Sensitivity of earthquake damage estimation to the input data: Case study in the Luchon valley, France

Rosemary Fayjaloun, Caterina Negulescu, Agathe Roulle, Pierre Gehl, Samuel Auclair, Marta Faravelli

▶ To cite this version:

Rosemary Fayjaloun, Caterina Negulescu, Agathe Roulle, Pierre Gehl, Samuel Auclair, et al.. Sensitivity of earthquake damage estimation to the input data: Case study in the Luchon valley, France. 3rd EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING & SEISMOLOGY Sep 2022, Bucarest, Romania, Sep 2022, Bucarest, Romania. hal-03749027

HAL Id: hal-03749027
https://hal-brgm.archives-ouvertes.fr/hal-03749027

Sensitivity of earthquake damage estimation to the input data: Case study in the Luchon valley, France

Rosemary Fayjaloun – BRGM, Orléans, France, rosemaryfayjaloun@gmail.com

Caterina Negulescu* – BRGM, Orléans, France, c.negulescu@brgm.fr

Agathe Roullé – BRGM, Orléans, France, a.roulle@brgm.fr

Pierre Gehl – BRGM, Orléans, France, p.gehl@brgm.fr

Samuel Auclair – BRGM, Orléans, France, s.auclair@brgm.fr

Marta Faravelli – European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy, marta.faravelli@eucentre.it

Abstract: This article studies the effects of the soil data and exposure data of residential building inventories, as well as their spatial resolution, on seismic damage and loss estimates for a given earthquake scenario. Our aim is to investigate how beneficial it would be to acquire higher resolution inventories, at the cost of additional effort and resources. Seismic damage computations are used to evaluate the relative influence of varying spatial resolution on a given damage model, where other parameters were held constant. We use soil characterization maps and building exposure inventories, provided at different scales from different sources: the European database, a national data set at the municipality scale, and local field investigations. Soil characteristics are used to evaluate site effects and to assign amplification factors to the strong motion applied to the exposed areas. Exposure data sets are used to assign vulnerability indices to sets of buildings, from which a damage distribution is produced (based on the applied seismic intensity). The different spatial resolutions are benchmarked in a case-study area which is subject to moderate-to-average seismicity levels (Luchon valley in the Pyrénées, France). It was found that the proportion of heavily dam-aged buildings is underestimated when using the European soil map and the European building database, while the more refined databases (national/regional vs. local maps) result in similar estimates for moderate earthquake scenarios. Finally, we highlight the importance of pooling open access data from different sources, but caution the challenges of combining different data sets, especially depending on the type of application that is pursued (e.g., for risk mitigation or rapid response tools).

Keywords: Damage and loss assessment, site effects, exposure modelling, spatial resolution, earthquake scenario.

1. Introduction

Earthquake risk assessment is a complex exercise, involving the assimilation of geological, seismological, engineering, demographic, and economic data within a risk assessment model (Corbane et al., 2017). Significant efforts have been made in the last 25 years towards the development of regional, national, continental, or even global seismic hazard and risk models, such as the National Risk Assessment (NRA) for Italy (Dolce et al., 2020), the Global Earthquake Risk Model developed by the Global Earthquake Model (GEM) foundation (Silva et al., 2020) and, more recently, the European Seismic Risk Model ERSSRM20, which is an output of the European Horizon 2020 SERA project (Crowley et al., 2020a), building upon the research efforts of many previous projects (e.g., LESSLOSS, SYNER-G, and NERA- SHARE) (Riga et al., 2021). Seismic damage assessment requires taking three main factors into consideration: hazard, exposure, and vulnerability. Hazard refers to a specific given scenario (deterministic study) or to the aggregation of all possible future occurrences of seismic events (probabilistic study) which may have adverse effects on vulnerable and ex-posed elements. On the other hand, exposure refers to the inventory of elements in an area in which the hazard may occur, while vulnerability refers to the susceptibility of exposed elements, such as physical components (e.g., buildings), human beings, and their livelihoods, to suffer adverse effects when subjected to the hazard. Several models have been developed for assessing the vulnerability of buildings and estimating the expected earthquake damages and losses for a given scenario. The methods developed may be empirical, analytical, or mechanical, based on fragility curves of buildings or hybrid methods (Calvi et al., 2006). The methodological and input data choices inevitably introduce uncertainty in the results of the seismic risk assessment. A variety of uncertainties, originating from different sources, are present at every step of the risk assessment process (e.g., natural variability of the phenomena under investigation, in-completeness of input data, or inadequacies in the models and methods). Bal et al. (2010) studied the geographical resolution of exposure data and of the ground motion (PGA amplified by the soil effect) for the sea of Marmara region in Turkey, using several different levels of spatial aggregation to estimate the losses due to a single earthquake scenario. They showed that, if only mean estimates are needed, the effort required to refine the spatial definition of exposure data is not justified. The average damage values over the simulations were almost insensitive to the resolution of the ground motion field. Their results indicated that a significant reduction in the variability of these estimates can be achieved by moving to higher resolution ground-motion fields. As the effect of moving to higher resolutions is to introduce some regions with higher-than-average damage and others with lower-than-average damage, these two effects largely cancel each other out.

