Responses to Anonymous Referee #2

Thank you for your helpful review. Please find our answers to each of your comments below.

General comments:

1. *<<”From the reviewer’s point of view, both the Central Voronoi Tessellations (CVT) itself and the application are topics of great interest since this is a useful method related to earthquake and tsunami risk assessment for communities affected or potentially affected by these threat”.*

   We sincerely thank you your positive comments.

2. *<<”However, some process details were not explained clearly. This article uses the scientific research results of several scholars to get the research results”.*

   You are right, we test the impact and benefits of variable resolution building exposure models on risk assessment making use of some previous “scholars” models as inputs. However, inputs such as seismic ground motion fields and tsunami inundation maps (for six scenarios) were constructed by us through our own computational resources. For this aim, of course we had to consider existing methods (i.e. GMPE, spatial cross-correlation, and wave propagation models) to construct ours for the study area. This is a conventional approach in research and maximises the reproductively and added value of the methods proposed by others.

   Please note that the aforementioned inputs, along with the use of existing fragility models are always transversally used throughout the processing risk chain. The main degree of freedom in our modelling correspond to the presence of various customised CVT-based geocells. They are indeed based on well-known mathematical developments (i.e. Lloyd, 1982; Voronoï, 1908). We fully agree that the CVT have been used in other hazard related applications, such climatological modelling (e.g. Ju et al., 2011; Zarzycki and Jablonowski, 2014) but only recently for exposure modelling using seismic vulnerability classes (Pittore et al., 2020). We present for the first time the manner of how they can be constructed using underlying combinations of geospatial distributions and then achieve a larger resolution where it matters for risk assessment. We have updated the introduction in order to better frame our scope and developments from the existing models used in the study.

3. <<”How to verify the research results?”

   In the submitted version of the manuscript we clearly stated that we do not aim to verify the resultant scenario-based loss estimates for Lima. In fact, such a validation is practically impossible without actually having experienced such events in Lima. Such an issue is recently discussed by Tozato et al., (2021). When catastrophe modelling is done out of the area where the empirical fragility models used were originally calibrated (e.g. Japan or the Indic Ocean), or based on the use of analytical fragility functions, then these studies are only presented to provide insights about the consequences of future risk scenarios.

Several studies have developed such strategy (i.e. Vera San Martín et al., 2018; Park et al., 2019) and following the discussions we had these last years with stakeholders both in Europe and South America such scenarios are useful for preparedness, planning as well as for a better understanding of the spatial distribution of the physical vulnerability of a city even if they cannot be verified.

Thorough the paper we also constantly compare our findings with similar features observed by other studies in order to check consistency of our results (e.g. Figueiredo and Martina, 2016; Markhvida et al., 2017; Park et al., 2017).

In the submitted text we had clearly stated in lines 596-600: *"(…) we are not claiming that the scenario-based economic losses we have presented for the residential building stock of Lima are completely exhaustive. Instead, through the adoption of the condition tree, we have drawn a branched methodological workflow to explore the differential impact of the exposure aggregation models, and the selection of building schemes on the epistemic and thematic uncertainties that are embedded in scenario-based risk applications".* We consider that keeping this sentence is prudent and necessary.

4. *<<"What is the innovative idea or technology of this article?*

This work presents for the first time a first contribution to find an adequate balance in the resolution of the exposure model with the spatial resolution and variability of the hazard intensities for risk assessment. The necessity of this research topic had been already suggested by other experts in that area (i.e. by Douglas, 2007; Ordaz et al. 2019; Zuccaro et al. 2018). We found that CVT-based models adequate to be used in the aforementioned purpose. As explained in the paper, our method contrasts with the current state of the art related to building exposure modelling (aggregation) that neglects the variability of the hazard intensities in their derivation. Current approaches simply uses administrative boundaries for exposure aggregation and risk computation. Thus, we consider that developing this new paradigm and the subsequent sensitivity analyses performed are themselves innovative. Moreover through the development of the manuscript the reader can realise characteristics related to the CVT models such as being computationally more efficient for risk computation. Although the former aspects are extensively described in the Introduction section of the paper, we make sure to emphasise this novelty in the new version of the manuscript.

