PHYSICAL VULNERABILITY OF BUILDINGS TO RAINFALL- AND EARTHQUAKE-INDUCED LANDSLIDES IN THE LISBON METROPOLITAN AREA

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Abstract: This study assesses the physical vulnerability of buildings in the Lisbon Metropolitan Area (LMA) to landslides triggered by rainfall and earthquakes. The susceptibility to rainfall-induced landslides was evaluated using the Information Value statistical model and validated through ROC curve analysis. Additionally, the susceptibility to earthquake-induced landslides was assessed using the Analytic Hierarchy Process, validated with historical landslide data. The vulnerability assessment considered all residential buildings registered by the 2011 Census, incorporating various parameters, such as the presence of reinforced structures, the number of floors, the conservation status, and the need for structural and non-structural repairs. These parameters, along with their respective weights, were determined based on expert opinion and literature. The analysis and the results reported in this paper revealed significant regional interactions between earthquake- and rainfall-triggered landslides, which can lead to complex damage scenarios for exposed buildings. This study not only contributes to enhancing our understanding of the physical vulnerability of buildings to rainfall- and earthquake-triggered landslides but also provides valuable insights for decision-makers and practitioners involved in hazard and risk management.

1 Context and study objectives

Landslides are complex geomorphological processes with multiple causes, which can occur simultaneously, but their final cause is a triggering mechanism responsible for the final push of a mass that was already on the verge of rupture. Rainfall and seismic activity are the main triggers of landslides in the Lisbon Metropolitan Area (LMA). In this study area, there are several studies characterising the susceptibility of rainfall-triggered landslides (RTL) (Zêzere et al., 2008; Zêzere et al., 2015). Works concerning earthquake-triggered landslides (ETL) in Portugal and the LMA are scarcer, as landslides triggered by earthquakes are less frequent and older (Vaz and Zêzere, 2016).

1.1. Rainfall-triggered landslides

According to Zêzere et al. (2005), most rainfall-triggered landslides identified in the Lisbon region are shallow translational slides, usually associated with intense precipitation events, with short durations ranging from 1 to 15 days. These landslides are small (average depth of 1 meter) and represent approximately 59% of the landslides identified in the Northern Lisbon Region, with an average area of 552 m^2.

Zêzere et al. (2005) assert that there is a link and influence between the negative monthly values of the North Atlantic Oscillation (NAO) and the landslide activity in the north region of Lisbon associated with longer periods of abundant precipitation. Additionally, they concluded that landslides are not primarily concentrated in areas with the highest rainfall, and the distribution of landslides is directly related to the location of the different lithological units. Rainfall alone is insufficient to trigger slope movements on land with stable slopes (Zêzere et al., 2008)

Vaz (2021) defined rainfall thresholds for landslide triggering in mainland Portugal through two empirical approaches: Approach I, based on antecedent precipitation, and Approach II, based on the accumulated precipitation during the event. Vaz (2021) highlighted a high concentration of landslides north of the river Tagus and concluded that the Lisbon area and the region north of Lisbon share very similar threshold values, suggesting they could be part of the same regional threshold. Moreover, rainfall episodes characterised by short or medium-duration with greater precipitation intensity and higher return periods occur earlier in the climatological year (November, December, and January) (Vaz, 2021).

Araújo et al. (2022) assessed the impact of extreme rainfall, defined as the amount of rainfall needed to trigger a landslide (rainfall triggering threshold - RTT), on future landslides. These authors projected possible changes in precipitation based on Regional Climate Model (RCM) simulations forced by Global Climate Models, considering the effect of climate change, and employing the Representative Concentration Pathways (RCP) emission scenarios: RCP 4.5 and RCP 8.5. Their analysis focused on Sobral de Monte Agraço, located in the Lisbon district. The RCP 4.5 scenario forecasts concerning days with accumulated precipitation indicate an increase in extreme precipitation, ranging from 3 % to 10 % across all mentioned cases. This implies that for the RCP 4.5 scenario (the most conservative one), there will likely be more extreme precipitation events, meeting the RTT requirements for triggering slope movements. In the case of the RCP 8.5 scenario, an increased occurrence of one-day extreme precipitation events is predicted. These events are characterised by isolated episodes with a high precipitation concentration, potentially meeting the RTT conditions necessary for triggering slope movements. This can lead to an increased number of shallow translational slides associated with intense precipitation events of short duration (Araújo et al., 2022).

1.2. Earthquake-triggered landslides

Seismic activity is acknowledged as one of the main triggers of landslides, often exacerbating the associated damage. Earthquakes can heighten the susceptibility to landslides, even if they do not directly cause damage, as they weaken the ground, acting as a preparatory factor for their occurrence during a heavy rainfall event. Portugal has experienced a significant impact from seismic events, with a well-documented history of such activity (Delgado et al., 2013). Nonetheless, earthquakes are not the primary factor triggering landslides in Portugal; they are less frequent and older, making it challenging to pinpoint the location of slope movements and reconstruct the preparatory and predisposing conditions leading to their occurrence (Vaz and Zêzere, 2016). Vaz and Zêzere (2016) have documented damages caused by earthquake-triggered landslides in the LMA by analysing historical records. The authors identified 28 landslides triggered by ten seismic events between 382 and 1969.

