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# PRIORITIZING MULTI-HAZARD RISK OF CULTURAL HERITAGE ASSETS

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## *Abstract*

Multi-hazard risk assessment of building portfolios is of primary importance in natural hazard-prone areas, particularly for the definition of prioritization schemes for implementing disaster risk reduction (DRR) and resilience-enhancing strategies. Among the most vulnerable buildings, Cultural Heritage (CH) assets are especially important because of their historical/cultural value, the lack of any hazard-resistant design (in most of the cases), and their material degradation due to aging. In this context, the *Cultural Heritage Resilience & Sustainability to multiple Hazards* (CHeRiSH) project, funded by the UK British Council, aims to develop a multi-level risk and resilience assessment framework for CH assets in the Philippines exposed to multiple natural hazards.

In this paper, an ad-hoc Rapid Visual Survey (RVS) form for the multi-hazard data collection and risk prioritization of CH assets, developed within CHeRiSH, is presented. Because of the multi-level architecture of the proposed RVS form, based on three levels of refinement/information, an increasing degree of accuracy can be achieved in the estimation of structural vulnerability and, ultimately structural risk of case-study assets. More specifically, the lowest information level (LV1), which is the focus of this study, allows estimating a multi-hazard risk prioritization index by only requiring limited information of the CH asset, which can be obtained through a desktop review and a survey of the building exterior. This data can be used to assign quantitative scores needed for the derivation of the final risk prioritization index. A simplified procedure is also proposed to consider the intangible value of CH assets in the calculation of the risk prioritization index. The procedure is based on the definition of a CH value index which reflects the significance as “monument” of the considered asset.

The proposed framework is applied to 25 heritage buildings in Iloilo City, Philippines, for which innovative, non-invasive techniques and tools for improved surveying have also been tested. Thermal and omnidirectional cameras have helped in the collection of structural data, together with drones for the inspection of roofs. The results of the study are presented and critically discussed, highlighting advantages and drawbacks of the use of new technologies in this field.

*Keywords: Multilevel methodology; cultural heritage; RVS form; multi-hazards risk prioritization.*

## 1. Introduction

National and international authorities across the world have recently highlighted the need for integrating the specific features of cultural heritage (CH) assets into disaster risk reduction (DRR) plans. In this context, the *Sendai Framework for Disaster Risk Reduction 2015-2030* [1], endorsed by the United Nations (UN) General Assembly, explicitly included CH in the overall agenda of DRR. Culture is recognised as a key dimension of DRR and CH is referred to under two priorities: understanding disaster risk; and investing in DRR for resilience. A rational understanding of natural-hazard risks of large building stocks, including CH assets, is needed to design and implement any DRR or resilience-enhancing strategy. The definition of robust prioritization schemes of building portfolios based on probabilistic risk assessment methods is needed to this aim. This is even more important in developing countries where limited financial resources/coping capacities are usually available, and the existing building stock has been designed/built according to obsolete codes.

CH assets require particular consideration because of their historical/cultural value, which, in this context, consists of both a tangible and an intangible value [2]. The tangible value is mainly related to the unique structural/architectural characteristics of a given asset and to its link to the economy of a region through cultural tourism (i.e., direct and indirect losses respectively). The intangible value is essentially related to the symbolic value of CH assets for a given community. Indeed, the citizens' sense of place is strongly linked to CH assets: their damage and partial/total collapse can have a huge impact on social cohesion, sustainable development and psychological wellbeing. In addition, the lack of any hazard-resistant design (in most of the cases) and presence of material degradation due to aging together with the possible presence of structural modifications/local repair and/or partial/total reconstructions over time result in high levels of vulnerability for CH assets (e.g., Despotaki et al. [3]).

Performing detailed structural analyses for a large number of buildings is cost-ineffective because it would require high-performance computing and specific technical resources (and skills). Simplified methods for multi-hazard risk prioritization of building portfolios (e.g., FEMA P-154 [4]) become thus fundamental. Such methods rely on scoring approaches and enable prioritization schemes to be derived with a small amount of data. In addition, multi-level frameworks [5] represent essential tools to also prioritize further detailed analyses and interventions (e.g., structural retrofit/repair).

In particular, several methodologies have been proposed for the vulnerability/risk prioritization of CH assets. Most of them rely on the definition of pre-determined building classes [6] and corresponding fragility/vulnerability relationships for each class. Alternatively, Rapid Visual Survey (RVS) forms and empirically calibrated vulnerability/risk indices based on the RVS results [7] are used. However, most of the existing approaches which also consider the CH value focus on a single hazard [3] and/or require detailed information on the construction features of the assets under investigation [8, 9]. The large amount of data (and its level of detail) needed for the application of such approaches can contrast with the nature of prioritization frameworks at regional level (e.g., for a building portfolios) which should be rapid and simple. Moreover, multi-hazard risk prioritization schemes are widely needed (and used) in developing countries, where specific data/details are usually not available, thus requiring several simplifying assumptions.

This paper addresses the above-mentioned issues by introducing a multi-level, multi-hazard risk assessment framework for CH assets. An ad-hoc RVS form is also proposed to gather information for three levels of analysis varying in refinement. The information at the lowest refinement level (LV1), the focus of this paper, can be used for the calculation of risk prioritization indices against various natural hazards, also considering the CH asset value. The seismic risk prioritization index proposed in this study is a scoring approach and it represents an extension of the index proposed within the *Indonesia School Programme to Increase Resilience* (INSPIRE) [10] to the case of unreinforced masonry (URM) buildings. The CH intangible value is considered through a simplified method reflecting the CH asset significance [11]. Weights and scores used in this study are calibrated through the analytical hierarchy process [12].

