Implementing open-source information systems for assessing and managing the seismic vulnerability of historical constructions

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Abstract: Reducing the uncertainty about the structural vulnerability of historical constructions comprises the selection of reasonably generalised approaches in a context of a significant typological variability; the difficulty of performing large-scale assessments with reasonable reliability; and the lack of dedicated infrastructures for efficiently storing, sharing, managing, and updating data – an issue that is even more relevant for small (and often isolated) settlements. This work presents a proposal to set up a geographic database for surveying, calculating and storing the seismic vulnerability index of masonry constructions using an adapted version of the GNDT-II approach. Some critical steps for setting up Geographical Information System (GIS) databases for storing and managing the fields of a parameter-based vulnerability assessment are presented. Then, some alternatives for distributing the database are introduced, including cloud-based distribution and Transactional Web Feature Service (WFS-T) protocols, even using virtual servers. Additionally, an alternative front-end for accessing data and calculating the vulnerability index of constructions and levels of damage is presented. The main objective is to offer a replicable and feasible workflow to be performed even with reduced infrastructure and computational resources but can be easily connected and associated to a progressively enlarged system based on free and open-source software.

Keywords: GIS, Seismic Vulnerability Assessment, GNDT-II, QGIS, GeoServer.

1. Introduction

The characterisation of the seismic vulnerability of large sets of constructions is a challenging task in which material and human resources must be optimised in order to obtain reliable information in a reasonable amount of time. This condition is compatible with the implementation of simplified and often parametric approaches, namely based on material and geometrical properties of structures. However, it is still common to perform data-acquisition campaigns based on paper datasheets that are later transferred and managed on informatics platforms. The use of digital tools for minimising the bridge between the on-field campaigns and outcomes obtention is still an open field in which a feasible and straightforward workflow could become a valuable resource for implementing large-scale seismic vulnerability assessments even for settlements in which human, computational and material resources are limited. As an example, the 2017 earthquakes in Mexico revealed that a large proportion of historical and vernacular constructions in rural regions (namely housing units) were vulnerable to intense seismic actions, which was reflected in a large number of collapses and losses (Galvis et al., 2017; Eudave and Ferreira 2021). An easy to apply workflow for assessing the seismic vulnerability of

masonry constructions is herein presented, emphasising the suitability and convenience of being implemented with open-source and free tools, facilitating its adoption and replication.

2. The vulnerability index-based methodology for assessing the seismic vulnerability of masonry buildings

Gavarini (2001) states that «…the seismic vulnerability of a building is a quantity associated with its 'weakness' in front of earthquakes of a given intensity so that the value of this quantity and the knowledge of seismic hazard allow to evaluate the expected damages from future earthquakes». To measure this "weakness", however, is the object of numerous approaches with different levels of complexity and accuracy. When dealing with large samples of constructions (e.g., in the context of a Historic Urban Landscape (Ramírez Eudave and Ferreira 2021a)), it is convenient to use simplified approaches for certain typologies. In the case of masonry constructions, the GNDT-II method has been widely used, calibrated and adapted. The original proposal (GNDT-SSN 1994) considered ten parameters that rule the seismic behaviour of unreinforced masonry buildings. Subsequent calibrations led to the inclusion of additional evaluation parameters keeping, however, the original rationale – each parameter is evaluated through four vulnerability classes corresponding to increasing levels of vulnerability, which are then associated to weights whose value represents the relative significance of that parameter for the global seismic vulnerability of the building. The model used for this workflow (from here named Vulnerability Index-based Methodology or "VIM") is the calibration used for the city of Atlixco (Puebla, México) of Ramírez Eudave and Ferreira (2021b), with a total of 14 parameters (Table 1).

Table 1. Parameters for the VIM approach based on (Ramírez Eudave and Ferreira 2021b).

