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A simplified procedure for risk assessment of cultural heritage: definition and application to religious architecture

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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. However, it is noticed a growing interest in disasters prevention, mainly following the agreement of the United Nations to declare the last decade of the twentieth century as the International Decade for Disaster Reduction [1]. Thus, countries have tried to change the population reactive attitude by increasing public awareness of the hazards and consequently reducing the vulnerability of people and infrastructures.
Disaster prevention in the field of built heritage conservation has been addressed by developing principles and manuals for risk management settled 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 Risk Map (*Carta del Rischio,* [2]) in Italy and the Disaster Prevention Program on Cultural Heritage (*PrevINAH,* [3]) in Mexico. However, some problems in the implementation of these methods still remain, mainly due to the fact that they develop universal principles without a comprehensive assessment of the threats and vulnerabilities of each cultural property, and the lack of precision on the information's management.
In this context, in a recent work [4] the risk assessment tools have been proposed based on a comparative analysis which systematizes the contributions of the above mentioned manuals, aiming to create risk maps at territorial level for programing the state and private action to increase the resilience of cultural property. These tools address the risk assessment at establishing a correlation between the identification of threats and vulnerabilities, and the causes of historic buildings deterioration, based on the document developed for the ICCROM [5]. There are several factors causing monuments deterioration, which generally act together and can be schematically divided into two groups: the intrinsic factors related to the origin and the nature of the monument, and extrinsic factors related instead to site conditions. By linking this approach to risk assessment, it was possible to determine that extrinsic factors correspond to threats, while the intrinsic factors are related to the vulnerability. Starting from these considerations, new tools for assessing the vulnerability and threats were defined in [4]. These tools are described and applied in the following paragraphs in two case studies: the San Francisco Church in Chiu Chiu (Chile); and the San Vito

Church in Ostuni (Italy).

SEISMIC VULNERABILITY ASSESSMENT (TOOL 1)

The first tool proposed by Díaz [4] consists on a form to evaluate the structural seismic vulnerability, where the considered parameters are defined from a comparative analysis of documents on structural analysis and post-earthquake evaluation of damage forms. Fig. 1 shows a diagram of the structure of the Tool 1 presenting the parameters for assessing the seismic vulnerability divided into three groups as follows: position of the building; inherent to the structure; and conservation status. In the Fig. 1 are also reported references of each parameter.