The proposed approach has been used for the multi-hazard risk prioritization of 25 CH assets in Iloilo City, Philippines, an important heritage hub for tourism in the country [13]. The historic street Calle Real, located in the old downtown district of Iloilo City, is home to several fine examples of historic luxury buildings constructed in the first half of the 20th century during the American colonization [14]. These have been surveyed during a fieldwork in 2019. Being located in a cyclonic region with the West Panay fault just 15 km away, Iloilo City represents a perfect case study to test the proposed multi-hazard risk and resilience assessment framework.

## 2. The CHeRiSH framework

### 2.1. Overview

The framework presented in this paper has been developed within the *Cultural Heritage Resilience & Sustainability to multiple Hazards* (CHeRiSH) project, funded by the UK Newton Fund, which aims to define a multi-level risk and resilience assessment framework for CH assets in the Philippines exposed to multiple natural hazards. Recent catastrophic events, e.g., the M7.2 2013 Bohol earthquake or the 2013 Typhoon Haiyan, have highlighted that Filipino CH assets are particularly vulnerable to natural hazards due to ageing and type of construction. In addition, cultural tourism is one of the priority sectors by which the Government of the Philippines aims to foster inclusive and sustainable socio-economic development, due to its potential for job creation and revenues. The main focus of the CHeRiSH project is on the exposure and physical vulnerability modelling of CH assets as well as on the prioritization of resilience-improving solutions for selected assets through multi-criteria decision making. Ultimately, the project will provide conceptual guidelines for the development and implementation of each component of the proposed modelling framework.

The overall risk and resilience assessment framework proposed in CHeRiSH has a multi-level structure consisting of three refinement levels which are directly linked to the amount of available information. At the lowest refinement level, the proposed framework allows CH assets to be prioritised against multiple hazards and considering their intangible value. The other two levels enable an analyst to estimate the structural vulnerability, and ultimately structural risk at building-specific scale, thus increasing the accuracy of the result. Arguably, the second and the last analysis levels can be performed only if refined data, recorded from both the interior and exterior, are available.

The lowest refinement level requires only few basic information about the assets under investigation. It can be thought as a five steps procedure: 1) data collection through a sidewalk survey (by means of the proposed RVS form); 2) selection of the hazard-intensity level (e.g., for a selected mean return period) for which the prioritization is needed; 3) calculation of risk prioritization indices for different hazards; 4) combination of the different single-hazard prioritization risk indices; and 5) calculation of multi-hazard risk prioritization indices which accounts for CH asset intangible values, and building ranking.

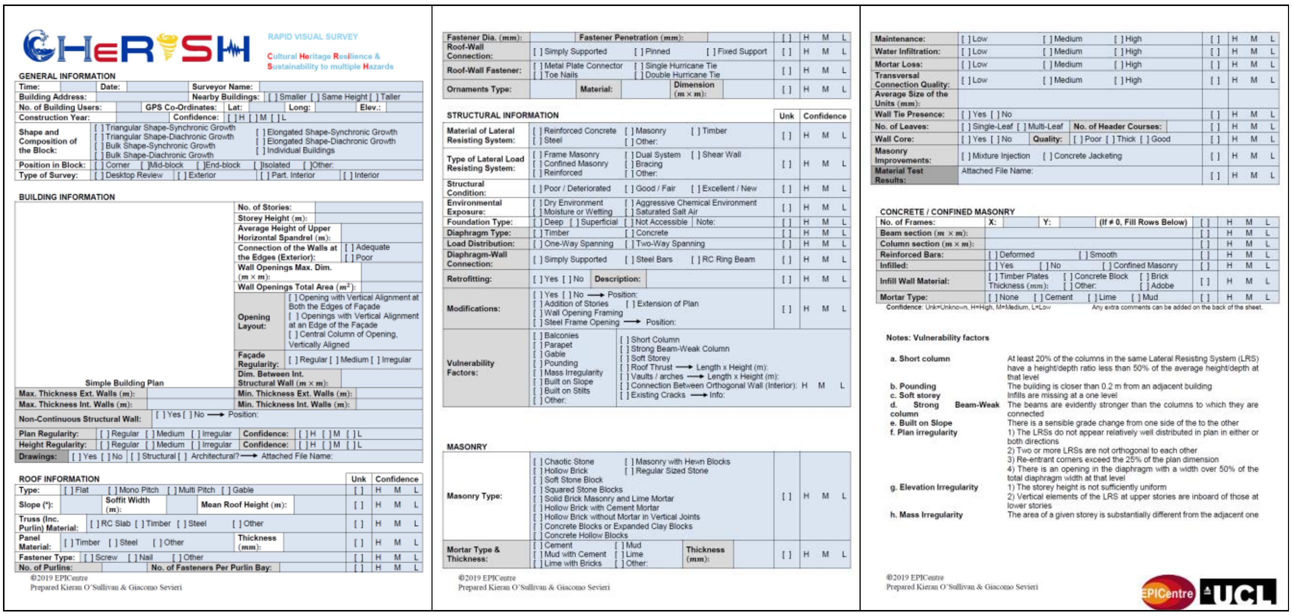
## 2.2. Rapid Visual Survey form

The Filipino CH portfolio consists of reinforced concrete (RC) frames and masonry or mixed structures. According to the Filipino Republic Act no. 10066 [15], also known as the National Cultural Heritage Act, the only “objective” criterion which defines a CH asset is the year of construction. Structures which are at least fifty years old can be declared to be a “Heritage House” by the National Historical Commission of the Philippines (NHCP). The Filipino law does not explicitly consider subjective features of buildings such as architectonical value and sociocultural factors. Fairly recent RC frame-type structures, with limited architectural and/or cultural features, are then often part of the Filipino CH portfolio. Considering these specific characteristics of the Filipino CH assets, the proposed RVS form is designed for various structural typologies employing different construction materials and lateral-load resisting systems.