Parameters	Class (C_{vi})				Weight (p_i)	Relative weight
	A	B	C	D		
Group 1. Structural building system						50/100
BP1. Type of resisting system	0	5	20	50	2.50	16.67
BP2. Quality of the resisting system	0	5	20	50	2.50	16.67
BP3. Conventional strength	0	5	20	50	1.00	6.67
BP4. Maximum distance between walls	0	5	20	50	0.50	3.33
BP5. Number of floors	0	5	20	50	0.50	3.33
BP6. Location and soil conditions	0	5	20	50	0.50	3.33
Group 2. Irregularities and interaction						20/100
BP7. Aggregate position and interaction	0	5	20	50	1.50	10.0
BP8. Plan configuration	0	5	20	50	0.50	0.33
BP9. Height regularity	0	5	20	50	0.50	0.33
BP10. Wall façade openings and alignment	0	5	20	50	0.50	0.33
Group 3. Floor slabs and roofs						18/100
BP11. Horizontal diaphragms	0	5	20	50	0.75	4.91
BP12. Roofing system	0	5	20	50	2.00	13.09
Group 4. Conservation status and other elements						12/100
BP13. Fragilities and conservation status	0	5	20	50	1.00	6.86
BP14. Non-structural elements	0	5	20	50	0.75	5.14

This methodology allows calculating a vulnerability index (Eq. 1), which, for ease of use, is usually normalised to range from 0 to 100 (Eq. 2). This normalised value can be subsequently used to calculate the vulnerability value V (Eq. 3), which, in turn, together with the ductility of the structure (Q) and the macroseismic intensity I_{EMS-98} allows for the

estimation of a mean damage grade, μ_D, as per Eq. 4, considering an adjustment for seismic intensities lower than 7 (Eq. 5).

$$I_{vf}^* = \sum_{i=1}^{14} C_{vi} \times p_i \qquad (1)$$

$$I_v = \frac{I_v^* \times 100}{750} \qquad (2)$$

$$V = 0.592 + 0.0057 \times I_v \qquad (3)$$

$$\mu_D = 2.5 + \left[3 \times tanh\left(\frac{I_{EMS-98} + 6.25 \times V - 12.7}{Q} \right) \right] \times f(V,I); 0 \leq \mu_D \leq 5 \qquad (4)$$

$$f(V,I) = \begin{cases} e^{\frac{V}{(2 \times I - 7)}} & I \leq 7 \\ 1 & I > 7 \end{cases} \qquad (5)$$

A practical systematisation of this methodology is relevant for performing urban-scale assessments and would desirably include the parameters' acquisition, the data treatment for calculating the vulnerability index and damage grades in the context of a certain seismic event.

3. Geodatabases for managing the GNDT-II survey

Using geodatabases is an efficient way of systematising the information related to vulnerability index-based approaches (Ramírez Eudave and Ferreira 2020). These environments facilitate the association of multiple types of data on georeferenced entities (points, lines, polygons etc.). Hence, these environments are very suitable for capturing, managing and displaying vulnerability-related surveys and outputs.

A very common free and open-source software for this purpose is QGIS. This project of the OSGeo Foundation is widely known and used for different purposes, including research. Given its popularity, there is a continuous development of plug-ins and enhancements from independent actors, facilitating a flexible and customisable use of this tool.

QGIS data organisation depends on managing several layers with geographical and geometrical entities in which every instance is related to several attributes with numeric, alphanumerical, Boolean or other types of data (Figure 1). This attribute table can contain all the fields needed for performing the VIM approach in a direct association with the spatial location of the construction. QGIS accepts the setup of customised attribute tables by using Python scripts.

