Seismic Vulnerability and Risk Assessment of Historic Constructions: The Case of Masonry and Adobe Churches in Italy and Chile

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Abstract. Nowadays, disasters in seismic-prone areas such as Italy and Chile, continue to cause dramatic human and economic consequences and affecting, among others, very ancient and historical churches, due to their high seismic vulnerability and probably due to the lack of risk management plans for the conservation of cultural property. This paper focuses on rapid seismic risk assessment by applying two simplified methods, based on expert judgement and observed damage, in old masonry churches, which aim to identify the most vulnerable elements and correlated threats that would act as site effects under the seismic action, for establishing intervention priority lists and for planning preventive conservation projects. The case studies are: the church of Sant'Agostino, built in stone masonry and located in Matera, an area with moderate seismicity in southern Italy; the church of San Francisco de Chiu Chiu, built in adobe and located in Calama, an area with average seismicity in the Andean northern Chile; and the church of San Francisco Barón, built in adobe and brick masonry, and located in Valparaíso, an area with high seismicity on the central coast of Chile.

Keywords: Cultural heritage · Masonry churches · Seismic risk assessment
Seismic vulnerability · Hazards

1 Introduction

The Italian and Chilean religious heritage is increasingly exposed to catastrophic events, which have generated irreversible damage and losses. In Chile, the 2010 earthquake, magnitude 8.8 (Mw) which hit centre and southern Chile, and the 2005 and 2014 earthquakes in northern Chile, magnitude 7.8 and 8.2 (Mw) respectively, evidenced the

great seismic vulnerability of stone, brick and adobe masonry churches. Likewise in Italy, starting in August 2016, a very large area of central Italy was hit by a major seismic swarm - Amatrice, Norcia, Visso sequence, producing large damage in churches due to their high vulnerability even for low seismic intensities. In order to preserve the historical and architectural heritage in seismic-prone countries, it is necessary to highlight the fragilies of such structures at territorial scale, by applying simplified seismic risk assessment methods at various geographical levels such as single site, region and nation. "Such a vision, apart from enabling a more rational organization of the resources, would allow a more effective management of emergencies as well, as a better post-seismic stage of securing and reconstructing buildings" [1].

Seismic vulnerability assessment of masonry churches has been significantly improved in Italy due to damage surveys and statistical analysis in more than 4,000 case studies after the recent earthquakes (Friuli-1976, Irpinia-1980, Umbria and Marche-1997, Lacio-1999, Toscana-1995, Piamonte-2000, Molise-2002, Aquila-2009, Emilia Romagna 2012, Centre Italy 2016). The collected data has allowed individuating the most vulnerable collapse mechanisms, for defining with acceptable certainty the modelling criteria, and for predicting damage scenarios. Thus, the Italian Guidelines on Cultural Heritage [2] define evaluation levels for the seismic assessment of churches, i.e. the LV1 method [2] is based on observed damage and measures the seismic vulnerability in terms of a vulnerability index and a safety index. On the other hand, recently a simplified method by Díaz Fuentes [3] - named LV0 on this paper - was proposed starting from a comparative analysis among the contributions of several international manuals [4, 5, 6, 7, 8, 9, among others], which aims to assess the risks in Latin America by analysing the vulnerabilities and correlated hazards as intrinsic and extrinsic causes of decay.

The LV0 and LV1 methods will be applied to three masonry churches located in Italy and Chile, as they analyse the architectural and constructive typology, and the parameters that influence the seismic behaviour of the churches. The evaluation of these parameters will allow characterizing the fragilities and possible causes of deterioration of the fabric, and the vulnerability index will allow comparing the churches by a score.

2   LV0. Qualitative Tools for the Seismic Vulnerability and Hazard Assessment as Causes of Decay

In this method by Díaz Fuentes [3], a correlation among the identification of threats and vulnerabilities and the causes of historic buildings deterioration has been derived, based on the guidelines developed by De Angelis [5]. To evaluate the risk, the method proposes three different tools. Tool 1 develops a priority framework based on cultural value, tool 2 describes and evaluates all the generic threats (not only the seismic one) and tool 3 evaluates the seismic vulnerability. In this work, the tool 1 will not be

applied, as cultural value between heritages from different countries is not comparable. As regards the tool 2, it performs a global analysis of threats affecting the cultural property for defining the worst scenario based on the greatest magnitudes recorded. The tool was founded on documents regarding territorial planning, such as *Carta del Rischio* in Italy [6]; the Guidelines for the assessment of natural risks for territorial planning in Chile [10], documents developed by the National Centre of Disaster Prevention [7, 8] in Mexico, among others. Making the focus on the seismic hazard, some threats have been selected, which may be grouped into sporadic events and continuous process (Table 1). It is also associated a partial score depending on the severity of damage that may occur, which might be no damage, low or gradual, or catastrophic. By adding the partial scores, the hazard index is calculated, which is a dimensionless parameter ranging, as it is derived, between 0 and 1.