Moreover, we make use of the concept of inter-scheme conversion matrices to further prove their usefulness to derive exposure models (i.e. spatial distribution of building classes and replacement costs). This is novel because if we can know these characteristics for a single exposure scheme (e.g. seismic-oriented), we could get the same descriptors for another vulnerability scheme (e.g. tsunamis). This procedure ensures the comparability across the different schemes and this compatibility had not been considered so far in the related scientific literature for multi-hazard exposure modelling. This aspect also outlines that various exposure models existing in the literature can actually be complemented and compared in a probabilistic manner.

Another innovative idea: we test the proposed method over the residential building portfolio of an important megacity that has been strongly affected during non-instrumental times by earthquakes, and tsunamis. We observe that the The importance of addressing such scenarios for Lima as well as the comparison of our results with the few existing scenarios for Lima may be of the interest of many readers interested by risk scenarios for this city.

5. *<<"The general comment for the whole paper is that the reviewer has not been able to find enough significant points regarding the principal criteria of the reviewing process".*

We sincerely expect that after having provided the former clarifications, the reviewer now can visualise the positive impact of our study and its novelty.

Specific comments:

1. *<<" Section 1 (page 4): The authors could highlight the advantages of the CVT, (1) (2) (3)…*

You are right. Following this comment we realise the need to provide since the beginning of the manuscript a brief description enumerating the advantages of the CVT-based models. Basic characteristics such as compactness, stability, contiguity are some of these features that have been mentioned more clearly and cited accordingly in the suggested part of the new paper.

Nevertheless we would prefer to also keep another list of advantages that we presented in the Conclusion section (lines 566-582). In these lines we have enumerated the main advantages of CVT-models to spatially aggregate the exposure model, risk computations, efficiently, and spatial representability. We believe that these statements require proper justifications that are only achieved throughout the development of ideas provided in the other sections of the paper.

2. *<<" Section 3.2: A numerical calculations table is needed to show the spatial resolution, time step, spatial range, and what water depth and elevation data is used. What governing equations are used in TsunAWI. Some detail about TsunAWI should be introduced"*

As suggested, we extended the section on tsunami modelling and included more information on the approach used in the study.

Part of the modified manuscript:

"The wave propagation and tsunami inundations are obtained through numerical simulations using the finite element model TsunAWI which employs a triangular mesh with variable resolution, allowing for a flexible way to discretize the model domain with good representation of coastline and bathymetric features. Since the simulation of the inundation process needs high resolution, the mean mesh resolution given by the triangle edge length amounts to around 20m in the coastal area of Lima and Callao. TsunAWI is based on the nonlinear shallow water equations including parameterisations for bottom friction and viscosity. Table 1 summarizes some of the most important model quantities. The wetting and drying scheme is based on an extrapolation method projecting model quantities between the ocean part and the dry land part of the model domain”.

Table 1. Summary of TsunAWI model parameters used in the tsunami simulations.

Numerical approach	Time step/ Integration time	Resolution range (Triangle edge length)	Bottom friction parameterization	Viscosity parameterization
Finite Elements	0.1sec / 4 hrs	From 6km (deep ocean) to 7m (coastal pilot areas)	Manning (n=0.02 constant value)	Smagorinsky

The model bathymetry and topography were built from several data sets. The ocean part is based on the GEBCO bathymetry (General bathymetric chart of the ocean, GEBCO_08 Grid, see http://www.gebco.net). The coastal topography is given by SRTM values (Shuttle radar topography mission, 30m resolution, see https://www2.jpl.nasa.gov/srtm/) whereas in the pilot area Lima/Callao additionally the measurements of the TanDEM-X mission (Krieger et al., 2007) given at a spatial resolution of 12m were provided by the project partner DLR to the RIESGOS consortium. In this region the available data sets were combined to a joint product and augmented by nautical charts in shallow areas by the project partner EOMAP. All these data were bilinearly interpolated to the triangular mesh and slightly smoothed to allow for stable simulations.”