Since layers can be stored as independent files, it is possible to perform both read and write operations externally to the GIS software. It is also possible to consult the layers from remote services, such as online sources. The capabilities of a VIM oriented geodatabase are summarised in Figure 2 and will be discussed in the subsequent sections. This data flow includes the potential data sources of the physical reality and the potential roles of portable devices, local storage on PC and remote servers that can host layers with reading/write capabilities from local-stored QGIS files.
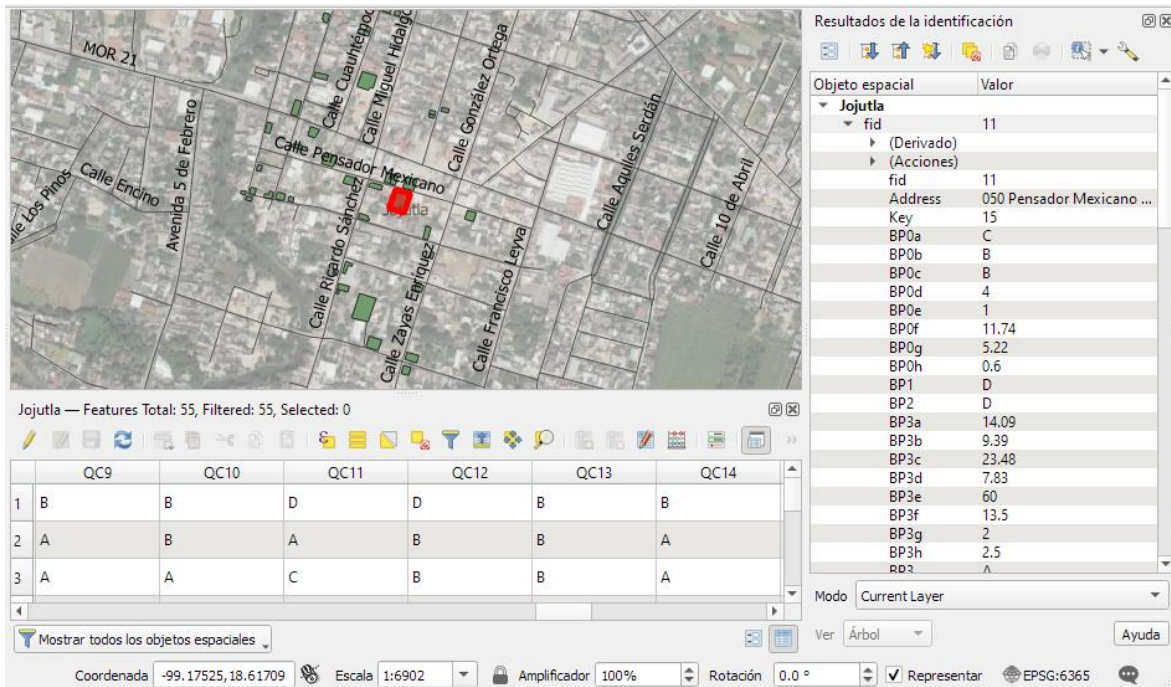
Figure 1. Screenshot of QGIS interface. The active layer includes a series of features associated to the Parametric Seismic Vulnerability Index for a specific set of constructions.
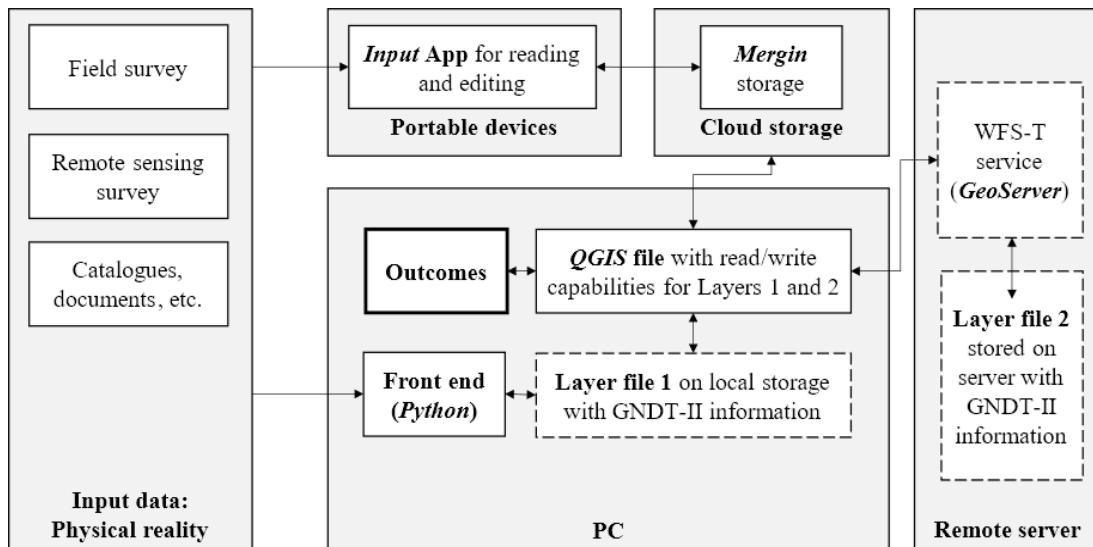

