SEISMIC RISK ASSESSMENT OF HISTORIC CONSTRUCTIONS: COMPARATIVE ANALYSIS OF MASONRY AND ADOBE CHURCHES IN ITALY AND CHILE

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Abstract – This paper proposes to compare seismic risk assessment of historic constructions in Chile and Italy - two seismic prone countries with their own seismological conditions, construction histories and heritage buildings - in order to contribute to the construction of a rapid seismic risk assessment method of heritage buildings in Chile by using innovations and lessons learned in past earthquakes in Italy.

To that end, this paper focuses on applying two simplified methods, based on expert judgement and observed damage in old masonry churches, with the aim of identifying 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 two churches in Matera, Italy; one church in the Andean northern Chile; and two churches in Valparaíso, Chile. Finally, the paper discusses the applicability of these methods for Chilean conservation management plans for cultural property.

Key Words – cultural heritage, seismic vulnerability, correlated hazards.

I. INTRODUCTION

The Italian and Chilean religious heritage is increasingly exposed to catastrophic events, which have generated irreversible damage and losses, most of all due to earthquakes. To characterize the seismic risk, rapid or simplified methodologies were used to analyze five case studies, which are sited in very different territories in terms of seismological conditions. The first cases are the churches of Sant'Agostino and San Giovanni Battista, built in stone masonry and sited in Matera, an area with moderate seismicity in southern Italy. Other case study is the church of San Francisco de Chiu Chiu, built in adobe and located in Calama, Chile, an area with average seismicity in the Andean northern Chile. Finally, the churches of San Francisco Barón and La Matriz were analyzed; both are built in adobe and brick masonry and are located in Valparaíso, an area with high seismicity on the central coast of Chile.

II. MATERIALS AND METHODS

To address the simplified assessment of seismic risk, the LV1 method [1] and the Díaz [2] method were used. The Italian Guidelines on Cultural Heritage have proposed the LV1 procedure to define a vulnerability index in the churches typology, based on the analysis of 28 collapse mechanisms in individual macro-elements. 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.

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

After, the Eq. (2) and Eq. (3) allow calculating the values of ground acceleration corresponding to the damage limit state (SLD) and the life-safety limit state (SLV). Then the 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.

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

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

The Díaz method [2], on the other hand, evaluates all the generic threats (not only the seismic one) and the resulting risks of historic buildings. In particular, this simplified method was applied through two 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 the building and its foundations; the floor plan configuration or geometry; the elevation configuration; the type, organization and quality of the resistant system; the alterations in the construction system; among others. All the parameters are evaluated with a score (v) and each parameter has a weight (p), related with their importance in the seismic behavior of the building. The vulnerability index (VI) is given by Eq. (4).

$$VI_j = \sum_{i=1}^{n} v_{j,i} p_i \quad (4)$$

On the other hand, the tool 2 assesses the seismic hazard by considering: the maximum macro-seismic intensity and the landslide or rock fracture threat; and continuous processes such as: erosion, physical stress, air pollution, socio-organizational threat and the 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 behavior of the building. The resulting risk is defined according to the expression:
Risk (R) = Vulnerability (V) x [Hazard (H)+1].

III. RESULTS AND DISCUSSION

In order to apply both procedures, five churches were analyzed. In Matera, Italy, the churches of Sant'Agostino (one-nave floor plan) and San Giovanni Battista (three-nave floor plan), which are built in calcarenite masonry with limestone vault systems (Figure 1). In Calama, Chile, the church of San Francisco de Chiu Chiu (one-nave floor plan), which is built in adobe and has a wood roofing called "par y nudillo" (Figure 2). In addition, in Valparaíso, Chile, the churches of San Francisco Barón and La Matriz, both three-nave floor plan churches, built in adobe with a brick masonry façade, and wooden columns and roofing (Figure 3).

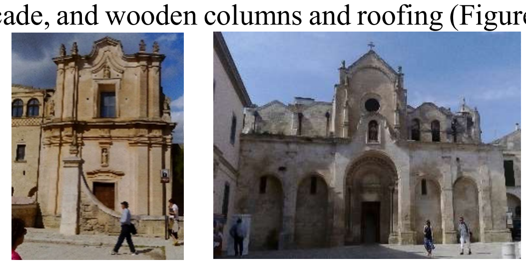

Figure 1. Churches of Sant'Agostino and San Giovanni Battista, Matera, Italy.

Figure 2. Church of San Francisco de Chiu Chiu, Calama, Chile.

Figure 3. Churches of San Francisco Barón and La Matriz, Valparaíso, Chile.

The church of San Francisco Barón was consolidated in 2012 with a wooden structure within the adobe walls. Since then, two fires have burned this structure, the roof and the wooden columns, leaving the church in a state of ruin (Figure 4). The adobe walls keep deteriorating due to weathering, and there are collapses near the apse.

Figure 4. Interior of the church of San Francisco Barón, Valparaíso, Chile.