1.3. Physical vulnerability of buildings to landslides

The physical vulnerability of buildings (PVB) refers to the buildings' susceptibility to suffering damage resulting from the occurrence of a potentially destructive event (Sterlacchini et al., 2014). This vulnerability is typically assessed on a scale from 0 (no damage) to 1 (total damage). The immediate consequences of physical vulnerability can manifest as structural damage or even the complete collapse of affected structures. Alternatively, long-term or indirect consequences may emerge, involving, for instance, the gradual deterioration of structures, which may initially appear undamaged (Van Westen and Kingma, 2011).

To understand the physical vulnerability of buildings, it is crucial to grasp how buildings can be impacted by landslides (e.g., landslide type, size, and velocity) and how the impact/interaction can lead to different damage patterns and failure mechanisms (from superficial cracks in the walls caused by shallow landslides to the complete destruction of buildings in the case of debris flows). Research on the interaction between buildings and slope movements has been conducted (Li et al., 2020; Luo et al., 2020, 2023; Zeng et al., 2015) through a range of methods: static analysis, field investigations, experimental tests, and numerical simulations (Luo et al., 2020). The interaction between buildings and landslides can vary depending on factors such as the material and type of structure, geometric characteristics, the conservation state/ integrity of the buildings or other affected structures, the direction of the movement, and the size of the slope movement (Papathoma-Köhle et al., 2017). Zeng et al. (2015) characterise the damage resulting from building-slope movement interaction for reinforced concrete buildings in the main building components. Following the initial frontal contact of the slope movement with the building, it is possible to observe different damage patterns: out-of-plane fractures in the front walls, in-plane cracks in the side walls, and bending failures or fractures in the columns. As the impact-induced stress increases, the building's foundations may also experience sliding (Luo et al., 2023; Zeng et al., 2015). The properties of the landslide (e.g., the constitution of the material and the presence of water) affect both the rupture mechanism in the building columns and the way the building collapses (Zeng et al., 2015).

Methods for assessing physical vulnerability can be categorised into two main types: qualitative methods, which encompass experience-based and indicator-based models, and quantitative methods, including data-driven and mechanism-based models (Luo et al., 2023).

Experience-based and indicator-based models are empirical approaches that rely on the analysis of statistical damage from observed events, expert opinion on physical vulnerability, or the assignment of scores, typically by conducting questionnaires with various parameters to evaluate the potential damage caused by different hazardous phenomena (Van Westen and Kingma, 2011). In the case of frequent events, gathering information about the degree of physical damage to buildings or infrastructures can be a swift and practical process by creating damage probability matrices or vulnerability curves. However, if there is limited prior data available regarding the damage, or if resources for the application of analytical methods are lacking, consulting a group of experts specialised in vulnerability or expected damage based on the intensity of the hazardous phenomenon becomes the most viable option (Silva and Pereira, 2014; Van Westen and Kingma, 2011). Indicator-based models utilise vulnerability functions that assign different scores to indicators, considering the characteristics of the exposed asset. These models offer flexibility in their implementation and are often used to support decision-making and implement measures to mitigate physical vulnerability, typically at a local scale. An advantage of these methods is their adaptability to similar areas with matching characteristics. However, models based on indicators have the drawback of not translating the results into monetary losses (not directly, at least). Both the model and the vulnerability index are subject to subjective evaluation, and a significant need exists for comprehensive information on the indicators.

1.4. Aims and research objectives

In the context described above, this work aims to assess the physical vulnerability of buildings in the Lisbon Metropolitan Area (LMA), situated in landslide-prone areas triggered by rainfall and seismic activity independently. The specific objectives are defined as follows:

- (i) Identify the buildings within the LMA located in highly susceptible areas to landslides triggered by rainfall and seismic activity;
- (ii) Develop a physical vulnerability index for LMA buildings using variables drawn from the 2011 census data and supported by relevant literature;
- (iii) Apply the physical vulnerability index to buildings located in the landslide toe within the most susceptible areas of the LMA, whether susceptible to landslides triggered by rainfall or seismic activity.

2 Study area

The LMA comprises 18 municipalities and 122 parishes, covering a total area of 3,015 km², distributed into two primary regions separated by the Tagus estuary: Greater Lisbon to the north and the Setúbal Peninsula to the south. On a national scale, the LMA is the most populous area of the country, with approximately 2,870,770 people as per the 2021 census. This population represents about 27.8% of the total Portuguese population.

2.1. Geological and geomorphological context

Mainland Portugal is in the south-western part of the Eurasian Plate and constitutes an important area of seismic activity, with seismicity resulting either from phenomena derived from movements in faults located at the boundaries of the plates (interplates) or from phenomena resulting from faults that are in the interior of the Eurasian plate (intraplates). The intersection of the Eurasian Plate with the African Plate, at the southern limit of the Iberian Peninsula, is responsible for the tension that causes the highest seismic activity, with the converging movement of the two plates in the NNW-SSE direction, translating the subduction of the Atlantic oceanic lithosphere under the Iberian continental lithosphere (Senos & Carrilho, 2003).