Figure 2. Integrated data flow on GIS databases for VIM surveys

4. Complementary resources for GIS data acquisition and management

The presented workflow schematises the role that some complementary tools can have for complementing the QGIS capabilities as VIM database, namely for performing read/write operations outside of QGIS software through a Front-end and remote services for hosting GIS layers or QGIS files (WFS-T protocol and Mergin service). In the context of the seismic assessment of historical constructions, this workflow is specifically significative for performing large-scale diagnosis by the means of remote access and real-time synchronisation.

4.1. Front-end

A front-end based on Python language can be an appropriate step for easing the interpretation, management, edition, and calculations related to data stored in GIS layers (Fig. 3).
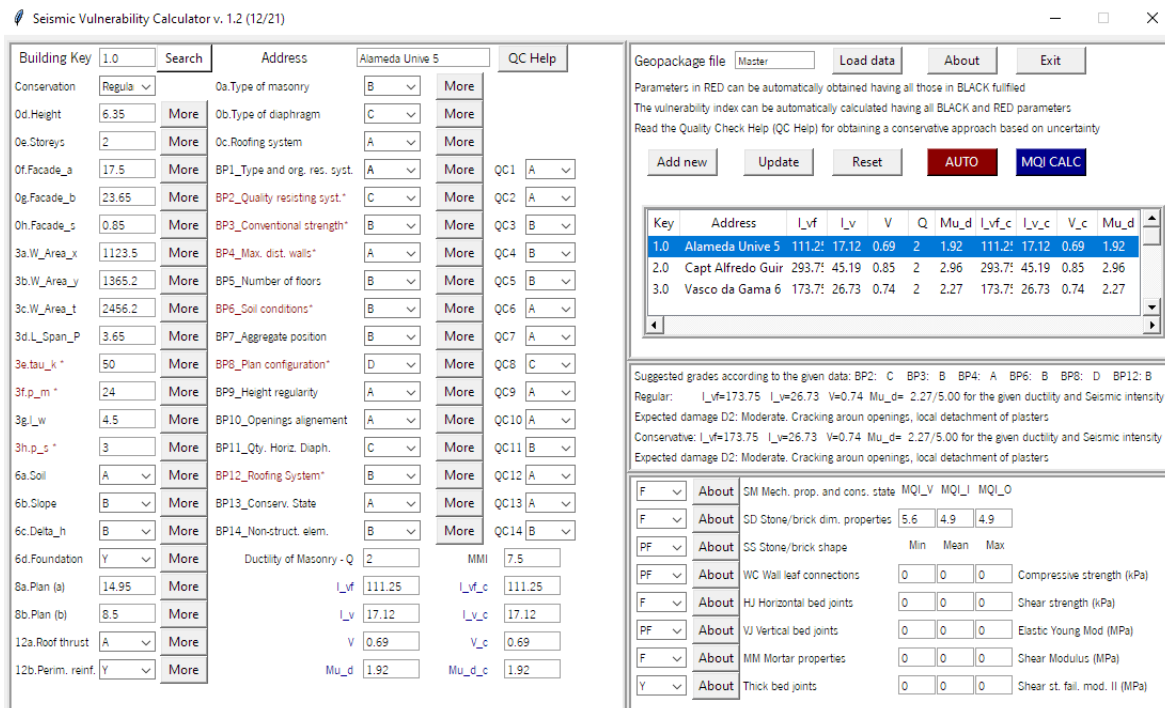

Figure 3. Main window of the Python-based front-end.

This program permits reading different formats of GIS layers thanks to the use of the *Geopandas* library. This library is an adaptation of the *Pandas* data framework that includes the compatibility with geographical entities, keeping the integrity of geographical data while working on the attribute table of the layer. The capabilities of the *Geopandas* library, together with the Graphical User Interface (GUI) package *Tkinter* permitted developing an easy-to-use interface in which all the parameters (and sub-parameters) are displayed for their read, capture and edition. Furthermore, every parameter is associated with a "More" button that displays an explanatory dialog for the user in order to contextualise the magnitudes and characteristics to be surveyed.