3. *<<” Section 3.6: What are the advantages of Suppasri's method and De Risi's method? Which method is the last choice? This issue should be discussed.*

The Suppasri et al., (2013) and De Risi et al., (2017) schemes, comprise different building classes (see figure 6 in the submitted paper). For instance, Suppasri define three types of wooden building classes (W1, W2, W3) whilst De Risi only accounts a single wooden class. As explained, this is because the storey range is only addressed in the first one. Moreover these models were derived in a very different manner whose implications are described in our paper as well in each of them. They even have different validity ranges of tsunami inundation height (20 m versus 10 m respectively). They have different number of damage states (six in Suppasri, five in DeRisi (it omits the damage state # 1) (see table 4 of the respective publication). The latter was mentioned in lines 435- 437 in our submitted paper.

At a first glance the model of De Risi might be considered as a better modelling approach because of its more robust derivation through multinomial logistic regression and with similar values as if flow velocity was accounted. Increasingly meaningful research in tsunami fragility should not rely on the material type as the only descriptor of the tsunami fragility, instead, building height and other attributes should be always addressed (Charvet et al., 2017). The aforementioned aggregation procedure imposed by the De Risi scheme (in terms of the storey ranges) can largely impact the results. A similar effect had already been described for seismic risk assessment by Crowley et al., (2005). Hence, the differences between their respective risk outcomes might not only due to the parameters that made up the fragility functions, but also due to the aggrupation of different building classes (Suppasri) into a less diversified one (de Risi). Due to these limitations, and crude adoptions of these models for a South American context (out of the calibrated area), we invited the reader to realise the importance of counting with locally calibrated exposure, fragility and financial consequence models (lines 534-536).

We therefore do not have a last choice of the selected model. We prefer to clearly inform the reader about the differences between the two models, show how these two models impact the final loss computation and use these two models to evaluate the epistemic uncertainty associated to this model choice.

Moreover, we kindly let you know that we have decided to provide the data models and scripts that we have constructed during the elaboration of our study. These models are supplementary data to the paper. They are assigned an independent DOI, and are accordingly cited in the new version of the manuscript. We consider that this is a transparent approach that could also benefit future readers who will be able to better understand, reuse and cite these datasets. Examples can be found accessing the following review links:

https://dataservices.gfz-potsdam.de/panmetaworks/review/f932840b5c130da18c3a9d407e85f086ce0874b80edbd796e0f096ba94d89cc4/

https://dataservices.gfz-potsdam.de/panmetaworks/review/0470cd1366982c5e319c5c39ca1c2e524b213d8f9b7868c98aad804fceba33d0/

We also let you know that we asked an editor (a native English speaker) to provide us a strict language review. The new version has been significantly been improved in that regard.

We sincerely thank the reviewer for the time invested in providing us the very constructive feedback and comments.

With best regards,

The team of authors.

References

Charvet, I., Macabuag, J., Rossetto, T., 2017. Estimating Tsunami-Induced Building Damage through Fragility Functions: Critical Review and Research Needs. Frontiers in Built Environment 3, 36. https://doi.org/10.3389/fbuil.2017.00036

Crowley, H., Bommer, J.J., Pinho, R., Bird, J., 2005. The impact of epistemic uncertainty on an earthquake loss model. Earthquake Engineering & Structural Dynamics 34, 1653–1685. https://doi.org/10.1002/eqe.498

De Risi, R., Goda, K., Yasuda, T., Mori, N., 2017. Is flow velocity important in tsunami empirical fragility modeling? Earth-Science Reviews 166, 64–82. https://doi.org/10.1016/j.earscirev.2016.12.015

Douglas, J., 2007. Physical vulnerability modelling in natural hazard risk assessment. Natural Hazards and Earth System Sciences 7, 283–288. https://doi.org/10.5194/nhess-7-283-2007

Figueiredo, R., Martina, M., 2016. Using open building data in the development of exposure data sets for catastrophe risk modelling. Natural Hazards and Earth System Sciences 16, 417–429. https://doi.org/10.5194/nhess-16-417-2016