The Lower Tagus Fault is one of the main active tectonic faults in the LMA. Tectonically, it is characterised by intra-plate movement, which was responsible for one of the most important earthquakes in the region (January 26, 1531 (Vaz and Zêzere, 2020). On the Meso-Cenozoic Basins, there are two important regional units in the AML territory: the mountains and hills between Montejunto and Lisbon and the Arrábida chain. The main relief unit in the LMA is the Serra de Sintra, a magmatic massif dome (528 m) and the Lisbon Volcanic Complex, dominated by hills that are what remains of old volcanic cones, deconstructed in the current relief, which has a maximum altitude of 400 meters. The Arrábida chain is a small WSW-ENE trending Alpine orogenic belt of Miocene age, with a maximum altitude of 501 meters.

The Lower Tagus and Alvalade Cenozoic Basins present in the LMA territory include the High Plain of Ribatejo, with essentially Miocene sediments; the High Plain of Alentejo, characterised by the sedimentary filling surfaces; and the low Tagus plain, a flat and lower area with alluvium and low sedimentary terraces of the Tagus river. The coastal platform between Peniche and Lisbon is limited by cliffs and steep slopes with small or non-existent beaches and the Setúbal Peninsula, located between the Tagus estuary and the Arrábida chain, where its southern flank plunges into the Atlantic Ocean through vertical sea cliffs.

The diverse and complex lithological features of the LMA influence the spatial distribution of landslides and the response of the terrain to seismic waves. Therefore, it is essential to consider the lithology and the distribution of the seismic hazard across the region.

2.2. Landslide inventory

As mentioned earlier, landslide inventories were obtained from three different databases: two records of landslides triggered by rainfall (DISASTER database and the National Authority for Emergency and Civil Protection - ANEPC database) and a historical inventory of landslides triggered by seismic events (Vaz & Zêzere, 2016).

DISASTER's national database only includes landslides that caused human damages (e.g., fatalities, injuries, or reports of evacuated, displaced and/or missing people) reported in national and regional newspapers. Between 2006 and 2020, there were five damaging landslides in the LMA, where two fatalities, five injured, four displaced people and ten affected buildings were recorded. The DISASTER cases are related to damaging landslides affecting the population and/or buildings.

The ANEPC database includes the reports of the civil protection authorities every time there is an emergency call. Seven hundred sixty-six landslides were then identified between 2006 and 2020 in the LMA, with Mafra and Loures municipalities being the most affected in these years, with 165 and 123 occurrences, respectively. The ANEPC database includes more dispersed landslide cases, often reporting landslides that caused obstructions on public roads and/or damages in buildings.

The inventory of historical landslides triggered by earthquakes identified by Vaz and Zêzere (2016) in historical documental sources contains ten occurrences in the LMA between 1512 and 1856. The 1755 earthquake caused the largest number of landslides (3), followed by the 1531 earthquake (2). Santa Maria Maior, located in the Lisbon municipality, was the most affected parish, with five landslides triggered by earthquakes. The landslide records triggered by earthquakes (Vaz and Zêzere, 2016) cannot be dissociated from the date of occurrence, the context of the urban fabric and the population distribution at the time of the events since it is in places with a greater population concentration and greater urban density that these occurrences have more visibility and impact, and therefore more documentary records are available.

2.3. Building environment

According to 2011 census data, the LMA comprises a total of 448,957 buildings, with 292,978 (65 %) being reinforced concrete (RC) structures, 97,116 (22 %) being “placa” buildings, and 48,138 (11 %) being masonry buildings. A small percentage of buildings, approximately 3 %, are constructed from materials like adobe or timber. The urban fabric includes accommodations built before 1919, totalling 22,297. Urban development showed significant growth until 1990, with 215,799 buildings constructed in the 30 years from 1961 to 1990, accounting for approximately 48 % of the current building stock.

Yet according to the Census 2011, around 69 % of buildings in the LMA have 1 or 2 floors (309,150), while buildings with more than two floors make up about 31 % (139,807). Within the category of 1 or 2-storey buildings, 59.7 % are reinforced concrete, 25.2 % are “placa” buildings, 12 % are masonry structures, and only

2.3 % are made of loose stone or adobe masonry. The remaining 0.8 % corresponds to buildings with 1 or 2 floors constructed using other structural systems. In the case of buildings with two or more floors, 77.6 % have a reinforced concrete structure, 13.7 % are slab buildings, 7.8 % are masonry walls, and only 0.4 % have walls made of loose stone or adobe masonry. The remaining 0.5 % of buildings with two or more floors were built using other structural solutions.

3 Data and methods

The physical vulnerability of the building located on the landslide toe (accumulated material), triggered by rainfall and seismic activity, is evaluated in this work for all buildings in the LMA situated in highly susceptible areas (9th decile) for both triggering mechanisms (Figure 1).

