Technical and technological qualification of ancient buildings. The case of churches in "Sassi di Matera"

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Abstract: It is widely recognized that historic buildings conservation cannot leave out the knowledge of its constitutive features such as: materials, constructive techniques, structural characteristics and building evolution.

Thus, the preliminary phase of data acquisition represents a crucial point of the designing process, that has to begin from direct recognition of the building characteristics with a survey of the observed alterations, and supported by the historical documentation (bibliographic and/or archival). The "critical" synthesis between these two aspects of the cognitive process (i.e. direct knowledge and historical analysis) is the essential condition for designing a "congruent" restoration intervention, that is, a restoration capable of synthesizing the dichotomous relationship among technical and philological issues.

This methodological approach is presented and applied in this paper to different case studies belonging to the churches typology of the *Sassi di Matera* UNESCO site in Southern Italy. The chosen cases differ completely for age, peculiar characteristics, shape and dimensions. Then, the case studies are evaluated with simplified procedures for seismic risk assessment, which have allowed us to draw the first conclusions in terms of the diagnosis that will lead to determining the restoration approach.

Key-words: technological qualification; masonry churches; limestone; seismic risk assessment.

1. Introduction: general identification of the churches in the *Sassi di Matera* UNESCO site

This article aims to show the first phase of identification and characterization of the churches in the *Sassi di Matera* UNESCO site, built since the IX centuries in both sides of the ravine "Gravina di Matera", where the north zone is the natural and archaeological park of the cave churches called "Parco della Murgia" and the south is where the Matera city was developed. The Matera *Sassi* site was included in the World Cultural Heritage List in 1993, in order to recognize it as an unique testimony of human activity. The outstanding universal value is derived from the symbiosis of its cultural and natural features, which represent the most comprehensive existing example of continuity in the Mediterranean region of this type of settlement, and where the man over time has excavated, perforated and sculpted to create tunnels, reservoirs, environments and elaborate architectural complexes underground (Colonna and Fiore, 2014).

Since Neolithic times, the same guiding principles have been used from the villages excavated on the highland up to the Matera city, continuity present in the religious architecture as well. Matera, for its central position between the Lombard Duchy of Benevento and the Byzantine provinces, became until the XIV century the center of ascetic irradiation, harmonizing the distant and opposite religious expressions of the Latin rite and Eastern rite, which were developed between the IX and XI centuries. The meeting of the two "civilizations" influenced the architecture, decoration and iconography of the churches in the Sassi of Matera (Tommaselli, 1998).

During the XVIII and XIX centuries, the agro-pastoral economy decline settled the end of the cave system infrastructure and the progressively abandonment of the cave habitat to the construction of the new city, along the edge of the valley and overlapping the existing underground complex and sophisticated system of water reservoirs and medieval warehouses. In the course of the XIX century the city, seeking for a renewed urban image, provided a set of "Regulations of public hygiene" and the first "Ornate Rules" in 1878, but only referred to the flat part of the city. Thus, the exclusion of the *Sassi* zone triggered definitively the abandonment of the medieval system (Colonna and Fiore, 2014).

In the XX century, the community capacity for managing the environmental resources disappeared, the modern city grew over the water lines and drainage courses to build roads, which destroyed the network of water collection and the old constraints. What followed was the densification, saturation and housing promiscuity, with the consequent collapse of the whole system. The storage caves, cavities for the animals and the reservoirs became dwellings, which explains the definition of the *Sassi* as a "national shame" in the fifties that led to its abandonment for hygienic and health reasons (Laureano, 2012 en Colonna and Fiore, 2014). The *Sassi* was declared uninhabitable, therefore, its 20,000 inhabitants were relocated, making it the largest historic center completely deserted in Europe.

In 1986, the 771 National Law was developed focused on the preservation criteria of the *Sassi* as an historic center with prominent residential function, with the aim of architectural, urban, environmental and economic restoration and recovery of the *Sassi* and the *Murgia* highland. Nevertheless, the first interventions performed questionable and excessive consolidations implemented with invasive techniques, situation that continued until 1993, when the inscription on the World Heritage List allowed to understand the site as a global system, promoting the knowledge of the old architectural practices and sustainable use of the available resources. After the pioneering cataloging contribution of the *La Scaletta* group in the sixties, in 1998 a systematic and computerized cataloging was achieved, commissioned by the City of Matera, called *Inventory of the landscape and environmental heritage* (Laureano, 2012 en Colonna and Fiore, 2014). Besides, investigations aiming to the recovery of the dwellings where based on articulated cartographic, historical, geographical, economical, ethnological, hygienic and demographic analysis. Afterwards, the *Management Plan 2014-2019* settled the objectives and strategies for responding to the World Heritage Site framework.