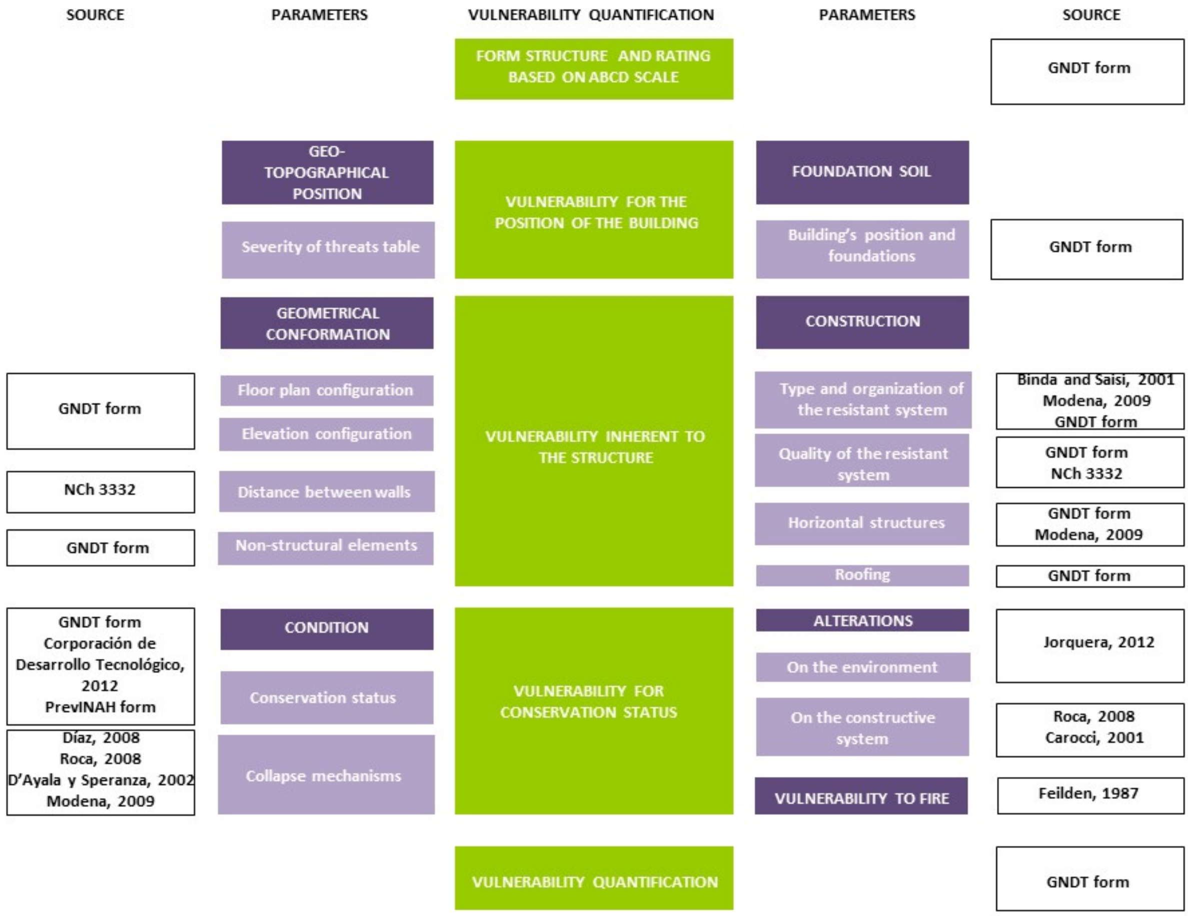

Fig. 1 Tool 1: Seismic vulnerability assessment proposed by Díaz [4].

Each church has been evaluated according to the parameters of seismic vulnerability assessment, ranking on the scale A, B, C and D, where A means very low vulnerability, and D a very high vulnerability. These classifications have a score and weight according to Table 1, which ultimately are added and scored with the following ranges: low vulnerability: $0 < V \leq 10.81$; medium vulnerability: $10.81 < V \leq 55.52$; and high vulnerability: $55.52 < V \leq 100$.

Table 1. Rating and weight of parameters to define vulnerability index proposed by Díaz [4]

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

Church of San Francisco in Chiu Chiu

The Church of San Francisco in Chiu Chiu (Fig. 2) is formed by an only nave with attached chapels. The walls and the bell tower are built in adobe masonry with mud plaster and lime, and the roof has a cactus wood structure and mud plaster as finishing.

Fig. 2 From left to right: General plan of the Church of Chiu Chiu in Archives of the National Monuments Council in Chile (2010); Location of the Church of Chiu Chiu (marked with a red circle) in Google Earth (2016).

The result of the application of the *Tool N°1 (seismic vulnerability assessment form)* was the following. 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 less or up to 10%, 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 6.9 m while its length is 29.2 m, implying an asymmetry that increases its vulnerability to an earthquake. Instead, regarding *elevation configuration* is classified as *Class A*, because it is a one-story building with mass distributions and resistant elements uniform throughout the height.
As regards the parameter of the *distance between the walls*, it was classified as *Class D*, because while the slenderness [6] of the walls is 5.71 and have no major out of plumbs, there are conditions that increase their vulnerability, as the location of some openings closer than three times the thickness of the wall from the nearest free edge, excessive length in plan between two transversal walls of the nave, and excessive amplitude on access openings [7]. On the parameter of *non-structural elements*, it is classified as *Class A*, because the building had no accessories, projections or overhangs that could fall in an earthquake.
In applying the parameters that assess the *type, organization and quality of the resistant system*, the building was classified as *Class B*, because it is an adobe structure with a good lock between orthogonal walls and a good connection between walls and floors by horizontal structures made with materials of the original construction system. Moreover, regarding the *horizontal structures* parameter, for its significant deformability in the plane of the mezzanine was classified as *Class C*, and the same class on *roofing* parameter, as it causes moderate thrusts on the walls and does not present a continuous horizontal structure on the walls to allow the monolithic behavior of the building.
The classification of the parameter that evaluates the *conservation status* was *Class A*, because the adobe is in good condition with no visible damage. Moreover, there are no *alterations in the construction system*, so it was also classified as *Class A*, and its *environment* has few alterations that increase its vulnerability, such as problems of accessibility and the location next to the Loa River, so it was classified as *Class B*. Regarding *vulnerability to fire*, it was 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 as indicated in Table 1, and the result was a medium vulnerability with a total score of 25.6.