Table 1. Rating of parameters to define the seismic hazard index

Parameters		Severity of damage			Hazard index
		No damage	Low or gradual	Catastrophic	
Sporadic events	Max. macro-seismic intensity	0	0.20	0.40	$H = \sum_{i=1}^{n} h_i$
	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	
	Lack maintenance	0	0.01	0.05	

The tool 3 [3], which evaluates the seismic vulnerability, takes into account the GNDT form [9], the Chilean Norm N° 3332 [11] for earthen built heritage, and recent research regarding historic masonry buildings [12–14], among others. Each parameter is classified on a scale from A to D, where A indicates a very low and D a very high vulnerability, having also a score (Table 2). The parameter's score (*v*) and weight (*p*) – based on the importance of the parameter in the seismic behaviour of the building - are based on the GNDT form [9], where a table for the vulnerability quantification was proposed. In this method [3], the numerical values and classes were modified for evaluating cultural property and adobe constructions, and they are proportional as to have a maximum vulnerability of 100. Finally, the global vulnerability score V is calculated by a summation.

Table 2. Rating and weight of parameters to define the seismic vulnerability index [3]

Parameters	Class				p_i	Vulnerability index
	A	B	C	D		
Position/foundations	0	1.35	6.73	12.12	0.75	$V = \sum_{i=1}^{n} v_i p_i$
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 resulting seismic risk, defined as the combination of the probability of an event occurring and its negative consequences [15], is calculated by multiplying the seismic vulnerability index by the seismic hazard index: Risk (R) = Vulnerability (V) x [Hazard (H) + 1].

3   LV1. Simplified Assessment for the Church Typology

The LV1 method proposed by [2] is based on the evaluation of the vulnerability index, derived from the analysis of 28 collapse mechanisms of macro-elements that have an autonomous behaviour under the seismic action. 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 seismic-resistant devices, and ρ_k is the weight of each collapse mechanism. The values of ground acceleration for activating the damage limit state (SLD) and the life-safety limit state (SLV) are given by Eqs. (2) and (3).

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

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

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

Thus, the acceleration factor (F_a) or seismic safety index is calculated by the relation between the acceleration which provokes the generic limit state (a_{SL}) and the acceleration expected on the site ($a_{g,SL}$) by Eq. (4). The building is in a safe condition when the F_a ratio is greater than or equal to 1.

$$F_a = \frac{a_{SL}}{a_{g,SL}} \tag{4}$$

4   Application to the Churches in Italy and Chile

In order to apply both procedures, three churches were analysed (see Fig. 1), i.e. Sant'Agostino in Matera, Italy - which is a one-nave basilica floor plan church, and it is built in calcarenite masonry with limestone vault systems, San Francisco de Chiu Chiu in Calama, Chile; which is a one-nave basilica floor plan church with chapels and towers, it is built in adobe and has a wood roofing called "par y nudillo"; and San Francisco Barón in Valparaíso, Chile - which is a three-nave church, built in adobe
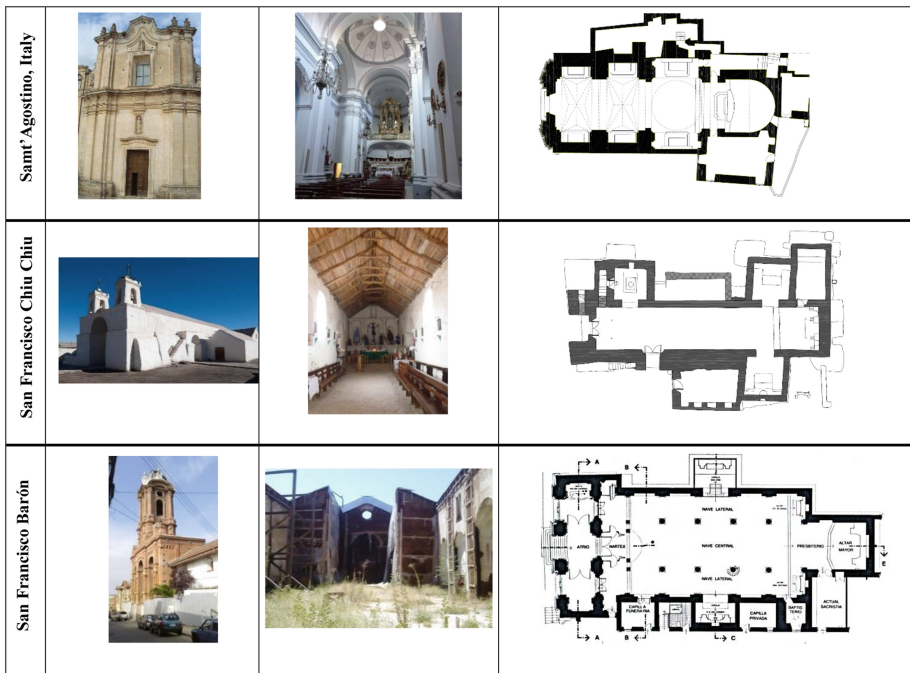
Fig. 1. Front and interior views and floor plan of the church of Sant'Agostino [16], San Francisco de Chiu Chiu [17] and San Francisco Barón [18].