Fig. 1 shows the CHeRiSH RVS form. The grey entries indicate the data required to derive the risk prioritization scheme (LV1). Such data can be collected by means of a sidewalk survey of the building by trained engineers in approximately 20-30 minutes, depending on the size of the construction. More detailed data recorded from both the interior and the exterior of the building (e.g., presence of non-continuous structural walls, type and quality of roof-to-wall connections, diaphragm typology, among many others) are indicated with light grey cells and they enable more refined analyses to be performed (LV2). The third level of refinement/accuracy (dark grey entries) of the proposed framework requires material test results and structural drawings to calibrate reliable numerical models (LV3).

The RVS form is composed of six sections over three pages; it includes various parts related to the general identification and geolocation of the building, its geometric properties (including space for sketching the building’s shape and footprint), and its structural characteristics and deficiencies, including the structural typology and the dimensions/details of the main structural members. A “Confidence Level” for each parameter can be assigned to account for the degree of accuracy in the collected data. The “Vulnerability Factors” section contains a list of vulnerabilities which can be found in the survey of masonry or RC structures. Recent catastrophic events have demonstrated how Filipino CH assets are vulnerable to typhoon-induced strong wind.

Since the main collapse mechanisms due to extreme wind and typhoons are related to the failure of roofs [16], specific data on this structural components are required in the "Roof Information". The data collected in the CHeRiSH RVS form are fully compatible with both the Global Earthquake Model (GEM) building taxonomy [17] and the Hazard United States (HAZUS) model [18]. Existing prioritization indices, based on these two models, can also be used within the CHeRiSH framework.



CHeRiSH
RAPID VISUAL SURVEY
Cultural Heritage Resilience & Sustainability to multiple Hazards

GENERAL INFORMATION

Time: Date: Surveyor Name:
Building Address: Nearby Buildings: [ ] Smaller [ ] Same Height [ ] Taller
No. of Building Users: GPS Co-Ordinates: Lat: Long: Elev.:
Construction Year: Confidence: [ ] H [ ] M [ ] L

| | |
|---|---|
| Shape and Composition of the Block: | [ ] Triangular Shape-Synchronic Growth<br>[ ] Triangular Shape-Diachronic Growth<br>[ ] Bulk Shape-Synchronic Growth<br>[ ] Bulk Shape-Diachronic Growth<br>[ ] Elongated Shape-Synchronic Growth<br>[ ] Elongated Shape-Diachronic Growth<br>[ ] Individual Buildings |
| Position in Block: | [ ] Corner [ ]Mid-block [ ]End-block [ ]Isolated [ ]Other: |
| Type of Survey: | [ ] Desktop Review [ ] Exterior [ ] Part. Interior [ ] Interior |

BUILDING INFORMATION

Simple Building Plan

| | |
|---|---|
| No. of Stories: | |
| Storey Height $(m)$: | |
| Average Height of Upper Horizontal Spandrel $(m)$: | |
| Connection of the Walls at the Edges (Exterior): | [ ] Adequate<br>[ ] Poor |
| Wall Openings Max. Dim. $(m \times m)$: | |
| Wall Openings Total Area $(m^2)$: | |
| Opening Layout: | [ ] Opening with Vertical Alignment at Both the Edges of Façade<br>[ ] Openings with Vertical Alignment at an Edge of the Façade<br>[ ] Central Column of Opening, Vertically Aligned |
| Façade Regularity: | [ ] Regular [ ] Medium [ ] Irregular |
| Dim. Between Int. Structural Wall $(m \times m)$: | |

| | | | |
|---|---|---|---|
| Max. Thickness Ext. Walls $(m)$: | | Min. Thickness Ext. Walls $(m)$: | |
| Max. Thickness Int. Walls $(m)$: | | Min. Thickness Int. Walls $(m)$: | |

Non-Continuous Structural Wall: [ ] Yes [ ] No ⟶ Position:
Plan Regularity: [ ] Regular [ ] Medium [ ] Irregular Confidence: [ ] H [ ] M [ ] L
Height Regularity: [ ] Regular [ ] Medium [ ] Irregular Confidence: [ ] H [ ] M [ ] L
Drawings: [ ] Yes [ ] No [ ] Structural [ ] Architectural?⟶ Attached File Name:

| ROOF INFORMATION | | Unk | Confidence |
|---|---|---|---|
| Type: | [ ] Flat [ ] Mono Pitch [ ] Multi Pitch [ ] Gable | [ ] | H M L |
| Slope (°): | Soffit Width $(m)$: Mean Roof Height $(m)$: | [ ] | H M L |
| Truss (Inc. Purlin) Material: | [ ] RC Slab [ ] Timber [ ] Steel [ ] Other | [ ] | H M L |
| Panel Material: | [ ] Timber [ ] Steel [ ] Other Thickness $(mm)$: | [ ] | H M L |
| Fastener Type: | [ ] Screw [ ] Nail [ ] Other | [ ] | H M L |
| No. of Purlins: | No. of Fasteners Per Purlin Bay: | [ ] | H M L |
| Fastener Dia. $(mm)$: | Fastener Penetration $(mm)$: | [ ] | H M L |
| Roof-Wall Connection: | [ ] Simply Supported [ ] Pinned [ ] Fixed Support | [ ] | H M L |
| Roof-Wall Fastener: | [ ] Metal Plate Connector [ ] Single Hurricane Tie<br>[ ] Toe Nails [ ] Double Hurricane Tie | [ ] | H M L |
| Ornaments Type: | Material: Dimension $(m \times m)$: | [ ] | H M L |