The collection of harmonized data at a regional scale, as well as at the local scale, still represents one of the major challenges in seismic risk assessment studies. Preparing for data inventory is usually the most time-consuming and costly aspect of a loss study. It is also the most frustrating as, in principle, it is ideal to develop a perfect inventory; however, in practice, compromises must be made. It is wise to compile and update inventories that are as accurate as possible, under the circumstances and re-sources available.

In this study, we focus on two key inventories that are needed to estimate seismic damage: the soil database, which is part of the hazard factor when considering site amplification, and the building database, which establishes the exposure and vulnerability factors. The first inventory is about the local site conditions that have a great effect on earthquake losses. The second inventory is related to the buildings and their vulnerability. It provides the spatial distribution of buildings at the territorial scale (i.e., the number of buildings in each territorial unit of analysis), as well as the vulnerability classification of these buildings.

A question thus arises: to what extent is acquiring a higher resolution inventory beneficial? This article aims to study the effects of spatial scale (i.e., the resolution of input data describing the soil conditions and the characteristics of residential buildings) on the estimation of damage and loss for a given earthquake scenario, by considering either ‘weak data’ (collected at a large-scale) or ‘more accurate,’ yet more difficult-to-obtain, detailed surveys. Specifically, we address the question of how detailed such data sets should be, in order to yield a robust enough estimation of damage and loss, and how this affects the information delivered to operational emergency managers. We conduct this investigation in the Luchon valley, located in the French Pyrenees, due to the wealth of available data on the exposure of residential buildings and on local site effects at different scales (Table 1 and Figure 1). More detailed description of the different soil and building exposure inventories are presented in Fayjaloun et al. 2021. The structural damage are estimated using the intensity-based empirical vulnerability relationships developed by Lagomarsino and Giovinazzi (2006), without considering site effects at first stage (constant PGA), to study the effect of exposure data resolution in a deterministic scenario; and with site amplifications at a second stage to study the effects of both soil and exposure data resolution on the damage estimates. Finally, two historical deterministic scenarios are studied. The findings of this study are detailed in Section 3. The objective of studying the two historical regional earthquakes is not to compare the damage prediction with the observed damages, but rather to illustrate the differences obtained using different resolution of the input data. Indeed, for these two earthquakes, documentary archives do provide descriptions of the damage observed following these two earthquakes, but these observations cannot be used for validation, because the distribution and vulnerability of the buildings in 1855 and 1923 are very different from today.

2. Scenarios and Methodology

The risk evaluation procedure used herein consists of various steps, which are briefly outlined in this section. The first step of the procedure is to set the level of strong motion for rock conditions (i.e., without site effects), expressed in Peak Ground Acceleration (PGA), using either (i) a user-defined PGA map, or (ii) calculation per-formed using a ground motion prediction equation (GMPE), based on the magnitude and location of the scenario-earthquake assuming rock site conditions. Then, the impact of site effects on the PGA due to local variations in the near-surface lithology—and, possibly, topography (not considered here)—are modeled, by applying soil amplification coefficients using a site classification map (ideally coming from a seismic microzonation study). The PGA maps are then converted into macroseismic intensity, in terms of the EMS98 European Macroseismic Scale (Grünthal, 1998), using a ground-motion-to-intensity conversion equation (GMICE developed by Atkinson and Sonley, 2000). The elements at risk (in this study, residential buildings) are characterized by vulnerability indices (Vi): a Vi value is assigned to each building type, defined in terms of its age, material, technique of construction and, potentially, other characteristics. Next, the damage degree is estimated, using the intensity-based empirical vulnerability relationships developed by Lagomarsino and Giovinazzi (2006) on the basis of the EMS98 macroseismic scale, where an analytical expression for the mean damage grade, μD (mean of the discrete beta distribution), is provided as a function of the macroseismic intensity and the Vi of a given building type. Finally, the distribution of damage at each location is assessed, based on μD and a value, t, which governs the spread of the discrete beta distribution. The outcome is the distribution, in terms of the six damage levels defined in the EMS98—D0 (undamaged), D1 (slight damage), D2 (moderate damage), D3 (heavy damage), D4 (partial collapse), and D5 (total col-lapse)—for each location, which are separately considered. This procedure was implemented in the in-house BRGM software Armagedom, which was used for the computations presented here. Armagedom software is accessible via BRGM VIGIRISKS platform, a web-tool for Single and Multi-Hazard Risk Assessment (https://vigirisks.fr/). Details on the procedure and the software have been provided by Sedan et al. (2013), Tellez-Arenas et al. (2019), Negulescu et al. (2019) and Negulescu et al. (2020).

