

Review article: Physical Vulnerability Database for Critical Infrastructure Multi-Hazard Risk Assessments – A systematic review and data collection

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Response to Anonymous Referee #1

I thank the authors for their efforts to review my comments. I particularly welcome the inclusion of Figures 1 and 2, which substantially improve the quality of the manuscript. However, there are a few follow up comments below that I think should be addressed before publication. The comment number provided at the start of each comment refers to the previous round of review.

[Authors' reply] We thank the reviewer for the kind words and for recognizing the improvements made to the manuscript. We greatly appreciate your thorough review and are grateful for your insightful feedback throughout the process. We carefully considered the minor comments provided and addressed them in the final version of the manuscript.

1. Main comment #2a: Suggest changing “at risk to natural hazards” to “exposed and vulnerable to natural hazards”

[Authors' reply] Thank you for your suggestion. We believe that the phrase ‘at risk to natural hazards’ effectively communicates the message that we would like to convey. In the sentence that follows, we directly explain why critical infrastructure are increasingly at risk to natural hazards and thus add context to our phrase (lines 26-28):

‘This is driven by both a growing demand for infrastructure associated with socio-economic development, and an observed and projected increase in the frequency and intensity of climate extremes (IPCC, 2022).’

2. Main comment #2b: The point I was trying to make here is that the output of a vulnerability curve is typically a continuous measure of loss, whereas the output of a fragility curve is a measure of damage. The authors refer to a damage factor as being the output of a vulnerability curve in line 41, but this is actually a financial loss ratio (as they define in the parenthesis). In other words, the “damage” output of a vulnerability curve is typically expressed in terms of percentage of replacement cost and is therefore actually a loss rather than a damage metric. I would suggest making the distinction between the two types of output more explicit, so that readers have a clear understanding of the differences between the two curves. Along the same lines, the authors should qualify that the “physical damages” captured by the database include consequences in the form of repair cost (i.e., financial loss) ratios (currently referred to as “damage factors”) output from vulnerability models.

[Authors' reply] Thank you for clarifying your comment from the first round of revisions. From your perspective, damage should only be used if referred to a physical state of damage and loss should be used when referred to consequences such as the ones expressed in monetary values. We

believe that in this sense the type of consequence is an important factor in determining whether one should refer to damages or losses. Damage refers to the physical harm or deterioration suffered by infrastructure or assets (which can be expressed in monetary values), whereas loss encompasses the broader consequences (e.g., increased travel time due to damaged infrastructure).

In our manuscript we only review curves that are associated with direct physical asset damages for a selection of hazards. However, we do not use the term ‘damage factor’ in the remainder of the original manuscript but use the term ‘mean damage ratio’ which is more commonly used in literature. We believe that introducing another term, such as ‘financial loss’ as proposed by the reviewer, could lead to confusion; financial losses are often interpreted as indirect economic losses, which are not considered in this study. To address the remark by the reviewer and improve clarity we decided to replace the term ‘damage factor’ in our introduction and now use ‘mean damage ratio’ throughout the revised manuscript instead. Lines 37-42 now read:

‘These curves relate given levels of a hazard intensity measure (e.g., flood inundation depth, wind speed) to the potential physical damage of an asset. The potential damage can either be expressed in absolute monetary terms, or in relative numbers that are often referred to as the mean damage ratio (MDR), which is commonly expressed as the ratio of the expected repair cost to the replacement costs of a structure (WBG, 2019). In the latter case, the MDR is then multiplied by a cost feature to obtain the potential damage for a given hazard intensity level.’

3. Minor comment #1: “level of susceptibility” seems a little vague to me. I would suggest using something like “level of loss experienced” or “level of impact experienced” to be slightly more specific.

[Authors’ reply] *Thank you for your comment. For consistency with the main text and clarity purposes, we adjusted the definition of vulnerability curves in the abstract to “...quantify the level of damage of an element under varying hazard intensities”.*

4. Minor comment #2: I don’t think the notation “ $E(C>c)$ ” makes sense when referring to a mean value, which is why I thought you were referring to a probability. I believe it should be rewritten as $E(C)$

[Authors’ reply] *Thanks for your insight. The notation “ $E(C>c)$ ” was indeed used to refer to a mean value and we have now rewritten this as $E(C)$. This has been adjusted in both the main text under section 2.3 and formula 1.*

5. Minor comment #4: To make this point clearer, I would suggest that you mention the development of both fragility and vulnerability curves being common practice within the earthquake community.

[Authors' reply] Whilst we agree that the earthquake community uses both fragility and vulnerability curves, as does the flooding community, the main purpose of the phrase is to emphasize that we do see a difference in focus in both the communities, which is also backed up by literature for reference purposes. To improve clarity, we have now adjusted our phrase (lines 44-46):

'The development of fragility curves is particularly emphasized within the earthquake community (Douglas, 2007), whereas the flood community tends to focus more on the development of vulnerability curves (Meyer et al., 2013).'