Nowadays, although there has been advances in the site management, regarding the churches inside the perimeter of the *Sassi* of Matera, a global study is needed to address a general identification, in terms of typological and technical characterization, legal and use condition, and diagnosis of their conservation state. This technical cadaster may facilitate the decision making for implementing the management plan and for guiding the preventive conservation projects, based on the identification of the causes of the main pathologies. This work addresses this cadaster in the perimeter of the *Sassi di Matera*, the zone built at the south of the ravine where the city was developed. This research has three main phases: the first aims to identify all the churches in the established area (around 60); the second aims to classify the churches according to architectural, technological, use and degradation typologies; and in the third phase, the seismic vulnerability of representative case studies will be analyzed.

Here the development of the three phases will be presented in three typologically different churches: the *San Nicola dei Greci* church, fully excavated in the rock; the *Santa Maria de Armenis* church, which is part-excavated and part-built; and the *San Pietro Caveoso* church, which is completely built.

2. Survey form for the typological characterization of the churches in the Matera *Sassi* site, cadaster and application to case studies

To address the identification of the churches a survey form has been developed, aiming to establish a first approach to the knowledge of the constitutive features of the buildings such as: materials, constructive techniques, structural characteristics, and building evolution. The survey form is divided in four parts, the first one includes a general identification of the building: localization map, property information, typological classification, original and actual use, legal protection, historic resume including alterations or changes in the structure, architectonic description, general dimensions and floor plan.

The second part aims to characterize the vertical elements of the church, starting with the general morphology which in Matera may be: built, built and excavated, or fully excavated in the limestone rock. Then, a classification of the exterior walls is defined by identifying the type, material and shape of the stones, and the typology of the wall which may be: irregular masonry; three-leaf masonry with rubble inside; regular cut stone masonry in soft stone; masonry of square stone blocks (limestone, sandstone); among others. After, a classification of the surfaces is defined: visible surfaces, plastered or whitewashed. The general decay of the walls is divided in: instability, which may be due to out of plumbs, isolated, diffuse or profound lesions; and degradation, which may be due to humidity (infiltration, capillary rise or condensation), biological patina, mosses, lichens or saline efflorescence.

The third part of the form aims to characterize the horizontal elements of the church: the typology, material, manufacture and degradation of the floor surface and the roofing, which may be: vault, wooden floor or roofing, rigid floor or roofing, or the excavated rock. The fourth part is the graphic back-up.

2.1 Identification

By using several references such as the City cadaster, the cadaster made by *La Scaletta* foundation, authors like Tomasselli, among others, 62 churches were found inside the perimeter of the Matera *Sassi* site. Currently, a field survey is being developed to identify these churches and to apply the survey form. At this point of the research 33 churches have been identified: 5 fully excavated, 10 built-excavated, and 18 built (Figure 1). Almost all the churches identified until now are accessible to the public and are administrated by the Church, by the city or by private foundations, which manage the tourists access.

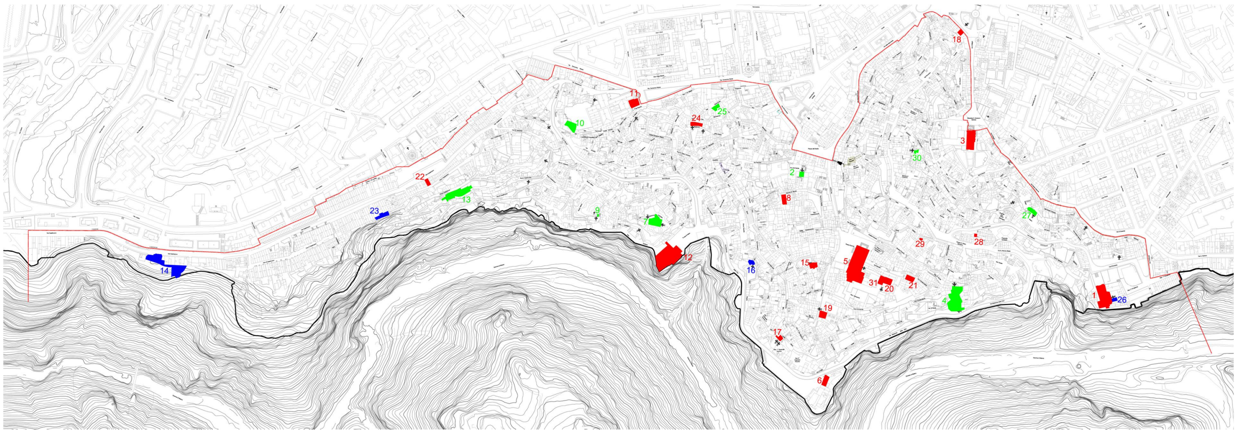

Figure 1 – First identification of the churches in the Matera *Sassi* site, divided in typologies: fully excavated (in blue); built and excavated (in green); and built (in red).