Ju, L., Ringler, T., Gunzburger, M., 2011. Voronoi Tessellations and Their Application to Climate and Global Modeling, in: Lauritzen, P., Jablonowski, C., Taylor, M., Nair, R. (Eds.), Numerical Techniques for Global Atmospheric Models. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 313–342. https://doi.org/10.1007/978-3-642-11640-7_10

Krieger, G., Moreira, A., Fiedler, H., Hajnsek, I., Werner, M., Younis, M., Zink, M., 2007. TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry. IEEE Transactions on Geoscience and Remote Sensing 45, 3317–3341. https://doi.org/10.1109/TGRS.2007.900693

Lloyd, S., 1982. Least squares quantization in PCM. IEEE Transactions on Information Theory 28, 129–137. https://doi.org/10.1109/TIT.1982.1056489

Markhvida, M., Ceferino, L., Baker, J.W., 2017. Effect of ground motion correlation on regional seismic lossestimation: application to Lima, Peru using across-correlated principal component analysis model, in: SBN 978-3-903024-28-1. Presented at the Safety, Reliability, Risk, Resilience and Sustainability of Structures and Infrastructure. 12th Int. Conf. on Structural Safety and Reliability, Christian Bucher, Bruce R. Ellingwood, Dan M. Frangopol (Editors), Vienna, Austria.

Ordaz, M., Salgado-Gálvez Mario Andrés, Huerta Benjamín, Rodríguez Juan Carlos, Avelar Carlos, 2019. Considering the impacts of simultaneous perils: The challenges of integrating earthquake and tsunamigenic risk. Disaster Prevention and Management: An International Journal 28, 823–837. https://doi.org/10.1108/DPM-09-2019-0295

Park, H., Alam, M.S., Cox, D.T., Barbosa, A.R., Lindt, J.W. van de, 2019. Probabilistic seismic and tsunami damage analysis (PSTDA) of the Cascadia Subduction Zone applied to Seaside, Oregon. International Journal of Disaster Risk Reduction 35, 101076. https://doi.org/10.1016/j.ijdrr.2019.101076

Park, H., Cox, D.T., Barbosa, A.R., 2017. Comparison of inundation depth and momentum flux based fragilities for probabilistic tsunami damage assessment and uncertainty analysis. Coastal Engineering 122, 10–26. https://doi.org/10.1016/j.coastaleng.2017.01.008

Pittore, M., Haas, M., Silva, V., 2020. Variable resolution probabilistic modeling of residential exposure and vulnerability for risk applications. Earthquake Spectra 36, 321–344. https://doi.org/10.1177/8755293020951582

Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., Abe, Y., Imamura, F., 2013. Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. Natural Hazards 66, 319–341. https://doi.org/10.1007/s11069-012-0487-8

Tozato, K., Takase, S., Moriguchi, S., Terada, K., Otake, Y., Fukutani, Y., Nojima, K., Sakuraba, M., Yokosu, H., 2021. Real-time Tsunami Force Prediction by Mode Decomposition-Based Surrogate Modeling. Natural Hazards and Earth System Sciences Discussions 2021, 1–36. https://doi.org/10.5194/nhess-2021-77

Vera San Martín, T., Rodriguez Rosado, G., Arreaga Vargas, P., Gutierrez, L., 2018. Population and building vulnerability assessment by possible worst-case tsunami scenarios in Salinas, Ecuador. Natural Hazards 93, 275–297. https://doi.org/10.1007/s11069-018-3300-5

Voronoï, G., 1908. Nouvelles applications des paramètres continus à la théorie des formes quadratiques. Premier mémoire. Sur quelques propriétés des formes quadratiques positives parfaites. Journal für die reine und angewandte Mathematik 1908, 97–102. https://doi.org/10.1515/crll.1908.133.97

Zarzycki, C.M., Jablonowski, C., 2014. A multidecadal simulation of Atlantic tropical cyclones using a variable-resolution global atmospheric general circulation model. Journal of Advances in Modeling Earth Systems 6, 805–828. https://doi.org/10.1002/2014MS000352

Zuccaro, G., De Gregorio, D., Leone, M.F., 2018. Theoretical model for cascading effects analyses. International Journal of Disaster Risk Reduction 30, 199–215. https://doi.org/10.1016/j.ijdrr.2018.04.019