3IMPACT OF EXPOSURE SPATIAL RESOLUTION ON SEISMIC LOSS ESTIMATES IN REGIONAL PORTFOLIOS

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Abstract: The spatial resolution of exposure data is one of the components of a seismic risk model that can have a substantial impact on the accuracy and reliability of seismic loss estimates. While several studies have investigated the influence of the geographical detail of urban exposure data in earthquake loss models, implications at the regional scale have so far been less explored. This study uses the exposure model of the European Seismic Risk Model 2020 to investigate the effects of exposure resolution on probabilistic seismic losses by simulating dozens of exposure and site models (630 models) representing a wide range of assumptions related to the geo-resolution of the locations of the exposed assets and the associated site conditions. Losses are examined in terms of portfolio average annual loss (AAL) and losses at different return periods at national and sub-national levels. Results indicate that neglecting the uncertainty related to asset locations and their associated site conditions within an exposure model can lead to significant bias in the risk results. The analyses also demonstrate that the accuracy of the estimated losses can be improved by either disaggregating exposure to a grid or weighting/relocating exposure sites and their amplification properties using a density map of the built areas.

Keywords: Exposure resolution, Site effects, Seismic risk, Europe

1. Introduction

An issue frequently encountered in the modelling of earthquake risk is related to the resolution level of the exposure data. The exposure information available from public sources is typically aggregated into administrative regions, and provides very limited information (if any) about the actual spatial distribution of assets (e.g., Dabbeek et al. 2020). This aggregation of the building portfolio usually leads to earthquake risk models representing all buildings in a region as located in a single site, which becomes the site at which the input ground motion is characterized, with the subsequent alteration of site properties and distance to earthquake sources. This matter is not independent from the resolution of the site model, which is itself aggregated across a spatial extent (e.g., 30 arc-sec grid cell) such that a range of site conditions are represented by a single, often uncertain, property such as topographically-inferred 30-m averaged shear-wave velocity, V_{S30}.

Though the practice of aggregating exposure may have its drawbacks in terms of accuracy and/or consistency with the seismic inputs, there are both practical and theoretical considerations that may necessitate it. The computational cost of the risk calculations and the extent to which this impacts the risk model users are overarching considerations. Running probabilistic loss calculations at a regional scale using high-resolution exposure models requires significant computational resources, in terms of both infrastructure and time. Moreover, even where the locations of the assets are known to a high level of accuracy, there may be other components of the risk model that are known or modelled at a coarser resolution, such as site properties within a grid cell or geological unit, or the proportion of different kinds of building structures within an administrative district. In these cases, the increased computational cost of using a higher resolution exposure may not yield a greater return in terms of accuracy than that of a more coarsely aggregated model. The critical question, however, is whether the adoption of coarser scale exposure introduces systematic biases into the loss estimates and, if so, how these manifest and how they can be mitigated.

The issue of spatial resolution has been investigated at the urban level in several studies (Bazzurro and Park 2007); Scheingraber and Käser 2019; Bal et al. 2010). Each of those studies considered spatial resolution to have a minimal influence when calculating portfolio mean loss/damage, due to an averaging effect of the over- and underestimation of the losses. However, these studies also indicated that uncertainty in location could lead to inaccurate loss estimates (both in terms of mean and distribution) when a single location is used to represent larger. Therefore, the first aim of this study is to investigate further the effect of exposure resolution beyond the urban scale, which is of particular importance for the national, regional and global studies of seismic risk (Crowley 2014).

The second aim of this study focuses on the need to determine a ground-shaking input that accounts for both the location and local site conditions that are closest to the conditions affecting most buildings in a spatial region, for use with aggregated exposure (DeBock and Liel 2015). No evidence can be found in the literature at the present time on which would be the most reliable method to geolocate buildings and assign site properties for aggregated portfolios.

The issues arising from low spatial resolution in exposure models have so far been managed in different ways, including modelling region-specific ground motions (e.g., Bazzurro and Park 2007; Stafford 2012), stochastic modelling of location uncertainty (Scheingraber and Käser 2019), relocation (Bazzurro and Park 2007), spatial disaggregation (Dabbeek and Silva 2020), and the use of Central Voronoidal Tessellations (CVT) (Gomez-Zapata et al. 2021; Pittore et al. 2020). This study will focus mainly on portfolio relocation and disaggregation methods as a way to treat the bias in risk arising from low spatial resolution.