Table 3. Application of the LV0 and LV1 methods

		Parameters	Sant'Agostino, Matera, Italy (2016)	San Francisco Barón, Valparaíso, Chile (before 2010 earthquake)	San Francisco de Chiu Chiu, Calama, Chile (before 2005 earthquake)
L V 0	1	Position and foundations	B	A	A
	2	Floor plan configuration	C	D	D
	3	Elevation configuration	A	D	A
	4	Distance between walls	C	D	D
	5	Non-structural elements	C	A	A
	6	Type-organization of R.S.	C	B	B
	7	Quality of the R.S.	A	A	B
	8	Horizontal structures	A	A	A
	9	Roofing	D	A	C
	10	Conservation status	A	D	A
	11	Environmental alterations	B	B	B
	12	Construction system alterations	D	A	A
	13	Vulnerability to fire	B	C	B
		Seismic vulnerability index (V)	33.66	37.38	18.86
	1	Maximum macro-seismic intensity	0.20	0.40	0.40
	2	Landslides / rock fracture	0.15	0.00	0.25
	3	Erosion	0.05	0.10	0.00
	4	Physical stress	0.00	0.00	0.10
	5	Pollution	0.05	0.01	0.00
	6	Socio-organizational	0.05	0.05	0.00
	7	Demographic decline	0.00	0.00	0.00
		Seismic hazard index (H+1)	1.50	1.56	1.75
		TOTAL SEISMIC RISK [V x (H+1)]	50.49	58.31	33.01
L V 1		i_v	0.55	0.41	0.33
		$a_{SLV}S$	0.165 g	0.217 g	0.259 g
		$a_{SLD}S$	0.042 g	0.054 g	0.065 g
		$a\,g_{SLV}$	0.168 g	0.400 g	0.300 g
		Fa (a_{SLV} S / $a\,g_{SLV}$)	0.98	0.54	0.86

with a brick masonry façade, and wooden columns and roofing. With the aim of proving the effectiveness of the LV1 predictive method in America Latina, the condition before the 2010 earthquake in the church of San Francisco Barón and the condition before the 2005 earthquake of the church of San Francisco de Chiu Chiu will be considered. Thus, the acceleration given on each case by the predictive method will be compared with the accelerations of these earthquakes and actual damages (Table 3).

4.1   Church of Sant'Agostino, Matera, Italy

As regards the application of the LV0 method, the maximum macro-seismic intensity observed in Matera has been VII and the ravine has the higher hydrogeological risk of the region because it is formed by a hard dolomitic calcareous, but fractured in layers and often with karst. Thus, the discontinuities in the rock mass deteriorated by karst erosion may affect the church of Sant'Agostino, sited on the ravine border. Concerning continuous processes threats, the air pollution acting together with rainfall and scarce maintenance might cause stone decay by rainfall acidulated by carbonic acid, which explains the surface degradation phenomenon observed on the façade. In terms of

vulnerability, Sant'Agostino presents an asymmetric floor plan, large openings in the façade, slender walls, openings near the edges of the structure, stone vaults that cause thrusts in the aisle and apse, and the vault was negatively altered with concrete injection. Regarding the LV1 method, the vulnerability index was 0.55 over a maximum of 1, and the most vulnerable collapse mechanisms were the apse overturning, due to the vaults thrust and the lack of contrast elements as buttresses; the shear mechanisms in the façade and apse walls, due to the high slenderness; the vault in the apse due to the concrete injection; and the bell tower.

