

# Learning from past earthquakes: a comparative analysis and unified framework for proactive seismic risk management of vernacular heritage in historic urban landscapes

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## ABSTRACT

Seismic hazard has historically shaped vernacular construction traditions that embody empirical knowledge accumulated through successive earthquake experiences. However, post-earthquake reconnaissance practices often remain reactive and insufficiently integrated into long-term risk mitigation strategies, particularly in the context of Historic Urban Landscapes. This article discusses the role of systematic post-disaster damage and loss documentation in fostering proactive seismic risk management tools for vernacular architectural heritage. Drawing on comparative experiences from Mexico, Chile, Italy, and Croatia, the study examines how major earthquakes have influenced regulatory frameworks and post-event assessment methodologies. The analysis highlights recurrent challenges, including data dispersion, limited institutional coordination, and pro-demolition biases affecting vernacular architecture heritage. It also identifies good practices, such as the development of structured digital databases, GIS-based reconnaissance systems, and vulnerability modelling employing parametric and machine-learning methods. The article argues that aligning post-earthquake surveys with international frameworks such as the Sendai Framework for Disaster Risk Reduction and the Post-Disaster Needs Assessment methodology can enhance interoperability, improve data quality, and foster international cooperation. Building on this comparative analysis, the article proposes the Resilient Vernacular Heritage (RVH) framework, an integrated conceptual structure articulated around four interdependent pillars (pre-event baseline, tiered reconnaissance, interoperable data architecture, and knowledge reuse) and operationalised through a standardised, additive four-tier reconnaissance model, a set of five interoperability indicators, and a transferable, phased methodological roadmap. By shifting from

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reactive emergency response to organised knowledge generation, post-seismic reconnaissance can become a cornerstone of long-term resilience, safeguarding both the material fabric and the cultural capital of historic urban landscapes.

## 1. Introduction

Seismic hazard shapes human settlements. Proof of that are the numerous vernacular construction typologies that have been developed over generations and are core components of urban landscapes. For the purpose of this work, the concept of vernacular architectural heritage is adopted for describing any building constructed using traditional techniques, based on the *genius loci*, without following contemporary seismic design codes.

In earthquake prone regions, vernacular architectural heritage materialises seismic-related traditions. The empirical knowledge obtained by observing the success and failure of structures has shaped our historical cities and has a long-standing tradition in the fields of structural and earthquake engineering [1]. This need to learn from post-event scenarios is still present in our cultures as an object of scientific research to understand the components of seismic risk: hazard (as a function of intensity and likelihood), exposure (the assets that are prone to loss or damage in case of a seismic event) and vulnerability (the expected impact due to and the ability to cope with that event) [2].

Since current science is still unable to predict when an earthquake will occur in a specific region, adequate preparedness is critical for mitigating its potential adverse effects. However, no effective levels of preparedness can be attained without a thorough and accurate comprehension of the likely impacts of future earthquakes on the exposed elements, which, in turn, cannot be achieved without looking at and learning from the effects of past events. Tracing back post-seismic scenarios is meaningful for promoting societal awareness towards seismic hazards and fostering adaptation and innovation towards safer built environments. This learning operates at multiple, interconnected levels: at the social level, by building risk awareness and encouraging the maintenance of existing structures; at the scientific and technical level, by generating empirical evidence to validate and improve assessment, retrofitting and predictive vulnerability modelling methodologies; and at the institutional level, by informing regulatory frameworks and policy decisions that govern the built environment, and by providing the technical and cultural arguments needed to counteract pro-demolition attitudes and safeguard the intangible values embedded in vernacular construction traditions.

### 1.1. From empirical observations to scientific surveys

Post-earthquake damage assessment is commonly performed through a hierarchy of procedures that differ in scale, purpose, required expertise, and level of detail. The need to systematise and characterise large-scale damage scenarios can be traced back in time, at least, to the Great Lisbon Earthquake of 1755, which left an unprecedented level of destruction and damage [3]. This event not only fostered the development of a novel seismic-resistant construction technique (the “Gaiola pombalina”) but was also key to the early development of seismology as a science [4]. A qualitative and descriptive survey of sixty questions (Parochial Memories of 1758) was performed in all parishes throughout the country as an early attempt to understand the extent of the damage not only caused by the earthquake itself but also by its cascading effects, which included a tsunami and massive urban fires [5,6]. This survey consisted of three main sections addressing the settlement (location, population, infrastructure, damaged constructions), the landforms (such as soil, minerals, water sources, agricultural production) and rivers (navigability, exploitation, physical characteristics). All this information was expected to provide a better description of the nature of earthquakes and their consequences in different environments throughout the Iberian Peninsula.

Several post-earthquake assessment frameworks have been developed internationally, ranging from rapid safety tagging procedures to detailed vulnerability and damage classification methods. Usability assessment systems are primarily intended to support immediate decisions on occupancy, whereas macroseismic damage scales, such as EMS-98 [7], provide a more structured description of damage grades at the building or typological level. Within this context, the Italian AeDES procedure represents one of the most widely documented examples of a standardised first-level post-earthquake form, combining information on building characteristics, observed damage, external hazards, short-term countermeasures, and usability outcomes. Similarly, FEMA rapid assessment procedures [8], including rapid visual screening and post-earthquake safety evaluation approaches, provide structured tools for identifying potentially unsafe buildings and prioritizing further inspection. However, both types of procedures are primarily intended for rapid classification and emergency decision-making, rather than for a detailed quantification of residual structural capacity. In response to these limitations, and supported by rapid technological advances, the range of available tools for recording post-seismic scenarios has expanded considerably in recent decades [9].

Nowadays, there is a wide variety of resources and means to record post-seismic scenarios: from standardised onsite parametric surveys [10] to more sophisticated surveying procedures based on remotely sensed data (e.g., photogrammetry and laser-scan point clouds) or Digital Image Correlation, just to name a few [11]. Nevertheless, the capacity to acquire large amounts of data implies the need for a critical discussion about its scope, usability, and extent. The (often) reactive nature of post-seismic surveys makes adopting systematised approaches challenging. Moreover, the instruments and records frequently result in a heterogeneous set of dispersed data. Finally, recent events worldwide demonstrate that post-event reconnaissance activities have rarely contributed to the development of databases or comprehensive scenarios crucial for informing future risk mitigation strategies, whether through the identification of vulnerabilities and implementation of effective risk mitigation measures or through the organised and systematic provision

of information necessary for the validation and calibration of assessment methodologies [12].

## 1.2. Aim of this work

Building on the above, this article discusses the need for establishing robust post-event reconnaissance frameworks not only for immediate response but also for long-term planning and resilience-building efforts. By revisiting past earthquake events in countries as diverse as Mexico, Chile, Italy, and Croatia, it aims to demonstrate the pressing need to shift from reactive disaster scenarios toward organised scientific knowledge and to discuss the potential impacts of this change on resilience and risk mitigation.

Because the experience accumulated in several past events shows that recording post-earthquake damage to masonry vernacular heritage is particularly challenging, this work will focus specifically on that typology of buildings. This choice is further supported by these buildings' high intrinsic seismic vulnerability and global prevalence. In fact, most vernacular heritage assets worldwide is made of masonry [13–15].

Finally, the role of standardised post-event scenario reconnaissance and characterisation in fostering international cooperation is discussed. Effective international collaboration in disaster response and recovery depends on unified methods for quantifying post-disaster needs and assessing the extent of damage. This discussion presents and evaluates current practices in the field, focusing on the significance of vernacular heritage losses within the broader context of post-disaster assessment.

To go beyond this comparative discussion and move from the diagnosis of recurrent shortcomings to an operational response, a Resilient Vernacular Heritage (RVH) conceptual framework for proactive seismic risk management in vernacular heritage is also proposed herein. This framework includes a standardised tiered reconnaissance model, a set of interoperability indicators that translate the framework into measurable practice, and a transferable, phased methodological roadmap for implementation across heterogeneous institutional contexts. Alongside, a set of recommendations and prioritised research directions intended to support near-term institutional adoption are also proposed. This framework is detailed in Section 4 and synthesizes the main outcomes of the comparative analysis (Section 2) and the discussion of the role of post-disaster surveys in international cooperation (Section 3).

## 2. Local experiences in different seismic environments

This section presents the experiences and developments of post-earthquake reconnaissance approaches in four countries where vernacular buildings face significant seismic risk. Two American countries, Mexico and Chile, have been selected to illustrate how seismic events have shaped the design and conservation of vernacular architecture, pre-event preparedness and post-disaster reaction. The approaches followed to gather and use reconnaissance information are examined to identify and discuss gaps and good practices. On the other hand, two paradigmatic examples of European countries with invaluable vernacular heritage in a highly seismically active region, i.e. Italy and Croatia, are also included in this analysis as an element of comparison with the Chilean and Mexican experiences.

### 2.1. Mexico

Under Mexican federal law, any structure built before the arrival of Hispanic culture in the national territory is recognized as an archaeological monument. Structures dating from the onset of the Hispanic period until the end of the 19th century are classified as historical monuments. The preservation of both archaeological and historical monuments has been a federal legal mandate since 1972 [16]. Testimonies about seismicity in the centre of Mexico have been documented since the pre-Hispanic period. There is evidence of more than 300 earthquakes recorded from 1469 to 1912 [17]. Even though no technical information can be extracted from these documents, they testify to the importance and scale of such events [18].

In recent history, the earthquake that occurred on 19 September 1985 deserves special attention due to its long-lasting effects and impacts. This  $M_w 8.0$  event caused extensive damage and resulted in an unprecedented civil emergency. It fostered the evolution of local building codes, which included seismic design criteria and substantially increased the ductility requirements for all new structures [19].

This quake attracted public attention to discuss risk preparedness and resulted in the design of a Seismic Alert System that provides a short (ca. 60–90 s) but precious period to get prepared when a significant earthquake hits the south coast of the country [20,21]. On the prevention side, extensive educational programs were also developed to teach people how to respond in the event of an earthquake, considering different scenarios [22]. Seismic-risk awareness has reshaped several aspects of life in Mexico City since then, including education, massive public events, and transport systems [23].

However, more recent earthquakes have shown that prevention and post-seismic response still need improvement, particularly concerning vernacular architectural heritage. The analyses performed after the Tehuacán-Puebla earthquake ( $M_w 7.0$ , 15 June 1999) revealed that many churches considered Cultural Heritage by Mexican legislation were subjected to damage since they were in a poor conservation state. Some of the agents of degradation recorded in damaged cultural assets included moisture and inadequate maintenance [24].

Despite the extensive surveys carried out during the reconnaissance of damaged vernacular heritage, much of these valuable data were soon dispersed and lost. A memorandum published by the National Coordination of Conservation of Cultural Heritage recognized the inconsistencies and the lack of documents to track these surveys, less than two decades later, in 2018 [25]. This is relevant because this Coordination is part of the same institution responsible for preserving architectural heritage in Mexico, the National Institute of Anthropology and History. Overall, this document emphasises the need for effective information transference and systematic data

organization.

Some authors, such as Tena-Colunga [26], have investigated the recurrent and systematic failures in the Mexican emergency and response system. Among many other considerations, vernacular architectural heritage emerges as being trapped in a chronic cycle of degradation - due to lack of maintenance, seismic damage, and post-seismic intervention. Although this process has been observed and reported for at least 25 years, little attention is still paid to the proactive assessment of seismic vulnerabilities as a strategy to mitigate damage and losses. In addition, there is a lack of understanding and sensitivity towards heritage at risk. This situation has reached extreme levels of institutional disinformation. As an example, by spreading the notion of adobe buildings as inherently dangerous constructions rather than promoting strategies and policies to enhance the structural behaviour of this widely spread vernacular construction [27].