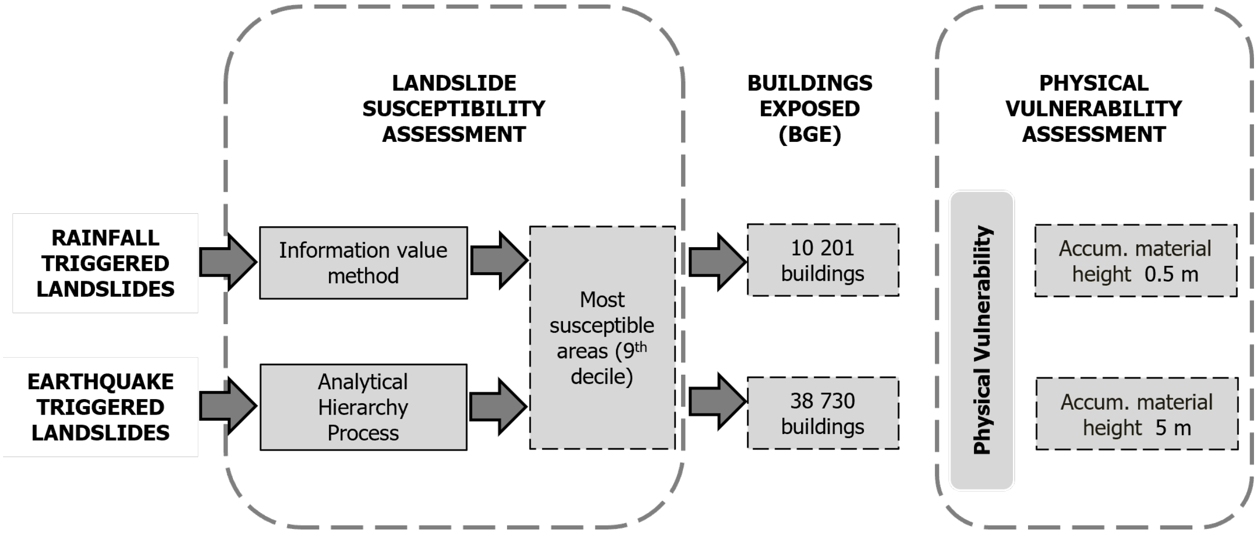

Figure 1. Methodological framework.

3.1 Most susceptible areas of rainfall- and earthquake-triggered landslides

The susceptibility to rainfall-triggered landslides was evaluated in a prior study (Zêzere et al., 2021) using a bivariate statistical model, the Information Value method (IV). This assessment involved seven predisposing factors with a cell size of 10 meters, which included slope angle, slope exposure, slope curvature (transverse profile), geology, land use, topographic position index and topographic wetness index. Landslides were inventoried for the Lisbon and Tagus Valley region based on the interpretation of aerial photos, orthophoto maps, and fieldwork in sample areas. The landslide inventory performed included 4,047 occurrences, most corresponding to slides (translational and rotational), which were used as a dependent variable. The quality of this rainfall-triggered landslide susceptibility model was assessed by computing the ROC curve and the corresponding Area Under the Curve (AUC). The susceptibility to rainfall-triggered landslides was divided into five classes (very high, high, moderate, low, and very low), defined through the percentage of accumulated validated landslide area: 50 %, 70 %, 90 %, 95 %, and 100 %, respectively. For delimiting, the areas currently subject to high and very high landslide susceptibility classes were selected and aggregated, which together validate 70 % of the landslide inventory and represent the 90th percentile of the susceptible area.

Susceptibility to landslides triggered by earthquakes was assessed with the multicriteria method of the Analytic Hierarchy Process to achieve the relative weights based on Saaty's scale of influence (Cardoso et al., 2023). This technique consists of comparing predisposition factors, ranking one in relation to the other through the attribution of weights (to the variables) and scores (to the classes of variables). This technique is quite subjective as it depends on specialised knowledge of the different predisposing factors to justify the ranking of priority scales (Saaty, 2008); in this case, this knowledge was justified with the support of bibliographic research. In this model, six predisposing factors (slope angle, slope curvature, topographic position index, geology, peak ground acceleration, and distance to faults and a historical landslide inventory based on documental sources (Vaz and Zêzere, 2016) were used to assess landslide susceptibility. The predisposing factors were reclassified, and the respective classes were ranked by decreasing order of importance, where a weight was assigned to each class and a score to each class of the variable. The area most susceptible to landslides triggered by earthquakes (90^{th} percentile) was selected to assess the physical vulnerability of each building exposed to landslides. A slope movement inventory with ten occurrences (Vaz and Zêzere, 2016) was used to assess the overall quality of the landslide susceptibility model triggered by seismic activity by calculating the ROC curve and the AUC.

3.2 Physical Vulnerability of Buildings (PVB)

The physical vulnerability of buildings located in the areas identified as more susceptible to landslide was assessed using the Building Georeferencing Base (BGE) of the Portuguese Institute of Statistics (INE). This database includes 449,473 buildings for the LMA and data about the building characteristics, building type, building structure, main use, number of floors, presence of elevator, accessibility to wheelchairs, number of lodgings, period of construction, the material used in the exterior cladding of the building, type of building cover and the need for repairs (rooftop, structure, walls, and window frames).

In this work, two scenarios were considered: (i) the scenario where a specific building is situated in the landslide toe with a 0.5-meter height of accumulated material, in a situation of slope instability triggered by rainfall, and (ii) a scenario where a specific building is positioned in the landslide toe with a 5-meter height of accumulated material, in a situation of slope instability triggered by seismic activity. The physical vulnerability index was computed for all buildings located in high and very high susceptibility classes (90^{th} percentile) in both scenarios, resulting in 10,201 buildings in scenario (i) and 38,730 buildings in scenario (ii).

The physical vulnerability index encompasses six parameters: construction material (CM), reinforced structure (RS), construction period (PC), need for repair in the structure (NRS), need for repair in the finishes (NRF), and number of floors (NF). Each parameter was categorised into a series of building classes derived from BGE (Table 1).