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| STRUCTURAL INFORMATION | | Unk | Confidence |
|---|---|---|---|
| Material of Lateral Resisting System: | [ ] Reinforced Concrete [ ] Masonry [ ] Timber<br>[ ] Steel [ ] Other: | [ ] | H M L |
| Type of Lateral Load Resisting System: | [ ] Frame Masonry [ ] Dual System [ ] Shear Wall<br>[ ] Confined Masonry [ ] Bracing<br>[ ] Reinforced [ ] Other: | [ ] | H M L |
| Structural Condition: | [ ] Poor / Deteriorated [ ] Good / Fair [ ] Excellent / New | [ ] | H M L |
| Environmental Exposure: | [ ] Dry Environment [ ] Aggressive Chemical Environment<br>[ ] Moisture or Wetting [ ] Saturated Salt Air | [ ] | H M L |
| Foundation Type: | [ ] Deep [ ] Superficial [ ] Not Accessible Note: | [ ] | H M L |
| Diaphragm Type: | [ ] Timber [ ] Concrete | [ ] | H M L |
| Load Distribution: | [ ] One-Way Spanning [ ] Two-Way Spanning | [ ] | H M L |
| Diaphragm-Wall Connection: | [ ] Simply Supported [ ] Steel Bars [ ] RC Ring Beam | [ ] | H M L |
| Retrofitting: | [ ] Yes [ ] No Description: | [ ] | H M L |
| Modifications: | [ ] Yes [ ] No ⟶ Position:<br>[ ] Addition of Stories [ ] Extension of Plan<br>[ ] Wall Opening Framing<br>[ ] Steel Frame Opening ⟶ Position: | [ ] | H M L |
| Vulnerability Factors: | [ ] Balconies<br>[ ] Parapet<br>[ ] Gable<br>[ ] Pounding<br>[ ] Mass Irregularity<br>[ ] Built on Slope<br>[ ] Built on Stilts<br>[ ] Other:<br>[ ] Short Column<br>[ ] Strong Beam-Weak Column<br>[ ] Soft Storey<br>[ ] Roof Thrust ⟶ Length x Height (m):<br>[ ] Vaults / arches ⟶ Length x Height (m):<br>[ ] Connection Between Orthogonal Wall (Interior): H M L<br>[ ] Existing Cracks ⟶ Info: | | |

| MASONRY | | | |
|---|---|---|---|
| Masonry Type: | [ ] Chaotic Stone [ ] Masonry with Hewn Blocks<br>[ ] Hollow Brick [ ] Regular Sized Stone<br>[ ] Soft Stone Block<br>[ ] Squared Stone Blocks<br>[ ] Solid Brick Masonry and Lime Mortar<br>[ ] Hollow Brick with Cement Mortar<br>[ ] Hollow Brick without Mortar in Vertical Joints<br>[ ] Concrete Blocks or Expanded Clay Blocks<br>[ ] Concrete Hollow Blocks | [ ] | H M L |
| Mortar Type & Thickness: | [ ] Cement [ ] Mud<br>[ ] Mud with Cement [ ] Lime<br>[ ] Lime with Bricks [ ] Other: Thickness $(mm)$: | [ ] | H M L |

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| | | | |
|---|---|---|---|
| Maintenance: | [ ] Low [ ] Medium [ ] High | [ ] | H M L |
| Water Infiltration: | [ ] Low [ ] Medium [ ] High | [ ] | H M L |
| Mortar Loss: | [ ] Low [ ] Medium [ ] High | [ ] | H M L |
| Transversal Connection Quality: | [ ] Low [ ] Medium [ ] High | [ ] | H M L |
| Average Size of the Units $(mm)$: | | | |
| Wall Tie Presence: | [ ] Yes [ ] No | [ ] | H M L |
| No. of Leaves: | [ ] Single-Leaf [ ] Multi-Leaf No. of Header Courses: | [ ] | H M L |
| Wall Core: | [ ] Yes [ ] No Quality: [ ] Poor [ ] Thick [ ] Good | [ ] | H M L |
| Masonry Improvements: | [ ] Mixture Injection [ ] Concrete Jacketing | [ ] | H M L |
| Material Test Results: | Attached File Name: | [ ] | H M L |

| CONCRETE / CONFINED MASONRY | | | |
|---|---|---|---|
| No. of Frames: | X: Y: (If ≠ 0, Fill Rows Below) | [ ] | H M L |
| Beam section $(m \times m)$: | | [ ] | H M L |
| Column section $(m \times m)$: | | [ ] | H M L |
| Reinforced Bars: | [ ] Deformed [ ] Smooth | [ ] | H M L |
| Infilled: | [ ] Yes [ ] No [ ] Confined Masonry | [ ] | H M L |
| Infill Wall Material: | [ ] Timber Plates [ ] Concrete Block [ ] Brick<br>Thickness $(mm)$: [ ] Other: [ ] Adobe | [ ] | H M L |
| Mortar Type: | [ ] None [ ] Cement [ ] Lime [ ] Mud | [ ] | H M L |

Confidence: Unk=Unknown, H=High, M=Medium, L=Low Any extra comments can be added on the back of the sheet.