We identified three sources for the databases, concerning the soil classification maps:
- The European map (issued from SERA project), Municipal level (Crowley at al., 2019);
- The National map (issued from collaboration between BRGM and CCR), Municipal level (Monfort and Roullé, 2016); and

- The maps issued from microzonation studies at the specific area (SISPyr project), District level (Roullé et al., 2012).

We also identified three databases for collecting data concerning building exposure:

- The European database (issued from SERA project), Municipal level (Crowley et al. 2018);
- Data from the French national statistics institute (INSEE), Municipal lev-el—in which the spatial distribution is juxtaposed with the occupancy areas (Sedan et al., 2008); and
- Data issued from site inspection at the specific area (SISPyr project), district level (Monfort et al., 2012).

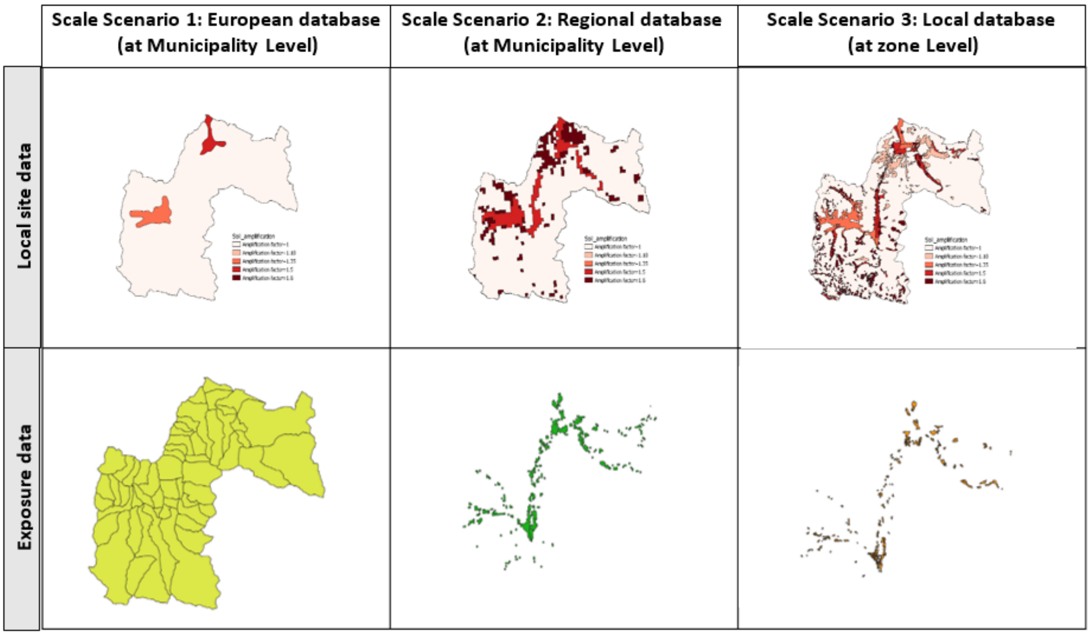

Fig. 1 - The site characterization maps and the building exposure used for the 3 scale-scenarios defined in this study.

Table 1. Scale-Scenario description based on the source of databases to characterize the site amplification as well as the building exposure.

Level of detail		**National statistics data**		**In-situ investigation data**
Scale-Scenario		**SS1: Europe**	**SS2: France**	**SS3: Luchon**
Hazard		Convention of the intensity from acceleration		
Soil	**Site effect zonation**	European Geological map	National geological map	Regional geological map
		Geol map (1/1'000'000)	Geol map (1/ 40'000) + Boreholes	Geol map (1/ 10'000) + boreholes + geophysical measurements
	Site effect amplification	3 classes (1 - 1.35 - 1.5) following EC8	6 classes (1 - 1.2 - 1.35 - 1.5 - 1.6 - 1.8) following EC8 (with 3 classes only in the area of study)	5 classes (1 - 1.18 - 1.35 - 1.5 - 1.8) following EC8
Exposure	**Inventory and zonation**	SERA	INSEE and soil occupation	Homogeneous census block
		53 zones (municipalities)	53 zones (municipalities)	203 zones (infra-municipal districts)
	Vulnerability index	Vi corresponding to SERA typology based on RISK-UE	Vi from INSEE statistics (based on age, type, number of floor)	Vi from INSEE statistics improved with Field inspection