Construction materials (CM) include four main types of building materials, ordered from the least to the most vulnerable: reinforced concrete, brick or stone walls, adobe, and other materials (e.g., wood and metallic). The presence of a reinforced structure (RS) was also considered, as it provides an additional level of resistance to the building.

The BGE database categorises the buildings according to 11 well-defined classes for the construction period (CP), ranging from buildings predating 1919 to constructions up to 2011. The construction period indirectly reflects the state of conservation and the quality of building construction during different historical periods. This variable was categorised into four classes, representing increasing building quality: (i) the period before 1919, encompassing the most ancient and historical buildings, often constructed with unreinforced masonry and timber floors; (ii) the period between 1919 and 1960, which includes the eras of the two World Wars and shortages of construction materials, such as steel. During this period, the emergence of "Placa" buildings in Lisbon, characterised by regular geometry, was notable; (iii) the period between 1960 and 1990, known for the use of better construction techniques, including the use of reinforced concrete; and (iv) the period after 1990, corresponding to modern structures buildings according to current design codes (Xofi, 2021)

The need for repair in the structure (NRS) and in the finishings (NRF) is categorised into five classes: does not require repairs, requires minor repairs, requires medium repairs, requires large repairs, and requires major repairs. The number of floors (NF) serves as a proxy variable for the depth of foundations, as taller buildings necessitate deeper and more robust foundations (Silva and Pereira, 2014). In this work, two categories for the number of floors were considered: 1 or 2 floors and more than two floors.

A score was assigned to each building class and the respective parameters for both triggering scenarios (Table 1). These scores and parameter weights were determined based on expert opinions and relevant literature. For example, information on construction material and reinforcement was sourced from Guillard-Goncalves et al. (2016), who assigned an average vulnerability value to a study area located in Loures municipality. The scores in Guillard-Goncalves et al. (2016) were derived from a questionnaire administered to a panel of 14 experts with field expertise in landslides in the northern Lisbon region.

Table 1. Vulnerability index formulation: parameters, classes, and respective weights.

Parameters and classes		RTL	ETL
		Accumulated material height of 0.5 m	**Accumulated material height of 5 m**
CM	Reinforced concrete	0.2	0.79
	Brick and stone	0.24	0.90
	Adobe	0.29	0.97
	Other (Wood. metallic. ...)	0.39	0.97
RS	Reinforced concrete	0.2	0.79
	Masonry walls with concrete elements	0.2	0.79
	Masonry walls. without concrete elements	0.24	0.90
	Walls of adobe or loose stone masonry	0.29	0.97
	Other (Wood, metallic...)	0.39	0.97
CP	> 1991	0.1	0.1
	1961 < 1991	0.3	0.3
	1919 < 1961	0.5	0.5
	< 1919	0.7	0.7
NRS and NRF	Does not require repairs	0.1	0.1
	Requires minor repairs	0.3	0.3
	Requires medium repairs	0.5	0.5
	Requires large repairs	0.8	0.8
	Requires major repairs	1	1
NF	> 2	0.1	0.1
	1 or 2	0.3	0.3

The PVI was weighted as follows:

$$PVI = (CM \times 0.3) + (RS \times 0.2) + (NF \times 0.2) + (PC \times 0.1) + (NRS \times 0.1) + (NRF \times 0.1) \quad (1)$$

Where the weights assigned to each parameter of the physical vulnerability index (PVI) were based on a previous publication by Pereira et al. (2020). In their study, the construction material held the most significant weight, followed by the reinforced structure and number of floors. Given that this index includes two additional variables compared to Pereira et al. (2020), adjustments were made to the weights, with the need for repairs to the structure and the need for repairs to the finishings (NRS and NRF) carrying the same weight as the construction period (PC) (0.1).

4 Results

Figure 1 shows the physical vulnerability of buildings (PVB) exposed to the 90th percentile of susceptibility to RTL for a 0.5 m height of accumulated material scenario, and Figure 2 shows the physical vulnerability of buildings exposed to the 90th percentile of susceptibility to ETL for a 5 m height of accumulated material scenario. Physical vulnerability is represented by five classes (Very Low, Low, Moderate, High, and Very High), divided into quintiles. The municipalities of Lisbon and Loures present the buildings with the highest physical vulnerability index in the case of RTL. The municipalities of Lisbon present the buildings with the highest physical vulnerability index in the case of ETL.