This front-end aims to facilitate the VIM processes for any stakeholder regardless of the familiarity or knowledge of GIS databases, protecting the integrity of geographical data. This capacity would be especially useful for performing small editions or consults on large databases. Besides including the VIM survey, a small calculator for performing the Masonry Quality Index approach (Borri and De Maria 2015) was implemented, exemplifying the ability to design more comprehensive and enriched tools in an integrated environment that would embrace the assessment of concrete-based structures as well as other approaches of interest.

4.2. Remote access and edition

Besides the setup and local storage of GIS layers, it is convenient to consider the advantages of hosting these files remotely. This approach has several purposes: it is suitable for distributing fieldwork tasks among several people, facilitates a redundancy on specific processes and facilitates data-sharing.

4.2.1. WFS-T service

The Web Feature Service (WFS) of the Open Geospatial Consortium (OGC) is a standard interface for allowing requests for geographical features on web services. This standard enables the remote storage of GIS layers for being imported and even edited in local GIS platforms (Atzl et al. 2016). Some free and open-source platforms facilitate publishing layers on local or remote hosts. For example, the *GeoServer* open-source server supports interoperability for many standards (Růžička 2016) and is, in fact, already implemented on QGIS on several supplements. *GeoServer* enables displaying GIS layers in a web browser but also permits importing layers into local GIS files as an online resource. GeoServer can be implemented on a virtual machine to work as a server, which is especially useful when taking advantage of the Transactional WFS (WFS-T), which allows querying and retrieving features with real-time synchronisation.

4.2.2. Cloud-based distribution for mobile devices

Another practical process is distributing GIS files for being consulted and edited on mobile devices. The app *QField*, for example, facilitates the edition of the attribute table of a GIS file by taking advantage of the geo-localisation of the mobile device. This app, however, depends on the local storage of the file and implies the upload or download of the file for sharing it. An alternative service is provided by the *Mergin* cloud service. This cloud service has been implemented as a plug-in for QGIS and offers free (but limited) cloud-based storage. This storage permits the distribution of a complete functional QGIS file with other users, including the capability of editing the files from portable devices by means of the free app *Input* (Fig. 4).
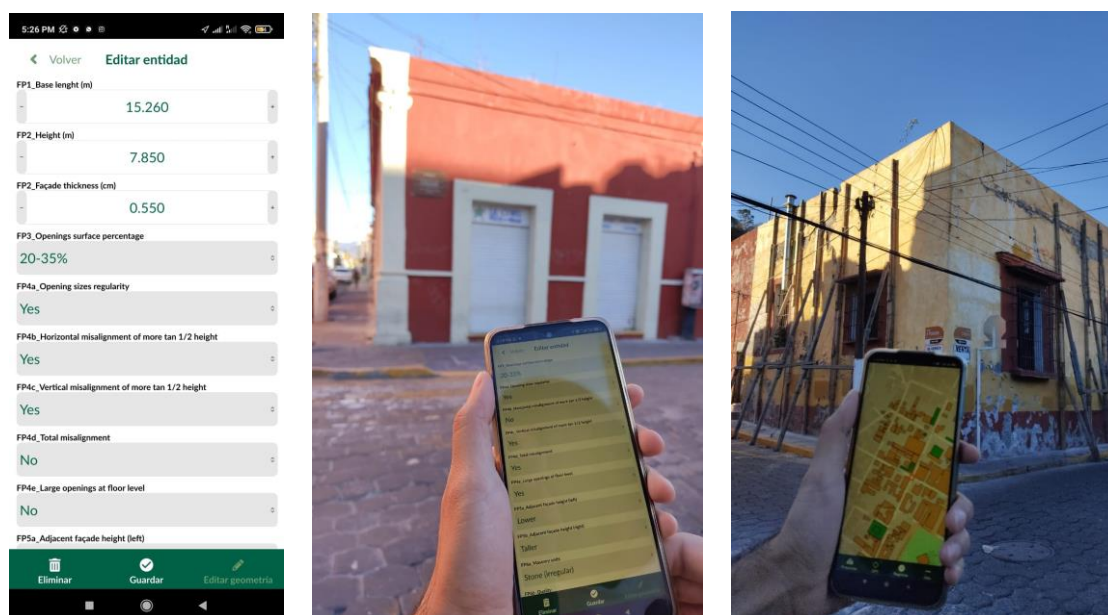

Figure 4. Example of the Input interface and its utilisation during on-site data acquisition.

