Learning from success, not catastrophe: using counterfactual analysis to highlight successful disaster risk reduction interventions

M. Rabonza, Y.C. Lin, & D. Lallemant

REVIEWER 3

We thank the reviewer for the constructive comments. We feel that following the reviewer's suggestions has improved the clarity, readability and strength of the paper. We have responded to each comment and made changes to the manuscript accordingly.

The reviewer's addressable comments have been listed in order below in the ***italic text***, followed by our responses and changes made to the manuscript in normal text.

The comments below are organised into three categories based on how Reviewer 3 sent their comments:

(1) General evaluation
(2) Specific comments
(3) Grammatical comments

1. GENERAL EVALUATION

1.1. *The results are presented from sections 2 to 5, including the results in the description of the methodology, while the results section is too short for a journal paper. I suggest that the authors rearrange the paper by separating the information on the methodology, which should be correctly reported in the first part. From the results section, where numerical results and relevant figures (in particular, figure 5 and 6) should be reported.*

REPLY:

We thank the reviewer for this suggestion. We have restructured the paper from Data/Methods/Results to Methods/Applications. In this restructuring, we have added more details in the methods section, and each case-study application contains all the relevant information on data (e.g. hazard model used, fragility curve used) and results (i.e. probability distribution of fatalities). We find that they are easier to read (e.g. no need to refer back to the data section) and more coherent. We've also changed the wording for concision and clarity throughout the paper.

CHANGES MADE:

- **Restructured the paper as follows:**

Original structure of the paper:

1. Introduction
2. Counterfactual risk analysis framework
3. Invisible success of seismically retrofitting schools in Nepal
4. Data
    - 4.1. Exposure: Building portfolio characteristics
    - 4.2. Vulnerability: Building fragility
    - 4.3. Hazard models
5. Methods
    - 5.1. Estimating lives saved amidst 2015 Gorkha earthquake
    - 5.2. Estimating lives saved throughout the program's lifetime
6. Results
    - 6.1. Lives saved amidst 2015 Gorkha earthquake
    - 6.2. Lives saved throughout the program's lifetime
7. Discussion
8. Conclusion

New structure:

1. Introduction
2. Counterfactual risk analysis framework
3. Invisible success of seismically retrofitting schools in Nepal
4. Methods
    - 4.1. School building database
    - 4.2. Building vulnerability modelling
    - 4.3. Expected fatalities from building collapse
5. Applications
    - 5.1. Lives saved during the 2015 Gorkha earthquake due to the school retrofitting in Kathmandu Valley
    - 5.2. Annual expected lives saved through scaling the retrofit programs to all schools in Kathmandu Valley
6. Discussion
7. Conclusion

- **In the Introduction, Line 76-78, we updated the paper's outline to reflect the new structure**
  In the subsequent sections, we present the data (Section 4), methods (Section 5) and results (Section 6) for two applications that shed light on the benefits of the retrofitting program.

Changed to: (now in Lines 89-90)

In the subsequent sections, we present the methods (Section 4) and two applications (Section 5) that shed light on the benefits of the retrofitting program.

1.2. *As reported in the comments below, in some parts of the paper it is not clear which data and results were produced by the authors, and which ones were instead produced by other authors and just used by the authors. In other words, the novel and original contribution of the paper should be highlighted more than it is done in the original submission.*

REPLY:

We believe the new structure of the paper will make this clear. In addition, we have added information in the introduction to clarify and highlight the original contribution of the paper. Our intent was not to produce a new hazard model, new fragility curves, or new database on school building inventory, but rather use these to conduct a probabilistic counterfactual fatality analysis for the realised and a counterfactual case in order to estimate the lives saved from important risk reduction interventions. We have provided additional information on the hazard model (by Chen and Wei 2019), fragility curves used (by Giordani 2021), and the school database (by OpenDRI). In addition (and also in response to Reviewer comment 2.8 we have conducted a new analysis to generate a stochastic seismic event set (100,000 simulations) to capture the seismic hazard in Kathmandu Valley, Nepal, and propagate it to expected fatalities. This enables us to calculate fatalities and reduced fatalities for the entire hazard curve, as well as the expected annual fatalities.