We present a sensitivity analysis that explores the effect of spatial resolution on exposure models (including site conditions) on seismic risk analyses as part of the testing activities of the European Seismic Risk Model 2020[1] (ESRM20, Crowley et al. 2021). The analysis focuses on 35 countries within the European exposure model (Crowley et al. 2020) and multiple test cases, exploring different spatial resolutions and strategies for best configuring the site and exposure models. Each test case is used to calculate portfolio loss for specific return periods and the average annual loss (AAL). These results are compared against the benchmark loss, calculated with the 30 arc-sec resolution exposure model, which is the highest resolution achievable with the input site characterization model, to identify the method that produces a desirable balance between accuracy and need for computational resources.

[1] To access risk services of the European Facilities for Earthquake Hazard and Risk (EFEHR), visit http://risk.efehr.org

2. Case study: European exposure and site models

The exposure data used in this study has been obtained from the European exposure model developed by Crowley et al. (2020a), which is aggregated by administrative zone with a resolution that varies across countries and occupancies (i.e., residential, commercial and industrial). The maximum available resolution of residential and commercial administrative units is illustrated in Fig. 1, where it is possible to observe large differences in the surface areas across countries and occupancy levels.

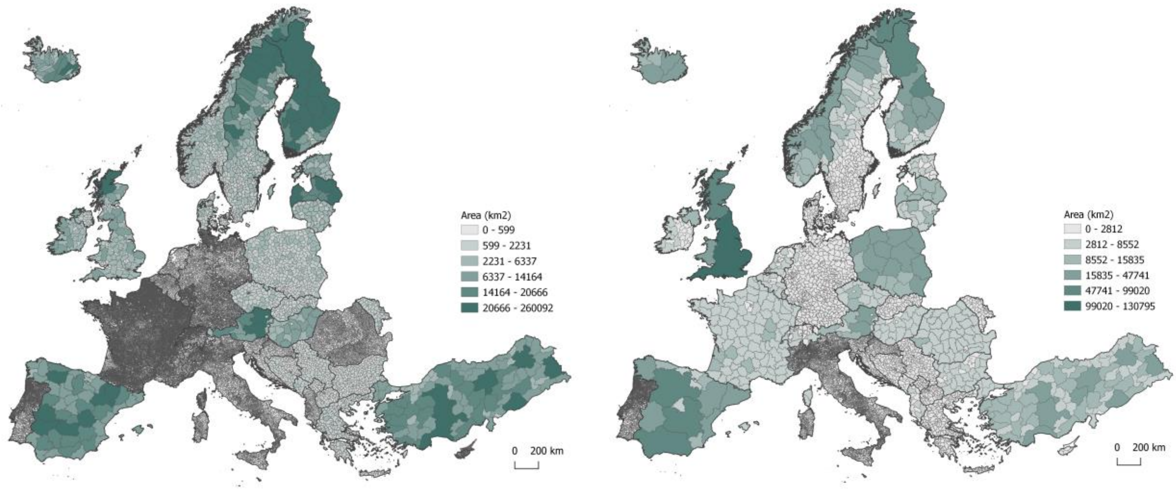

Fig. 1 - ESRM20 maximum available administrative resolution for residential (left) and commercial (right) exposure

The site model used in the analyses has been developed for ESRM20 and makes use of two proxy datasets, topography and geology, both of which are rendered onto a regular 30-arcsec grid (Weatherill et al. 2022).

2. Sensitivity analysis design

2.1. Administrative workflow

In this type of exposure, each administrative unit is represented by a single location and site property. We considered four workflows (wf1, wf2, wf3, wf4), designed to allow independent testing of the effects of location and site conditions. These properties are either taken using the geometric centroid of the admin unit or are obtained using the 30 arc-sec grid of the built-up area density grid, interpolated from the 250 x 250 m resolution built-up area density map (Pesaresi et al. 2015). In detail:

- wf1, base model: geometric centroid of the admin unit used for both exposure and site properties;
- wf2: geometric centroids used for locations, site properties represented by a (built-up area) density weighted-average of all the site conditions in the 30 arc-sec grid cells covering the admin unit;
- wf3: density weighted-centroid of all the 30 arc-sec grid cells used for locations, density-weighted average values adopted for site conditions
- wf4: locations placed at the maximum built-up area density within the admin unit, site properties as per the density weighted-average.