Church of San Vito in Ostuni

The Church of San Vito in Ostuni (Fig. 3) has an only nave. Its walls, dome and bell tower are made of limestone masonry and the nave is covered by vaults.

Fig. 3 From left to right: General plan of the Church of Ostuni in Municipality of Ostuni, Italy (2016); Location of the Church of Ostuni (marked with a red circle) in Google Earth (2016).

The application of *Tool N°1 (seismic vulnerability assessment form*), yields to the following score. Regarding the parameter that evaluates the *position of the building and foundations*, this church is *Class B* because it is founded on rock on a slope between 10% and 30%, and in terms of its *floor plan configuration or geometry* was classified as *Class C*, because the width of the nave of the church is 17 m while its length is 31.38 m, implying an asymmetry that increase its vulnerability to an earthquake. Also regarding *elevation configuration* was classified as *Class C*, because it has a tower bell and a dome of a height over the 10% and below or equal to 40% of the total height of the building.

On the other hand, on the evaluation parameter of the *distance between the walls* it was classified as *Class D*, because while the slenderness of the walls is 6.34 and has no major out of plumbs, there are conditions that increase their vulnerability as the location of some openings closer than three times the thickness of the wall from the nearest free edge, excessive length in plan between two transversal walls of the nave, and excessive amplitude on access openings. On the parameter of *non-structural elements* it was classified as *Class C*, because the building has a large gable but well connected to the front wall.

In applying the parameters that assess *the type, organization and quality of the resistant system*, the building was classified as *Class D*, because has a system of double walls with internal rubble with edges built with cut stones, with orthogonal walls not efficiently embedded. Regarding the *horizontal structures,* they have an effective connection with the walls so they were classified as *Class A*, and *Class B* on *roofing* parameter, as the vaults cause low thrusts on the walls for the presence of buttresses and have a reinforcement with metal chains.

Regarding the parameter that evaluates the *conservation status* it was classified as *Class B*, because presents lesions on the surface but not generalized. Moreover, there is neither *alteration in the construction system* or its *environment,* so it was classified as *Class A* on both parameters. Regarding *vulnerability to fire*, it was classified as *Class C* for containing flammable ornaments and furniture, accumulation of dust and dirt, inadequate means of escape and faulty wiring.

These evaluations have been rated in according to the Table 1 scores, and results a high vulnerability with a score of 57.56.

DESCRIPTION, HIERARCHY AND HAZARD MAPPING (TOOL 2)

The second tool was designed in [4] 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 cultural property aiming to evaluate the worst scenario, and considering the greater magnitude and intensity of each of the threats based on historical information. The threats are prioritized based on the severity of damage that they might cause on the building. In Fig. 4 the reported diagram shows the division of the threats into three main groups: natural hazards of occasional action; threats of physical nature; and man-made and chemical hazards. Information references are also shown in each case (Fig. 4).