As regards the application of the Díaz method [2], 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 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 affecting the church of Sant'Agostino, sited on the ravine border, due to the discontinuities in the rock mass deteriorated by karst erosion. Concerning continuous processes threats which might cause material deterioration, 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, where there are compact and resistant stone blocks along with eroded ones – since it depends of the quarry location [3].

The application of the Díaz method [2] in the Oasis of Chiu Chiu in Calama, highlighted that there might be a catastrophic scenario due to the seismic threat, because in about 100 years, 20 earthquakes have occurred over the magnitude 7 (Mw), with a top of 8.3 (Mw) in 1950 and a macro-seismic intensity of X (MMI) [4]. Moreover, there is landslide threat as well, since 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, which could generate differential settlements [5]. On the other hand, physical stress may generate material deterioration as practically all the year, temperatures reach 0°C [6] and when this meets the rainy season, it could produce the icing of water particles and the gradual deterioration of adobe walls.

The results of the application of the Díaz method [2] in Valparaíso highlighted the possibility of reaching a macro-seismic intensity of XI, which is a devastating earthquake with large damage in most of the buildings, as the 1730 earthquake with epicenter offshore Valparaíso, is the largest historical earthquake known in Central Chile. Hence, the ravines in Valparaíso show high mud-debris flow susceptibility, but limited on the downstream ravine sides, and fall susceptibility, mainly localized in the escarpments connecting hillsides and coastal flat [7]. 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 [8], the vehicular congestion and the presence of the seaport increase the air pollution and contribute to worsen the phenomena.

Regarding the seismic vulnerability, the results are shown in Table 1.

Table 1 Application of the LV1 (2011) and Díaz (2016) methods

Parameters	Matera, Italy		Calama, Chile	Valparaíso, Chile	
	S. Agosti-no	S. Giovan ni Battista	S. Francis-co Chiu Chiu	S. Francis-co Barón	La Matriz
(LV1) i_v	0.55	0.49	0.33	0.75	0.43
(LV1) $a_{SLV}S$	0.165	0.186	0.259 g	0.109 g	0.211 g
(LV1) $a_{SLD}S$	0.042	0.047	0.065 g	0.027 g	0.053 g
(LV1) $a\ g_{SLV}$	0.168	0.121	0.300 g	0.400 g	0.400 g
(LV1) IS (a_{SLV} S / $a\ g_{SLV}$)	0.98	1.53	0.86	0.27	0.53
(Díaz 2016) V	33.66	18.53	19.88	53,88	33.34
(Díaz 2016) H+1	1.50	1.30	1.75	1.51	1.66
(Díaz 2016) R [V x (H+1)]	50.49	24.09	34.79	81.36	55.34

In terms of vulnerability, the Italian churches present: an asymmetric floor plan, large openings in the façade, slender walls, openings near the edges of the structure and stone vaults which cause thrusts in the aisle and apse. Regarding the LV1 method, the vulnerability index of Sant'Agostino is 0.55 and of San Giovanni is 0.49. The most vulnerable collapse mechanisms were the apse overturning and the damage at the top of the façade respectively.

As regards the churches in Valparaíso, they present an asymmetric floor plan, a high bell tower, large openings in the aisle and openings near the edges of the structure. In the case of San Francisco Barón, the loss of the roofing and the wood columns left the church incapable of developing a box-behavior and exposed to weathering. Concerning the LV1 method, the vulnerability index of San Francisco Barón is 0.75 and of La Matriz is 0.43, and in both churches, the most vulnerable collapse mechanisms were the bell tower and the bell cell.

Finally, the church of 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 roofing. It has a vulnerability index of 0.33, 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 adobe walls.

IV. CONCLUSION

According to the seismic zoning of Chilean Standard No. 433 [9] Valparaíso corresponds to the zone 3, thus, an expected ground acceleration of 0.40 g was considered in the predictive vulnerability model. Therefore, the church of San Francisco with high vulnerability, and La Matriz with medium vulnerability, resulted both under the safety range. The same Chilean Standard classifies Calama as zone 2, meaning an expected ground acceleration of 0.30 g. Thus, even with a low vulnerability of 0.33, the church of San Francisco de Chiu Chiu results under the safety range.

Finally, while the Italian church of San Giovanni Battista presents a low vulnerability and a save condition, the church of Sant'Agostino, instead, presents an unsafe condition even in the moderate-seismicity area of Matera.

In conclusion, the seismic risk assessment on a territorial scale of masonry churches by rapid or simplified methods is a very relevant issue, as they are vulnerable even to low intensity seismic events, which are frequent also in moderate seismic-prone areas. Therefore, the LV1 and Díaz simplified methods might help to establish intervention priorities and to guide and program preventive conservation projects in masonry churches in Italy, but also in Chile. Both by providing priority lists and by identifying the most vulnerable collapse mechanisms for local interventions, which may be programed in the framework of conservation management plans for heritage sites.

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