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

Authors: Sadhana Nirandjan, Elco E. Koks, Mengqi Ye, Raghav Pant, Kees C.H. Van Ginkel, Jeroen C.J.H. Aerts, and Philip J. Ward

Response to Anonymous Referee #2

This study undertakes a systematic literature review with the aim of creating a vulnerability functions database for evaluating critical infrastructure (CI) in the face of multiple hazards. While the subject matter is intriguing, the manuscript suffers from unclear methodology and lacks a clear rationale for the study. Several major concerns need addressing before considering the manuscript for publication.

[Authors' reply] *We thank the reviewer for the positive remark and are pleased that he/she recommends publication in Natural Hazards and Earth System Sciences following a further exploration of several caveats, mainly with regards our methodology and rationale for the study. We have made major and minor revisions, including a clarification of the systematic literature review, as described in the following paragraphs.*

Major comments

1. The study builds upon the argument of a deficiency in a centralised repository of vulnerability functions for assessing CI against multiple hazards. However, the introduction lacks a thorough examination of how this absence hinders researchers or practitioners. The discussion in the third paragraph primarily focuses on distribution and formatting issues of existing functions, neglecting considerations of resolution, adaptability, and transferability, which may have more significant impacts. It is recommended that the authors critically assess the implications of the current state of vulnerability functions

   [Authors' reply] *Thank you for your comment. Whilst we agree that considerations of resolution, adaptability and transferability are very important, the main purpose of our current manuscript is to review the status-quo of the literature on fragility and vulnerability curves for infrastructure and collect these curves for the database, rather than a quality check of the curves. In the first paragraph of our original introduction, we state the following (lines 30-32):*

   > *'Indeed, the United Nation's Sendai Framework for Disaster Risk Reduction underscores that enhanced work is needed to reduce vulnerabilities, and that freely available and accessible vulnerability information should be promoted for effective risk management (UNDRR, 2015).'*

   With this statement, we highlight the necessity of vulnerability databases to aid effective risk management. In paragraph three, we apply this statement within critical infrastructure context to explain that a vulnerability database is lacking to date and provide examples of reasons that have led to this. However, we did adjust our statement about that the absence of a database like this hampers the research community. Lines 60-62 now read:

   > *'A consistent overview of existing curves and an associated centralized, freely accessible database are lacking, despite the benefits they would provide to the disaster risk*

community. These resources would enable them to perform risk assessments supported by well-informed decisions based on the current state of the fragility and vulnerability literature.'

With the vulnerability review and database that we provide, we support researchers and practitioners to take well-informed decisions regarding fragility and vulnerability curves. Not only do we provide the most complete publicly available vulnerability database, we have also collected characteristics for each curve, such as the derivation methodology (Supplementary Table Table_D1_Summary_CI_Vulnerability_Data). We did not perform a quality check for each curve, but we do present the curves as they are with important additional information so that this can be used in the decision-making process. We are aware of the resolution, adaptability and transferability concerns, and we provide an example of this in paragraph three of section 4.3 in our original manuscript for a specific case (lines 848-856):

*'Third, 'object-based' functions represent the vulnerability of a specific infrastructure type in more detail and specifically account for structure-specific attributes (e.g., Van Ginkel et al., 2021; Kellermann et al., 2015). However, also in these studies, the damage functions cannot be seen in isolation from the type and resolution of the hazard model for which they were initially developed. For example, both Van Ginkel et al. (2021) and Kellermann et al. (2015) anticipate a coarse 100*100 m inundation model that cannot 'see' the local elevation of highways and rail embankments. Therefore, their vulnerability curves start from ground level, and not from the local embankment level. A high-resolution (e.g. 1*1 m) inundation model would detect this embankment level as the ground level, resulting in much lower water depths. The original vulnerability curves would therefore need to be corrected before they are used in a higher-resolution model.'*

We now also raise these concerns in our Conclusion and recommendations (Section 5) in lines 870-874 to emphasize that these need to be accounted for when applying the database:

'Additionally, we wish to highlight that we have not conducted a quality check of the curves, but rather focused on establishing an overview of the current literature on the curves and the collection of these for the database. When considering their usage, it is essential to also account for the resolution, adaptability, and transferability of the curves in assessing and managing risks to CI across various settings and scenarios. In supporting this, we consistently summarized characteristics of each curve in Table D1 of our database.'