Notes: Vulnerability factors

| | |
|---|---|
| a. Short column | At least 20% of the columns in the same Lateral Resisting System (LRS) have a height/depth ratio less than 50% of the average height/depth at that level |
| b. Pounding | The building is closer than 0.2 m from an adjacent building |
| c. Soft storey | Infills are missing at a one level |
| d. Strong Beam-Weak column | The beams are evidently stronger than the columns to which they are connected |
| e. Built on Slope | There is a sensible grade change from one side of the to the other |
| f. Plan irregularity | 1) The LRSs do not appear relatively well distributed in plan in either or both directions<br>2) Two or more LRSs are not orthogonal to each other<br>3) Re-entrant corners exceed the 25% of the plan dimension<br>4) There is an opening in the diaphragm with a width over 50% of the total diaphragm width at that level |
| g. Elevation Irregularity | 1) The storey height is not sufficiently uniform<br>2) Vertical elements of the LRS at upper stories are inboard of those at lower stories |
| h. Mass Irregularity | The area of a given storey is substantially different from the adjacent one |

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Fig. 1 – CHeRiSH RVS form.

## 2.3. The CHeRiSH seismic prioritization index

The CHeRiSH seismic risk prioritization index $I_S$ consists of two components: a baseline score $I_{BL}$ and a performance modifier $\Delta I_{PM}$, that is,

$$I_S = I_{BL} + \Delta I_{PM}. \quad (1)$$

The baseline score calculation is based on the fragility curves available in the HAZUS model [18], that express the seismic performance of archetype buildings. These fragility curves are classified based on four basic parameters: *material*, *basic structural system*, *building height* and *seismic code level*. In particular, the definition of the *seismic code level* is based on the indications provided by the Uniform Building Code 1994 (UBC-1994) [19]. The Philippines have adopted seismic provisions which are consistent with the recommendations of the UBC 1994, this justifies the use of the HAZUS model as a starting point for the definition of the proposed seismic risk prioritization index. The calculation of $I_{BL}$ requires the selection of a target damage state (DS), a set of building classes (characterized by a combination of the basic parameters), and one or more hazard levels (expressed in terms of the considered intensity measure (IM)). The hazard level must be selected based on the seismicity of the considered building portfolio/geographic area and the considered performance objective. The DS exceeding probability for each considered building class can then be computed for different IM level(s) from the HAZUS fragility curves. Baseline scores are finally derived in order to be proportional to such exceeding probabilities after a rescaling in the range [1%, 50%] based on the minimum $P_{HAZUS,min}$ and maximum $P_{HAZUS,max}$ DS exceeding probability in the complete (non-filtered) HAZUS database,

$$I_{BL} = \left(\frac{50-1}{P_{HAZUS,max}-P_{HAZUS,min}}\right)\left(P_{HAZUS} - P_{HAZUS,min}\right) + 1. \quad (2)$$

where, $P_{HAZUS}$ is the DS exceeding probability of the considered building. The performance modifier represents the perturbation of the baseline score due to the presence of vulnerability factors. Its calculation requires the definition of secondary parameters selected with respect to the construction features of the investigated portfolio in order to complement the information in the HAZUS fragility curves. The baseline score provides the (conditional) seismic risk of a given building class, while the secondary parameters are related to building-specific vulnerability factors.

The performance modifier is calculated as weighted average of the scores assigned to various secondary parameters belonging to four macro-categories. These latter account for the material quality, the out-of-plane local mechanisms, global (in-plane) behaviour and presence of façade ornaments. These factors determine the seismic performance of a URM building (e.g., , Sorrentino et al. [20], Lagomarsino et al. [21]) and they interact each other. The quantification of the *Material Quality* is based on the *Masonry Typology* (e.g., Chaotic stones, Solid brick masonry with lime mortar, Concrete blocks) and the *Masonry Degradation*. If the *Material Quality* is not sufficiently high, the structure cannot develop the so-called out-of-plane local mechanisms [22]. Therefore, this parameter must be considered more important than the others. The *Local Behaviour* is the second most important macro-category. Indeed, if out-of-plane local mechanisms are not avoided, the structure cannot behave as a unique fabric. When the material quality is sufficient and the out-of-plane local mechanisms prevented, then the *Global Behaviour* can be studied and it is clearly more important than the presence of non-structural *Façade Ornaments*.

The secondary parameters collected within each macro-category have been selected based on the fundamental rules of masonry structure design [23] and the commonly observed post-earthquake damage on URM structures. Parameters related to the geometry and the regularity of the façade (*Opening Layout*, *Wall Slenderness*, *Façade Regularity* and *Opening Area*) as well as those related to connections (*Wall-to-Wall connection*, *Wall-to-Diaphragm connection* and *Wall-to-Roof connection*) are then considered for the definition of the *Local Behaviour*. It is well known that the activation of out-of-plane local mechanisms is strictly linked to the geometry of the piers, the connection with orthogonal walls, diaphragms and roof. Filipino CH portfolio is characterised by buildings with regular opening layouts but various diaphragm typologies. Therefore, in this study, the presence/quality of connections is valued more important than the geometry/regularity of the facades. Regularity (*Plane Shape* and *Storey Height Uniformity*) and vulnerability factors (*Added Storeys*, *Pounding* and *Unfavourable Soil*) are used to quantify the *Global Behaviour* of URM buildings. Filipino CH assets are usually regular buildings, so greater importance is assigned to vulnerability factors, such as *Pounding* and *Unfavourable Soil*. The performance modifier is then defined as,

$$\Delta I_{PM} = \frac{1}{2}\sum_{m=1}^{M} w_{MC,m} \sum_{n=1}^{N_m} w_{SP,n} SCORE_{seismic;m,n} \qquad (3)$$

where $w_{MC,m}$ is the $m$-th macro-category weight, $w_{SP,n}$ is the $n$-th secondary parameter weight and $SCORE_{seismic;m,n}$ is the score associated to the status of the $n$-th secondary parameter within the $m$-th macro-category. Expert judgments are used to calibrate the weights of Eq. (3), while the AHP is applied to transform expert judgments into quantitative weights. The decision matrix adopted in this study reflects the characteristics of the Filipino CH assets and the expert opinion of the authors (academic and professional engineers across the UK and the Philippines); it should be calibrated before the entire procedure can be applied for the analysis of different building portfolio. As an example, Table 1 reports scores, weights and alternatives related to the macro-categories and secondary parameters of URM buildings, further details can be found in Sevieri et al. [24].