Therefore, we defined three scale-scenarios, in order to estimate the seismic damage corresponding to a given ground-motion scenario, using the various data sources:
SS1—Europe: using the European soil map and the European database for the buildings, at the municipal level;
SS2—France: using the National soil map and the national statistics database for the buildings, at the municipal level; and
SS3—Luchon: using the soil maps and building data issued at the district level.
Then, we estimate the seismic damage, using a constant ground acceleration of 200 cm/s2 in rock conditions. This is the value of the PGA for a return period of 475 years, given by the French Annex of Eurocode 8 (Eurocode C.E.N., 2004). In the first run, rock conditions and the site amplifications due to the variations in local site conditions were taken into account, in order to locally modulate the amplitude of strong motions. The resulting ground motion field was then applied to the buildings, in order to compute the associated damage. This allowed us to study the effects of both soil and exposure data resolution on the damage estimates. In a second time, we calculated two historical deterministic scenarios, for which the PGA was estimated by a GMPE applied to the magnitude and epicenter location of the scenario-earthquakes (M 5.4 event of 1855 and M 5.6 event of 1923). By using these two scenarios with the characteristics of historical regional earthquakes, and by applying them to the current building, the objective is not to validate the damage prediction, but rather to illustrate the differences that may appear in terms of loss assessment, depending on the data used.

3. Results and Discussion

3.1. Damage estimation for the hazard of pga = 200 cm/s2 (on rock conditions)

First, we observed the results for the simulations with a constant moderate ground acceleration of 200 cm/s2 applied to the buildings, without considering the local soil effect (Figure 2, values “w/o”). Next, we observed the results of the simulations computed for the three scale scenarios, where the ground motion was amplified by the corresponding site amplification factors (Figure 2, values “w”). SS1 (using the European soil map with an amplification factor up to 1.5 and the European exposure database) showed that 12.7% of buildings would face heavy damage to complete collapse, versus 18% following SS2 (using the regional soil map with an amplification factor up to 1.8 and the National statistics database) and 20.3% following SS3 (using the local soil map with an amplification factor up to 1.8 and the field-investigation database). The impact of the soil conditions was not linear/translational. We noticed that the low resolution of the European soil map in SS1 barely changed the results when comparing the results with and without consideration of the soil amplification map, with a difference factor of only 1.1. This factor was about 2.2 and 2.5, respectively, for SS2 and SS3. Thus, SS1 highly underestimated the proportion of heavily damaged to collapsed buildings (D3–D5). Even though SS3 had the lowest vulnerability indices, it estimated the largest damages, due to the site effects highly amplifying the local ground motion at buildings.