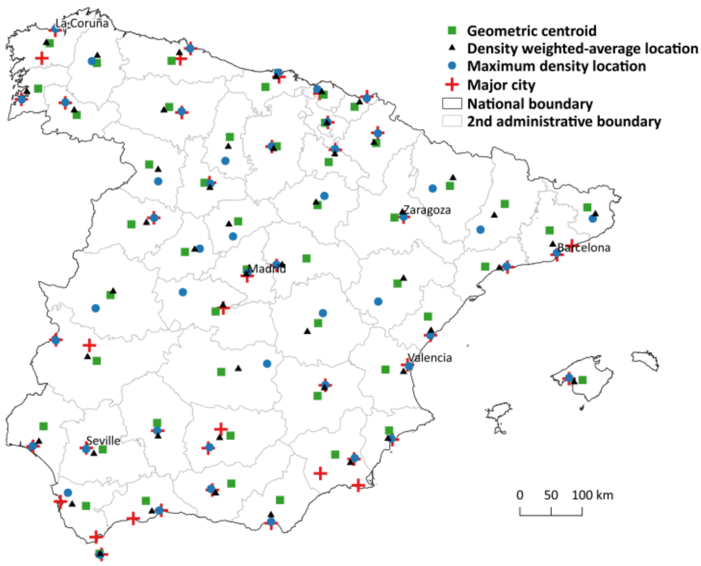

Fig. 2 - Comparison between exposure location weighting methods for the 2nd administrative level in Spain

2.2. Gridded workflow

The gridded exposure (wf5) is a regularly spaced grid of points disaggregated from the base model, using the Global Human Settlement Layer (GHSL) 250 x 250 m resolution built-up areas density map (Pesaresi et al. 2015). For this type of exposure, building locations and site properties correspond to the centre of the grid cell which is considered with six resolutions: 30, 60, 120, 240, 480 and 960 arc-sec, all of which were downsampled from the 250 x 250 m resolution built-up area density map. The maximum resolution was restricted to 30 arc-sec in order to manage the computational demand of the risk calculations, while the lowest resolution was limited to 960 arc-sec, a level that is similar to the resolution of some administrative units.