2. The use of the term "multi-hazard" in the title appears vague, with potential differences between "Multi-hazard" and "multiple hazards." The authors should either redefine "multi" in the title or refocus the article exclusively on multi-hazard events. If opting for the latter, reference to relevant articles (a few suggested below) for clarification on the definition of multi-hazard events is encouraged.

   https://doi.org/10.1016/j.scitotenv.2023.169120
   https://doi.org/10.1038/s43017-020-0060-z
   https://doi.org/10.1002/2013RG000445

[Authors' reply] *Thank you for pointing this out. We have now made sure that the manuscript is clear in its terminology. In our research we exclusively focus on fragility and vulnerability curves for single hazards. We have replaced multi-hazard by either multiple hazards or hazards, including a change of the manuscript's title to 'Review article: Physical Vulnerability Database for Critical Infrastructure Hazard Risk Assessments – A systematic review and data collection'.*

In addition, we extended our statement in lines 831-834 to communicate that vulnerability research for CI progresses in multi-hazard context, and we also used reviewer's #2 recommended literature for this:

> *'Moreover, recent studies have also begun to assess the vulnerability of CI due to the joint effect of multiple hazards (e.g., Argyroudis et al., 2018; Teoh et al., 2019; Zhu et al., 2022), aligning with the growing field of multi-hazard research aimed at elucidating the interactions of hazards (e.g., Gill and Malamud, 2014; Lee et al., 2024).'*

And we have also edited the sixth point (point 5 in original manuscript) in our list of recommendations for the expansion of our database in Section 5 (lines 876-880):

> *'We strongly encourage users to expand the database with: (1) existing curves that are currently not included, (2) curves for other hazard types, such as wildfires and extreme cold, (3) curves for other important infrastructures types, such as bridges, (4) curves for various building typologies with regard to form (e.g., low-rise) and construction materials, (5) curves that consider the joint effect of multiple intensity measures of a single hazard, and (6) curves that consider the interaction of multi-hazards.'*

3. Referring the statement ""We conducted a literature search for CI vulnerability to flooding, earthquakes, windstorms and landslides over the period January 2022 to March 2023 by systematically using combinations of keywords on the general concept of hazards, critical infrastructure and vulnerability" in section 2.1, methodological concerns include the choice of four specific hazards, the short 14-month (January 2022 to March 2023) search window, and ambiguity regarding whether an established approach like the PRISMA Protocol was followed for the systematic literature search. The authors should specify the databases considered (e.g., Scopus, WoS, PubMed) and provide the search term syntax. Additionally, the number of initial references found, inclusion/exclusion criteria, and handling of duplicate references should be clarified.

[Authors' reply] *The reviewer raises an important concern regarding the methodology applied for our systematic review. We agree that various aspects of our methodology should be clarified to clearly demonstrate that we followed the PRISMA Protocol for the systematic literature search and have made major revisions to do so.*

Firstly, we included a schematic flow chart to show the methodological framework (new figure 1), including the number of references included/excluded throughout the process of literature search, screening and final selection, which aligns with the established PRISMA protocol. We added the following text to the first paragraph of Section 2.1 (lines 76-77 and lines 83-86):

'The schematic workflow for the literature search, screening and final selection of articles for the systematic literature review on the CI vulnerability to flooding, earthquakes, windstorms and landslides is summarized in figure 1.'

'The literature search yielded 2,590,003 initial records, gathered from 125 search term syntaxes listed in Appendix A. It became apparent that a substantial number of papers did not address CI vulnerability in context of natural hazards. As a result, we decided to select the first 250 records for each search term syntax, totalling 31,250 records for the screening procedure.'