2.2 – Application of the survey form in the church of *San Nicola dei Greci*

The church of *San Nicola dei Greci* (Figure 2) corresponds to the fully excavated typology and currently it is open to the public and used as a site museum. It is approximately 6 m width and 7 m long, is divided by monolithic columns and still preserves two naves with their presbyteries in the cavity, in the right one there are two graves, and both accesses are built with an arched iconostasis. Regarding the constructive vertical elements of the church, three of them correspond to the excavated limestone rock, having the façade a column made in situ with the same limestone tuff. All of them have surfaces covered with frescoes. The main pathologies observed are the humidity infiltration, the presence of a biologic patina, mosses, lichens and saline efflorescence. The infiltration of rainfall has also produced the decay of the limestone rock due to a karst process. Regarding the horizontal elements, the original floor and roofing is basically the same excavated rock but shaping a vault in the ceiling, which has the same pathologies of the walls due to the infiltration of rainfall water.

Figure 2 – Floor plan and photo of the excavated church of *San Nicola dei Greci.*

2.3 – Church of *Santa Maria de Armenis*

The church of *Santa Maria de Armenis* (Figure 3) corresponds to the built and excavated typology and currently it is open to public and used as a site museum. It has a maximum width of 37.2 m and a maximum long of 33.1 m, it is divided in two main spaces and presents a rich late Romanesque façade with series of pointed arches, and typical pilasters of the XII and XIII centuries. The interior rooms have large compartments and the pillars with trapezoid chapitels mark the liturgical spaces. Only traces of frescoes testify the pictorial presence (Tommaselli, 2002). Regarding the structural vertical elements of the church, three of them correspond to the excavated limestone rock, and the façade is a three-leaf masonry wall built with squared blocks of limestone tuff without finishing. The main pathologies observed are the humidity infiltration, the presence of a biologic patina, mosses, lichens, chromatic alteration and saline efflorescence. Regarding the horizontal elements, the floor has been recently covered by bricks, and there are vaults of limestone blocks forming the roof under the excavated rock, which has the same pathologies of the walls due to the infiltration of rainfall water.

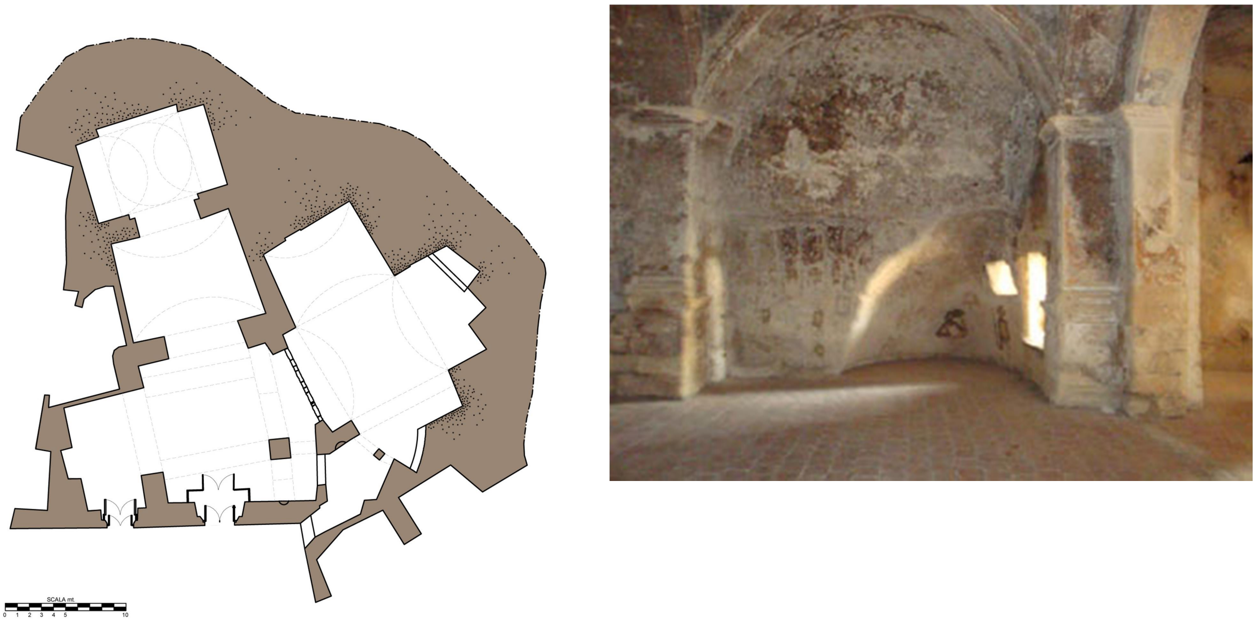

Figure 3 – Floor plan and photo of the nave walls with efflorescence in *Santa Maria de Armenis.*