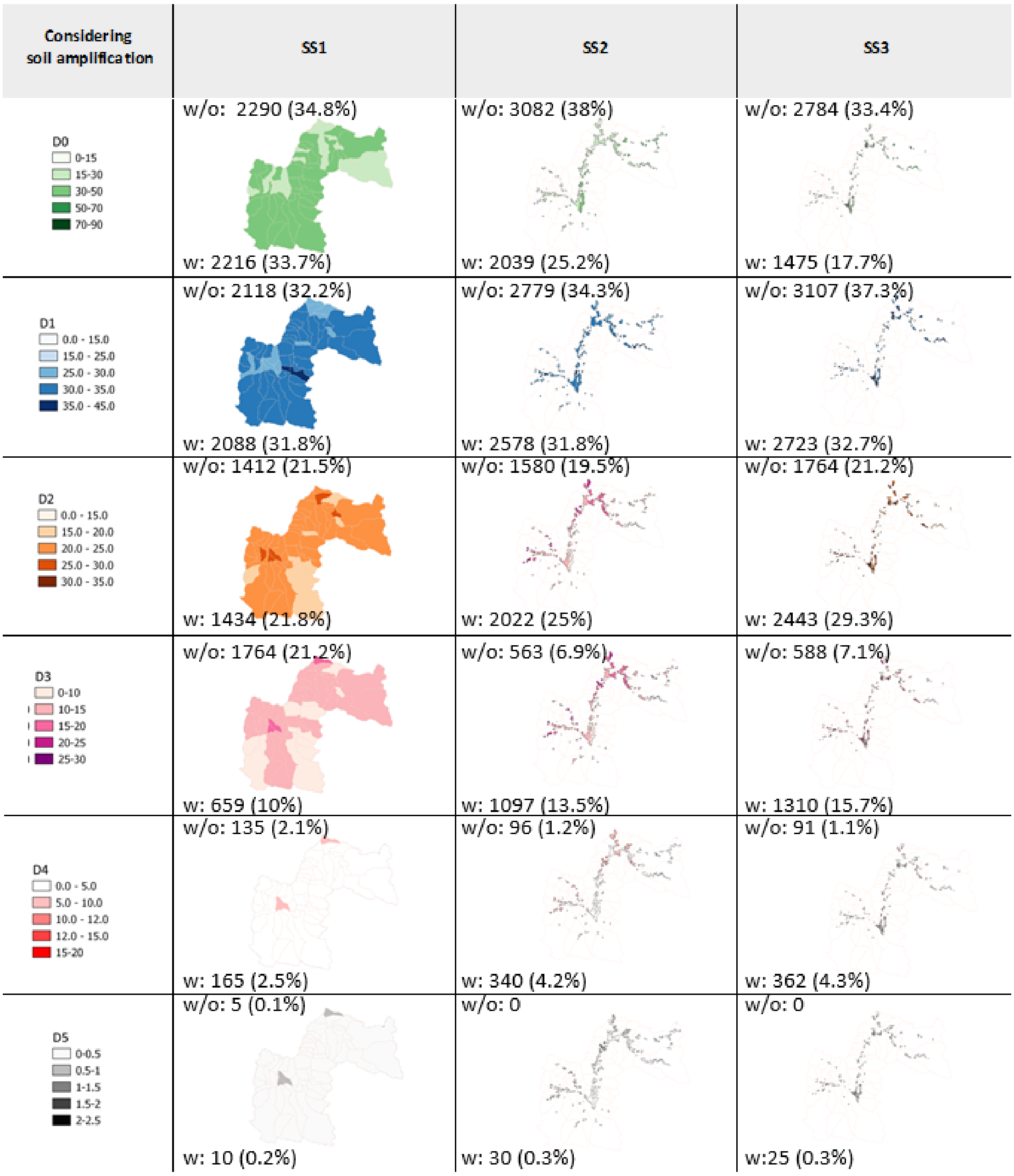

Fig. 2 - The damage distribution per scale-scenario considering the ground motion amplification due to soil effects. The color shows the percentage of buildings per level of damage. The number shows the total number of damaged buildings: "w/o" for the scenario without considering the local soil effect and "w" for the scenario with local soil effect

For the Luchon area and for moderate earthquakes, we conclude that SS1 overestimated the heavy damages, when considering the building database only, and under-estimated the heavy damages, when additionally considering the soil characterization maps. We also conclude that SS2 and SS3 generated comparable results, in terms of heavy damages. These results are in accordance with Kalakonas et al. (2020), who mentioned that the loss estimates become accurate and stable beyond a certain (fine) spatial resolution. They also proposed that a potential way to reduce this type of uncertainty is by improving the detail of information, concerning the location of the building inventory; however, this process can be time- and resource-demanding and, in many cases, it is simply impractical (e.g., for risk analysis at the national level). When we compare the simulations of the three data sets at the municipality level, the results were quite consistent; however, if we are interested in the infra-municipality level, better resolution of the building data can provide some information about the spatial distribution of damage inside a municipality.

We note that more outliers (or extreme values) were present for SS1 and SS2 than for SS3, where the latter database was collected from field inspections. The percentage of damages D3–D5 was, however, more uniformly distributed for SS3, compared to SS2 (for which the values of Vi were more variable). Pittore et al. (2020) concluded that an adaptive model is favorable, with higher spatial resolution in highly urbanized areas (where most of the assets are located) and lower resolution in rural, less-inhabited regions (where higher spatial aggregation could increase the robustness of the risk estimates).

5.2. Application to two historical earthquakes

Several destructive earthquakes have occurred in the past around the Luchon area, as evidenced by the historical seismicity database SISFRANCE (BRGM-EDF-IRSN: www.sisfrance.net; Scotti et al., 2004); including, in particular, two earthquakes that occurred in the 19th century—in 1855 and then in 1870—with an epicentral macro-seismic intensity of VII, felt in the Luchon valley with maximum macroseismic intensities of VII and VI, respectively. However, the most important recent regional earthquake remains that of Viella, which occurred on November 19, 1923 in Spain in the Aran Valley, with an epicentral macroseismic intensity of VIII, felt with a macroseismic intensity of VII in the Luchon valley: in Bagnères-de-Luchon, some walls, chimneys, and roofs had cracked. Considering the epicentral positions and the macroseismic intensity level in the area of interest, we evaluated the seismic damage in Luchon region for the two historical earthquakes (i.e., those of 1855 and 1923). Utilizing the characteristics of these two earthquakes (location, magnitude, and depth) determined by Manchuel et al. (2018) in their FCAT-17 parametric catalog, we use the GMPE of Ambraseys et al. (2005) to estimate the ground motion in the region, in terms of PGA. Then, the PGA estimated under rock site conditions was convoluted with site effects, following the three soil characterization maps corresponding to each of the three scale-scenarios.