CHANGES MADE:

- **In the Introduction, Line 48, this sentence is inserted: (now in Line 59)**

  The paper’s main contribution is in combining the probabilistic risk analysis framework and counterfactual analysis to calculate and highlight lives saved from successful disaster risk reduction interventions.

- **Added more info on the school building database in Section 4.1: (now in Lines 151-168)**

  The analyses in this paper are carried out on a database of Nepalese school buildings surveyed and georeferenced in 2013 through the partnership of the Open Data for Resilience Initiative (OpenDRI) and the Government of Nepal with support from Kathmandu Living Labs (OpenDRI, 2012) (Figure 2). The building database covers Kathmandu Valley and was produced with the aim of understanding the seismic risk in the education and health infrastructure. Parts in the dataset related to educational infrastructure were tagged as either *school, college, university, or kindergarten*. The database provides information on the location, number of daytime occupants on a school day, structure type, and whether the school building was retrofitted or not. We chose the OpenDRI dataset for this paper because these building attributes allow us to determine which school buildings were retrofitted under SESP before the 2015 Gorkha earthquake. In addition, the buildings’ structure type can be used to identify the buildings’ vulnerability, while the number of daytime occupants can be used for fatality calculations.

  After screening the raw OpenDRI dataset for missing information or non-school buildings, the final dataset we use for this work consists of 5029 school buildings, of which 70 were retrofitted. We highlight that the OpenDRI dataset we use for this study provides information on only 70 out of the 160 retrofitted school buildings identified by NSET in Kathmandu Valley's affected areas (Marasini, 2019). The database consists of buildings with URM-type and RC-type structures. The daytime occupancy for the 70 retrofitted schools go up to 800, with a mean of 134, whereas the occupancy for the 5029 school buildings go up to 2000 with a mean of 120.

- **Additional information on the fragility curves used in Section 4.2 (see response and changes made for Comment #2.5)**
- **Additional information on the hazard model (by Chen and Wei 2019) used in Case #1 in Section 5.1 (see the first change made for Comment #2.6)**
- **New analysis for Case #2 in Section 5.2**

1.3. As a consequence to point 1 and 2, I think that the authors should elaborate more on the obtained results, and also add some figures regarding the methodology (see comments below about hazard curves used, values of PGA, Ground Motion models.

REPLY:

Thank you for this recommendation. The new structure shifts the weight of the paper towards the applications (formerly 'results'). We have also added more information on the hazard model used (by Chen and Wei 2019). The first application is based on a re-analysis of the actual 2015 earthquake (and focused on 70 schools that were retrofitted), while the second application looks at the expected annual fatalities for 5029 school buildings as described in Comment 1.2.

CHANGES MADE:

- **In Section 5.2, we added the following sentences: (now in Lines 276-283)**

  A probabilistic seismic hazard analysis (PSHA) was developed for the school building sites based on twenty-three independent seismic source zones for Nepal identified by Ram and Wang (2013) and adopted inChaulagain et al. (2015)'s PSHA model. The ground motion prediction equation by Chiou and Youngs (2014) for active shallow crust regions is used within a logic tree for an event-based probabilistic seismic hazard calculation in the OpenQuake-engine (Silva et al., 2014). To reach statistical convergence, 100,000 stochastic event sets with a 1-year time interval were generated (Silva, 2016). The result of the simulation is a large number of realisations of seismic events and corresponding shaking at the locations of the schools within a year. The resulting hazard curves for some selected schools in the database are shown in Figure 6.

1.4. The information provided in the conclusions are not satisfactory. The real conclusions of the work are only reported in the last 5 lines of the conclusions. I encourage the authors to insert highlights from the discussion section in the conclusions.