2.4 – Church of *San Pietro Caveoso*

The church of *San Pietro Caveoso* (Figure 4) corresponds to the built typology and it is currently open to the public in order to maintain the original church use. It is 17.2 m width and 43 m long and is divided into three naves, having four of the original eight chapels on the left lateral nave. It also has a deep choir containing the presbytery with a XVIII century altar. The church façade has three portals according to the three naves configuration, and above, three semicircular niches contain the statues of the Saints Peter and Paul, and Our Lady of Mercy in the central position. To the left of the façade, rises the bell tower with three orders, decorated with a balustrade with geometric motifs and culminating with a pyramidal spire. The church has been recently consolidated, with a comprehensive project including soil consolidation and general anchor between the macro-elements of the building, and between the building and the foundation rock.

Regarding the constructive vertical elements of the church, the walls are built with a three-leaf masonry with squared blocks of limestone tuff without finishing. In terms of pathologies, there are some isolated fissures in the façade which may be due to differential settlements near the ravine, and there is exterior humidity infiltration that has caused chromatic alterations and saline efflorescence. Moreover, there is capillarity humidity generating karst erosion in the base of the walls. Regarding the horizontal elements, it has a ceramic pavement in the floor, a wooden structure in the main nave roofing, and groin vaults built with the same limestone tuff in the lateral naves. The horizontal elements do not have evidence of decay.

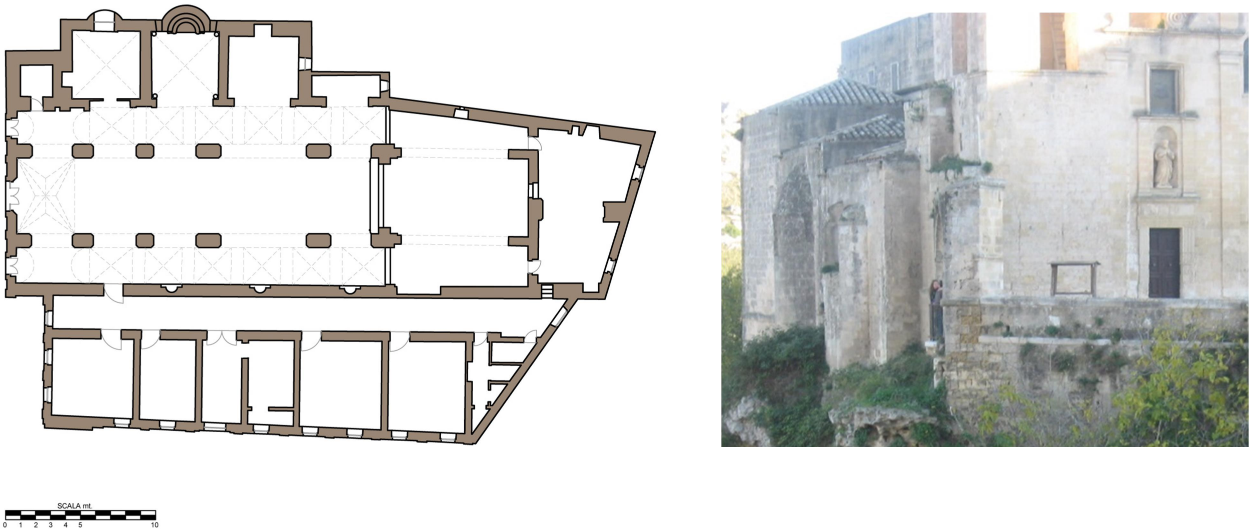

Figure 4 – Floor plan and photo of the fissures in the buttresses due to differential settlement in *San Pietro Caveoso.*

3. Simplified assessment of seismic risk

3.1 – LV1 procedure or first level of seismic vulnerability assessment (DCCM 2011)

The analysis of the seismic behavior of existing buildings is, in fact, affected by significant margins of uncertainty related to the level of knowledge acquired. Moreover, even a detailed study together with experimental investigations might not be able to achieve a more reliable evaluation. However, the 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, from which statistical damage data has been collected and linked to the seismic intensity. Based on this data, the Italian Guidelines on Cultural Heritage have proposed the LV1 procedure, or the first level of seismic vulnerability assessment, which is a simple calculation model that quantifies the strength of the building against the expected seismic intensity in the site, based on three main assumptions: infinite compressive strength of the masonry, absent tensile strength and monolithic behavior of the panels.

The LV1 procedure considers that the damage of masonry buildings is due to technological-constructive reasons, more than for reaching the ultimate resistance of the masonry. The frequent absence of effective connections between the building parts (walls, horizontal structures and roofing) creates local-response mechanisms which, very often, generate partial collapse situations due to the loss of balance of the weaker macro-elements. Consequently, the evaluation of the seismic vulnerability based on such concepts begins from the assumption that the building is not able to perform a box-behavior, therefore, the quantification of the seismic response is based on the identification and analysis of the individual macro-elements which respond independently to the seismic stress.