Another event that is worth of being mentioned is the Puebla-Morelos earthquake of September 2017 in central and southern Mexico, which caused extensive damage to vernacular architectural heritage. The reports, produced in the aftermath of this event, revealed that, in most constructions, the alerts advocating for maintenance and proactive identification of seismically vulnerable assets raised after the Tehuacán-Puebla Earthquake of 1999 were not attended [28]. The Mexican Civil Protection Authority [29] estimated 369 human losses and more than 180000 damaged houses (from which 28% was reported as total loss), whilst the Mexican Secretary of Culture estimated that some 2340 historical monuments were affected, including 1680 temples [30]. Nevertheless, the number of damaged historical housing units is still unknown. Damage among vernacular houses was particularly significant in the states of Morelos and Puebla, where adobe constructions are still common [31]. The magnitude of the damage in several settlements after the Puebla-Morelos earthquake forced immediate intervention to address a rapidly unfolding humanitarian crisis [32].

Numerous experts agree that the lack of adequate surveys and expertise in the field (e.g., structural assessments performed by military engineers rather than experts in historical constructions) led to a more pro-demolition attitude rather than recovery and repair [33]. Demolition of cultural assets has become a regular practice due to the lack of an adequate culture of appropriate structural assessments and intervention procedures [34].

Social distrust, often a symptom of the lack of preparedness and risk mitigation, limits the effectiveness of long-term actions [35]. In addition, some authors suggest that another factor contributing to the loss of vernacular heritage is the deliberate demolition of historical buildings by their inhabitants to obtain economic support and/or better housing [36]. According to professionals who were enrolled in the primary actions after the 2017 events, a significant fraction of the vernacular heritage lost following these events resulted from unnecessary demolitions [37].

The lack of a systematic and organised reaction resulted (as in 1999) in the dispersion and loss of the post-event reconnaissance documents and materials despite their generalised digitisation. Nevertheless, recent studies have demonstrated that standardised post-seismic approaches can be carried out by leveraging existing databases and catalogues. A remarkable example in Mexico is the National Catalogue of Historic Monuments, which contains more than 100.000 records of historical assets (predominantly vernacular architectural heritage).

The feasibility of feeding parametric seismic vulnerability models with the information in this catalogue was demonstrated through the analysis of post-seismic scenarios for some cities following the 2017 earthquake [38]. Such a process enabled relatively fast data acquisition based on visual evidence of damage and was sufficient to achieve reasonably accurate predictions of damage for a given seismic intensity [39]. This constitutes a valuable precedent for demonstrating the effectiveness of preventive, proactive vulnerability assessments in addressing recurrent challenges observed in the 1999 and 2017 earthquakes. Furthermore, the use of remote-sensing tools and Geographic Information System (GIS) databases (Fig. 1) served as a practical demonstration that these data can feed machine-learning-supported assessments for the early identification of vulnerable assets [10].

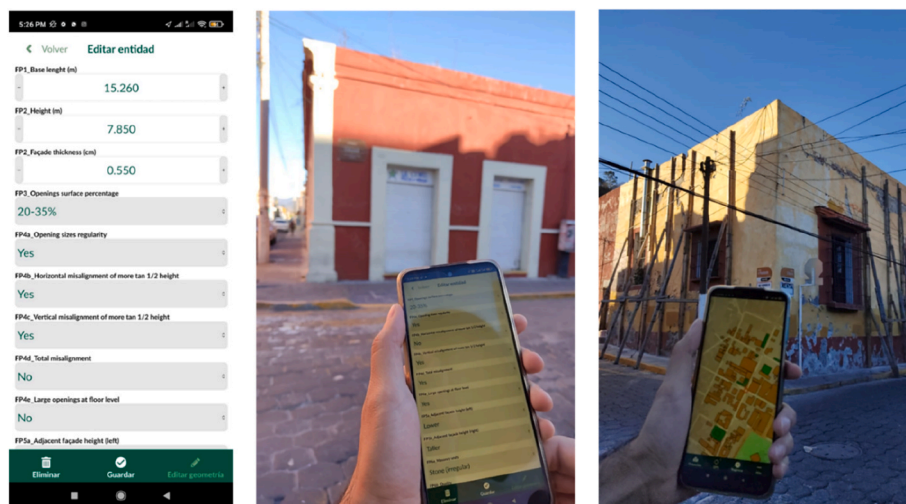


**Fig. 1.** Post-seismic damage reconnaissance in the city of Atlixco, Puebla, carried out using a mobile tool that allowed for the real-time upload of data into a GIS database.

Altogether, the situation of Mexican vernacular heritage at seismic risk, primarily protected under federal law, is challenged by a lack of post-seismic reconnaissance strategies. Even though the protection and documentation of these buildings is institutionally centralized, the National Catalogue of Historic Constructions represents an outstanding opportunity for managing vulnerability and damage information in post-seismic events. However, the absence of specific regulations and building codes oriented toward the assessment and intervention of vernacular structures [40] hinders the adoption of common reference frameworks regarding serviceability thresholds and damage, thereby facilitating demolition regardless of the reparability of seismic damage. Furthermore, the atomization of expertise and historical data related to seismic damage in historic constructions, the lack of a systematic approach to post-seismic scenarios, and the uncontrolled participation of non-expert decision-makers (e.g., military engineers) have, according to the empirical evidence presented in this section, led to an increase in loss rather than effective prevention.

## 2.2. Chile

Chile is one of the most seismically active countries in the world due to its location along the western edge of the South American Plate, where the Nazca and Antarctic Plates converge, creating subduction zones – see Fig. 2 (a). One of the earliest documented earthquakes in Chile occurred in 1570, with an estimated magnitude of 8.3 M. Centred in the city of Concepción, this event marks the beginning of the country's historical records of seismic activity. Significantly later, the 1906 Valparaíso earthquake (8.2 Mw) represented a turning point in Chile's seismic history, resulting in approximately 3000 fatalities and exposing the vulnerability of existing structures. This event prompted the installation of the first seismograph at the National Astronomical Observatory in 1908, initiating the systematic monitoring of seismic activity in Chile [41], it led to the development of construction standards and advancements in seismic engineering, laying the foundation for a more structured approach to seismic risk management.

As can be seen in Fig. 2 (b), seismic design standards and regulations in Chile have been developed based on lessons learned from past earthquakes. The 1928 Talca earthquake (7.6 Mw) marked a significant milestone, driving the introduction of construction regulations, such as the Law No. 4563 of 1929, which culminated in the enactment of the General Law and Ordinance on Construction

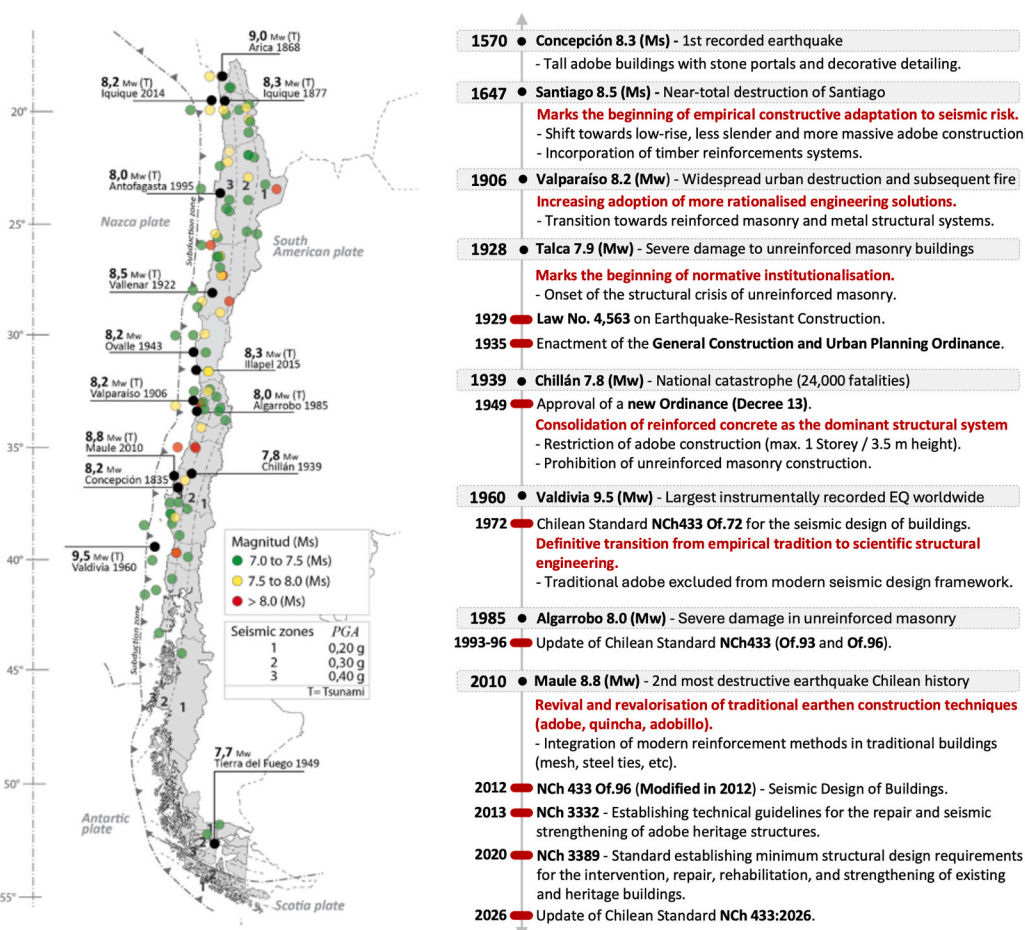


Fig. 2. (a) Major and/or Destructive Earthquakes in Chile (1570–2020), with Ms or Mw ≥ 7.0. Epicentral locations were obtained from the Chilean Seismological Centre database ([www.sismologia.cl](http://www.sismologia.cl)). (b) Evolution of Seismic Standards in Chile.

and Urbanisation in 1936 [42]. This legal framework introduced the concept of “city plans,” which determined street layouts, widths, and maximum building heights. The 1960 Valdivia earthquake (9.4 Mw), the most powerful earthquake ever recorded, led to the development of Chile's first seismic design standard. The NCh433 Of.72 standard [43] was formalised in 1972 [44] and superseded by new editions in 1993 and 1996 [45,46], which incorporated the concept of seismic zoning, assigning different levels of risk to various regions of the country. Following the 2010 Maule earthquake (Mw 8.8), which caused widespread structural damage to buildings and infrastructure, the standard was complemented by supreme decrees. In particular, Decree 61 [47] revised the seismic soil classification system, establishing six foundation soil categories with differentiated seismic behaviour and strengthening site-specific design requirements. The most recent version, NCh433:2026, consolidates these decrees into a single document, without substantially changing existing seismic design practice in Chile.

Nevertheless, seismic standards have been exclusively thought for the design of new reinforced concrete (RC), steel, reinforced masonry, and timber structures. Until 2013, traditional constructions, made of adobe, brick, stone, and rammed earth, for example, remained unregulated. After the 1906 Valparaíso (8.2 Mw) and 1985 Algarrobo (8.0 Mw) earthquakes, many of the traditional structures were retrofitted with RC, which increased the mass and stiffness of the structure and altered its seismic response; often with undesirable outcomes, including crushing, hammering and torsional effects [48]. RC strengthening interventions proved particularly inadequate for adobe structures, given the mechanical, physical and chemical incompatibility of materials, and negatively impacted the preservation of vernacular architectural heritage. According to the Inventory of Built Cultural Heritage [49] over 40% of heritage buildings in Chile, protected by the law of National Monuments [50], were built resorting to raw earth materials, primarily adobe, highlighting the vulnerability of this heritage to seismic events.