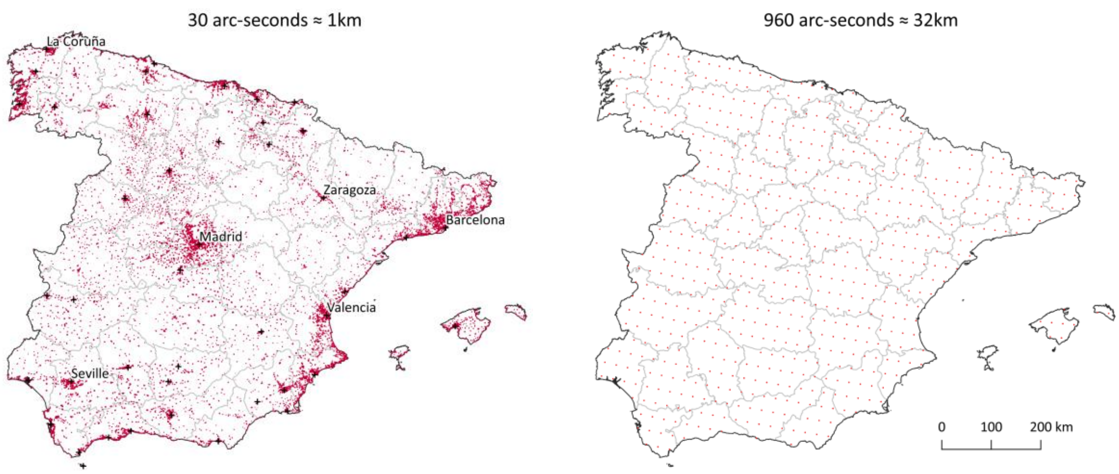

Fig. 3 - Gridded exposure for Spain, 30 and 960 arc-sec

3. Sensitivity analysis results

3.1. Effect of administrative-based exposure on portfolio loss

The first set of analyses focuses on the impact of admin resolution on the cumulative portfolio loss when using the most common type of aggregated exposure models (wf1). Fig. 4 illustrates the difference in AALs (relative to the results with the benchmark 30-arcsec gridded exposure model) for five countries obtained from administrative divisions 1, 2 and 3. A clear association can be observed between admin resolution and the percentage change in AAL. The largest bias occurs at admin1 (mostly underestimation), followed by the higher resolutions (admin2 and 3). Portfolios that aggregate larger regions are likely to be associated with higher uncertainty in building locations and site conditions, due to the inability of a single point to adequately characterize the variability of site conditions and building locations across such a large surface area.

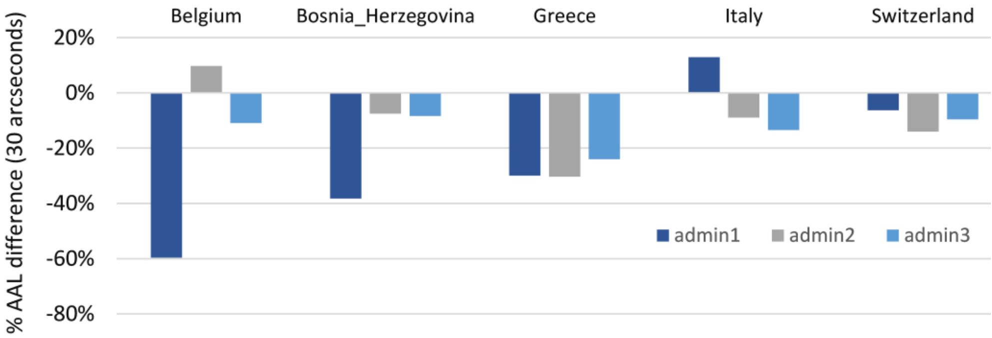

Fig. 4 - Relative change in national AAL (with respect to the 30-arcsec benchmark case) for the exposure model aggregated at admin levels 1, 2, and 3

To facilitate the comparison of the numerous case studies analyzed herein, we used an index to evaluate the overall performance of each model. The index describes the frequency distribution of performance between the workflows, that is, how frequently (i.e., in how many countries) a model ranks as the best, second-best, third-best and worst option, as shown in Table 1. According to this index, the best performing model is wf3 followed by wf2, wf4 and wf1. The highest index value indicates that wf3 (weighted centroids and sites) stands as the best (1st rank =13) and also as the second-best model (2nd rank =13). On the other hand, the lowest index value indicates that wf1 (geometric centroids and their site conditions) is the least effective model overall, even if it ranks as the best model in 7 cases. It should be noted that the meaning of the index is limited if the margin of difference is small (see, for example, Switzerland in Fig. 5). An alternative is to measure the sum of absolute changes in AAL for the 35 countries, which are 940%, 830%, 600%, 730%, for each of wf1, 2, 3 and 4. Accordingly, these values confirm that there is a significant margin in the performance.

Table 1 Performance index of administrative-based exposure workflows for admin1 level

Workflow	Rank [a]				Index [b]
	1st	2nd	3rd	4th	
wf1	7	7	5	16	53.57
wf2	7	9	16	3	64.29
wf3	13	13	6	3	75.71
wf4	8	6	8	13	56.43
	N cases = 35				

[a] 1st = best, 2nd = second-best, 3rd = third-best, 4th = worst. w_{Rank} = 1, 0.75, 0.5, 0.25, respectively

