitation CINPAR*. October 26-29, Porto, Portugal.

Norme Tecniche per le Costruzioni, 2008. D.M. 14/01/2008, e la Circolare 2 febbraio 2009, n. 617 - Istruzioni per l'applicazione delle *Nuove norme tecniche per le costruzioni* di cui al D.M. 14 gennaio 2008.

Modena, C. et al., 2009. Structural Interventions on Historical Masonry Buildings: Review of Eurocode 8. Provisions in the light of the Italian experience. In E. Cosenza (ed.), 2009. *Eurocode 8 Perspectives from the Italian Standpoint Workshop*, Naples, Doppiavoce, pp. 225-236.

Subdere, 2011. *Guía de análisis de riesgos naturales para el ordenamiento territorial*, Santiago, Subdere (Subsecretaría de Desarrollo Regional y Administrativo).

UNISDR, 2009. *Terminology on Disaster Risk Reduction.* Ginebra, UNISDR (United Nations International Strategy for Disaster Reduction).