Table 2: Percentage and number of residential buildings per damage level per scale-scenario for the earthquake event of 1855 and 1923

	D0			D1			D2			D3			D4			D5		
1855	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**
%	65	50	43	21	25	27	9	14	18	4	7	9	1	3	3	0.1	0.4	0.3
#	4262	4065	3562	1359	2037	2292	608	1172	1471	252	584	745	81	214	243	10	31	26
1923	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**	**SS1**	**SS2**	**SS3**
%	87	85	83	11	12	14	2	3	3	0	0	0	0	0	0	0	0	0
#	5691	6857	6897	712	1004	1162	147	211	243	21	30	34	1	2	2	0	0	0

Concerning the 1855 earthquake, due to the proximity of the epicenter to the study area, high PGA values were obtained, resulting in damages up to D4 and D5 (Table 2). The distribution of the damage differed from one scenario to another and it was very sensitive to the soil characterization map, as well as to the resolution of the building distribution. Without considering site effects, SS1 generated higher D5 damages (almost double, compared to SS1 and SS2) and less D2–D3 damages, whereas SS2 and SS3 exhibited a similar distribution of damages. When considering the amplified ground motion due to site effects, the conclusions were reversed: SS2 and SS3 generated considerably more damages at levels D3–D5. Here, we focused on the Bagnères-de-Luchon municipality, where important differences appeared: only 10 buildings were expected to have D3 damage in this area when using SS1; however, 195 buildings were expected to have D3 damage when using SS2, and 190 in total with SS3, which were spatially dispersed.

For the event of 1923 (Table 2), the epicenter being further away from the study area, low to moderate levels of PGA gave rise to relatively similar distributions of damage. Damages were dominated by levels ranging from D0 to D3. Without considering any soil amplification, SS1 scenarios were the most conservative, whereas SS2 and SS3 gen-erated a similar distribution of damages. When considering the amplified ground motion, this observation did not hold and SS3, followed by SS2, was slightly more conservative. Through observation of Figure 3, which shows the spatial distribution of D3 for the three scale-scenarios in the municipality of Bagnères-de-Luchon, we can estimate that six buildings reached damage level D3 using SS1, and 11 buildings using SS2; how-ever, checking SS3 at the infra-municipality level, we can notice that the buildings with damage D3 are spatially distributed with unit values. When collectively aggregated at the municipality level, the number rose to 10. SS2 and SS3 gave similar results.

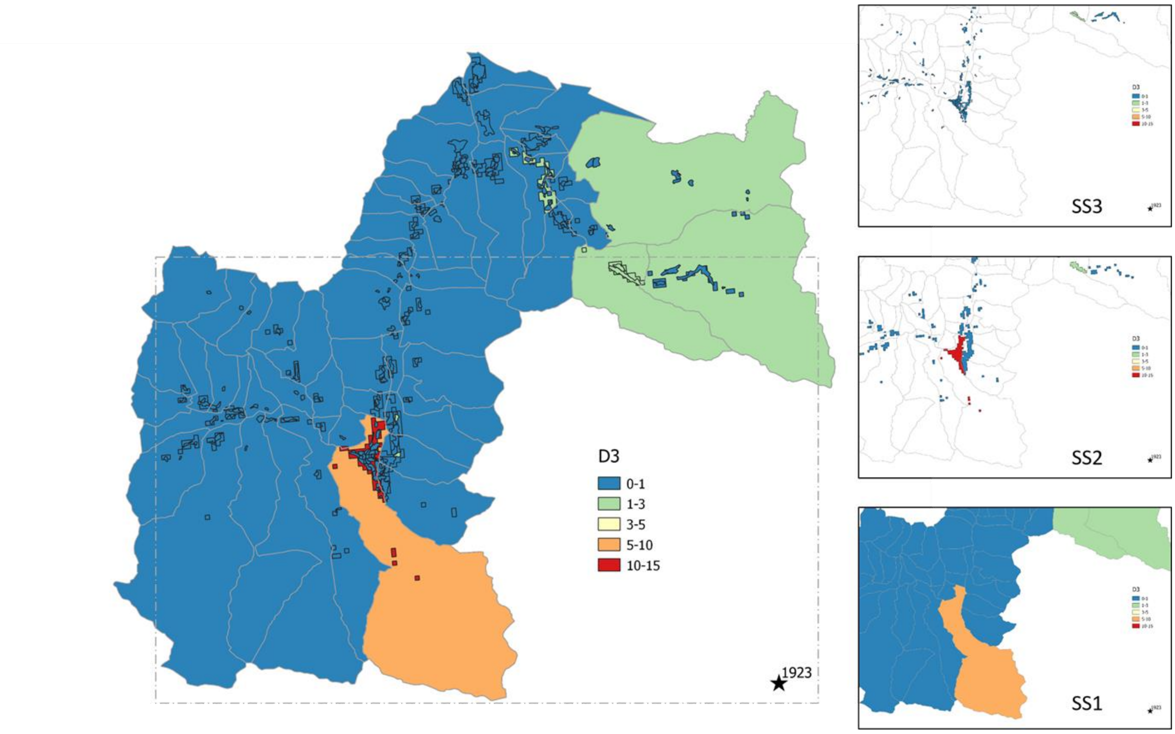

Fig. 3 - D3 damage distribution in the Luchon area in number of buildings at the 53 municipalities, due to the 1923 earthquake. The site effect is considered here.