In recent history, the 2010 Maule earthquake (Mw 8.8) is recognized as one of the most devastating seismic events in Chile. The earthquake significantly impacted the central-southern region of the country, producing a rupture zone approximately 450 km long (north-south) and 150 km wide. Vertical crustal displacements ranging from 1.9 m to 2.0 m were recorded in the Arauco Peninsula [51]. This event affected a region inhabited by over 12 million people and resulted in 521 fatalities. Regarding structural damage, the earthquake destroyed 81,149 houses, of which 27% were adobe structures (Fig. 3a) [52]. Following the 2010 earthquake emergency and the need to halt unwarranted demolitions (Fig. 3b), as well as to establish a regulatory framework to include vernacular constructions in seismic standards for adobe reconstruction, the NCh3332 standard, *Intervention Standard for Earthen Heritage Buildings* [53] was developed. This standard aimed to standardise methods for damage assessment, guide interventions during the reconstruction phase, and enhance the structural safety of earthen heritage buildings.

However, the NCh3332 standard provides only general criteria, without specifying minimum requirements for structural design or the consolidation of historic earthen constructions. These issues were only addressed by the recent implementation of standard NCh3389: *Structures — Seismic Stabilisation of Historic and Existing Buildings — Requirements for Structural Design* [54], which establishes guidelines for the structural design of interventions in heritage buildings aimed at repair, rehabilitation, or restoration. This standard seeks to safeguard both the integrity of the properties and the safety of their occupants. It provides criteria for interventions in heritage structures predating current national codes, methods for analysing and evaluating their seismic performance, and requirements for seismic analysis based on construction type, materials, size, use, and expected seismic behaviour. Despite the significant innovations introduced by this standard, its application remains highly limited, and there is no empirical evidence to validate the seismic performance of heritage structures retrofitted in accordance with its guidelines.

Beyond its physical impacts, the 2010 Maule earthquake also exposed significant weaknesses in institutional frameworks and specific regulatory systems. These shortcomings were highlighted by a United Nations team that evaluated the progress in implementing the Hyogo Framework for Action (2005–2015), prompting a series of institutional and regulatory transformations [55]. The institutional framework governing cultural heritage came under significant pressure. Given the scale of the disaster, standardised tools became essential for systematically documenting damage and providing a comprehensive overview of the conservation status of national monuments in a short timeframe. The Technical Secretariat of the National Monuments Council (ST-CMN), the institution responsible for protecting and overseeing monumental heritage (Law No. 17.288, 1970), in collaboration with the Architecture



**Fig. 3.** (a) Traditional adobe buildings in Lolol damaged after the 2010 Mw 8.8 Maule earthquake in Chile. (b) Building misclassified as “Collapsed” and designated for demolition following field assessment.

As shown in Fig. 4, the form consisted of several sections: (i) building use and number of users; (ii) morphological characteristics and aggregation system typology; (iii) identification of the materials of each structural and non-structural element together with damage grading across three levels (no damage/good condition, regular condition, and damaged); (iv) condition of building services and installations; (v) summary of structural and non-structural damage (referring to the European Macroseismic Scale); (vi) description of observed damage and recommended emergency measures; and, finally, (vii) photographic record. This form was applied to 473 heritage buildings across the Metropolitan to Biobío regions. The assessment outcomes were summarised in damage reports that classified buildings as undamaged, slightly damaged, moderately affected, or severely affected. Some of this data was included in the publication *Nuestro Patrimonio Hoy* [56] aimed at securing reconstruction funding. The collected information also helped prioritise emergency stabilisation interventions and reconstruction projects through initiatives such as the Heritage Value Enhancement Programme (SUBDERE), the Heritage Recovery Support Programme (National Council for Culture and the Arts), and the Heritage Reconstruction Programme (Ministry of Housing and Urban Development).

However, the assessment process presented certain limitations. The survey was incomplete, as not all buildings were covered, and records were kept on paper, with detailed information on damage types never transferred to a digital database. This restricts their usefulness both for subsequent scientific studies and analyses and for developing predictive analyses of future events. In addition, part of the fieldwork was carried out by architecture students from different universities, with limited training, which introduced a degree of heterogeneity in the records. Despite these shortcomings, this constituted the first national effort to systematically record and georeference earthquake damage to heritage buildings and to use that evidence to prioritise interventions, laying the groundwork for the instruments that would later be refined.

It is also important to highlight that the Chilean experience of the 2010 earthquake demonstrated that traditional seismic-resistant technologies are both effective and sustainable. Although many buildings collapsed, most earthen structures remained standing, highlighting the importance of traditional knowledge and the need to preserve local construction techniques adapted to the territory's characteristics. In response, the ST-CMN published *Cartilla: Patrimonio en Tierra* [57], which provides practical guidance for property owners to protect adobe buildings from earthquakes and aftershocks. The subsequent NCh3332 Standard also provided the regulatory framework that enabled the Ministry of Housing and Urban Development (MINVU) to release reconstruction subsidies for properties built with earthen materials. However, the reconstruction process was hindered by a lack of training in traditional construction techniques among private contractors.

In 2013, the ST-CMN promoted the development of tools to assess the vulnerability of national monuments to risks such as earthquakes, fires, floods, and human interventions. However, these tools remained incomplete due to a lack of political will and insufficient resources. Since 2019, the ST-CMN has developed two damage assessment forms based on the European Macroseismic



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COODIGO: VI.1

**INFORME DE DAÑO SISMO 2010**

FECHA: 04/03/2010

ENCUESTADOR: Karina A Lagos y Miria Diaz

PROFESION ENCUESTADOR: Arquitecta

TELEFONO Y GOBIERNO ELECT:

**DATOS GENERALES**

NOMBRE EDIFICIO: Iglesia de Guasima

NUMERO REGISTRO DE DISEÑO N°: MH 00 344 del 16 / 09 / 91

MANIFIESTO EN ZONA TIPO: Zona Urbana

OCCUPACION: Plaza Parroquia de Guasima

COMUNA REGION: LA ANTONADA, ARAUCO

PROPIETARIO: ASOCIACION DE PROPIETARIOS

ADMINISTRADOR: Nombre: \_\_\_\_\_

PROFESION: \_\_\_\_\_

USO ACTUAL Y NUMERO DE USUARIOS:

| EDIFICIO          | USUARIO                     | EN CONSTRUCCION | SIN USO DESALOJADO POR SISMO |
|-------------------|-----------------------------|-----------------|------------------------------|
| CULTO             | X ESPARO, TURISMO, DEPORTE. |                 |                              |
| HABITACION        | SERVI. P. VULCOS            | ESTACIONAL      | N° DE USUARIOS DEL EDIFICIO  |
| OTRO (N° Y TIPO): | CULTURA                     | OTROS           |                              |

**MORFOLOGIA Y SISTEMA DE AGRUPIAMIENTO**

| N° DE PISOS | ALTURA (MTS) | SUPERFICIE (M2) | TIENE ANTEALCANTON |
|-------------|--------------|-----------------|--------------------|
| ABOLADO     | PARADO       | X CONTINUA      |                    |

**MUROS ESTRUCTURALES (INTERIORES Y EXTERIORES)** (pies de distintos materiales indicar porcentaje de cada uno)

| ESTRUCT. ACERO        | ALBAÑ. BLOQUE | ESTRUCT. MADERA        | MATERIALIDAD |
|-----------------------|---------------|------------------------|--------------|
| ESTRUCT. HORMA ARMADA | ALBAÑ. PIEDRA | OTROS                  |              |
| ALBAÑ. REFORZADA      | ALBAÑ. ADOS   | X ALBAÑ. ALBAÑ. SIMPLE |              |
| ALBAÑ. LIGERO         |               |                        |              |

DATOS (indicar porcentaje si corresponde)

| SIN DAÑO / BUNO | REGULAR | CON DAÑO / MALO | X |
|-----------------|---------|-----------------|---|
|                 |         |                 |   |

**MUROS NO ESTRUCTURALES (TABIQUES)** (pies de distintos materiales indicar porcentaje de cada uno)

MATERIALIDAD: NO TIENE

| ESTRUCT. ACERO        | ALBAÑ. BLOQUE | ESTRUCT. MADERA | MATERIALIDAD |
|-----------------------|---------------|-----------------|--------------|
| ESTRUCT. HORMA ARMADA | ALBAÑ. PIEDRA | OTROS           |              |
| ALBAÑ. LIGERO         | ALBAÑ. ADOS   |                 |              |

DATOS (indicar porcentaje si corresponde)

| SIN DAÑO / BUNO | REGULAR | CON DAÑO / MALO | X |
|-----------------|---------|-----------------|---|
|                 |         |                 |   |

**INSTALACIONES** (describir e indicar porcentaje si corresponde)

| DESCRIPCION    | EXISTE SERVICIO, SIN O PARCIALMENTE |
|----------------|-------------------------------------|
| AGUA POTABLE   | SI                                  |
| ALCANTARILLADO | SI                                  |
| ELECTRICIDAD   | SI                                  |
| OTAS           |                                     |
| OTROS          |                                     |

**DAÑO EN EL SISTEMA ESTRUCTURAL (MUROS, FUNDACIONES Y TECHUMBRE)**

| Sin daño Bueno                                                                      | Regular                                                                             | Con daño / Malo                                                                      | X                                                                                     |
|-------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
|  |  |  |  |

| SIN DAÑO O DAÑO LEVE                                      | DAÑO MODERADO                                                               | DAÑO CONSIDERABLE | DAÑO SEVERO Y GENERALIZADO 70%                                                     | DESTRUCCION          |
|-----------------------------------------------------------|-----------------------------------------------------------------------------|-------------------|------------------------------------------------------------------------------------|----------------------|
| Sin daño o daño que solo afectan elementos de terminación | Fisuras en algunos partes de muros, desplazamiento de planchas de techumbre | DAÑO CONSIDERABLE | Grande fuga en diagonal en algunos muros, pérdida de techos entre muros o tabiques | Colapso del inmueble |

**DAÑO EN ELEMENTOS NO ESTRUCTURALES (TABIQUES, PUERTAS, CIELOS, PAVIMENTOS, ORNAMENTOS)**

| Sin daño Bueno                                     | Regular                                               | DAÑO MODERADO                                              | DAÑO CONSIDERABLE                                     | Con daño / Malo DAÑO SEVERO Y GENERALIZADO                | DESTRUCCION |
|----------------------------------------------------|-------------------------------------------------------|------------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------------|-------------|
| En inmueble en uso, en buen estado de conservación | Reparaciones detalladas. Cuestionar en regular estado | Señala a daño moderado pero en la mayor parte del inmueble | Afecta muros en la zona, elementos de muros vaciados. | Señala a daño severo, pero en la mayor parte del inmueble |             |

**DESCRIPCION DE DAÑOS Y OBSERVACIONES.**

Se debe describir los tipos de daños por: (1) Separación de muros, desplazamiento de materiales, asentamientos de pisos, grietas horizontales, grietas 45° y otras

Desmembre de la zona de la grieta

Despiece de torre - campanario

Un muro lateral en pie pero desplazado y separa de contrafuertes, altar en pie en buen estado

**RECOMENDACIONES DE EMERGENCIA**

Retro de escombros de manera planificada para realizar partes del inmueble, adobe, tejas, madera, puertas y vestantes, etc.