This app also facilitates the edition of the attribute table and a real-time edition of the geographic layer, offering also a convenient real-time synchronisation of the file throughout all the devices. This last feature is especially meaningful for distributing files when working on teams and covering large areas. Examples of applications, such as the one described in Eudave and Ferreira (2021), have found that the joint use of QGIS-Mergin-Input is a feasible and robust framework for supporting field data acquisition campaigns.

5. Outcomes and potential use for mitigating damage and loses

The data acquisition process for a determinate urban environment may involve many of the strategies described in Section 4 for achieving the parametric description of all the considered constructions. The calculation of the vulnerability index of the buildings can be easily obtained by using the front-end software, including the results in the database as well. The vulnerability index of a set of constructions is easily representable by using straightforward maps from QGIS, for example. These maps represent thresholds for the vulnerability of buildings, intuitively providing a base for identifying the most sensitive elements of a determined city.

The use of the front-end software also facilitates the obtention of damage grades for the set of constructions, given a certain seismic intensity and the structure's ductility. This process is intended to be more flexible and direct than operating the QGIS file, for example. As shown in Fig. 5, both outcomes permit highlighting those constructions that are more likely to fail or suffer damage when facing a certain scenario. This semi-quantitative information is of great value for numerous stakeholders that have a decision tool for prioritising interventions and immediate actions that can also consider some aspects that are not contained in the VIM approach but can be mapped on the GIS database: social vulnerabilities, number of users, economic indicators, cultural values, protection status, etc.
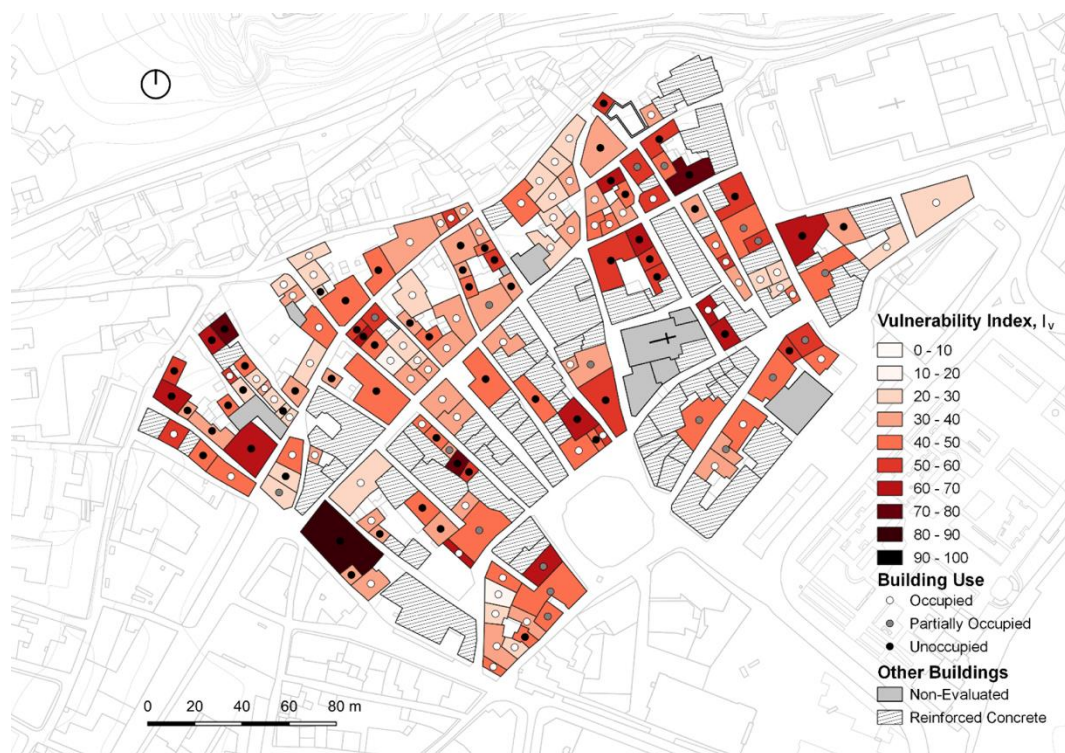
Figure 5. Example of outcome representing the vulnerability index for constructions of the city of Leiria, Portugal (Anglade et al. 2020).