REPLY:

Thank you for the suggestion. We have added highlights from the Discussions to the Conclusions.

CHANGES MADE:

From Conclusion (Lines 325-335)

In a field focused on long-term resilience to rare (i.e. volatile) hazard events, perceptions are biased by realised outcomes. Perceiving no impacts when DRM work is so successful can result to policy makers and society at large to undervalue the importance of proactive intervention. Shedding light on successes and 'what might have been' not only recognizes the outstanding work of those in the industry but is also a crucial component of encouraging decision-makers to continue investment in measures that keep our communities and world safe.
We highlight the need to celebrate the often invisible successes of disaster risk reduction interventions, in order to incentivise, better learn and replicate investments in such interventions. We further propose and demonstrate the use of counterfactual analysis risk framework to identify, quantify and highlight these invisible successes. The framework demonstrates that judgement of a risk reduction intervention should be based on a broad exploration of possible outcomes, not only on specific outcomes.

Changed to: (now in Lines 377-400)

This study combines the probabilistic risk analysis framework and counterfactual analysis to quantify and highlight the significant benefits of successful disaster risk reduction interventions that often go unnoticed. By using an appropriate counterfactual scenario as a baseline against which to compare realised outcomes, it makes clear that the impact of hazards would be much worse without important investments in risk reduction.

Using this approach, we demonstrate that an estimated 25 lives were saved (probabilistically) during the 2015 Gorkha earthquake from the retrofitting of 70 schools in Kathmandu Valley alone. If such a retrofitting program were scaled to all the approximately 5,029 schools in Kathmandu Valley, we estimate a reduction of 12 annual school children fatalities based on the significant seismic hazard of the region. These are clearly important programs that should be prioritised, celebrated, scaled, and replicated in areas with high seismic risk.

Loss of life reduction is an important metric for risk reduction, not only because the life-safety of children and all people is paramount, but also because doing so centres attention on high-vulnerability areas and buildings, even if the financial losses associated may be small. However loss-avoidance is not the only invisible benefit of disaster mitigation, and the many co-benefits can also be included to further highlight the value of risk reduction interventions.

While this study demonstrates the application of probabilistic counterfactual risk analysis to quantify the life-saving value of a school earthquake retrofitting program in Kathmandu Valley, the methodology can be used in other contexts and hazards. Programs for typhoon and tsunami early warning, hazard informed urban development planning, flood-management through nature-based solution are all examples of important programs whose true benefits could be more accurately valued through the use of probabilistic counterfactual analysis. In so doing, such analysis would provide increased incentives to invest in risk reduction programs, learn from ones with demonstrated success, and serve to encourage those whose humble work is critically important even when often unnoticed.

---

2. SPECIFIC COMMENTS

2.1. Line 21: ***Change:*** ***"..natural hazard events do not <u>become</u> disasters.."***
To: ***"..natural hazard events do not <u>cause</u> disasters.."***

<u>REPLY:</u>

Thank you for the suggestion. Writing this phrase as direct causation might take away the social, political, economic (all the non-hazard related) context in the creation of disasters. Thus, we picked a phrase that accounts for the role of disaster risk management and human actions as natural hazards turn into disasters.

<u>CHANGES MADE:</u>

- **Line 21:**
  From: "..natural hazard events do not <u>become</u> disasters.."
  Changed to: "..natural hazard events do not <u>turn into</u> disasters.."

2.2. Line 36: ".. Lallemant and Rabonza et al. (Forthcoming, 2022) ..."
<u>I don't think you can cite it unless it was accepted for publication.</u>

<u>REPLY:</u>

This paper was accepted for publication. We updated the citation and reference entry accordingly.