[b] Index = $\sum \frac{frequency \times w_{Rank} \times 100}{N_{cases}}$

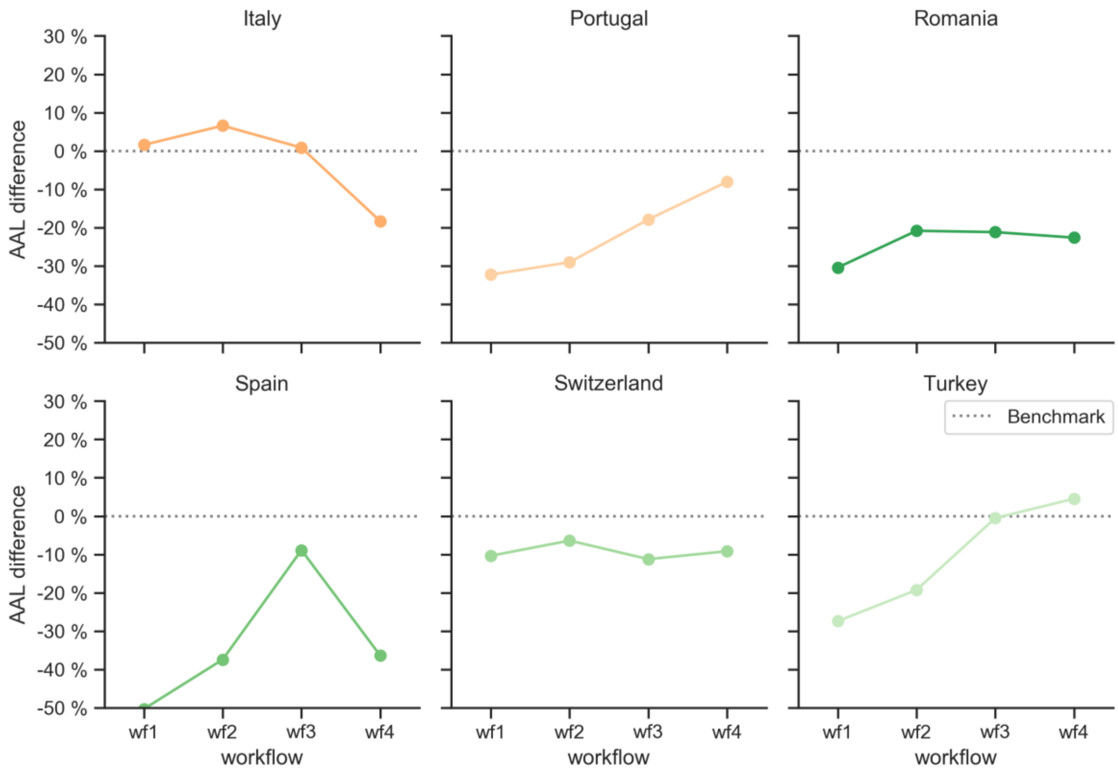

Fig. 5 Change in national AAL relative to the benchmark case (30 arc-sec model) for 6 countries, using admin1 exposure

Fig. 6 shows the change in loss for different loss return periods for each of the four administrative workflows calculated using the admin1 exposure. Similar to observations by Bazzurro and Park (2007) and Scheingraber and Käser (2019), aggregation tends to underestimate losses for events with shorter return periods (i.e., 50 years) and overestimate losses for longer return periods (i.e., 2000). Assigning the same ground motion values to all structures within a broad area is effectively introducing an artificial correlation that broadens the uncertainties in the tails of the distribution, meaning higher probabilities of high losses and higher probabilities of lower losses than the case when correlations are weaker or absent.