Furthermore, the calculation of damage grades would be the basis for more complex urban-level analysis. As exemplified in Fig. 6, it is possible to build a damage curve for the constructions in which seismic intensities are associated with a certain level of damage. Hence, given a certain seismic intensity, it becomes feasible to anticipate levels of damage throughout the sample, identifying which constructions are more likely to have severe damages or even complete failures. The activation of total or partial failures due to out-of-plane mechanisms would imply a partial obstruction of certain streets or

communications because of accumulation of debris, which is relevant for emergency planning actions and evacuation plans.
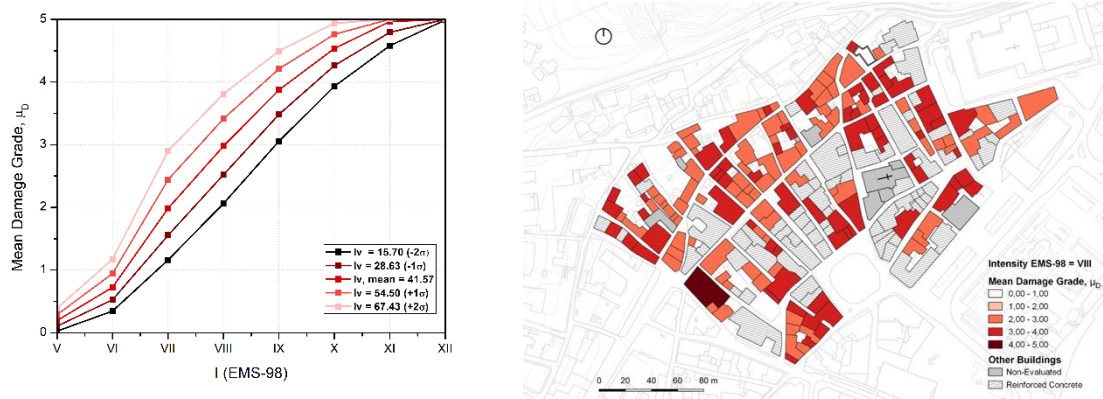

Figure 6. Example of vulnerability curves (left) and mapping of the Mean Damage Grade given a certain seismic intensity (right) for the city of Leiria, Portugal (Anglade et al. 2020).

Besides collapses, the thresholds of unusability of constructions are relevant indicators for anticipating the loss of urban critical functions (commerce, housing, health, and education services, etc.), favouring nominal life estimates based on the return periods associated with certain seismic intensities. Hence, this information is a relevant element for performing long-term urban planning. It is important to recall, however, that the elements considered for this workflow are also intended to offer a flexible and user-friendly environment for updating and/or correcting data, which implies the possibility of having up-to-date outcomes, including updates on the city (for example, when a better knowledge of a certain construction is available) or in the seismic vulnerability approach (for example, when calibrated after a seismic event).

6. Conclusions

This paper discusses the pertinency of using a parameter-based seismic vulnerability assessment approach to carry out large-scale vulnerability assessments in the context of historical cities. Furthermore, the feasibility and convenience of implementing the entire workflow on geodatabases are discussed, focusing on the open-source GIS software QGIS. Besides supporting this implementation, the suitability of using complementary approaches and tools is herein presented and explored.