<u>CHANGES MADE:</u>

- **Line 36:**

From: Lallemant and Rabonza et al. (Forthcoming, 2022)

Changed to: Lallemant and Rabonza et al. (2022)

- **In the paper's Reference entry:**
  Removed 'Forthcoming' as the publication status

2.3. Equation 2: $I_{counterfactual} = f(\theta_H + \delta_H, \ \theta_E + \delta_E, \theta_V + \delta_V)$

I think the equation is formally correct, but as a concept of Engineering seismology, Hazard cannot be reduced by any intervention, because it depends on events (the occurrence of an earthquake) that cannot be changed. Therefore I would suggest to erase the deltaH.

REPLY:

We agree with the reviewer that the hazard cannot be reduced. However, we do not want to limit the counterfactual exploration only to parameters that can be reduced. For instance, we might want to explore a counterfactual for an earthquake at a slightly different location, or with opposite directivity of rupture. In this paper we focus only on counterfactuals with changing vulnerability, but the application is broader. We have added clarification about this in the text following the equation, and also in the caption of Figure 1.

CHANGES MADE:

- **In Line 93, right after Equation 2, we inserted the following sentences: (now in Lines 105-111)**

  The purpose of the deviations, δ_H, δ_E, and δ_V , to the realised event's parameters is to explore counterfactuals. δ_H helps us explore counterfactuals in the hazard (e.g. what if the earthquake had occurred at a slightly different location, or with opposite directivity of rupture?). δ_E helps us explore counterfactuals in the exposure (e.g. what if the 1906 San Francisco earthquake were to hit today's building stock?). δ_V helps us explore counterfactuals in vulnerability (e.g. what if all unreinforced masonry buildings had been retrofitted?). In this paper, we focus on δ_V, while δ_H and $\delta_E = 0$, in order to highlight the value of effective risk reduction programs that often go unnoticed.

2.4. Line 125-127:

"Recognizing the need to strengthen more than 60,000 school buildings all over Nepal (Marasini et al., 2020), one of the activities in the Master Plan is to retrofit school buildings in earthquake-affected areas."
<u>How did the authors choose the case study?</u>

REPLY:

Thank you for the comment. We have added sentences to clearly explain why the authors chose the case study.

CHANGES MADE:

- **In Section 5.2, first paragraph, we added the following sentences: (now in Lines 271-275)**

  Part of the Comprehensive School Safety Master Plan is the ambition to scale earthquake retrofitting to all vulnerable schools (CEHRDC, 2018). As such, we develop a second case-study to better understand the life-saving impact of such a program. We assess expected fatalities if the 5029 schools in Kathmandu Valley were retrofitted, and if they remained in their current state. This analysis is conducted for the entire seismic hazard of Nepal, to better reflect the distribution of potential events to impact Kathmandu Valley.

2.5. Line 147:

"Fragility curves for the retrofitted buildings are not available, so we instead adopt the fragility curve for a specially designed reinforced concrete (RC) building (Building class C3).

Can the authors please elaborate why?

REPLY:

Thank you for this comment. In fact since the original submission, two new papers were published on fragility of school buildings in Nepal (Giordano 2021a and 2021b). We have updated the analysis and description using these more reliable fragility curves. This includes a table, figure, and section 4.2 which describes the fragility curves.

CHANGES MADE:

- **We have included a table with the curve parameters and reference.**

Table 1. Fragility curve parameters adopted in the analysis for the school buildings in the OpenDRI database. The parameters follow a lognormal model where η (g) is the median PGA and β is the lognormal standard deviation.