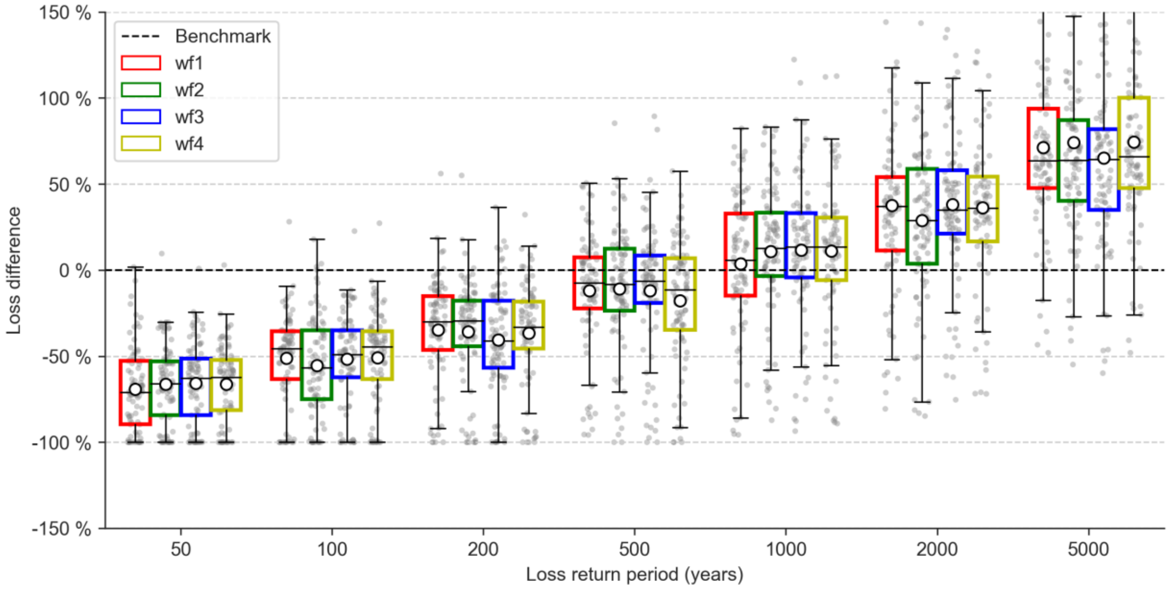

Fig. 6 - Change in loss for different return periods compared to the benchmark case (30 arc-sec model) for admin1 regions

3.2. Effect of grid-based exposure on portfolio loss

The previous sections demonstrated that coarse administrative exposure could bias portfolio loss. Despite the improvements brought about by relocating exposure and site conditions in wf3, aggregation effects remain a concern, especially for exposure models developed at the first administrative division (e.g. Spain, Turkey, Austria). Fig. 7 presents a comparison between the grid and administrative-based resolutions for three countries. Admin resolutions (admin1, admin2 and admin3) correspond to wf3 (density weighted-average). The results indicate that the 120 and 240 arc-sec range or the admin level 3 generally leads to higher accuracy than the lower resolution grids (480 and 960 arc-sec) and coarser administrative levels (admin2 and admin1). The improvements below 120 arc-sec are minor, suggesting that resolutions smaller than an (approximately) 2 x 2 km^2 grid are largely insignificant for calculating the AALs at the national scale. Overall, the sum of absolute change in AAL (35 countries) for the 60, 120, 240, 480 and 960 arc-sec gridded exposure is 35, 48, 140, 185 and 418%, respectively. Note that the low AAL bias for Italy at admin1 resulted here by chance as the underestimated and overestimated losses counterbalance each other.

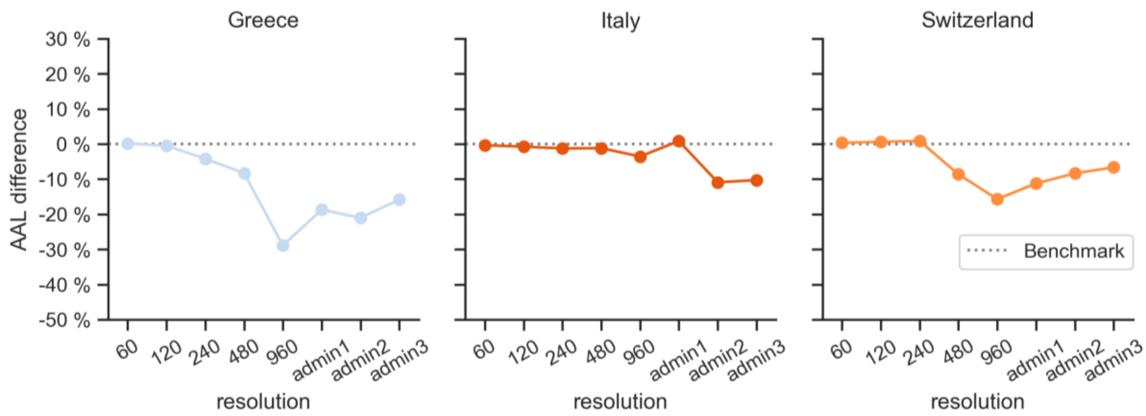

Fig. 7 - National AAL difference compared to the benchmark case (30 arc-sec model) by exposure spatial resolution for selected countries

In terms of the effect of the spatial resolution on specific event losses (i.e., 50, 100, 200, 500 and 1000 years), Fig. 8 illustrates that bias becomes more evident at lower resolutions (480, 960 and admin 1). The influence of artificial correlation on the losses becomes more evident as the spatial resolution decreases, with the frequent loss events (50, 100 years) seemingly more sensitive. Generally, smaller, more frequent events lead to ground shaking that covers smaller extents and thus, any location shift in the assets can change the level of estimated shaking at the site (and therefore damage and loss) significantly. Additionally, there is a high sensitivity of small numbers to change. This sensitivity might be influenced by the types of structures dominating the portfolio as well. As short period motion attenuates more rapidly than long-period motion, regions with low-rise structures (shorter vibration period) will be more sensitive to this attenuation.