Firstly, it is explored the possibility of developing and implementing a Python-language based front-end for reading, managing, and editing GIS layers. This would not only facilitate the management of geodatabases outside of GIS environments but would also offer a user-friendly interface for collecting core and complementary input data for the methodology and a semi-automatic calculator for obtaining the vulnerability index and mean damage grade results.

Secondly, two alternatives for remote distribution of GIS databases are presented and discussed. The use of the WFS-T protocol is a valuable resource for publishing GIS layers that can be locally consulted and edited. On the other hand, using cloud-based tools opens the possibility of distributing GIS data on several devices with reading and writing privileges. This capability is highly relevant for performing field campaigns involving many actors and can have an almost immediate synchronisation, minimising the time invested in data treatment. Both approaches represent strategies for implementing a free, enlargeable and potentially online system for data acquisition, treatment and representation

of the seismic vulnerability of constructions. Some alternatives that are a matter of future research are browser-based front ends for online database services.

Finally, some relevant uses of the outcomes of the VIM – GIS implementation are discussed. The generation of vulnerability maps is a valuable tool for representing the overall vulnerability state of a city or certain regions. Furthermore, the damage curves are the base for anticipating damage and losses scenarios given a determined seismic intensity, which might reasonably impact the design of emergency planning and nominal-life oriented urban decisions aimed to mitigate the negative impacts of earthquakes.

Acknowledgements

References

Anglade E, Giatreli A-M, Blyth A, Di Napoli B, Parisse F, Namourah Z, Rodrigues H, Ferreira TM (2020) Seismic damage scenarios for the Historic City Center of Leiria, Portugal: Analysis of the impact of different seismic retrofitting strategies on emergency planning. Int J Disaster Risk Reduct 44:101432 . https://doi.org/https://doi.org/10.1016/j.ijdrr.2019.101432

Atzl C, Vockner B, Mittlboeck M (2016) Online Visualization of Streaming Data. GI_Forum 2:57–66 . https://doi.org/10.1553/giscience2016_02_s57

Borri A, De Maria A (2015) Indice di Qualità Muraria (IQM): correlazione con le caratteristiche meccaniche e livelli di conoscenza Masonry Quality Index (MQI): correlation with the mechanical characteristics and knowledge levels. Progett Sismica 6: . https://doi.org/10.7414/PS.6.3.45-63

Eudave RR, Ferreira TM (2021) Proposal for a suitable workflow for assessing the seismic vulnerability of historical buildings. Atlixco (Puebla, México) as a case study. In: 1st Croatian Conference on Earthquake Engineering. University of Zagreb Faculty of Civil Engineering, pp 23–34

Galvis F, Miranda E, Heresi P, Dávalos H, Silos JR (2017) Preliminary Statistics of Collapsed Buildings in Mexico City in Puebla-Morelos Earthquake. Tech Rep 17

Gavarini C (2001) Seismic risk in historical centers. Soil Dyn Earthq Eng 21:459–466 . https://doi.org/10.1016/S0267-7261(01)00027-6

GNDT-SSN (1994) Scheda di Esposizione e Vulnerabilità e di Rilevamento Danni di Primo e Secondo Livello (Murata e Cemento Armato). Rome, Italy

Ramírez Eudave R, Ferreira TM (2021a) Characterisation of the Historic Urban Landscape through the Aristotelian Four Causes: Towards Comprehensive GIS Databases. Remote Sens 13:1879 . https://doi.org/10.3390/rs13101879

Ramírez Eudave R, Ferreira TM (2021b) On the potential of using the Mexican National Catalogue of Historical Monuments for assessing the seismic vulnerability of existing buildings: a proof-of-concept study. Bull Earthq Eng. https://doi.org/10.1007/s10518-021-01154-5

Ramírez Eudave R, Ferreira TM (2020) On the suitability of a unified GIS-BIM-HBIM framework for cataloguing and assessing vulnerability in Historic Urban Landscapes: a

critical review. Int J Geogr Inf Sci 00:1–31 . https://doi.org/10.1080/13658816.2020.1844208

Růžička J (2016) Comparing speed of Web Map Service with GeoServer on ESRI Shapefile and PostGIS. Geoinformatics FCE CTU 15:3–9 . https://doi.org/10.14311/gi.15.1.1