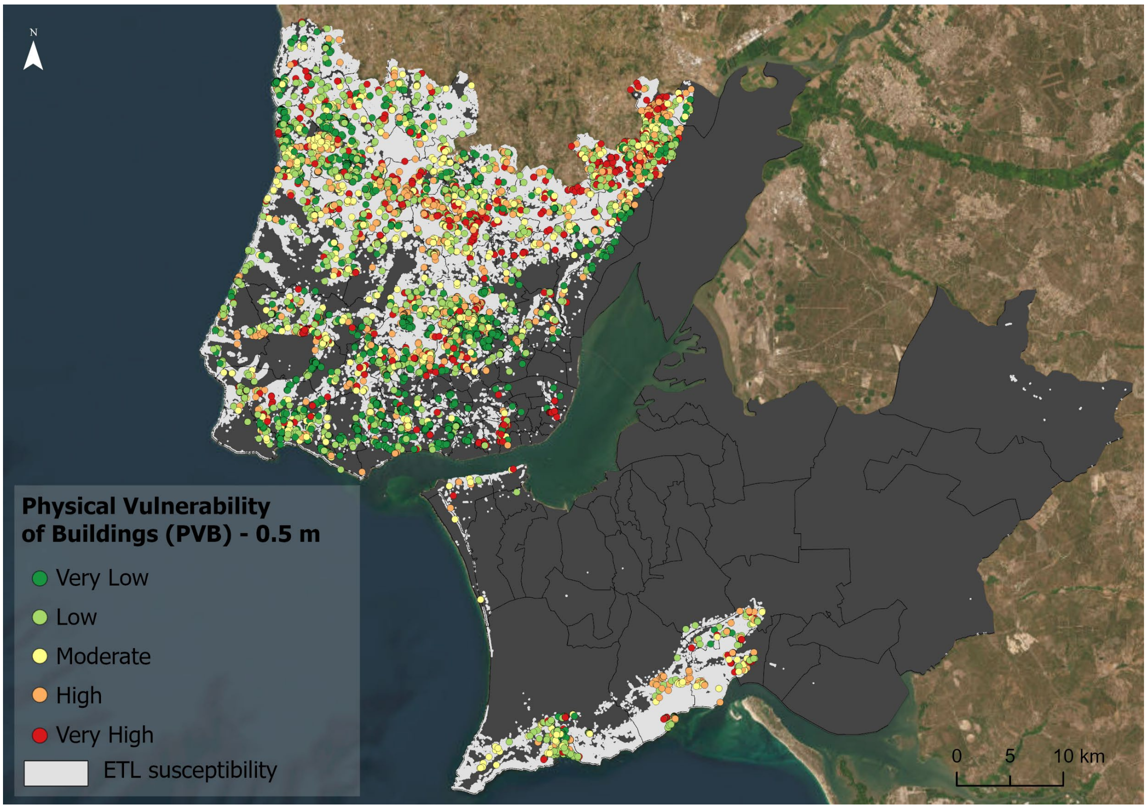

Figure 1. Physical vulnerability of buildings located in the 90th percentile of RTL susceptibility across the LMA (0.5 m accumulated material height scenario).

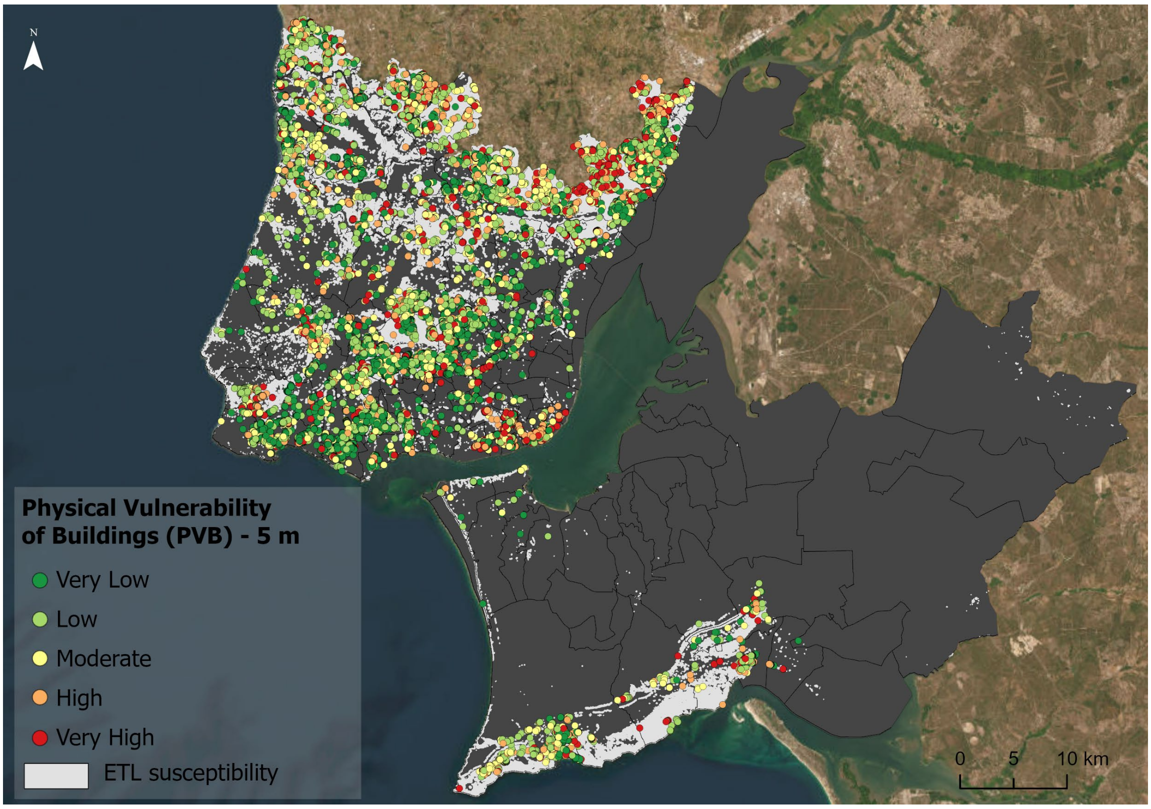

Figure 2. Physical vulnerability of buildings located in the 90th percentile of ETL susceptibility in the LMA (5 m accumulated material height scenario).