Reference	Building class	Structural state of building	Collapse state parameters	
			η	β
(Giordano et al., 2021a)	Non-retrofitted URM - Unreinforced masonry bearing wall, low-rise (pre-code)	Un-retrofitted	0.55	0.76
(Giordano et al., 2021a)	Non-retrofitted RC - Concrete frame buildings with unreinforced masonry infill walls, low-rise (low code)	Un-retrofitted	1.13	0.84
(Giordano et al., 2021b)	Retrofitted stone masonry buildings	Retrofitted	1.133	0.452

- **We have added a figure with the curves (Figure 3)**

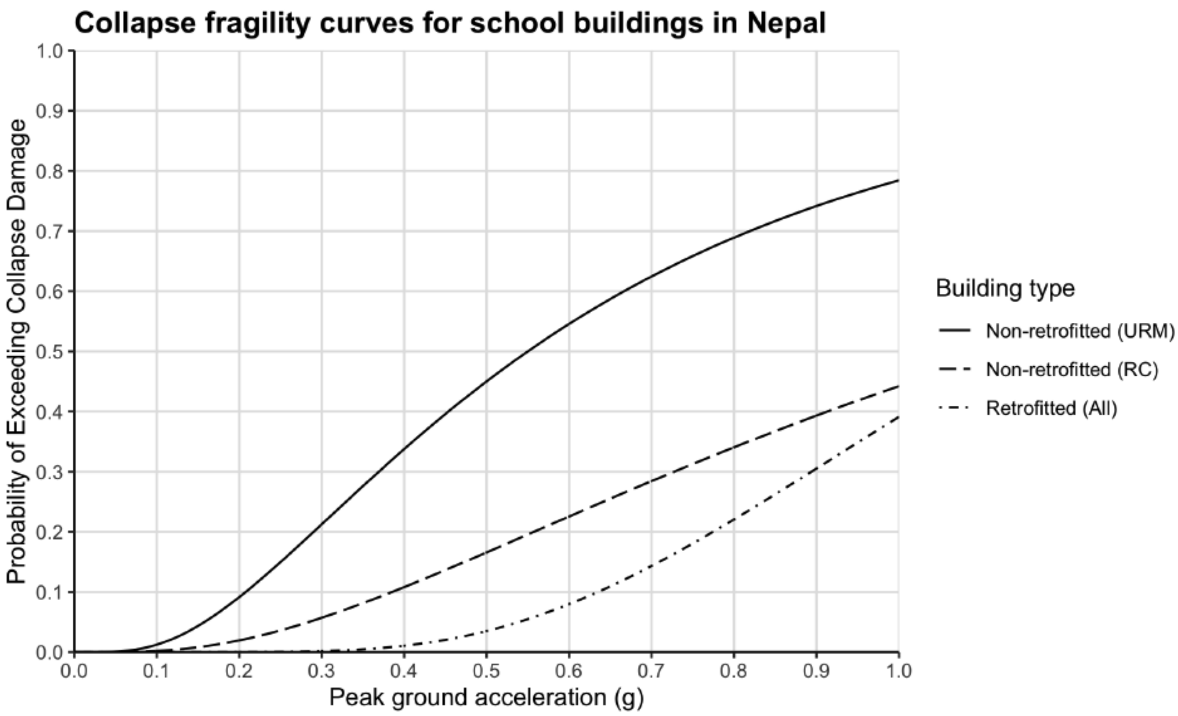

Figure 3. Collapse fragility curves adopted in the analysis.

- **We have added a section describing the curves (Section 4.2): (now in Lines 175-194)**

In this work, we have adopted collapse fragility curves developed by other authors to represent the probability of collapse of the buildings at their retrofitted and non-retrofitted states. The collapse fragility curves we use for the Nepalese school building stock in this study are presented in Figure 3. The median η and lognormal standard deviation β of the fragility curves expressed as PGA lognormal distributions are shown in Table1.

For non-retrofitted buildings, we adopt Giordano et al. (2021a)'s empirical-based fragility curves specifically developed for Nepalese school buildings. The curves were generated using a Bayesian approach to incorporate well-established fragility models such as the HAZUS database (Federal Emergency Management Agency, 2015) and World Bank's Structural Integrity and Damage Assessment database (SIDA) that was conducted under the Global Program for Safer Schools (Worldbank, 2019). The collapse fragility curves from Giordano et al., (2021a) were assigned to the buildings in the OpenDRI dataset based on their structure type - unreinforced load-bearing wall schools were assigned the URM collapse fragility curve, while reinforced concrete schools were assigned the RC collapse fragility.