Agrupamiento de la parte con a pie, torre campanario, altar y muro lateral

Registro fotográfico del inmueble colapsado

Colapso general de la estructura, desmembre

Desplazar los zona y evitar tránsito de transeúntes en la plaza parroquial

Ver factibilidad del proyecto de reconstrucción

REPONSTRUCCION DE DAÑO SISMO 2010

CONTROL DE MONITOREO INICIAL - OBSERVACIONES INICIAL DEL MONITOREO DE DAÑO SISMO

REPONSTRUCCION DE DAÑO SISMO 2010

CONTROL DE MONITOREO INICIAL - OBSERVACIONES INICIAL DEL MONITOREO DE DAÑO SISMO

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**Fig. 4.** Extract from the ST-CMN damage assessment form (developed with DA MOP).

Scale [7]: a general form for rapid post-event screening and a detailed form that disaggregates damage by structural element. These instruments, however, have not yet been disseminated among the other institutions involved in cultural heritage protection, nor have assessment teams been trained in advance of an emergency. Their effectiveness in a future event will therefore depend on prior dissemination, inter-institutional coordination, and the systematic training of assessors.

Despite Chile having experienced significant events such as the Algarrobo earthquake (1985) and the central region earthquake (2010), a consistent damage and loss assessment methodology, such as the Post-Disaster Needs Assessment (PDNA) [55], has not been systematically applied, even though the headquarters of ECLAC are in Santiago. This methodological gap is noteworthy, as consistent assessments are essential for effective reconstruction planning and risk mitigation.

One of the most significant initiatives undertaken by the Heritage and Disaster Risk Management Working Group (*Mesa de Patrimonio y Gestión del Riesgo de Desastres*), a thematic group of the National Platform for Disaster Risk Reduction co-led by the CNCR, the ST-CMN and SENAPRED, has been the collaboration between ECLAC and the Ministry of Culture, Arts, and Heritage to establish a baseline of assets and flows in three categories: museums, libraries, and heritage buildings [58]. Developing an updatable sectoral baseline is essential as it enables a more detailed assessment of the cultural capital exposed to multiple hazards. This inclusion ensures that the cultural sector is accounted for in future disaster evaluations in Chile, an area that has been largely neglected until now.

Altogether, although the *National Policy for Disaster Risk Reduction (PNRRD) 2020–2030* and the *National Strategic Plan* have established a solid and promising framework for risk management in Chile, there are still significant challenges that undermine their effectiveness in the context of immovable cultural heritage. These challenges include the inconsistent application of methodologies for damage assessment, the absence of updated information on the conservation status of heritage sites, and the insufficient resource allocation and staff training within the cultural sector, and the lack of comprehensive plans that adequately address prevention, mitigation, and recovery phases. To ensure the effective and sustainable protection of cultural heritage against future threats, it is crucial to strengthen inter-institutional coordination and prioritise the collection, systematisation, and updating of data, thereby enabling informed and strategic decision-making in disaster risk management.

### 2.3. Italy

Italy has a long history of earthquakes that have shaped local architecture and informed both modern seismic design criteria [59] and post-disaster policies for the seismic upgrading of vernacular heritage. The most devastating seismic events over the centuries occurred along several complex fault systems spanning mountainous chains and volcanic areas. This can be clearly observed from Fig. 5, which depicts the epicentres of the major earthquakes ( $M_w > 5.8$ ) that occurred in Italy from the 17th century to the mid-20th century.

The evolution of seismic-resistant constructions in Italy can be characterised by two distinct phases. In the initial phase, construction practices were largely governed by empirical rules derived from past observations and experience, leading to robust approaches for building reliable masonry structures capable of withstanding seismic actions. This experience-based knowledge allowed builders of the past to develop a series of straightforward geometric rules and construction details (e.g., rules of thumb), which ensured relatively good seismic performance.

In this period, the most significant measures against earthquakes included the use of local materials during post-event reconstruction, and the identification and replication of techniques that proved to contribute positively to the seismic response of buildings. An example can be found following the reconstructions after the 1703 and 1706 Central Italy earthquakes [60], which involved the widespread use of wooden elements. Although ancient builders did not have precise scientific knowledge of the strength of materials, their primary goal was to leverage the tensile strength of wood to offset the masonry's limited tensile capacity and to diminish the

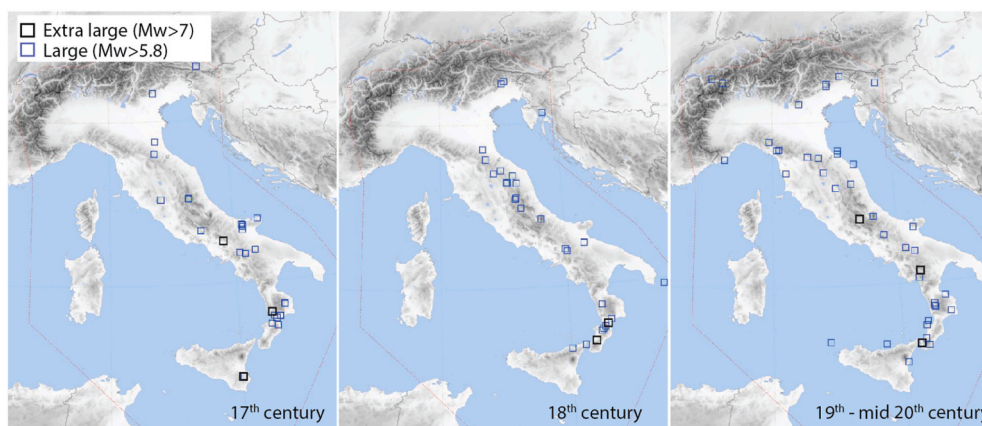


**Fig. 5.** Earthquakes in Italy during the centuries: (a) 17th century; (b) 18th century; (c) 19th - mid 20th century. “Large” ( $M_w \geq 5.8$ ) and “Extra-large” ( $M_w \geq 7.0$ ) earthquakes are marked by blue and black squares, respectively (data retrieved by ASMI—Italian Archive of Historical Earthquake Date: <https://emidius.mi.ingv.it/ASMI/>, accessed in May 2021).

likelihood of mutual sliding phenomena between stones [61].

Subsequently, formal regulatory codes were established, providing standardised guidelines and requirements to enhance building resilience to earthquakes [62]. The turning point was the 1908 Messina earthquake, an event that caused over 80,000 deaths from the earthquake itself and a tsunami that further exacerbated its devastating impact. The 1908 Messina earthquake forced engineers and builders to re-evaluate their building methods and led to the first formal seismic design code. This document, enacted in 1909, introduced specific regulations for construction in high-seismic-hazard areas, establishing the first seismic-resistance criteria that must be met during the construction of new buildings. Specifically, it limited building heights, required the verification and elimination of horizontal roof thrusts, and outlined a series of rules of art that must be followed during the construction of new masonry buildings.

Beyond the introduction of new codes, the catastrophic 1908 Messina earthquake catalysed innovative engineering solutions, leading to further developments in earthquake-resistant construction. In this regard [63], analysed the results of a competition held in Milan in 1909, one year after the Messina earthquake, aimed at proposing different construction methods to enhance structural resistance to withstand seismic forces. On this occasion, the earliest applications of computational analysis in earthquake engineering were presented, fostering the establishment of systematic procedures for construction in seismic-prone regions.

Later, after the 1976 Friuli earthquake, the first studies aimed at a comprehensive seismic classification of the Italian territory began, including territories that were not affected by recent earthquakes. Until 2003, Italy was classified into three seismic categories, each associated with a different hazard level, but some areas were classified as aseismic. In these areas, wind actions or conventional lateral forces, assumed as a small percentage of the weight, were considered. However, in 2003, following the dramatic San Giuliano earthquake in Molise (2002), new criteria were introduced dividing the whole national territory into four seismic zones. This classification was based on the latest studies and quantitative analysis of seismic hazard, which involved assessing the probability that an area will experience an event exceeding a specified intensity or magnitude threshold within a specified timeframe (typically 50 years).

Currently, the seismic zonation of the Italian territory into four zones is primarily used for statistical and administrative purposes. However, following the 2009 L'Aquila earthquake, the implementation of the Technical Standard for Construction [64] introduced a new calculation method based on a point-based statistical approach for seismic design. In detail, the Italian territory has been divided using a grid of square cells with 5 km spacing. At each node ground acceleration values (Peak Ground Acceleration), as well as other parameters that allow the identification of the spectral shape, have been assigned for different probabilities of occurrence. Moreover, interpolation formula have been provided for obtaining site-specific values. This classification, based on the work of [65], was also adopted by the most recent code [66].

Beyond the new seismic zonation, recent earthquakes have not only contributed to raising awareness with respect to the seismic upgrading of buildings, but also posed new challenges, such as the need to reconcile safety requirements with conservation needs in the context of built cultural heritage. For this reason, in the last 50 years, following the most significant seismic events, such as the 1976 Friuli earthquake [67], the 1980 Irpinia earthquake [68], and, more recently, the 2009 L'Aquila [69] and the 2016 Central Italy earthquakes [70], a thorough understanding of seismic damage to vernacular architectural heritage has become a critical point.

Extensive surveys and investigation campaigns allowed researchers to collect data for scientific analysis on the seismic behaviour of old buildings. The data were gathered thanks to the joint effort of various institutions, including the Civil Protection Department and the Ministry of Heritage and Cultural Activity and Tourism (MIC), with the crucial help of researchers from the RELUIS inter-university consortium, which focuses on research and development in the field of seismic engineering [71].

The main survey tool currently used in Italy for post-earthquake reconnaissance is the AEDES form [9], which is conceived to assess

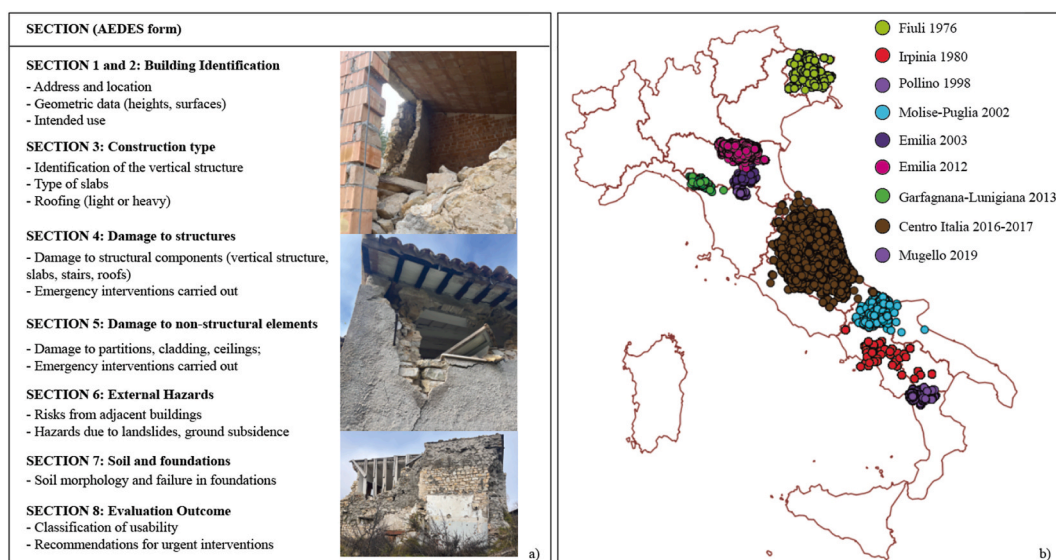


**Fig. 6.** Data collected after seismic events in Italy: (a) Main sections of the AEDES form currently in use; (b) geographical distribution of AEDES forms collected for each event (source Da.D.O. database, accessed in January 2025).

the usability and level of damage of residential buildings. This form is a crucial tool in post-earthquake assessments due to its standardised methodology, which ensures consistency and comparability across events. Over time, it has been refined through field experience, making it more effective at identifying structural vulnerabilities and guiding reconstruction efforts. Moreover, for almost a decade, this form has been completed exclusively by specialized technicians who have undergone specific training courses. This has made it possible -particularly in the case of the 2016 Central Italy earthquake- to obtain assessments that are comparable in terms of reliability and based on the same criteria. As shown in Fig. 6 (a), the AEDES form consists of several sections: (i) building identification, which collects general and typological data; (ii) damage assessment, which documents structural and non-structural damage; (iii) construction characteristics, useful for understanding the building's vulnerability; (iv) external hazard analysis, which considers risks from the surrounding environment; and, finally, (v) evaluation outcome, which assigns a usability classification and suggests urgent interventions.