## 2.4. Combination of risk prioritization indices and CH asset value

Prioritization indices related to different hazards must be properly combined to derive a comprehensive indicator of the relative multi-hazard risk of the assets within the portfolio under investigation. In this study, the multi-hazard risk prioritization index $I_{multi}$ is calculated as the Euclidian norm of the vectors whose components are the $k$ single-hazard prioritization indices $I_k$,

$$I_{multi} = \sqrt{\textstyle\sum_k I_k^2}. \tag{4}$$

Table 1 – Macro-categories and secondary parameters for URM buildings: alternatives, scores and weights.

| **Macro-category** | $w_{MC}$ | **Secondary Parameters** | $w_{SP}$ | **Alternatives** | **Scores** |
|---|---|---|---|---|---|
| Material Quality | 0.4607 | Material Typology | 0.5 | Chaotic stones | 100 |
| | | | | Hollow brick / Regular sized Stone | 50 |
| | | | | Solid brick masonry and lime mortar / Concrete blocks | 0 |
| | | Material Degradation | 0.5 | Significantly affecting performance (Poor structural condition) | 100 |
| | | | | Moderately affecting performance (Good structural condition) | 50 |
| | | | | Not affecting performance (Excellent structural condition) | 0 |
| Local Behaviour | 0.2894 | Opening Layout | 0.0582 | Opening with vert. alignment at both edges of the façade | 100 |
| | | | | Opening with vert. alignment at only one edge of the façade | 50 |
| | | | | Opening with vert. alignment at the centre of the façade | 0 |
| | | Wall Slenderness | 0.0346 | High ($h/l \geq 10$)$^*$ | 100 |
| | | | | Medium ($5 \leq h/l \leq 10$) | 50 |
| | | | | Low ($h/l \leq 5$) | 0 |
| | | Façade Regularity | 0.0975 | Irregular (openings are not aligned) | 100 |
| | | | | Medium (openings are vertically aligned) | 50 |
| | | | | Regular (openings are horizontally and vertically aligned) | 0 |
| | | Opening Area | 0.0468 | High (more than 50% of the total façade area) | 100 |
| | | | | Medium (between 25% and 50% of the total façade area) | 50 |
| | | | | Low (less 25% of the total façade area) | 0 |
| | | Wall-to-Wall Connection | 0.1923 | Poor | 100 |
| | | | | Adequate (mechanical connection) | 0 |
| | | Wall-to-Diaphragm Connection | 0.3696 | Poor | 100 |
| | | | | Adequate (ring beam) | 0 |
| | | Wall-to-Roof Connection | 0.2010 | Poor | 100 |
| | | | | Adequate (mechanical connection) | 0 |
| Global Behaviour | 0.1901 | Plan Shape | 0.1732 | L-shape or irregular | 100 |
| | | | | C-shape | 50 |
| | | | | Rectangular or regular | 0 |
| | | Storey Height Uniformity | 0.1125 | Significantly non-uniform (more than 0.5m difference) | 100 |
| | | | | Moderately non-uniform (difference between 0 and 0.5 m) | 50 |
| | | | | Uniform | 0 |
| | | Added Storeys | 0.1021 | Yes | 100 |
| | | | | No | 0 |
| | | Pounding | 0.4307 | Pronounced (less than 0.1m gap) | 100 |
| | | | | Moderate (gap between 0.1m and 0.2m) | 50 |
| | | | | None (more than 0.2m gap) | 0 |
| | | Unfavourable Soil | 0.1815 | Yes (very soft soil; liquefaction is not explicitly considered) | 100 |
| | | | | No | 0 |
| Façade Ornaments | 0.0598 | | | Yes | 100 |
| | | | | No | 0 |

Even if the single-hazard risk prioritization indices must be defined within the same interval of variation, the resulting multi-hazard risk prioritization index requires to be finally rescaled. This can be done in any other desired range without affecting the prioritisation list of the considered building portfolio. The proposed combination rule does not introduce any further subjectivity into the framework, and it can be applied even when numerous hazards are considered. However, this method does not consider neither the interaction of different hazards at the various levels of the risk assessment chain nor weights for the different hazard prioritization indices.

The CH intangible value is finally integrated within the prioritization scheme through the definition of an index $I_{CH\ value}$ which expresses the significance as “monument” of CH assets. This simplified approach assumes that the tangible values (direct and indirect costs) is constant for the entire portfolio, so that it does not affect the prioritization scheme. Whereas, the intangible value is peculiar to each specific CH asset, and then it cannot be considered constant for the entire portfolio. A score approach based on the classification issued by Kerr [11] is adopted for the calculation of $I_{CH\ value}$. Four categories are then considered for the definition of the scores: *Word Heritage* ($I_{CH\ value} = 1$), *National Heritage* ($I_{CH\ value} = 0.5932$), *National/Local Heritage* ($I_{CH\ value} = 0.3426$) and *Local Heritage* ($I_{CH\ value} = 0.2042$).