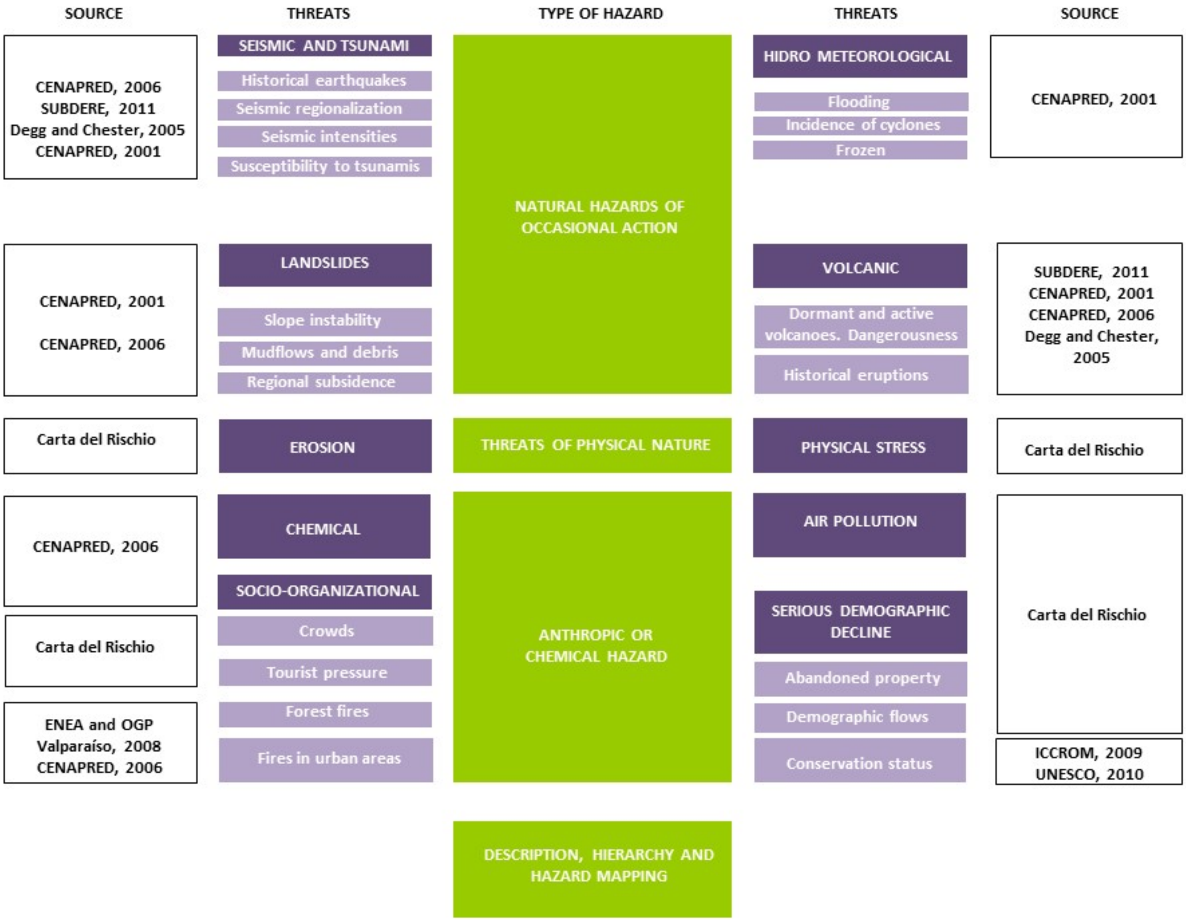

Fig. 4 Structure of Tool 2: Description, hierarchy and hazard mapping proposed in Díaz [4].

In the current study only the *seismic* risk is assessed. *Landslide threat* will be analyzed because it is a likely consequence of an earthquake, as well as the continuous processes threats: *erosion, physical stress, air pollution, socio-organizational and serious demographic decline (lack of maintenance)*, since their main consequence is the material damage. Therefore, *volcanic, hydro meteorological, chemical, forest and urban fire threats,* in this study are neglected.

San Francisco Church in Chiu Chiu

The worst scenario in the oasis of Chiu Chiu would be produced by the *seismic threat*, which could result in a catastrophic scenario because the historical maximum Richter magnitude was 8.3 with an intensity of X [8]. Other catastrophic scenario could occur by the threat of *landslides*, because the soil is made of unconsolidated material, systems faults and graben structures that make it unstable [9]. Moreover, every year rainfall in the highland winter causes river flooding and mudslide situation that may lead to differential settlements.