The physical vulnerability to RTL ranges from 0.150 (minimum value and 1st quartile) to 0.525 (maximum value), with an average value of 0.202, and the median corresponds to 0.190 (Figure 1). The buildings with the highest physical vulnerability in this scenario are in Alhandra, São João dos Montes and Calhandriz (Vila Franca de Xira), Lousa (Loures), Mafra and Venda do Pinheiro and Santo Estêvão das Galés (Mafra). The parishes of Ajuda, Penha de França, Beato, Alcântara and Campo de Ourique, in the municipality of Lisbon, have the highest average physical vulnerability. The parishes with the most buildings classified with "Very High" physical vulnerability are Alhandra, São João dos Montes and Calhandriz (Vila Franca de Xira), with 159 buildings and Lousa (Loures) with 135 buildings with very high vulnerability. The parishes with the lowest physical vulnerability averages are Belém, Avenidas Novas, Alvalade (Lisbon), Águas Livres, Venteira (Amadora), Sacavém and Prior Velho (Loures).

The physical vulnerability index for ETL ranges between 0.445 and 0.815, with an average value of 0.521 and a median of 0.505 (Figure 2). The PVB for RTL exhibits lower values than for ETL, reflecting the variance in scores assigned to the classes of variables related to the construction material and the reinforced structure for both scenarios. The buildings with the highest physical vulnerability are located in Bucelas, Fanhões (Loures), Enxara do Bispo, Gradil and Vila Franca do Rosário, Azueira and Sobral da Abelheira, Encarnação, Milharado, Igreja Nova and Cheleiros and Venda do Pinheiro and Santo Estêvão das Galés (Mafra), and Alhandra, São João dos Montes and Calhandriz, and Vila Franca de Xira (Vila Franca de Xira). The parishes with the most buildings classified with "Very High" physical vulnerability are Alhandra, São João dos Montes and Calhandriz (Vila Franca de Xira) with 377 buildings, Campo de Ourique (Lisbon) with 194 buildings with very high vulnerability, and Bucelas (Loures) with 175 buildings.

Figure 3 illustrates the physical vulnerability parameters and corresponding mean values of PVI for each PVI class to RTL (A) and ETL (B) scenarios.

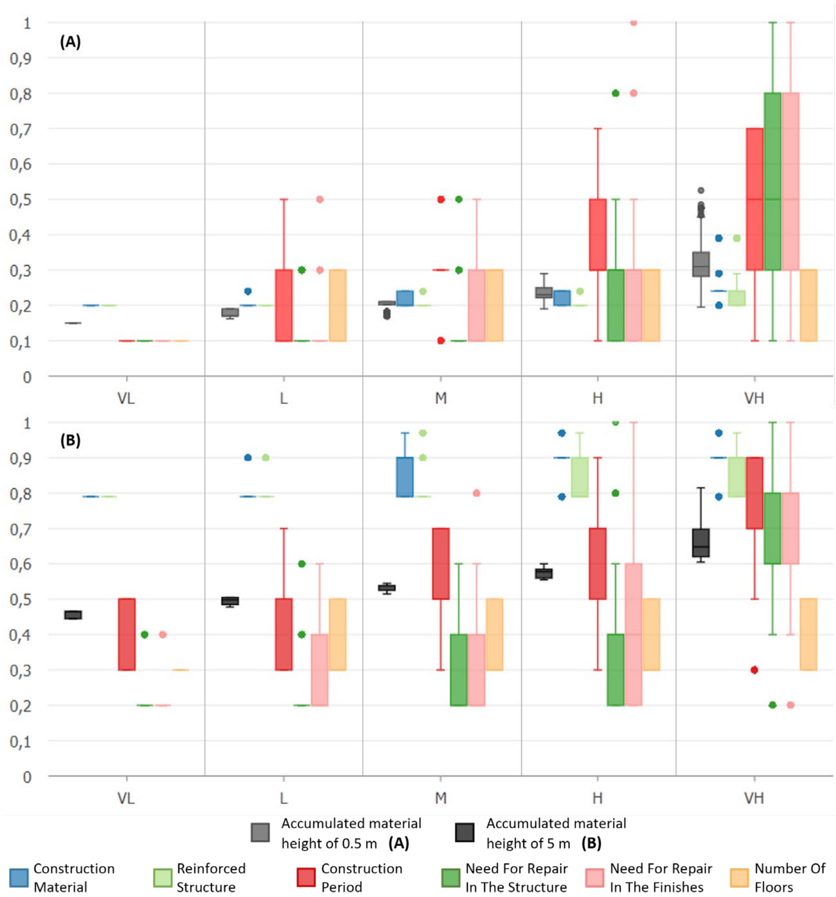

Figure 3. Physical vulnerability parameters and corresponding mean values of PVI for each PVI class to RTL (A) and ETL (B) scenarios.

In scenario A (RTL), the Very Low vulnerability class shows the lowest PVI of each variable. In the Low vulnerability class, variables relating to the time of construction and the number of storeys show a greater amplitude of extreme values. The variable relating to the number of floors, as it only has two classes (0.3 and 0.5), is equally representative of the other higher physical vulnerability classes. In the Moderate and High vulnerability classes, the variables construction material, need for repairs to the cladding and number of floors show the same average vulnerability values. In the Very High vulnerability class, the average values of the variables are the highest.