The primary Italian database containing all the data collected through the AEDES forms after seismic events is the Da.D.O. Database [72]. This database played a fundamental role in organising and analysing post-disaster information, facilitating a data-driven approach to emergency response and urban planning. Fig. 6 (b) illustrates the number of AEDES forms collected in Da.D.O. for each seismic event that has occurred in Italy in the last 50 years. As shown, the most recent Central Italy earthquake, which occurred in 2016-2017, led to the cataloguing of a significant number of forms (approximately 4.000) covering a territory that spans four Italian regions: Abruzzo, Lazio, Umbria, and Marche.

To date, a substantial amount of post-event data has been systematically collected and stored in structured databases, allowing research to advance across a wide range of earthquake-related topics. Analysis of these data has enabled researchers to examine the characteristics of Italian buildings and their response to seismic actions, e.g. Masciotta et al. [73]. The obtained findings indicate that the most severe damage occurred in structures lacking codified construction regulations. Masonry buildings were particularly affected, especially those characterised by heterogeneous masonry, lacking transverse connections, and featuring incompatible interventions, such as unsuitable reinforced concrete roofs.

With this valuable information, it was also possible to assess the efficiency of past interventions. Some authors, such as [74], discussed, for example, the response of reinforced masonry buildings in Norcia during the Central Italy earthquakes of 2016-2017. Despite the magnitude of the event, these buildings, which were strengthened after previous earthquakes (1971, 1979, and 1997), performed better than the original, unreinforced masonry buildings in the same areas, which sustained more extensive damage than the strengthened ones. Specifically, the study by Sisti et al. [74], which analysed 670 masonry structural units in Norcia, showed that replacing traditional timber roofs with RC roofs - an intervention that, when applied alone, is highly detrimental to the seismic performance of traditional masonry buildings - can be effective and even beneficial when complemented by the strengthening of the underlying load-bearing walls. In fact, this technique proved effective in preventing the severe damage often observed in recent Italian earthquakes, where heavy roofs were added without strengthening the load-bearing masonry walls. Also, this study showed that the masonry quality and the effectiveness of wall-to-floor connections are critical factors in ensuring an adequate seismic performance.

Although the Norcia case study stressed the effectiveness of preventive mitigation measures in reducing earthquake-related losses, the same cannot be said for interventions applied to some masonry churches after past earthquakes. De Matteis et al. [75] emphasised this following the 2016-2017 seismic sequence in Central Italy, during which many churches sustained significant damage and even collapsed. In some cases, RC ring beams or heavy roofs were applied without additional interventions, exacerbating out-of-plane mechanisms due to increased weight and inadequate restraint capacity. An example is provided by Sferazza Papa and Silva [76], who studied the Church of San Salvatore in L'Aquila, showing that replacing the original heavy roof with lighter systems reduced the crack pattern induced by seismic actions in subsequent events.

Currently, Italian researchers are focusing on new reversible techniques compatible with traditional materials. Given the poor performance of typical concrete-based reinforcement solutions on masonry structures, new materials and methods are emerging, such as externally bonded reinforcements with Fabric-Reinforced Cementitious Matrix (FRCM) composites [77] or the reticulatus method for fair-face masonry elements and exposed facades [78].

Despite these advances and lessons learned from past earthquakes, the boundary between conservation and safeguard of such vast historical heritage remains a significant challenge. Maintaining the original appearance to preserve identity often does not comply with stringent regulations. Past seismic events have significantly shaped Italy's mid-to long-term policies and decision-making processes, influencing land-use planning, urban development, and infrastructure resilience. Additionally, they have influenced resource allocation for seismic research, emergency preparedness, and post-disaster reconstruction efforts. However, achieving consensus on comprehensive and sustainable strategies remains difficult, requiring concerted efforts among policymakers, stakeholders, and communities.

## 2.4. Croatia

Croatia has experienced many earthquakes throughout its history. One of the most severe events occurred in Dubrovnik in 1667, resulting in widespread destruction in the city and its surrounding areas. The 1880 earthquake in Zagreb was the next major event and played a key role in shaping the city's development and construction practices. At that time, northern Croatia was part of the Austro-Hungarian Empire, undergoing economic growth and expansion in construction. Many architects who designed buildings in Zagreb were educated in Vienna and incorporated Viennese architectural principles into their work, largely neglecting seismic considerations since Vienna is not an earthquake-prone area. As a result, most ancient buildings in Zagreb's city centre are unreinforced masonry structures with timber floors and roofs, constructed without considering aspects related to seismic resistance.

The use of RC floors gradually became common between 1920 and 1940, while broader adoption of this material occurred after

World War II. Nevertheless, the layout and structural configuration of Zagreb's historic urban core (and almost all cities and towns in continental Croatia) have remained essentially unchanged for over a century. Seismic codes were first introduced in Croatia in 1964 after the Skopje earthquake. After this point, new buildings were designed with some degree of seismic resistance, and masonry buildings were systematically constructed with horizontal and vertical confining elements.

Nevertheless, a large portion of buildings, especially in historic centres, were constructed before these regulations were in place. Among those, unreinforced masonry structures are especially at risk. In recent years, many buildings have been renovated to improve energy efficiency, but structural upgrades were rarely part of the process. Modern multi-story apartment buildings follow seismic design principles, yet cities remain a mix of old and new constructions.

Buildings with RC load-bearing systems were constructed after 1960 in accordance with the old Yugoslav norms and regulations. These buildings were built in accordance with the seismic regulations of 1964 and 1981 and are considered modern by the scientific standards of the time. From 1981 to 2007, buildings were designed in accordance with the Yugoslavian seismic codes. After Croatia gained independence, as part of the process of joining the European Union and harmonizing its national regulations with European standards, the introduction of Eurocode 8 began. The implementation of Eurocode standards in Croatia began with the introduction of pre-standards (HRN ENV 1998 series) in 2005. The formal adoption of Eurocode 8 (HRN EN 1998 series) occurred in 2007, with full implementation completed in 2013 following Croatia's access to the European Union. Fig. 7 illustrates the evolution of building practices and construction typologies in Croatia over the past 150 years. More information on the norms and regulations can be found in [79,80], and [81].

Over a century had passed, during which no major earthquakes occurred in the country. This prolonged period of seismic quiescence led to widespread public unawareness and low levels of preparedness. Seismological infrastructure in Croatia was limited, with only 17 active stations, which showed a clear need for further investment in seismic monitoring and research. Until recently, earthquake engineering had little visibility in public discourse and was often overlooked in national policies.

This changed in 2020, when two major earthquakes hit the country. The first struck Zagreb in March with a magnitude  $M_L$  of 5.5, followed by a stronger quake near Petrinja in December, with an  $M_L$  of 6.3 - see Fig. 8(a). Both events caused severe damage due to the poor condition of many buildings, thereby highlighting the significant vulnerability that still characterises the existing building stock. Fig. 8(a) presents the recorded earthquake intensities in the regions affected by the 2020 events. In turn, Fig. 8(b) shows a map of significant earthquakes in Croatia, including their magnitudes ( $M_L$ ) and intensities based on the European Macroseismic Scale 1998 (EMS-98).

The Zagreb earthquake occurred during the COVID-19 lockdown, which complicated response efforts. Still, the city quickly organised a crisis team and activated the Civil Protection system. Structural engineers, primarily from the Faculty of Civil Engineering at the University of Zagreb, led the assessment of building safety. Guidelines from international organisations, particularly from Italy, were followed closely. Building usability assessments were conducted using EMS forms and Croatia-specific risk assessment forms (Fig. 9).

However, the instructions provided to engineers were brief, and many professionals lacked sufficient experience or training to conduct rapid assessments. During the first two days after the earthquake, due to lockdown restrictions, only around 50 civil engineers participated in inspections. Instructions were disseminated through a website, and communication primarily occurred through WhatsApp groups. COVID-19 was the primary focus of national attention at that time, and travel restrictions, coupled with limited media coverage of the earthquake, led to delays and frustration among field engineers. By the third day, a mobile application for documenting damage was developed, replacing paper forms and significantly improving inspection efficiency and speed.

The earthquake damaged many utilities, leaving heating systems inoperable in most buildings. Additionally, the unexpected snowfall and cold temperatures - unusual for March - made the engineers' work more difficult and added to citizens' discomfort. By the end of the first week, approximately 300 experts, including both civil engineers and architects, were involved in the assessments.

Communication problems arose due to WhatsApp limitations, necessitating the creation of multiple groups, which further complicated coordination. Because many buildings were damaged and assessment criteria varied among inspectors, multiple surveys of the same buildings took place. Initially, inspections were assigned through the application based on priority reports elaborated from residents' input. However, the system did not optimise the geographic assignment of engineers, resulting in significant logistical inefficiencies (Fig. 10). By the fourth week, payments for inspections began, leading to an increase in the number of participating engineers. However, this also led to a noticeable decline in assessment quality, as early voluntary inspections typically applied stricter

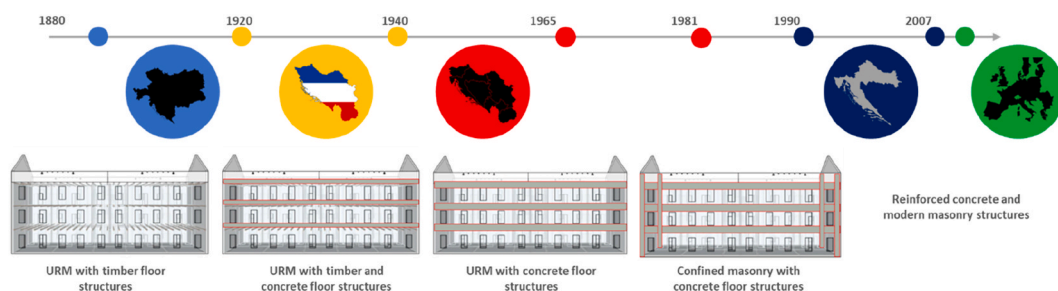


Fig. 7. Evolution of buildings with respect to the evolution of norms and historical terms in Croatia. Source: Authors.