The method for the typology of “churches, places of worship and other structures with large spaces, without intermediate horizontal elements” defines a vulnerability index by analyzing the collapse mechanisms on each macro-element of the church, which are 28: 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, lantern and triumphal arch.

In order to define the vulnerability index, each collapse mechanism is assessed considering fragility indicators and possible anti-seismic devices, assigning a score ranging from 0 to 3, and then, the vulnerability index is given by Eq. (1), 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.

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

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. This permitted the definition of the Eq. (2) and Eq. (3), which allow to calculate the values of ground acceleration corresponding to the damage limit state (SLD) and the life-safety limit state (SLV).

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

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

Afterwards, a security index (IS) is calculated by dividing the acceleration corresponding to the limit state by the maximum ground acceleration. The building is in a safe condition when the security index is greater than or equal to 1.

3.2 – Díaz procedure (2015)

Recently an alternative simplified approach has been proposed, addressed to evaluate all the generic threats (not only the seismic one) and the resulting risks for historic buildings. In this method, a correlation between 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. In particular, this simplified approach may be applied by the means of the following tools: tool 1: seismic vulnerability assessment form; and tool 2: description, hierarchy and hazard mapping.

The tool 1 evaluates parameters such as: the position of building and its foundations; the floor plan configuration or geometry; the elevation configuration; the distance between the walls; the non-structural elements; the type, organization and quality of the resistant system; the horizontal structures and roofing; the conservation status; the alterations in the construction system and in the environment; and the vulnerability to fire. All the parameters are evaluated with a score on a scale A, B, C and D, where A means not vulnerable, and D indicates a high vulnerability on the parameter, and each parameter has a weight, related with their importance in the seismic behavior of the building according to Table 1.

Table 1 –Rating and weight of parameters to define seismic 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

On the other hand, the tool 2 assesses the seismic hazard by considering the maximum Mercalli Intensity; the landslide or rock fracture threat, since is a likely consequence of a strong earthquake; and continuous processes which main consequence is the material damage: erosion, physical stress, air pollution, socio-organizational threat and serious demographic decline, linked to lack of maintenance.

The first step to assess the *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 (Díaz 2015)

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

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: Risk (R) = Vulnerability (V) x [Hazard (H)+1].

The new simplified methodology proposed in Díaz (2015) and the LV1 level provided by the Italian Guidelines on Cultural Heritage (2011) are applied in the three case studies already described, for evaluating the seismic risk.

4. Application of the seismic risk assessment procedures to the case studies

4.1 – Application of the tool 2 (Díaz 2015)

Due to the same location of the three case studies, near the ravine of the Matera *Sassi* site, the assessment of the seismic hazard is similar in all the case studies, but it is increased by site conditions. As regards the macro-seismic intensity, the maximum 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. The score in all the case studies regarding this parameters is 0.20.

Moreover, the gorge of Matera has the higher hydrogeological risk of the region because it is formed by a hard dolomitic calcareous 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 excavated churches, since the discontinuities in the rock mass deteriorated by karst, may constitute a vulnerability under the seismic action. The score in *San Pietro Caveoso* is 0.15 because the rock slope is 2% and does not have man-made interventions or decay increasing the threat. Instead, in *Santa Maria de Armenis* there is a slope of 42.2% and humidity inside the cave provoking biologic patina and efflorescence; and in *San Nicola dei Greci*, although the slope is 8.8%, there is also humidity inside the cave provoking karst and loss of material, and there is a recent construction above the cave which might be provoking overweight. Therefore, the score in these two cases is 0.25.

On the other hand, concerning continuous processes threats which might cause material deterioration, there is no threat provoked by physical stress nor serious demographic decline. Although the velocity of the prevalent winds and the rainfall are not as strong to provoke 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 is causing a karst process in the limestone rock, therefore, in these cases the score is 0.10.

On the other hand, the score due to socio-organizational threat is 0.05, given the strong concentration of touristic activities with likely presence of crowds of people, which might produce damage for condensation of vapor inside the churches. Besides, the air pollution acting together with rainfall and scarce maintenance may provoke rainfall acidulated by carbonic acid, which may deteriorate the limestone rock and stones, therefore, the score is 0.05. This material deterioration varies depending of the point of extraction of the limestone tuff in Matera, 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" (Giufrè, 1993). This condition explains the phenomenon of surface degradation (Cotecchia, 1974 in Giuffrè A, Carocci C, 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 in the more severe cases.