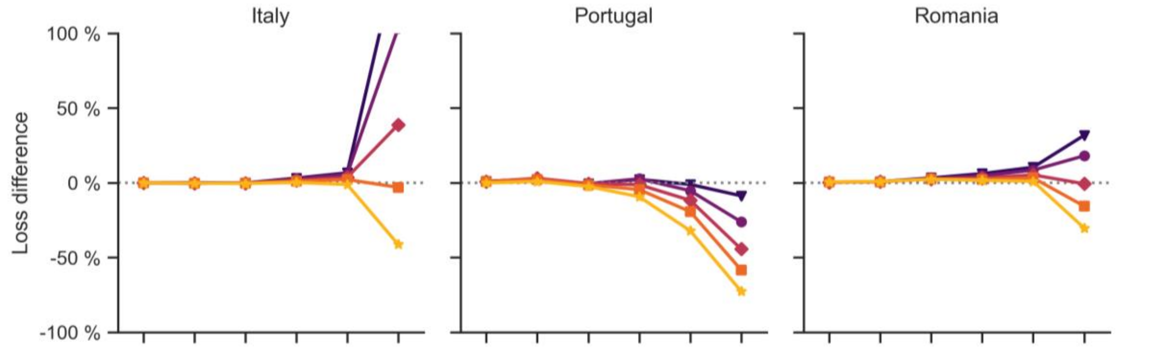

Fig. 8 - Loss difference per spatial resolution (admin and gridded) and corresponding return period by country

4. Portfolio size, hazard and site property effects on the estimated loss

The relationship between the area of the administrative divisions in km^2 and the corresponding average change in AAL relatively to the gridded 30 arc-sec model is clearly depicted in Fig. 9, which was generated based on 23,000 regions from admin1, admin2 and admin3. As can be seen, the bias in the AAL increases with the increase in the administrative area. Interestingly, the standard deviation values (named sigma) in Fig. 9 indicate a significant scatter around the average, demonstrating that the bias in equally sized regions can be much higher or lower than the average. For further discussion about the effect of the hazard variability and site effects please refer to the journal version of this paper (Dabbeek et al. 2021).

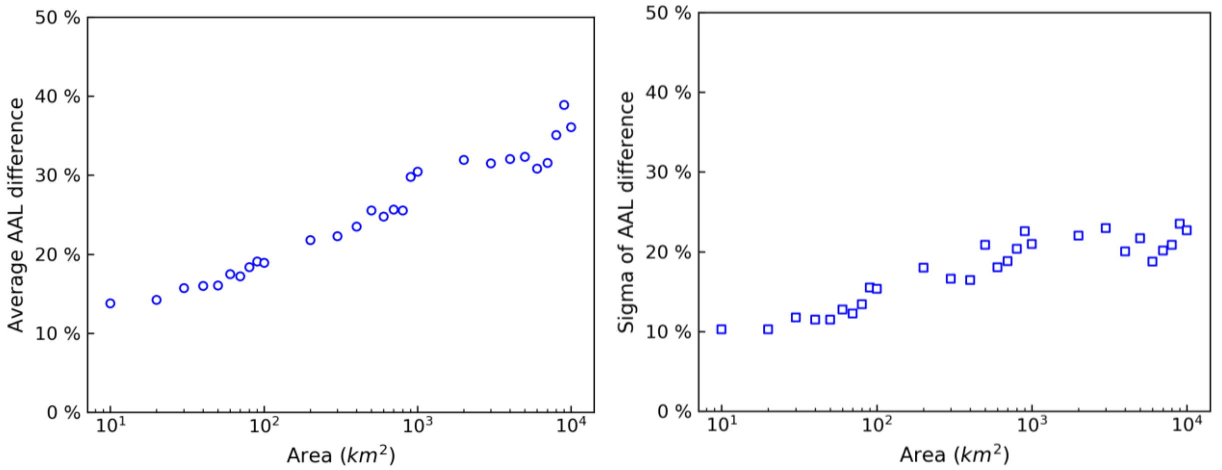

Fig. - 9 Admin area (logarithmically-spaced bins) versus the average AAL loss difference, compared to benchmark case (30 arc-sec model) (left), and the sigma of AAL difference (right)