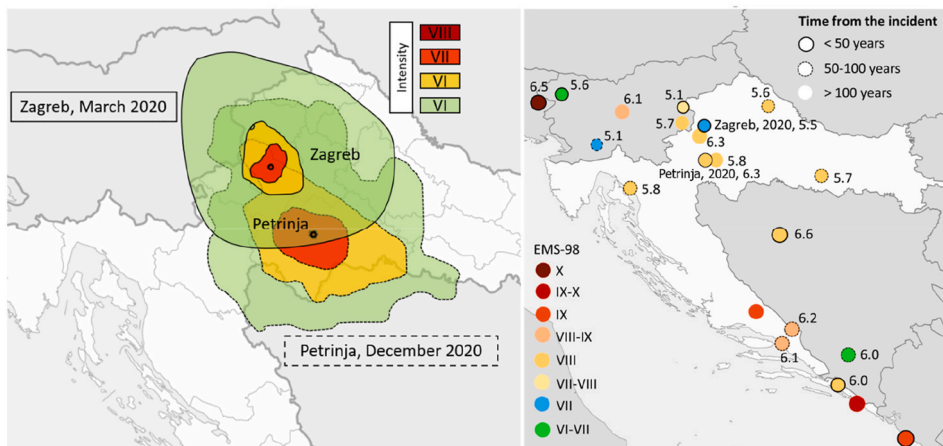


Fig. 8. (a) Spatial distribution of earthquake intensities recorded during the 2020 Zagreb and Petrinja earthquakes. (b) Historical earthquakes in Croatia. Adapted from [79].

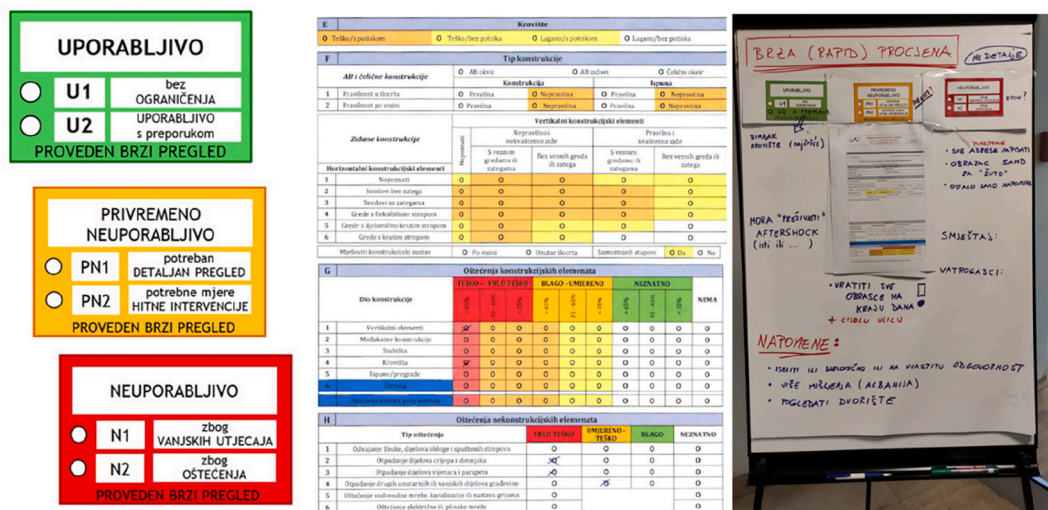


Fig. 9. Usability labels, paper forms and rapid instructions on assessments, taken during the rapid assessment phase. Source: Authors.

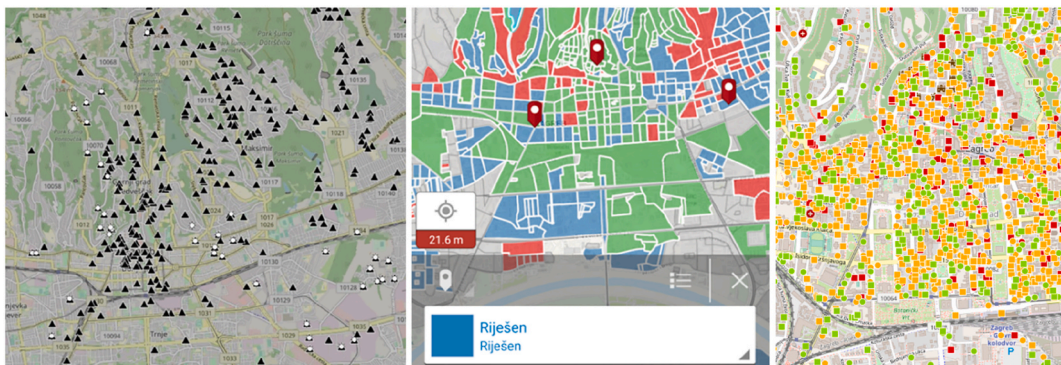


Fig. 10. Screenshot from the emergent application developed during the rapid assessment phase. Source: Authors.

criteria.

Discussions arose about new regulations, political debates, and public discourse surrounding the earthquake recovery. The World Bank reported eventually estimated damages and noted that they were notably higher than expected for a moderate earthquake [82]. Within three months, over 25,000 buildings had been inspected [83], making the earthquake a primary media topic. The first law governing post-earthquake reconstruction was enacted only in September 2020, defining reconstruction levels in accordance with Eurocode 8. However, this law explicitly mentioned the counties affected by the March earthquake.

In December 2020, when interest in the Zagreb earthquake was slowly fading from the public eye and its consequences were increasingly overlooked, another quake struck the Petrinja region. This region was previously considered to have relatively low seismic hazard. The rapid assessment procedures had to be repeated. At the time, Croatia was under a second lockdown, but restrictions were quickly eased for engineers and volunteers involved in the assessments. This earthquake was significantly more destructive, damaging many more buildings. Further details on this earthquake and the improved assessment methods implemented after the Zagreb earthquake are provided in [84–86].

After the earthquakes, a special reconstruction law was enacted. However, it took six months to become effective, delaying recovery [87]. The law outlines four levels of reconstruction based on the extent of damage and the building's function, with costs shared between the government and private owners. Only buildings labelled as “unusable” or “temporarily unusable” were eligible for funding, leading to inconsistencies and disputes over which buildings qualified. Also, many damaged buildings were illegal or isolated units in larger blocks, and the law didn't clearly address how they should be treated. This left many owners without support.

Croatia lacks a centralized database to track buildings' structural conditions, year of construction, and use, making it difficult to assess risks at the national level. It was observed that many damaged buildings were built without permits or were renovated informally: unauthorised structural changes, such as adding floors or removing load-bearing walls, exacerbated the situation. This reflects a broader problem: the public does not fully understand earthquake risk, and policies often fail to support prevention or awareness efforts. The case studies of 103 buildings in Zagreb [88], analysed after the earthquake, confirm these findings. Most failures involved poorly connected structural components, weak materials, and outdated design methods.

The new Ordinance on guidelines for the preparation of risk assessments for natural hazards and large accidents for the Republic of Croatia and local and regional administrative units represents a step toward harmonisation with the Eurocode guidelines. In February 2021, an updated version of the Law on Reconstruction of Buildings Damaged by Earthquakes was adopted [89], applicable to the City of Zagreb as well as the counties of Krapina-Zagorje, Zagreb, Sisak-Moslavina, and Karlovac. This legislation, together with amendments introduced to the Technical Regulation for Building Structures [90], defines four distinct reconstruction categories, each reflecting the building's level of mechanical resistance and structural stability. Buildings undergoing renovation must comply with seismic resistance criteria stipulated by the HRN EN1998 standard [91].

For buildings protected as cultural heritage, the reconstruction process is also conditioned by the Act on the Protection and Preservation of Cultural Goods [92], which regulates the protection regime, responsibilities, and permissible interventions for immovable cultural property. Consequently, earthquake reconstruction of individually protected buildings or buildings located within protected cultural-historical ensembles cannot be treated solely as a structural engineering procedure, since design solutions are generally subject to conservation requirements, special conservation conditions, and approval by the competent conservation authority. In practice, this creates a specific regulatory interface between seismic safety, technical reconstruction requirements, and the obligation to preserve the architectural, historical, material, and urban values of the building.

### 3. The role of post-disaster surveys for international cooperation

The weaknesses and challenges identified in the previous sections underscore the pressing need for a unified framework for collecting and sharing disaster impacts. Moreover, an effective response to disasters depends on standardised methods for quantifying post-disaster needs and assessing the extent of damage to complex assets, namely vernacular heritage. The adoption of the Sendai Framework for Disaster Risk Reduction 2015-2030 (SFDRR) [93] by UN Member States was a step forward in this direction as it highlighted the critical role of post-event damage and loss data in achieving the global objective of reducing disaster risk. More particularly, four of its seven global targets require these quantitative data to monitor progress in implementation, which reinforced the indispensable nature of disaster loss and damage data for strategic decision-making related to disaster risk reduction [94,95].

Systematic collection of post-earthquake damage and loss data, in particular, is vital for understanding seismic risk. These data can support the identification of loss trends and the underlying risk factors associated with exposure and vulnerability, providing the foundation for developing and validating new seismic risk modelling approaches for loss prediction from future earthquakes and risk mitigation. Beyond these, the importance of these data extends to governance aspects such as defining compensation mechanisms for affected populations, determining financing needs for recovery and reconstruction after earthquakes, or declaring a state of emergency and requesting international aid [96].

Currently, identifying the necessary post-earthquake recovery measures is the primary motivation for damage and loss surveys. Still, the need to document the temporal trend of these impacts to assess the effectiveness of previously implemented risk-reduction measures is emerging as an important incentive to ensure the sustainability of disaster risk management strategies. However, this requires high-quality data (i.e., with low levels of uncertainty [97] with adequate temporal and spatial resolution to establish the historical reference needed to monitor the impacts of an earthquake on a community or region. Achieving high-quality data usually requires careful, detailed identification of affected assets and the types of losses to be considered, as well as standardised processes for collecting, recording and sharing this information [98].

This standardisation is hindered by the diversity of institutions involved in collecting these data, each for its own specific purposes.

At the national level, various government agencies record damage and loss data according to their respective mandates and regulations, depending on the type of event and the affected assets [99]. On the other hand, at the global level, these data are collected by insurance companies for commercial purposes and by academic institutions for research. Overall, data obtained by these different institutions are not always compatible since they are collected and recorded in different ways [100,101], which limits their use for comparative studies across time and space [102]. These issues are increasingly more challenging when dealing with architectural heritage or historic urban environments, given the difficulties in identifying the range of direct and indirect earthquake impacts due to the intangible nature of several relevant values [103,104]. As seen from the Chilean and Mexican experiences, the loss of adobe structures is not merely a loss of housing units but also a disruption of local construction traditions.

As an attempt to contribute to the referred standardisation needs, specific indicators of disaster impacts have been proposed in previous research, as well as by institutions and policies [99,105,106]. These indicators can be categorised as social, economic, and socioeconomic, often reflecting information that can be directly surveyed and counted. For example, social indicators include the number of deaths, injuries, or missing persons. Economic indicators, generally expressed as losses, usually require transforming the data using a model to generate new data. Losses are often classified as direct or indirect; both can be further subdivided into tangible and intangible losses, depending on whether they can be quantified in monetary terms. For example, direct (tangible) losses include repair/reconstruction costs and require the collection of physical evidence of the asset's damage. In contrast, indirect (tangible) losses can be estimated from the interruption of services and productive activities (e.g., due to physical damage to infrastructure) or the interruption in the flow of economic value (e.g., due to a reduction in consumption or in the revenue of certain activities). Socio-economic indicators, by contrast, often involve intangible (direct or indirect) losses. This means that measuring them remains very challenging despite their crucial importance for obtaining a comprehensive view of disaster impacts. These indicators include, for example, losses associated with prolonged or chronic illnesses (psychological impacts, permanent physical disability), loss of quality of life and social well-being, cultural losses, biodiversity losses, etc. Given the multidisciplinary nature of many of these impacts, measuring them requires the integration of different types of expertise and the use of a unified framework that can bridge the gap between technical structural damage and the broader socioeconomic consequences. Moreover, the successful identification of these consequences loss requires availability of adequate pre-disaster baseline data about the assets and flows of the sectors affected by the disaster. Initiatives like the one carried out by the Heritage Working Group in Chile are, therefore, essential to achieve this objective.