4.2 – Application of the tool 1 (Díaz 2015) and LV1 (DCCM 2011) vulnerability assessment procedures to the church of *San Pietro Caveoso*

In order to apply the tool 1 (seismic vulnerability assessment form), 13 parameters which assess the seismic vulnerability were evaluated. Regarding the parameter that assesses the *position of the building and foundations*, this church is *Class A* because it is founded on rock on a slope of 2%, and in terms of its *floor plan configuration or geometry* was classified as *Class D*, because the width of the nave of the church is 13.39 m while its length is 42.88 m, implying an asymmetry that increases its vulnerability to an earthquake. Regarding the *elevation configuration* is classified as *Class D*, because has a bell tower which is more than 40% higher than the total high of the building.

As regards the parameter of the *distance between the walls*, it was classified as *Class D*, due to the slenderness of some walls, the large opening in the access and the proximity of some openings to the structure edges. On the parameter of *non-structural elements*, it is classified as *Class A*. In applying the parameters that assess *the type and organization of the constructive system* and *quality of the resistant system*, in both it is classified as *Class A*, due to the reinforcement of the church according to the seismic norms with compatible materials (metal chains), and the good quality of the three-leaf walls, which were built with squared stones, diatons and effective connections in the edges. Since this is a one storey building, the *horizontal structures* parameter does not apply, but regarding the *roofing* parameter, it is classified as *Class B*, as it causes moderate thrusts on the walls but presents a continuous horizontal structure to allow the monolithic behavior of the building.

The classification of the parameter that evaluates the *conservation status* is *Class A*, because the limestone masonry is in good condition with local damage but not provoking a weakening in the resistance. In terms of the alterations, as the church is located in the border of the Gravina River, it was classified as *Class B* in the *environment alteration* parameter, and also has *alterations in the construction system*, built with compatible materials but not reversible, so it is classified as *Class B*. Regarding the *vulnerability to fire*, it is classified as *Class B* for containing flammable ornaments and furniture, for lack of compartmentalization and internal divisions, and for the danger from fires caused by lit candles.

These evaluations have been rated based on a score and weight for each parameter (Table 1) and the total score was 23.24. The score was then multiplied by the seismic hazard score for obtaining the seismic risk which is 33.7 (Table 3).

On the other hand, regarding the application of the LV1 procedure (DCCM 2011), the collapse mechanisms analyzed in terms of the presence of vulnerability elements or anti-seismic features were 15: regarding the façade: overturning, mechanisms in plane and in the top of the façade; in the nave: transversal and longitudinal response, columns longitudinal response and the vault response in the lateral naves; regarding the chapels: overturning and shear mechanisms in walls, and vault response; and related to roof components: mechanisms in the lateral walls of the nave. Other mechanisms analyzed were: interactions in proximity of irregularities in plan or elevation; related with the bell tower, belfry and triumphal arch.

Starting from these mechanisms, the more vulnerable ones are: the mechanisms in plane and in the top of the façade for the presence of big openings; the transversal response of the nave for the presence of vaults and arches without anti-seismic devices as exterior buttresses or transversal metal chains; and the interactions in proximity of irregularities in elevation, due to the possibility of concentrated actions transmitted by the connection element.

After applying the Eq. 1, the *vulnerability index*, which rates from 0 to 1, was 0.217. The acceleration to achieve the life-safe limit state and damage limit state was given by Eq. 2 and 3, and were respectively 0.323 g and 0.081 g (Table 3). By making the relation with the maximum ground acceleration, the security index obtained for the life-safe limit state was 2.26, implying that the building is in a safe condition.

4.3 – Application of the tool 1 (Díaz 2015) and LV1 (DCCM 2011) vulnerability assessment procedures to the church of *Santa Maria de Armenis*

In order to apply the tool 1 (seismic vulnerability assessment form), 13 parameters which assess the seismic vulnerability were evaluated. Regarding the parameter that evaluates the *position of the building and foundations*, this church is *Class C* because it is founded on rock on a slope of 42,2%, and in terms of its *floor plan configuration or geometry* was classified as *Class D*, because it has a large chapel that constitutes an asymmetry in the floor plan that increases its vulnerability to an earthquake.

Regarding the *elevation configuration*, it is classified as *Class A*, because it is one storey excavated building, with homogenous mass distributions in all the high of the church. As regards the parameter of the *distance between the walls*, it can only be applied in the façade wall and it was classified as *Class A* due to the low slenderness, small openings and the presence of transversal walls. On the parameter of *non-structural elements*, it is classified as *Class A*, since it does not have elements connected to the main structure which may fall in case of an earthquake.