We can notice that, for the two studied events, the site effect had a large impact on the proportion of destructive damage, and SS2 and SS3 resulted in similar damage distribution estimates, with SS3 having better spatial resolution of the building locations on the map. However, as this comparison is not based on damage observations, this study is not a validation of damage predictions, but rather an illustration of the variations expected in terms of loss assessment in the event of a major earthquake.

5. Conclusions

A major source of uncertainty in damage estimations is the intrinsically difficult inventory problem. Despite these limitations, it is important to thoroughly document the manner in which the inventories were established and damages were estimated, and that the main findings and conclusions are presented in a way that is useful and clear. Seismic damage studies which are properly conducted and used with an under-standing of the strengths and limitations of the used method(s) can be of great value in planning, initiating, and updating programs for earthquake risk reduction and in emergency planning.

This paper explored the impact of the resolution of both the ground motion field due to the soil effect and building exposure data on the estimation of seismic damages. The study was limited necessarily to a single seismic ground shaking affecting the region, and the damage calculations were carried out using only one methodology.

For the Luchon area and for moderate earthquakes, use of the European soil map (with an amplification factor up to 1.5) and the European building database led to underestimation of the heavy damage classes (D3–D5). Using the regional soil map (with an amplification factor up to 1.8) and the National statistics building database resulted in similar estimates to those using the local soil map (with an amplification factor up to 1.8) and a field-investigation database for the buildings; however, the spatial resolution to detect the locations of buildings of interest was unsurprisingly better when using the better-resolved exposure database. We would like to highlight that the main conclusions from this study are valid for the case of the Luchon area and, as such, their application to other countries or cities should be carefully considered.

Acknowledgements

This research was funded by the European Union’s Horizon 2020 research and innovation program, grant number 821046, project TURNkey.

References

- Negulescu C., A. Hohmann, A. Tellez-Arenas, F. Smai, A web platform for storing, sharing and executing scientific workflows for Natural Risk Assessment: part 1–data, approaches and case studies Geophys. Res. Abstr., 21 (2019)
- Negulescu, C., Benaïchouche, A., Lemoine, A. et al. Adjustability of exposed elements by updating their capacity for resistance after a damaging event: application to an earthquake–tsunami cascade scenario. Nat Hazards 104, 753–793 (2020). https://doi.org/10.1007/s11069-020-04189-0
- Fayjaloun R, C Negulescu, A Roullé, S Auclair, P Gehl, M Faravelli, 2021. Sensitivity of Earthquake Damage Estimation to the Input Data (Soil Characterization Maps and Building Exposure): Case Study in the Luchon Valley, France, Geosciences 11 (6), 249
- Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. (2005). Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: horizontal peak ground acceleration and spectral acceleration. Bulletin of earthquake engineering, 3(1), 1-53.
- Atkinson, G. M., & Sonley, E. (2000). Empirical relationships between modified Mercalli intensity and response spectra. Bulletin of the Seismological Society of America, 90(2), 537-544.
- Bal, I. E., Bommer, J. J., Stafford, P. J., Crowley, H., & Pinho, R. (2010). The influence of geographical resolution of urban exposure data in an earthquake loss model for Istanbul. Earthquake Spectra, 26(3), 619-634.
- BRGM. (2019). Zonage sismique de la France. http://www.planseisme.fr/Zonage-sismique-de-la-France.html.
- Corbane, C., Hancilar, U., Ehrlich, D., & De Groeve, T. (2017). Pan-European seismic risk assessment: a proof of concept using the Earthquake Loss Estimation Routine (ELER). Bulletin of earthquake engineering, 15(3), 1057-1083.
- Calvi, G. M., Pinho, R., Magenes, G., Bommer, J. J., Restrepo-Vélez, L. F., & Crowley, H. (2006). Development of seismic vulnerability assessment methodologies over the past 30 years. ISET journal of Earthquake Technology, 43(3), 75-104.
- Crowley H, Rodrigues D, Silva V, Despotaki V, Romao X, Castro JM, Akkar S, Hancılar U, Pitilakis KPD, Belvaux M, Wiemer S, Danciu L, Correia AA, Bursi OS, Wenzel M (2018) Towards a uniform earth-quake risk model for Europe. In: 16th European conference on earthquake engineering. Thessaloniki, Greece