In scenario B (ETL), in the Very Low vulnerability class, except for the time of construction, the variables have the lowest averages. In the Low and Moderate vulnerability classes, the values of the variables relating to the number of floors and the need for repairs to the cladding did not vary much. The variables relating to the need for repairs to the structure and the need for repairs to the cladding are the ones with the highest average in the High class. In the Very High vulnerability class, the average values of all variables are higher.

The greatest disparity between the average of RTL and ETL values is observed in the variable of construction material and reinforced structure, with an average difference of more than 0.5 for every class. In the construction material variable, the greatest difference between the average of RTL and ETL values is found in the high vulnerability class (0.2 and 0.8, respectively), while in the reinforced structure variable, the class with the biggest difference in average value is the Very High vulnerability class, with an average value of 0.24 for RTL and 0.88 for ETL. For the construction period variable, the greatest difference between the average RTL and ETL values is found in the High vulnerability class (0.34 and 0.66, respectively). The variables concerning the need for repairs to the structure and the need for repairs to the cladding have a greater disparity of average values, between RTL and ETL, in the Moderate vulnerability class, with an average value of 0.14 and 0.30, to RTL, and an average value of 0.15 and 0.33, to ETL, respectively. In the number of floors variable, the greatest difference between the average RTL and ETL values is found in the Low vulnerability class (0.17 and 0.39, respectively).

5 Discussion and conclusions

In this work, two landslide-triggering scenarios were analysed to identify the most vulnerable residential buildings in the LMA. A landslide susceptibility model was produced for each triggering scenario. The RTL susceptibility model was validated through photo-interpretation inventories (4,047 landslides) and field validation in critical points, while the ETL susceptibility model was validated through a small historical inventory (10 landslides), which, unfortunately, did not present precise location information. This case can affect the results, and therefore, it would be important in the future to attest to the quality of models with recent events.

The susceptibility to ETL was modelled through the Analytic Hierarchy Process (multi-criteria analysis method), which implies a subjective hierarchy based on expert opinion and previous studies, lacking a ground validation of the quality of susceptibility and validation of the model through occurrences of landslides triggered by future seismic events. The very high susceptible areas to RTL are more restricted to the most hazardous slopes in the LMA (339.54 km^2) located in the hills in the north of Lisbon and the Arrábida chain, and the very high susceptible areas to ETL (309.91 km^2) are around the same main locations but with larger features. This is the first time these approaches have been evaluated jointly for the entire LMA.

The analysis of a scenario where the buildings are exposed at the landslide's toe, for the two scenarios, was only carried out for areas with very high susceptibility; this limited the analysis to the 90th percentile of susceptibility. This does not mean that there cannot be damage to buildings belonging to areas with high susceptibility, like, for example, areas within the 80th percentile of susceptibility; however, in this work, it was assumed to only consider 10 % of the most susceptible areas in the entire LMA, for both scenarios (RTL and ETL). Sliding failure of foundations, depth of the landslide and impact direction affect the building damage. For instance, longitudinal impact leads to a larger contact area and a small resistance moment, which can generate severe damage to the buildings, although these scenarios were not considered. Future studies should encompass a wide range of worst scenarios in landslide–building interaction studies.

The physical vulnerability index (PVI) was based on literature (Guillard-Goncalves et al., 2016; Pereira et al., 2020). Uncertainties can be quantified from the input parameters to the vulnerability estimates, and the weights are often based on expert judgment, which seems subjective. However, for the LMA, there is not a good inventory of damages generated by landslides and the characteristics of the respective buildings affected. This makes it difficult to legitimise the scores and weights assigned to classes and variables, respectively, and to apply a quantitative vulnerability model developed by statistical analysis or post-events data. The variables used to perform the physical vulnerability index (PVI) were taken from the Building Georeferencing Base (BGE) of the 2011 census date. This information is out of date since there is already a 2021 census; however, information and data about the characteristics of the buildings were not made available at the time of this work, and there may be missing information regarding new buildings built in the last ten years.

In the LMA, it was found that the most problematic PVB areas for both scenarios correspond to the parish of Lisbon, presenting an average of buildings with higher physical vulnerability. There is a large difference in the variation of the PVB index values for a 0.5 m height of accumulated material scenario for an RTL (ranges between 0.15 and 0.525) and a 5 m height of accumulated material scenario for ETL (ranges between 0.445 and 0.815). This reflects the different scores attributed to the variables of construction material and reinforced structure in the two scenarios (Guillard-Goncalves et al., 2016; Pereira et al., 2020), which correspond to the variables with greater weight in the PVI.

This study was carried out on a building scale for the entire territory of LMA, which corresponds to a large study area with a small scale. However, this work presents a great potential for analysis and future complements; for example, in a larger scale study, at the level of street/block analysis, through the identification of multi-risk hotspot areas and the identification of safe areas evacuation areas for the resident population. Through the hotspots, it would be possible to identify priority risk prevention areas and implement local strategies to reduce the physical vulnerability of buildings and their exposure to landslides triggered by future rainfall and earthquake events, with detailed studies and detailed technical protection interventions (on-site intervention). This more in-depth study can also be carried out at the level of the municipality (making the hierarchy of parishes according to the average value of PVI) and at the parish level.

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