5. Conclusions

This study has investigated the influence of exposure spatial resolution on seismic risk analyses for large building portfolios, using eighteen different methods for modelling exposure and site models for 35 countries in Europe. Twelve of these methods are based on administrative distributions and consist of three resolutions (admin1, admin2 and admin3), and four workflows to assign buildings locations and site properties: a) geometric centroid and closest site property b) geometric centroid and density weighted-average sites c) density weighted-average location and sites d) maximum density location and density weighted-average sites. The other six methods are grid-based with spatial resolutions of 30, 60, 120, 240, 480, 960 arc-sec. All the workflows described in this study and more can be readily configured to allow risk modellers to explore these approaches themselves using a free and open set of tools:

- Exposure Disaggregating Tool[2] (https://github.com/GEMScienceTools/spatial-disaggregation)
- Site Preparation Tool (https://gitlab.seismo.ethz.ch/efehr/esrm20_sitemodel)

The sensitivity analysis has shown that the spatial resolution of exposure has a significant impact on probabilistic seismic risk at the national and regional scale. Using admin1, admin2 and admin3 exposure with geometric centroid and closest site properties (*wf1*) leads to an average bias of 27%, 19% and 15% in the national AAL, respectively, while the 60, 120, 240, 480, 960 arc-sec gridded exposure models lead to an average bias per country of 1%, 1.5%, 4.5%, 14%, 27%, respectively. Based on these results, it is worth increasing the resolution to 120 or 240 arc-sec in order to keep the bias below 5%. However, resolutions higher than 120 arc-sec did not bring meaningful improvements for the increased amount of computational resources they required. At the resolutions higher than that of the national level (i.e., provinces, cities, etc), the spatial resolution has more significant effect on the AAL. Therefore, lower ranges of the recommended spatial resolutions (i.e. 120 arc-sec or finer) can be considered when assessing risk at the sub-national level.

The results also demonstrated that the bias of the administrative-based exposure models can be reduced by using the density weighted-average location and site properties (*wf3*). For admin1 level, a reduction from 27% to 18% in the AAL was observed, on average, per country when using this workflow. This method seems to work when there is a high sensitivity to the choice of location caused by the high variability of hazard and soil properties within a region. In most cases, these regions are large enough (i.e., area larger than 500 km^2) to allow hazard and site properties to change over space. The higher the resolution of the admin level, the less likely it is that any weighting method could significantly improve the accuracy of portfolio loss.

Before extrapolating results to other regions, however, it is important to keep in mind the role of site model resolution, ground motion attenuation and seismogenic sources. Although this study explored a handful of strategies for modelling exposure resolution and site properties, there are others to be investigated, some of which are also available in the Site Preparation Tool. For example, the gridded exposure can be improved by weighting site properties within each grid cell or considering variable grids denser around the main faults and where site properties tend to vary. In addition, while this work has focused on regional scale risk studies, further analysis at sub-regional and urban scale is needed in order to understand where a suitable balance can be struck between exposure resolution, uncertainty characterization and computational cost, when more detailed information may be available. Since the effects of data resolution depend strongly on the variation in the hazard (see journal version of the paper), future studies should focus on mitigating the bias at the ground motion level.

This sensitivity analysis was carried on as part of the testing activities of the European Seismic Risk Model (ESRM20, Crowley et al. 2019), initiated within the European Horizon 2020 Project SERA (www.sera-eu.org), and continuing under the umbrella of the European Facilities for Earthquake Hazard and Risk (EFEHR) Consortium (www.efehr.org).

[2] Note that the Exposure Disaggregation Tool uses WorldPop population by default, but it supports other raster datasets including the GHS built-density layer used herein available for download at: https://gitlab.seismo.ethz.ch/efehr/esrm20_exposure/-/tree/master/spatial_disaggregation

For more detailed information about this work please refer to the journal version of this paper (Dabbeek et al. 2021).

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