To address these issues in loss quantification, methodologies have been developed over the years. Most of them can be traced to early contributions by the Economic Commission for Latin America and the Caribbean (ECLAC) in the 1970s, which developed the disaster damage and loss assessment (DaLA) methodology (ECLAC, 2014). Adaptations have since been proposed, such as the one by Emergency Management Australia [107] and the one addressing culture-related losses by [108]. In 2008, the European Union, the World Bank, and the United Nations Development Group started working on the Post Disaster Needs Assessment (PDNA) methodology, aimed at standardising post-disaster assessment methods. The PDNA framework guides the evaluation of human recovery needs and the quantification of damage and losses [109]. It integrates sector-specific tools created by UN agencies with the DaLA methodology from ECLAC, and its main objectives are to assess disaster impacts across all affected economic sectors and to address needs related to recovery, relief, reconstruction, and risk management [109]. The PDNA methodology also includes a chapter on culture-related assets that refers to the recommendations of [108] for quantifying economic impacts.

While the successful implementation of the PDNA methodology also depends on the availability of the previously referred pre-disaster baseline data, its standardised reporting approach is essential for prioritizing and justifying recovery efforts. In particular, it can support the development of more culturally mindful repair interventions, like those reported by the Italian experience, and limit the unnecessary demolitions of vernacular constructions that have characterised post-disaster response in Mexico. Furthermore, implementing a systematic approach to damage and loss recording helps prevent the loss of critical post-event reconnaissance data. Centralizing and sharing this information within digital databases provides the empirical foundation that can foster the necessary international cooperation for developing better predictive modelling and achieve a more realistic assessment of future disaster risks.

Despite their importance, the SFDRR and the PDNA methodology are general-purpose instruments that specify what should ultimately be reported, but not how heritage-specific, pre-event-anchored reconnaissance should be organised so that its outputs are interoperable with those instruments. Bridging this gap requires a dedicated, heritage-aware framework that explicitly links pre-event baselines with post-event reconnaissance, and ensures systematic data interoperability and reuse. The buildings blocks of such a framework are proposed in the following section.

#### 4. A unified framework for proactive seismic risk management in vernacular heritage

The comparative analysis of the Mexican, Chilean, Italian, and Croatian experiences, combined with the standardisation needs previously discussed, reveals a set of recurrent gaps that current post-earthquake reconnaissance practices fail to address in a consistent manner. More specifically there is (i) an absence of pre-event baseline data that explicitly include vernacular heritage assets and their intangible values, (ii) a lack of hierarchical assessment protocols that articulate rapid usability and damage grade evaluations with heritage-specific damage characterizations, (iii) limited interoperability between national survey instruments and international reporting frameworks such as the SFDRR and PDNA, and (iv) a limited capacity for feeding empirical observations back into proactive risk mitigation strategies in a structured and comparable manner. In addition, the PDNA framework may become too broad when applied to vernacular heritage, since damage, loss, and recovery needs are often treated through generic sectoral or economic categories. Building on the good practices previously identified, a new integrated conceptual framework is proposed herein, which includes a standardised tiered reconnaissance model, a set of interoperability indicators, and a transferable methodological roadmap.

#### 4.1. The Resilient Vernacular Heritage (RVH) framework

The proposed Resilient Vernacular Heritage (RVH) framework is defined around four interdependent pillars that connect the empirical knowledge generated by post-earthquake observations with the management of seismic risk in Historic Urban Landscapes (Fig. 11). The first pillar, *Pre-event Baseline*, addresses the development and continuous maintenance of digital, georeferenced inventories of vernacular heritage assets. These inventories must record not only the typological and geometrical attributes traditionally associated with structural vulnerability, but also conservation states, previous interventions, and intangible values such as those associated with construction traditions and local craftsmanship.

The second pillar, *Tiered Reconnaissance*, structures post-event data collection into nested levels of detail with predefined objectives, timeframes, and minimum datasets. The third pillar, *Interoperable Data Architecture*, ensures that information collected at different scales and by different actors can be aggregated, compared, and shared in alignment with international reporting frameworks. The fourth pillar, *Knowledge Reuse*, transforms the data generated after each event into validated inputs for vulnerability models, retrofitting strategies, regulatory updates, and capacity-building actions. Together, these four pillars define a continuous cycle in which each earthquake contributes to a cumulative, organised body of knowledge in a way that represents a modern continuation of the empirical learning process that originally shaped the evolution of vernacular constructions.

#### 4.2. A standardised, tiered reconnaissance model

The variability observed in the survey forms and procedures used across the four analysed countries highlights the difficulty of establishing a single, universal data collection tool. Nevertheless, the Italian AEDES form, the Chilean ST-CMN form, and the rapid assessment instruments deployed in Croatia in 2020 share more commonalities than differences, and they converge towards similar information requirements. Building on this convergence, a tiered reconnaissance model is proposed, structured into four nested levels.

*Tier 0*, the pre-event level, corresponds to the inventory-based characterisation of vernacular heritage assets. The data can be based on existing national or regional catalogues complemented with low-cost remote sensing, archival data, and past post-earthquake (or other post-disaster) surveys if they are available. The outputs of Tier 0 can feed parametric vulnerability models and machine-learning-supported classifiers to provide a probabilistic prediction of possible damage scenarios that can be used to support preparedness and proactive mitigation actions.

*Tier 1*, the rapid post-event assessment, is activated in the immediate aftermath of an earthquake and aims to determine the usability of buildings, identify life-safety hazards, and provide a preliminary overview of damage distribution. Its outcomes include the identification of the asset and its construction typology, damage classification compatible with the European Macroseismic Scale, and georeferenced photographic evidence. Tier 1 surveys should be deployable through mobile applications connected to a centralized GIS database, and should be conducted by personnel that has received certified, standardised training.

*Tier 2*, the systematic damage characterisation, expands the dataset generated by *Tier 1* to include detailed information on damage mechanisms (in-plane, out-of-plane, wall-to-wall and wall-to-diaphragm connections), pre-existing pathologies, previous interventions, and contextual hazards. Tier 2 provides the empirical foundation for the validation and calibration of vulnerability models and informs intermediate decisions regarding emergency stabilisation and prioritization of further inspections.

*Tier 3*, the heritage-specific deep assessment, is reserved for assets of recognized cultural significance and complements Tier 2 with information on materials, construction techniques, intangible values, and reversibility of potential interventions. Tier 3 is explicitly

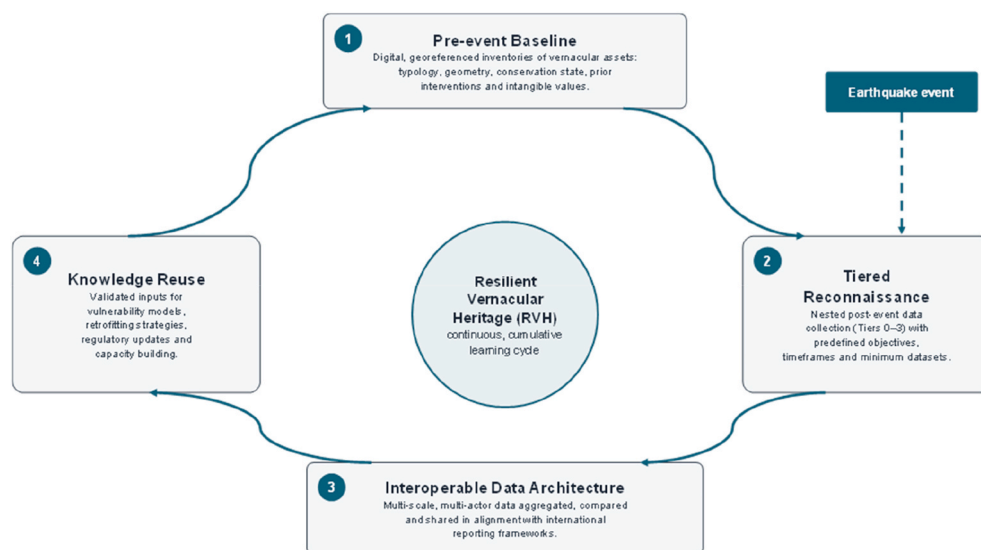


Fig. 11. Resilient Vernacular Heritage framework.

**Table 1**

The four-tier reconnaissance model of the RVH framework.

| Tier   | Phase/timing                                      | Objective                                                                                                            | Responsible actors                               | Minimum dataset                                                                                                                                                                                                        | Main outputs and use                                                                                                                                  |
|--------|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Tier 0 | Pre-event (ordinary times)                        | Inventory-based characterisation of vernacular heritage assets                                                       | Cultural-heritage and research institutions      | Typological and geometrical attributes, conservation state, previous interventions, intangible values; based on national/regional catalogues complemented with low-cost remote sensing, archival data and past surveys | Feeds parametric and machine-learning-supported vulnerability models; probabilistic damage scenarios supporting preparedness and proactive mitigation |
| Tier 1 | Rapid post-event (immediate aftermath)            | Determine building usability and damage grade, identify life-safety hazards, provide preliminary damage distribution | Certified, standardised-trained first responders | Asset and construction-typology identification, EMS-compatible damage classification, georeferenced photographic evidence                                                                                              | Mobile-/GIS-based rapid triage; basis for emergency management and entry point for higher tiers                                                       |
| Tier 2 | Systematic damage characterisation (weeks–months) | Detailed characterisation of damage and conditioning factors                                                         | Specialized technicians                          | Damage mechanisms (in-plane, out-of-plane, wall-to-wall and wall-to-diaphragm connections), pre-existing pathologies, previous interventions, contextual hazards (inherits Tier 1 data)                                | Empirical basis for validation/calibration of vulnerability models; informs emergency stabilisation and prioritization of further inspections         |
| Tier 3 | Heritage-specific deep assessment (weeks–months)  | Heritage-aware characterisation for assets of recognized cultural significance                                       | Heritage experts                                 | Materials, construction techniques, intangible values, reversibility of potential interventions (inherits Tier 2 data)                                                                                                 | Technical and cultural arguments supporting repair-oriented decision-making and countering pro-demolition attitudes                                   |

Note. The data collected at lower tiers are inherited by higher tiers, and all tiers share a common identifier system anchored to the Tier 0 baseline, so that data captured by first responders is neither lost nor duplicated when specialized actors enter the process.

conceived to counter the pro-demolition attitudes previously reported by providing the technical and cultural arguments required to support repair-oriented decision-making, in line with internationally recognized principles underpinning the development of post-disaster recovery interventions in cultural heritage.

A defining feature of this model is that it is additive rather than substitutive (see Table 1). The data collected at lower tiers are inherited by higher tiers, and all tiers share a common identifier system anchored to the Tier 0 baseline. This ensures that the data captured by first responders is not lost or duplicated when more specialized actors enter the assessment process, addressing one of the most persistent shortcomings observed across the previously four analysed contexts.