The expert judgments adopted in this study to express the relative importance of each category as well as the criteria that define the significance of specific CH asset can be found in Sevieri et al. [24]. They are calibrated in order to reflect the idea that the intangible value increases with the significance of the analysed CH asset. The multi-hazard risk prioritization index which considers the CH value $I_{multi,CH\ value}$ is then calculated as,

$$I_{multi,CH\ value} = I_{multi} I_{CH\ value} \tag{5}$$

## 3. Case-study: cultural heritage assets in Iloilo City, Philippines

### 3.1. Data collection

The proposed multi-hazard framework for risk prioritization of CH assets has been tested on 25 CH buildings located in Iloilo City, Philippines (Fig. 2), one of the most important touristic hubs in the country, which contains a collection of historic sites, monuments, and CH buildings. Realizing the importance of preserving its heritage, the city government has actively pursued the advocacy of promoting the city's culture, by identifying heritage zones and instituting a Heritage Conservation Council to oversee and promote CH preservation. Iloilo City is listed under Seismic Zone 4 in the official seismic map of the Philippines by the Philippine Institute of Volcanology and Seismology [25]. The seismic hazard in Iloilo City (in terms of PGA with a 10% of probability of exceedance in 50 years) is in the range 0.35g to 0.55g [26]. The city is also situated in Zone II of the Philippines Wind Zone Map (i.e., the three-second gust speed at 10m above the ground is equal to 117 km/h by assuming a return period of 50 years). Therefore, Iloilo City is a perfect case study to show the feasibility of the proposed approach. The analysed building portfolio is composed of URM and RC frame-type structures, whose construction years are dated around the beginning of the last century. The Iloilo City CH assets also experienced catastrophic events (e.g., earthquake and fire), during their operational life, which led to their partial or total reconstruction.

New technologies have played a fundamental role in helping surveyors during the data collection. In particular, drones have been extensively used for façade and roof inspections. Most of the roofs were inaccessible and/or characterised by a high degradation level (Fig. 2). Therefore, the drone was the only practicable tool for collecting roof data/information. The photos in Fig. 2 were taken by the drone. The only limitation on their use was the strong wind during the fieldwork, which affected the flight capability. This important aspect must be considered when a survey campaign has to be organized in a cyclonic region.

Photogrammetry is another powerful tool that helps surveyors to speed up the data collection. It allows for the construction of exterior point clouds of building façades through the elaboration of pictures taken by smartphone and photo camera. Therefore, surveyors do not need to take measurements of the building during the fieldwork, but they can elaborate point clouds once in the office. This is key when the assets under investigation are located in complex/crowded urban contests where measurements cannot be easily acquired. Photogrammetry requires high quality pictures of the façades with a specific overlapping, according to the software used during the elaboration step. A good quality point cloud can be obtained only if the façade is clear enough of obstacles, such as cars and people. This aspect must be considered during the planning phase of the survey campaign. Ideally, the pictures needed for photogrammetry should be taken during the hours in which there is less traffic, usually early morning.

ID 01-001 ID 01-002 ID 01-003 ID 01-004 ID 01-005
ID 01-006 ID 01-007 ID 01-008 ID 01-009 ID 01-010
ID 01-011 ID 01-012 ID 01-013 ID 01-014 ID 01-015
ID 01-016 ID 01-018 ID 02-001 ID 02-002 ID 02-003
ID 02-004 ID 02-005 ID 02-006 ID 02-007 ID 02-008

Fig. 2 – Surveyed CH assets, Iloilo City, Philippines.

Most of the surveyed CH assets are two-story, plan-regular buildings, somehow justifying their good performance during extreme events (e.g., the M7.8 1948 Lady Caycay earthquake). The surveyed buildings are located within a complex urban context, in fact they are parts of blocks with different shapes and compositions. Degradation and lack of maintenance are widely diffused among the CH assets under study, thus affecting their structural performances. Most of the structure deficiencies are due to a poor quality of the construction materials. The unusual large dimension of the aggregates together with an extreme heterogeneity in their distribution within the structural elements are the main causes of the bad performance of the materials. Most of them (i.e., 60%) show degradation levels that can moderately affect the building performances (e.g., presence of small cracks concentrated on a limited number of structural elements and/or infill panels, and/or limited damage of the roof). Whereas, 36% of the considered assets shows structural conditions which may significantly affect the building performance, such as widespread cracks on structural elements, concrete cover crushing with rusty rebars and extended damage of the roof.

Vulnerability factors of different natures have also been observed during the fieldwork. Potential for pounding and the presence of short columns can be commonly found among the surveyed CH assets. This fact can be explained by the use of obsolete codes during the design and construction of these assets. Another reason that can partially justify the potential for pounding is the high annual population growth rate in Iloilo City, that has led to construction in all the available space, without concern for the distance between buildings.