This wording suggests that while fragility curves are prominent in earthquake studies, vulnerability curves are more commonly emphasized in flood risk assessments, without implying that one community does not use the other approach.

6. Minor comment #6: The statement provided here does not specifically mention that the cost values are country-specific.

[Authors' reply] Thank you for your comment. We specify in the statement provided that the cost-values are specific to certain country/countries. We refer to this as 'the geographical application', and this term is also consistently used throughout the database itself.

7. Minor comment #8: By using the term "building typologies", I think you are still welcoming the possibility of the database being extended beyond the critical infrastructure depicted in Figure 2. This is fine if it is your intention, but, if not, then I would remove the word "building" and use something along the lines of "various forms of critical infrastructure (e.g., in terms of construction material)"

[Authors' reply] Thank you for pointing this out. Our original intention was to suggest that our database could be further enriched with curves that represent various building typologies with regard to form and construction materials as these play an important role in the level of vulnerability to a hazard. For example, a high-rise hospital may be more vulnerable to windstorms compared to low-rise hospitals, and concrete schools are more vulnerable to earthquakes compared to schools with steel-reinforced concrete. We believe that the database should be expanded with curves that better capture these variations in vulnerability due to these kind of characteristics. However, this not only applies to buildings (e.g., health and educational facilities) but to other critical infrastructure types as well. Based on your suggestion, we now made a slight adjustment to our wording to now read (lines 876-877):

'We strongly encourage users to expand the database with: [...] (4) curves for various infrastructure characteristics, such as form (e.g., low-rise) and construction materials'

8. Additional comments: a. I think that Figure 1 should also account for the “vulnerability” and “critical infrastructure” search terms, in addition to hazards

[Authors' reply] Thank you for your comment. The number of records found for the 125 search term syntaxes are listed in Appendix A. This appendix clearly demonstrates the number of records found for the 'vulnerability' and 'critical infrastructure' search terms. In figure 1, we decided to show the 'number of records removed' categorized per hazard to be aligned with sections 3.1-3.4 which are also organized per hazard type. Moreover, the keywords that we used for the “vulnerability” and “critical infrastructure concepts” for the literature search are presented in Table 1. We believe that we provide sufficient information about the search terms syntaxes and the number of records in the main text and the figures, and that the reader should refer to Appendix A for more detailed information regarding the number of records found for the 'vulnerability' and 'critical infrastructure' search terms.

Response to Anonymous Referee #3

The authors have done an excellent job revising the manuscript. A few minor comments are provided for the authors to consider in the final version.

[Authors' reply] We thank the reviewer for the positive remarks and are pleased that he/she recommends publication in Natural Hazards and Earth System Sciences following a revision of technical corrections. We have addressed these points in the revised manuscript and agree that this has led to a further refinement of the manuscript.

1. It is suggested to review the definition of vulnerability curves in the abstract "...quantify the level of susceptibility of an element under varying hazard intensities"; it is not clear how susceptibility is defined here - and make it consistent with the definition given in the main text "These curves relate given levels of a hazard intensity measure to the potential physical damage of an asset".

[Authors' reply] Thank you for your comment. For consistency with the main text and clarity purposes, we adjusted the definition of vulnerability curves in the abstract to "...quantify the level of damage of an element under varying hazard intensities".

2. It is suggested to include a generic example (figure) of a fragility and vulnerability curve.

[Authors' reply] Thank you for your suggestion. We have now added a generic example of fragility and vulnerability curves to our manuscript as figure 2 under section 2.3 and adjusted the numbering of the other figures accordingly.

3. An alternative version of the title is the following: "Physical Vulnerability of Critical Infrastructure: A Systematic Review and Database for Hazard Risk Assessment"

[Authors' reply] Thank you for your suggestion regarding the title of the manuscript. After careful consideration, we believe that the current title 'Physical Vulnerability Database for Critical Infrastructure Hazard Risk Assessments – A systematic review and data collection' accurately reflects the focus and content of the manuscript. We included the 'data collection' aspect to our title because it is integral to our work and highlights the significant effort put into compiling and organizing the data.

4. Check the references, eg the following is a repetition:

Kakderi, K. and Argyroudis, S.: Fragility Functions of Water and Waste-Water Systems, in: Geotechnical, Geological and Earthquake Engineering, vol. 27, edited by: Pitilakis, K., Crowley, H., and Kaynia, A., Springer, Dordrecht, 221–258, 1060 https://doi.org/10.1007/978-94-007-7872-6_8, 2014a.

Kakderi, K. and Argyroudis, S. A.: Chapter 8 Fragility Functions of Water and Waste-Water Systems, in: Fragility Functions of Water and Waste-Water Systems, <https://doi.org/10.1007/978-94-007-7872-6>, 2014b.

[Authors' reply] Thank you for pointing this out. This is indeed a repetition and we have now corrected this in both the main text and the reference list.