Among the threats that could generate minor or gradual damage scenarios there is the *physical stress*, because there are under 0° temperatures almost all year coinciding with the rainy season, a situation that could lead to the freezing of water particles and the gradual damage of the adobe masonry. On the other hand, *socio-organizational, erosion and air pollution threats* and *serious demographic decline producing lack of maintenance* are not present.

San Vito Church in Ostuni

The historic center of Ostuni falls within a low *seismic risk* area: the historical maximum Richter magnitude is 5.36, with a maximum intensity of VII [10]. This scenario could lead to injuries or elements collapse if they are inefficiently connected to the structure, however, it does not have *landslides threat*.

Among the threats that could generate scenarios of minor or gradual damage, the worst is the *air pollution* because its concentration along the direction of the prevailing winds from the north, where an industrial zone is located [11] may produce acidulated rainfall for carbonic acid which may cause the dissolution of the limestone blocks of the Church of San Vito. Other threat is the *erosion* due to the constant rainfall throughout the year, the high relative humidity (above 70%) [12] and the proximity to the coast, conditions that could produce a gradually increasing deterioration without adequate maintenance. On the other hand, in summer time the *socio-organizational threat* may be presented as the Church of San Vito is the only museum in the old town and it is located in the main touristic route, so if there were crowds of people inside the building there might be damage for condensation of vapor. The *serious demographic decline producing lack of maintenance* and the *physical stress threats* are not present.

CONCLUSIONS

In this paper a new procedure for the risk assessment of cultural heritage has been proposed. The procedure has been applied to two churches focusing only for the seismic risk since other threats in the cases analyzed are irrelevant.

The considered Chilean church, despite having been built in adobe and wooden roof of cactus results with a final rate of 25.6, while the Italian church, built in limestone masonry and vault in 1752 resulted with a final rate of 40.0 (Table 2).

Table 2. Rating parameters for the churches and vulnerability index

Table 2: Rating parameters for the churches and vulnerability index			
Parameters		*Church*	
		San Francisco in Chiu Chiu	*San Vito in Ostuni*
1	Position of the building and foundations	A	B
2	Floor plan configuration or geometry	D	C
3	Elevation configuration	A	C
4	Distance between walls	D	D
5	Non-structural elements	A	C
6	Type and organization of the resistant system	B	D
7	Quality of the resistant system	B	C
8	Horizontal structures	C	A
9	Roofing	C	B
10	Conservation status	A	B
11	Environmental alterations	B	A
12	Construction system alterations	A	A
13	Vulnerability to fire	B	C
Rating parameters		25.6	40.0

As shown in Table 2, although both churches have a similar seismic vulnerability in parameters such as the *distance between walls* and *roofing*, the vulnerability of the Church of Ostuni is higher for have been built with a double wall with rubble inside, without a proper connection between orthogonal walls. In a lesser extent the vulnerability is also increased by the position of the building on a slope, the presence of vertical elements like the tower and dome, and non-structural elements that could fall as the large gable. However, both churches have a medium seismic vulnerability.

In according to the proposed procedure, the seismic risk assessment is obtained by applying the *Tool 2* in which the worst hazard scenario is supposed. Therefore, the vulnerability of the Church of Chiu Chiu to the seismic threat is increased by its high seismic location, and also there might be a catastrophic scenario caused by rainfall, which produces every year the Loa River flood and mudslide. Considering that the church is sited within 10 meters from the river, differential settlements and humidity in the basement of the church could be presented, which may affect the resistance of the adobe walls (Fig. 5).
On the other hand, although the seismic vulnerability of the Church of Ostuni is reduced by being located in a low seismicity area, some mitigation actions shall be done in reducing erosion and air pollution threats which are causing the dissolution of the limestone blocks of the church tower. Therefore, monitoring of the material deterioration is necessary and conservation actions shall be addressed to avoid the material worn out (Fig. 5).

Fig. 5 From left to right: Church of Chiu Chiu and landslide of the eastern slope of Loa River due to flooding in Google Earth (2015); Stone deterioration in the tower of San Vito Church.

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