Secondly, we have added 'Appendix A: Search term syntax and number of records' in which we provide an overview of the 125 search term syntax used for our systematic literature review. Additionally, we provide the number of records per search term syntax in Appendix A. Furthermore, we also updated Table 1 that contains the search terms categorized per general concept accordingly. Thirdly, we have also taken care to clarify our methodological framework throughout 'Section 2.1'.

With regard to our choice considering the four specific hazards that we include in our research, we added lines 77-79:

'The hazards were chosen based on their widespread occurrence, significant potential for damage to CI and historical evidence of their impact on communities.'

With regard to our choice of the search window, we would like to highlight that the mentioned 14-month period of January 2022 to March 2023 is not the search window of our systematic review, but the period in which we conducted our systematic literature search. We edited lines 105-106:

'However, we did not limit the search window and the geographical scope of the study and are thus still able to provide insight into vulnerability curves in various contexts.'

With regard to the search engine, we added lines 80-82 to the first paragraph of section 2.1:

'Our review is not restricted to peer-reviewed academic articles as curves are also published in 'grey literature', such as research reports released by governments or engineering firms. We therefore use Google Scholar as search engine that is not limited to academic literature in order to minimize the possibility of excluding relevant information within our research scope.'

With regard to the inclusion and exclusion criteria, we have included these in the schematic flow chart of the methodological framework. We now also better indicate the inclusion criteria in the text that were already described in the original manuscript (now lines 91-98). Furthermore, we also added to the description of exclusion criteria in Section 2.1 (lines 100-104).

'If multiple records present the same curves, we only include the original source reference. We also excluded records that describe the probability of an asset failing to operate rather than the damage probability of being in a certain physical damage state,

as we confine the scope of this research to fragility curves that specifically involve the physical damage (see inclusion criteria 1). Note that we exclude curves at subcomponent level (e.g., circuit switcher), but do include them if they are at asset- or system level.'

4. Referring the statement "We excluded bridges from our database as there is an excessive amount of bridge literature that deserves a review article on its own" in section 2, the exclusion of bridges from the database lacks a clear rationale, merely stating there is an excessive amount of bridge literature deserving a separate review article. A more explicit justification or reconsideration of this decision is necessary.

   [Authors' reply] *Thank you for the useful comment. We added a more explicit justification of our decision to not include bridges. It now reads (lines 116-120):*

   'We would like to stress that our database does not encompass all types of infrastructure. There is already vast literature available for limited infrastructure types. For bridges, for example, 224 bridge damage curves for 28 primary bridge types are offered by FEMA (2020) and a dedicated review is provided by Muntasir Billah and Shahria Alam (2015). Moreover, retrieving curves is labour-intensive. Instead, our focus was on delivering as comprehensive a review as possible for the infrastructure types as presented in table 1.'

5. The temporal discrepancy between the search window (January 2022 to March 2023) and data in Figure 1 (1984-2023) raises confusion. The methodology lacks clarity on whether vulnerability functions were extracted from literature or other sources. A comprehensive methodology section, including a flow diagram, is needed to elucidate the study's process.

   [Authors' reply] *The time window of January 2022 to March 2023 is the period during which we conducted the literature search and screening. The fragility and vulnerability curves are extracted from the 95 references that can be found in the reference list of our manuscript as well as in the reference list presented in the publicly available database itself. In fact, for each single curve we indicate in the database's 'Table D1 Summary CI Vulnerability Data' the reference from which this information is sourced from. As per reply of the reviewer's comment #3, we have clarified the search window and have added a flow diagram of the methodology to elucidate the study's process.*

6. The unclear methodology and data sources undermine the meaningfulness of the results at this stage.

   [Authors' reply] *We have taken care to elucidate the methodology, such as described in reviewer's comments 3-5.*

Minor comments

1. In the abstract, the phrase "essential vulnerability information for CI" requires clarification.

[Authors' reply] *We have adjusted the abstract as per reviewer's #1 minor comment on a missing definition of vulnerability in the abstract. We have added a definition for fragility and vulnerability curves for CI for clarification.*

2. The statement, "even within these non-public databases, CI is often limited represented," lacks clarity and needs rephrasing for better understanding.

   [Authors' reply] *As per reviewer's #1 minor comment, we have adjusted this statement.*