- Crowley, H., Despotaki, V., Rodrigues, D., Silva, V., Toma-Danila, D., Riga, E., Karatzetzou A., Fotopoulou S., Zugic Z., Sousa L. Owcebe S., Gamba, P. (2020a). Exposure model for European seismic risk assessment. Earthquake Spectra, 36(1_suppl), 252-273.
- Crowley, H., Weatherill, G., Riga, E., Pitilakis, K., Roullé, A., Tourlière, B., Lemoine, A., Gracianne Hidalgo, C. (2019).- Delivrable SERA : D26.4 Methods for Estimating Site Effects in Risk Assessments
- Dolce, M., Prota, A., Borzi, B., da Porto, F., Lagomarsino, S., Magenes, G., Moroni, C., Penna, A., Polese, M., Speranza, E., Verderame, G.M., Zuccaro, G., 2020. Seismic risk assessment of residential buildings in Italy. Bull. Earthq. Eng. 1–34. https://doi.org/10.1007/s10518-020-01009-5.
- Eurocode, C. E. N. (2004). 8: Design provisions for earthquake resistance of structures–Part 1: General rules, seismic actions and rules for buildings. Brussels: European Committee for Standardization.
- Grünthal, G. (ed.): European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg, 99 pp., 1998.
- Kalakonas, P., Silva, V., Mouyiannou, A., & Rao, A. (2020). Exploring the impact of epistemic uncertainty on a regional probabilistic seismic risk assessment model. Natural Hazards, 104(1), 997-1020.
- Lagomarsino, S., & Giovinazzi, S. (2006). Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. Bulletin of Earthquake Engineering, 4(4), 415-443.
- Manchuel, K., Traversa, P., Baumont, D., Cara, M., Nayman, E., & Durouchoux, C. (2018). The French seismic CATalogue (FCAT-17). Bulletin of Earthquake Engineering, 16(6), 2227-2251.
- Monfort, D., Negulescu, C., Roulle, A., Colas, B., Lantada, N., Valcarcel, J., et al. (2012, September). Seismic risk scenarios in a cross-border zone of the Pyrenees Pyrenees. In 15th World Conference on Earthquake Engineering (WCEE) (p. dd).
- Monfort D., Roullé A. (2016). -Estimation statistique de la répartition des classes de sol Eurocode 8 sur le territoire français. Phase 1. Rapport final. Rapport BRGM/RP-66250-FR, 48p., 14 fig., 7 tab., 1 ann.
- Pittore, M., Haas, M., & Silva, V. (2020). Variable resolution probabilistic modeling of residential exposure and vulnerability for risk applications. Earthquake Spectra, 36(1_suppl), 321-344.
- Riga, E., Karatzetzou, A., Apostolaki, S., Crowley, H., & Pitilakis, K. (2021). Verification of seismic risk models using observed damages from past earthquake events. Bulletin of Earthquake Engineering, 1-32.
- Roullé, A., Macau, A., Figueras, S., Monfort, D., Lantada, N., Susagna, T., & Irizarry, J. (2012, June). Performing seismic scenarios in the Luchon-Val d'Aran area, Central Pyrenees. In 7th EUropean Congress on REgional GEOscientific cartography and Information systems: 7th EUROGEO.
- Scotti, O., Baumont, D., Quenet, G., & Levret, A. (2004). The French macroseismic database SISFRANCE: objectives, resultsand perspectives. Annals of geophysics.
- Sedan, O., Terrier, M., Negulescu, C., Winter, T., Roullé, A., Douglas, et al. (2008). Scénario départemental de risque sismique - Méthodologie et processus de réalisation. Rapport BRGM/RP-55415-FR, 459p, 96 fig., 45 tabl., 25 annexes. , France.
- Sedan, O., Negulescu, C., Terrier, M., Roulle, A., Winter, T., & Bertil, D. (2013). Armagedom—a tool for seismic risk assessment illustrated with applications. Journal of earthquake engineering, 17(2), 253-281.
- Silva, V., Amo-Oduro, D., Calderon, A., Costa, C., Dabbeek, J., Despotaki, V., ... & Pittore, M. (2020). Development of a global seismic risk model. Earthquake Spectra, 36(1_suppl), 372-394.
- Tellez-Arenas, A., Hohmann, A., Quentin, A., Negulescu, C., & Smaï, F. (2019, January). A web platform for storing, sharing and executing scientific workflows for Natural Risk Assessment: part 2-description of an interoperable architecture based on open-source components. In Geophysical Research Abstracts (Vol. 21).