4.2   Church of San Francisco Barón, Valparaíso, Chile (Condition Before the 2010 Earthquake)

The results of the LV0 application highlighted the possibility of reaching a macro-seismic intensity of XI in Valparaíso, which is a devastating earthquake with large damage in most of the buildings. Due to the location of the church at the top of a hill, the mud-debris flow and fall threats [19] do not affect it. Regarding the continuous processes threats, the erosion is the most severe hazard for the location in the coast, associated with saline efflorescence and erosion of porous materials, due to the movement and evaporation of the water in the porous system of the materials in which the salts dissolve. The 75% of relative humidity of Valparaíso [20], the vehicular congestion and the presence of the seaport increase the air pollution and contribute to worsen the phenomena. In terms of vulnerability, San Francisco Barón presents an asymmetric floor plan, a high bell tower on a narthex, large openings in the aisle, openings near the edges of the structure, cracks due to past earthquakes, vulnerability to fire, among others. Regarding the LV1 method, the vulnerability index was 0.41 over a maximum of 1, and the most vulnerable collapse mechanisms were the bell tower and the bell cell.

4.3   Church of San Francisco de Chiu Chiu, Calama, Chile (Condition Before the 2005 Earthquake)

Regarding the application of the LV0 method, there might be a catastrophic scenario due to an earthquake with a macro-seismic intensity of X [21]. Moreover, there is landslide threat because the church is sited on unconsolidated material and 15 m far from the Loa River, which increases its water flow because of torrential rains in the summer season. In fact, there is subsoil erosion in the west side of the church that could generate differential settlements [22]. On the other hand, physical stress may generate

material deterioration as practically all the year, temperatures reach 0 °C [23] and when this meets the rainy season, it could produce the icing of water particles and the gradual deterioration of adobe walls. In terms of vulnerability, San Francisco de Chiu Chiu presents an asymmetric floor plan, a large opening in the façade, openings near the edges of the structure and a flexible wooden roof. Regarding the LV1 method, the vulnerability index was 0.33 over a maximum of 1, and the most vulnerable collapse mechanisms were the mechanisms in the top of the façade and the ones regarding the hammering effect produced by the wooden beams on the masonry.

5   Conclusions

According to the seismic zoning of Chilean Standard No. 433 [24] Valparaíso corresponds to the zone 3, thus, an expected ground acceleration of 0.40 g was considered in the predictive vulnerability model. Therefore, with a vulnerability of 0.41, the church of San Francisco Barón results under the safety range, because the acceleration for activating the life safety limit state is 0.217 g. However, as in the 2010 earthquake seismic accelerations did not exceed 0.20 g in the hills of Valparaíso [25], damages were expected but not reaching the life safety limit state, which is coherent with the actual damages. However, considering the high seismicity of Valparaíso and taking into account that the condition of the church of San Francisco Barón has been worsen due to the 2010 earthquake and two fires, which have wipe out all the wooden columns and roofing, it is urgent to reinforce the structure as soon as possible. This standard classifies Calama as zone 2, meaning an expected ground acceleration of 0.30 g. Thus, with a vulnerability of 0.33, the church of San Francisco de Chiu Chiu results under the safety range, because the acceleration for activating the life safety limit state is 0.259 g, being lower than the expected acceleration at the site. In the 2005 earthquake, seismic accelerations reached 0.075 g in Calama [26], meaning that damages were expected because the acceleration for activating the damage limit state was 0.065 g, this was coherent with the real damages. Finally, the Italian church of Sant'Agostino, which presents an unsafe condition even in the moderate-seismicity area of Matera, will not be capable to withstand an expected ground acceleration, reaching a life-safety limit state. Therefore, preventive vault reinforcement, thorough mechanic soil studies and constant maintenance and monitoring of the limestone blocks shall be addressed [27].

The seismic risk assessment at territorial scale of masonry churches by rapid simplified methods is a very relevant issue, as they are vulnerable even to low intensity seismic events, which are frequent even in moderate seismic-prone areas, therefore, the LV0 and LV1 simplified methods might help to establish intervention priorities and to guide preventive conservation projects in masonry churches.

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