In applying the parameters that assess the *type and organization of the resistant system* it is classified as *Class C*, because there is a good connection between most of the walls, but not between the masonry walls and the rock of the cave. In terms of *quality of the resistant system*, the building was classified as *Class A*, because the masonry walls are built with square stones and with good quality mortar. Regarding the *horizontal structures* parameter, it does not apply because it is a one storey building, but in the *roofing* parameter is classified as *Class D*, because the church has vaults provoking thrusts and does not have a continuous horizontal structure connecting the roofing with the walls nor facilitating the monolithic behavior of the building.

The classification of the parameter that evaluates the *conservation status* is *Class C*, due to the localized biologic patina and efflorescence. As regards the *environmental alteration*, it was classified as *Class B*, due to the decay of the limestone rock, and in the *construction system alterations*, it is classified as *Class B*, as the modifications were built with compatible materials in terms of strength and stiffness, but they are not reversible. Regarding the *vulnerability to fire*, it was classified as *Class A* for not containing flammable ornaments.

These evaluations have been rated based on a score and weight for each parameter (Table 1) obtaining a total score of 40.73. The score was then multiplied by the seismic hazard score for obtaining the seismic risk which is 67.20 (Table 3).

On the other hand, regarding the application of the LV1 procedure (DCCM 2011), it was considered that the church of *Santa Maria de Armenis* is formed by a multiplicity of spaces excavated in the rock, closed on the east front by a three-leaf masonry façade built with squared blocks of calcarenite, which has diatons ensuring a partial transversal connection between the exterior leaves of the wall, in order to achieve its monolithic behavior. Therefore, among the 28 collapse mechanisms known in the literature, the simple façade overturning is a reasonable scenario that may occur: in this case, the scarce connection between the masonry wall of the façade and the excavated rock makes autonomous the behavior of the façade macro-element when affected by the seismic action, which justifies the hypothesis of loss of balance of the façade that, pushed by an action perpendicular to its own plane, would tend to overturn as a result of the formation of a horizontal hinge on its base. Consequently, the collapse mechanism analyzed in terms of the presence of vulnerability elements or anti-seismic devices was only the façade overturning.

After applying the Eq. 1, the *vulnerability index*, which rates from 0 to 1, was 0.666. The acceleration to achieve the life-safe limit state and damage limit state was given by Eq. 2 and 3, and were respectively 0.130 g and 0.032 g. By making the relation with the maximum ground acceleration the security index was obtained for the life-safe limit state, which was 0.9 implying that the building has a vulnerability in the façade macro-element that shall be addressed.

4.4 – Application of the tool 1 (Díaz 2015) and LV1 (DCCM 2011) vulnerability assessment procedures to the church of *San Nicola dei Greci*

In order to apply the tool 1 (seismic vulnerability assessment form), 13 parameters which assess the seismic vulnerability were evaluated. Regarding the parameter that evaluates the *position of the building and foundations*, this church is *Class A* because it is founded on rock on a slope of 8,88%, and in terms of its *floor plan configuration or geometry* was classified as *Class C*, because it has a chapel that constitutes an asymmetry in the floor plan that increases its vulnerability to an earthquake. Regarding the *elevation configuration*, although the church is one storey excavated building, it might be classified as *Class C*, because a recent masonry construction was built above the church, implying an overweight and a discontinuity in terms of stiffness.

As regards the parameter of the *distance between the walls*, it cannot be applied because there are no masonry walls. On the parameter of *non-structural elements*, it is classified as *Class A*, since it does not have elements connected to the main structure which may fall in case of an earthquake.

The classification in the parameter that assesses the *type and organization of the constructive system* is *Class A*, because the material continuity of the excavated building guarantees the monolithic behavior, and in terms of *quality of the resistant system*, the building was classified as *Class A*, since it has no discontinuities in the vertical limits of the cave. Regarding the *horizontal structures parameter*, it does not apply because it is one storey building, and in the *roofing parameter* it is *Class A*, as there is a perfect structural continuity between the rock-roof and the rock-walls, and the thrusts of the arcs and vaults are contrasted by the rock mass.

The classification of the parameter that evaluates the *conservation status* was *Class D*, due to the karst process and biologic patina, which might be provoking a weakening of the columns for the loss of material.

As regards the *alterations in the environment,* it is classified as *Class B*, due to the continuous deterioration of the cave, and *Class B* in the *alterations in the construction system*, as it was recently consolidated with compatible materials in terms of strength and stiffness, but the intervention is not reversible. Regarding the *vulnerability to fire*, it is classified as *Class A* for not containing flammable ornaments.

These evaluations have been rated based on a score and weight for each parameter (Table 1), and the total score was 22.89. The score was then multiplied by the seismic hazard score for obtaining the seismic risk which is 33.19 (Table 3).

On the other hand, regarding the application of the LV1 procedure (DCCM 2011), it was considered that the church of *San Nicola dei Greci* is fully excavated in the rock mass, therefore, the seismic vulnerability is closely linked to the level of stability/instability of the underground system. Consequently, the LV1 procedure is not applicable to the case study, as it is not possible to identify portions or macro-elements performing an autonomous behavior in the building under seismic action.