#### 4.3. Interoperability indicators

To translate the principles of the RVH framework into measurable practice, a set of five interoperability indicators is proposed (see Table 2). These indicators operate at two complementary levels by assessing the internal quality of national reconnaissance systems and measuring their alignment with international reporting frameworks. The *Baseline Coverage Indicator* (BCI) measures the proportion of vernacular heritage assets in a given administrative unit that are documented in a digital, updatable inventory containing the minimum Tier 0 dataset. The *Reconnaissance Activation Time* (RAT) measures the median time elapsed between the earthquake and the completion of Tier 1 surveys for the affected vernacular assets. The *Reconnaissance Coverage Indicator* (RCI) records the proportion of pre-inventoried vernacular assets in the affected area that have been the object of a Tier 1 (or higher) survey within predefined reference windows (e.g., 30, 60, and 90 days). The *Data Completeness Indicator* (DCI) quantifies, for each surveyed asset, the proportion of fields effectively populated against the minimum dataset of the corresponding tier. Finally, the *Reactive Demolition Indicator* (RDI) tracks the share of vernacular assets demolished in the post-event phase that were not classified as collapsed or structurally unrecoverable in the corresponding Tier 1 or Tier 2 survey. This last indicator is particularly relevant given the previously highlighted evidence that a non-negligible fraction of vernacular heritage losses results not from the earthquake itself but from inadequate post-event decision-making.

These indicators are not intended as standalone metrics but as components of a composite diagnostic instrument that allows performance comparison across events and countries, supports monitoring against SFDRR targets, and helps identify the specific weaknesses that should guide capacity-building investments. It should be noted that reference thresholds and acceptable ranges for these indicators are not prescribed herein. Their empirical calibration through retrospective application to well-documented events is a necessary next step for their operational deployment.

#### 4.4. A transferable methodological roadmap

The implementation of the RVH framework requires a phased, context-sensitive roadmap that acknowledges the heterogeneity of institutional, regulatory, and technical conditions across countries. The roadmap proposed herein is organised in four phases, each with explicit deliverables and decision gates (Fig. 12).

*Phase I — Preparedness and Baseline Construction* takes place during ordinary times and focuses on building or consolidating the Tier

0 inventory, defining the institutional governance of the framework, training certified surveyors, and harmonizing national survey forms with the minimum datasets defined in the RVH tiers. This phase also includes the development or adoption of mobile applications and centralized GIS infrastructures, as well as memoranda of understanding between cultural heritage institutions, civil protection agencies, academic networks, and international partners.

*Phase II — Emergency Activation* covers the first hours and days following an earthquake. It includes the deployment of certified Tier 1 surveyors through the previously validated mobile platform, the activation of the centralized data hub, and the dissemination of clear, pre-defined operational guidance to all participating institutions. Lessons learned from previous experiences point to the importance of pre-existing communication protocols to prevent reliance on improvised tools such as ad-hoc messaging groups, and to the value of geographically optimized task assignment algorithms within the deployment application.

*Phase III — Systematic Damage and Loss Survey* includes Tier 2 and, where applicable, Tier 3 assessments and runs over the weeks and months following the event. This phase is also when the indicators proposed in Section 4.3 must be obtained and reported. Phase III includes a formal validation step in which Tier 2 outputs are confronted with the predictions of the parametric and machine-learning models fed by the Tier 0 baseline. This comparison generates updated model calibrations whose contribution to enhance their predictive accuracy for future events should be explicitly quantified, so that the incremental value of each post-event cycle becomes a measurable outcome.

*Phase IV — Integration and Feedback* transforms the post-event experience into a permanent contribution to seismic risk management. It includes the public release of standardised datasets, the update of regulatory documents and intervention guidelines, the integration of validated retrofit solutions, and the public communication of lessons learned. Phase IV closes the loop by feeding Phase I of the next cycle, in line with the cumulative, iterative nature of the empirical knowledge that originally shaped vernacular construction traditions.

The transferability of the roadmap lies in its modular architecture. Countries with mature reconnaissance systems can adopt it to formalize existing practices and to strengthen their alignment with the SFDRR. Countries with extensive heritage inventories but limited post-event organization can prioritise the deployment of Tier 1 mobile platforms and the formal articulation between national catalogues and emergency procedures. Countries with experienced response systems but limited specific provision for vernacular heritage can focus on enriching the existing rapid assessment instruments with the heritage-specific data required by Tiers 2 and 3.

## 5. Final remarks

Documenting the consequences of earthquakes has continuously reshaped construction cultures, retrofitting practices, and regulatory frameworks. Yet the comparative analysis of experiences from Mexico, Chile, Italy, and Croatia shows that this learning remains uneven and, crucially, discontinuous: empirical knowledge is repeatedly regenerated after each event rather than accumulated. Moreover, these four cases also show different levels of institutional development in addressing these issues. Italy demonstrates the value of a standardised instrument (AEDES) coupled to a persistent database (Da.D.O.) and multi-institutional coordination, yet still struggles to reconcile conservation with safety in heritage assets. Chile shows that regulatory innovation for earthen heritage can advance faster than the institutional capacity to apply it, leaving assessment tools undigitized and untransferred between events. Mexico illustrates that an inventory such as the National Catalogue of Historic Monuments can enable parametric and machine-learning vulnerability screening even where dedicated heritage policy is absent. Croatia exposes how a century of low earthquake activity translates into improvised tooling, uneven surveyor training, and the absence of a centralized building database. Together, these are not four isolated problems but four facets of a single structural problem: the lack of a pre-event, interoperable, heritage-aware baseline that survives the transition from emergency to recovery.

**Table 2**

The five interoperability indicators of the RVH framework, their level of assessment, data sources and role in SFDRR-aligned monitoring.

| Indicator (acronym)                     | Definition — what it measures                                                                                                                                     | Assessment level                         | Primary data source                           | Role in SFDRR-aligned monitoring                                                             |
|-----------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|-----------------------------------------------|----------------------------------------------------------------------------------------------|
| Baseline Coverage Indicator (BCI)       | Proportion of vernacular heritage assets in an administrative unit documented in a digital, updatable inventory containing the minimum Tier 0 dataset             | Internal quality (preparedness)          | Tier 0 inventory                              | Measures exposure-baseline readiness underpinning risk-reduction targets                     |
| Reconnaissance Activation Time (RAT)    | Median time elapsed between the earthquake and completion of Tier 1 surveys for the affected vernacular assets                                                    | Internal quality (response speed)        | Tier 1 survey timestamps                      | Tracks timeliness of post-event response                                                     |
| Reconnaissance Coverage Indicator (RCI) | Proportion of pre-inventoried vernacular assets in the affected area surveyed at Tier 1 or higher within predefined reference windows (e.g. 30, 60, 90 days)      | Internal quality (response completeness) | Tier 0 baseline + Tier 1+ records             | Quantifies completeness of the post-event survey effort over time                            |
| Data Completeness Indicator (DCI)       | Per surveyed asset, proportion of fields effectively populated against the minimum dataset of the corresponding tier                                              | Internal quality (data quality)          | Tier 1–3 records                              | Underpins data quality required for cross-event/country comparison                           |
| Reactive Demolition Indicator (RDI)     | Share of vernacular assets demolished post-event that were not classified as collapsed or structurally unrecoverable in the corresponding Tier 1 or Tier 2 survey | Outcome (international alignment)        | Tier 1/2 classifications + demolition records | Flags avoidable heritage loss from inadequate decision-making against loss-reduction targets |

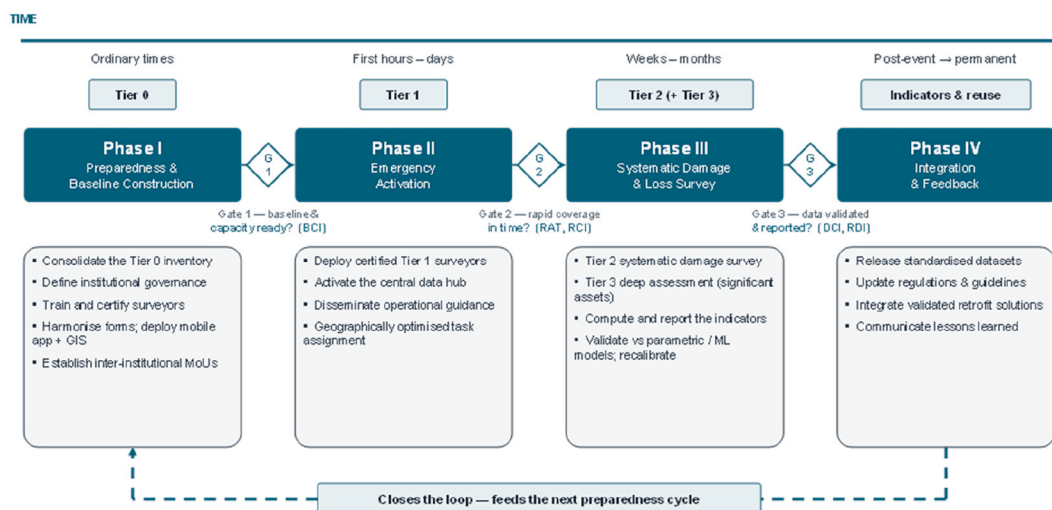


Fig. 12. Transferable methodological roadmap.

The RVH framework proposed herein answers directly to this issue, and its value lies in its ability to be operational. In this context, three concrete recommendations are made for institutions seeking near-term improvement. First, Tier 0 should be treated as a standing obligation: existing national catalogues should be enriched with information about the conservation state, prior interventions, and intangible values, and should be maintained as updatable digital inventories rather than static records. Second, the Reactive Demolition Indicator (RDI) should be adopted as a mandatory reporting metric, since there is evidence that a substantial share of vernacular heritage loss originates not from the earthquake but from avoidable post-event decisions. Therefore, measuring this loss is a precondition for reducing it. Third, certified surveyor training and pre-agreed communication protocols should be institutionalized during ordinary times, since evidence has also shown that improvised coordination degrades data reliability.

The validation of the proposed RVH framework requires, nonetheless, progress along certain research directions. The proposed interoperability indicators require empirical calibration. Reference thresholds for the RAT and RCI should be derived by retrospectively applying them to documented events from which there is enough data available. Moreover, the proposed tiered model needs validation through controlled inter-surveyor reliability studies, given the expected variability between surveyors. The formal validation step in Phase III, confronting Tier 2 observations with Tier 0 model predictions, should be benchmarked to quantify how much each post-event cycle improves predictive accuracy, turning the framework's closing loop into a testable claim. Finally, the monetary and intangible valuation of vernacular heritage loss within PDNA-compatible reporting remains underdeveloped and requires dedicated research and methodological work.

The wider implication is that post-earthquake reconnaissance should be reframed not as emergency documentation but as the recurring data-generation phase of a permanent risk-management cycle. Only by anchoring each event to a maintained baseline, measuring performance through shared indicators, and feeding validated knowledge forward can historic urban landscapes escape the chronic cycle of starting over, preserving not only their material fabric but the cultural capital embedded in vernacular construction traditions.

### CRedit authorship contribution statement

**Rafael Ramírez Eudave:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Tiago Miguel Ferreira:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Xavier Romão:** Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Pilar Baquedano-Juliá:** Conceptualization, Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nuria Chiara Palazzi:** Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Mislav Stepinac:** Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. **Maria Giovanna Masciotta:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Giorgia Cianchino:** Investigation, Visualization, Writing – original draft. **Giuseppe Brando:** Formal analysis, Investigation, Supervision, Writing – review & editing.

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## Data availability

No data was used for the research described in the article.

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