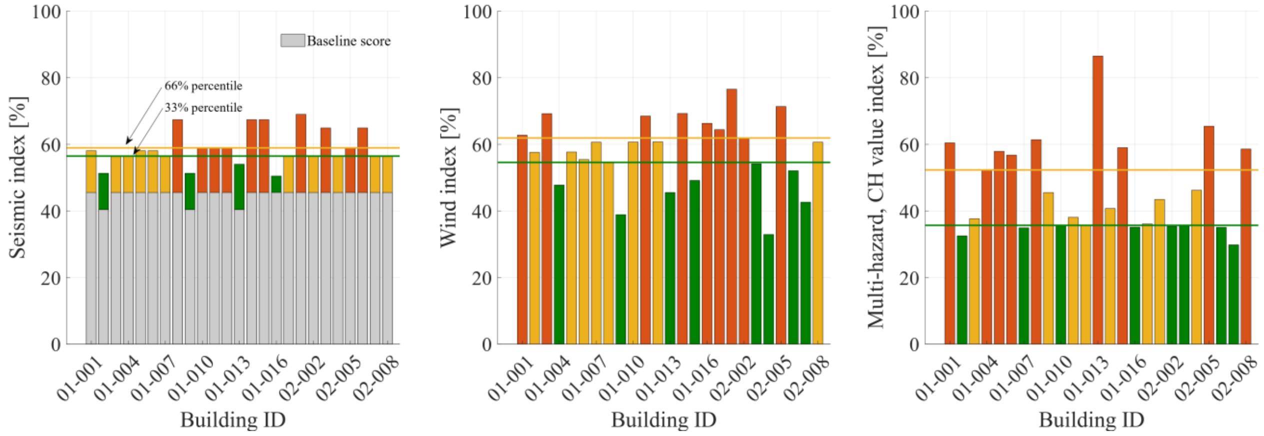
Various typologies of roof made of different construction materials have been also found. Flat roofs are mainly made of concrete, while gable, mono- and multi-pitch ones are generally characterised by a timber structure and metal roof sheets. An advanced degradation level affects the elements of the roofs, the structure and also the connections, i.e. fasteners and roof-to-wall connections, thus further increasing their vulnerability.

### 3.2. Prioritization scheme

The collected data have been finally used for the calculation of the CHeRiSH seismic risk prioritization index and the wind risk prioritization index proposed by Sevieri et al. [24]. Splitting the resulting prioritization indices into groups can help an analyst to better understand the prioritization scheme. In this study, three categories, “green, yellow and red tags” respectively, are arbitrarily selected. In particular, the two thresholds that define the three categories are assumed equal to 33% and 66% for the calculated seismic, wind or multi-hazard indices. The definition of such thresholds is essentially a subjective (often political) choice that shapes the prioritization scheme, based for instance on resources availability.

The seismic risk prioritization indices (Fig. 3a) show fairly homogeneous baseline scores (grey bars). In fact, most of the surveyed CH assets are regular RC frame structures built before the 1970 with common construction features. Fig. 3a also highlights the important role of the performance modifiers, representing the vulnerability factors, in the definition of the seismic prioritization scheme. The analysed CH assets show common vulnerability factors, in particular potential for pounding, and diffused degradation. These increase the values of the seismic risk prioritization indices, only four assets are in fact below the 33-th percentile. This also leads to a relatively small variability of the results. Due to relatively small extension of the survey area, the same soil conditions are assumed for all CH assets. The wind risk prioritization indices (Fig. 3b) show a higher variability if compared with the seismic ones. This is mainly due to the different construction features and degradation conditions of CH asset roofs. Highly degraded roofs are strongly penalised by the scores considered in this study, and so structures with the worst maintenance conditions show the highest values of the wind risk prioritization indices.

The multi-hazard prioritization indices which consider the CH intangible values (Fig. 3c) are finally calculated. In order to assess the validity of the proposed procedure, the analysed CH assets are assumed to be characterised by *local significance*, except for the building 01-013, one of the assets which behave better, whose significance is considered recognised at *national level*. Their trend is the same of the wind prioritization index, which in this study plays a substantial role in determining the prioritisation scheme, but the relative position of building 01-013 changes. This simple example shows that if the intangible value of CH assets within a given portfolio is not homogeneous it can drive the prioritization scheme.



a) b) c)

Fig. 3 – Prioritization indices: a) Seismic risk prioritization index; b) Wind risk prioritization index; c) Multi-hazard risk prioritization index which considers the CH intangible value.

## 4. Conclusions

This paper presents the multi-hazard risk prioritization framework for CH assets developed within the *Cultural Heritage Resilience & Sustainability to multiple Hazards* (CHeRiSH) project, which aims to develop a multi-level, harmonized, and engineering-based risk and resilience assessment framework for CH assets in the Philippines exposed to multiple natural hazards. To this aim, an ad-hoc RVS form designed for CH assets has been introduced. Once new detailed information is available the multi-level architecture of the proposed RVS form enables the estimation of the structural fragility and risk to be improved. At the lowest refinement level (the main focus of the paper), the data gathered in the RVS form are used for the calculation of the seismic and wind prioritization indices. They represent empirical proxies for the relative risk of CH assets within the analysed portfolio and then they can be used only for prioritization purposes.

The proposed seismic risk prioritization index extended the one developed within the INSPIRE project to the case of URM buildings. It consists of two parts: a baseline score and a performance modifier. The baseline score calculation is based on the HAZUS model fragility curves, while the performance modifier is computed as weighted summation of scores related to macro-categories and secondary parameters, which, if present, are deemed to jeopardise the building performance. The macro-categories express the seismic failure chain peculiar of URM buildings. Each of them contributes to the calculation of the performance modifier through secondary parameters which express specific structural features which can prevent or promote the activation of failure mechanisms, as observed during post-earthquake surveys.

A simple method to combine risk prioritization indices related to different hazards and which allows considering the intangible value of CH assets has been finally introduced. The multi-hazard risk prioritization index is calculated as the Euclidian norm of the vector whose components are the single-hazard prioritization indices. The intangible CH asset value is considered by multiplying the multi-hazard risk prioritization index by a score that account for the significance of the asset as CH.

The Analytic Hierarchy Process has been extensively used to calibrate combination weights and scores, thus reducing the subjectivity involved in the procedure. The application of the proposed prioritization framework on the CH assets of Iloilo City, Philippines, has shown its feasibility in practice. Findings from the fieldwork highlight the important role played by the widespread vulnerability factors, strongly affecting the performance of the surveyed CH assets. The case study highlighted the need of considering the intangible value of CH assets within prioritization procedures.

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