The continuity of all the structural elements excavated in the rock mass, make the church safe regarding the damage mechanisms, because it is able to perform an excellent response regarding the out-of-plane mechanisms. Therefore, this church presents a low vulnerability to the seismic action.

5. Conclusions

In this work, part of the ongoing analysis of the churches in the Matera *Sassi* site has been shown, first by the cadaster, which identifies the churches in the study area in terms of architectural typology; second by the survey form that was proposed and applied in three case studies, aiming to classify the churches according to architectural, technological and degradation typologies; and third, the seismic risk of the three case studies was assessed by means of the new simplified methodology proposed in Díaz (2015) and by the first level of assessment LV1 provided by the Italian Guidelines on Cultural Heritage (DCCM 2011). The resume of the outcomes of the application of tool 1, tool 2 and LV1 to the study cases are shown in Table 3.

After the application of the tool 1 (seismic vulnerability) to the case studies, it was noticed that *San Pietro Caveoso* and *San Nicola dei Greci* had a similar vulnerability index mainly as a result of the high score obtained in the parameters that evaluate the type, organization and quality of the resistant system: the built church due to the recent consolidation, and the excavated church due to the material continuity and monolithic behavior. Instead, the church of *Santa Maria de Armenis* obtained the higher vulnerability index due to the scarce connection between the façade masonry wall and the rock cave, and due to the location on a slope.

As regards the application of the tool 2 (seismic hazard) the parameter which established the main difference between the case studies was the rock fracture threat, in *Santa Maria de Armenis* due to the 42.2% slope and the humidity inside the limestone cave provoking biologic patina and efflorescence; and in *San Nicola dei Greci*, due to the humidity inside the cave provoking karst and loss of material, and the recent construction above the cave which may be provoking overweight.

Regarding the application of the LV1 procedure, it was only possible to apply in the built church, which result was a safe condition, and in the built-excavated church, which result was a vulnerable condition due to the façade overturning mechanism. 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 in the excavated churches, even though in the built-excavated typology it is possible to recognize, in certain cases, macro-elements susceptible of kinematic mechanisms known in the literature. 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.

For both excavated typologies arises the importance of the seismic hazard assessment, specifically regarding the rock fracture threat, which was evaluated by means of the tool 2 of the Díaz procedure by assessing: the topography and geometry of the slopes; the ordinary and extraordinary rainfall; the surface and underground hydrology; and the identification of man-made 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. However, deeper studies shall be addressed to assess the mechanical properties of the soil, the geological stratification distribution and the stress status.

In conclusion, in terms of seismic risk assessment, both procedures are complementary, they allow making a numerical priority, and from a qualitative point of view allow identifying the main vulnerabilities and threats which may guide the preventive conservation and mitigation projects, for acting on a territorial scale in the Matera *Sassi* site.

Table 3 – Application of the tool 1, tool2 and LV1 procedure

Parameters			**Churches in the Matera *Sassi* site**		
			San Pietro Caveoso	**Santa Maria de Armenis**	**San Nicola dei Greci**
VULNERABILITY	1	Position of the building and foundations	A	C	A
	2	Floor plan configuration or geometry	D	D	C
	3	Elevation configuration	D	A	C
	4	Distance between walls	D	A	0
	5	Non-structural elements	A	A	A
	6	Type and organization of the resistant system	A	C	A
	7	Quality of the resistant system	A	A	A
	8	Horizontal structures	0	0	0
	9	Roofing	B	D	A
	10	Conservation status	A	C	D
	11	Environmental alterations	B	B	A
	12	Construction system alterations	A	B	B
	13	Vulnerability to fire	B	A	A
		Seismic vulnerability index (V)	**23.24**	**40.73**	**22.89**
HAZARDS	1	Maximum Mercalli Intensity	0.20	0.20	0.20
	2	Landslides / rock fracture	0.15	0.25	0.25
	3	Erosion	-	0.10	0.10
	4	Physical stress	-	-	-
	5	Air pollution	0.05	0.05	0.05
	6	Socio-organizational	0.05	0.05	0.05
	7	Serious demographic decline	-	-	-
		Seismic hazard index (H)	**0.45**	**0.65**	**0.65**
		TOTAL RISK [V x (H+1)]	**33.70**	**67.20**	**37.77**
LV1		**iv**	**0.217**	**0.666**	-
		$a_{SLV}S$	0.323 g	0.130 g	-
		$a_{SLD}\,S$	0.081 g	0.032 g	-
		$a\,g_{SLV}$	0.143 g	0.143 g	-
		IS ($a_{SLV}\,S / a\,g_{SLV}$)	**2.26**	**0.91**	-

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