For retrofitted buildings, we use the collapse fragility curve developed by Giordano et al., (2021b) for retrofitted stone masonry buildings in Nepal that are considered to have good quality material. The fragility curves in Giordano et al., (2021b) were produced analytically using a non-linear static pushover analysis for stone masonry buildings retrofitted with the 'RC strong-back approach'. It should be noted that the selected fragility curve for retrofitted school buildings does not necessarily represent the variation in the retrofit solutions available in Nepal, as well as the workmanship and original quality of the buildings, rather this is the best information available to the authors at the time of writing.

- **We have updated the analysis results accordingly. Fatality calculations shown in Figure 5, Figure 7 (see changes made for comment #1.8) and a paragraph in Section 5.1 (see changes made for comment #1.7) all use the updated fragility curves.**

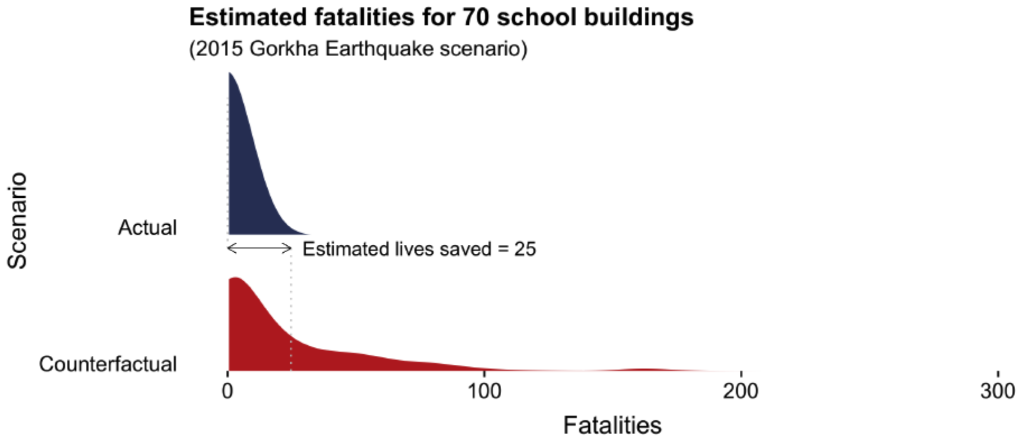

Figure 5. Distribution of estimated fatalities from the 2015 M_w 7.8 Gorkha earthquake based on earthquake intensity values from Chen and Wei (2019). Two scenarios are shown: the actual scenario where all 70 school buildings were retrofitted prior to the 2015 Gorkha earthquake, and a counterfactual scenario where the schools were not retrofitted. Our analysis show an estimated 25 lives in the 70 retrofitted schools.

- **Added Giordano 2021a and 2021b in the reference list:**

Giordano, N., De Luca, F., Sextos, A., Ramirez Cortes, F., Fonseca Ferreira, C., and Wu, J. (2021a). Empirical seismic fragility models for nepalese school buildings. Natural Hazards 105, 339–362

Giordano, N., Norris, A., Manandhar, V., Shrestha, L., Paudel, D. R., Quinn, N., et al. (2021b). Financial assessment of incremental seismic retrofitting of nepali stone-masonry buildings. International Journal of Disaster Risk Reduction 60, 102297

2.6. Line 156:
"To best represent the shaking at the school buildings' sites at the time of the 2015 Gorkha earthquake, we use peak ground acceleration (PGA) values produced with stochastic simulations (high frequency) for Kathmandu (Figure 2)."
In my opinion, it is not clear enough:
A1) Which method was used to generate the PGAs.
A2) Which Ground Motion model was used
Can the authors clarify? Is it possible to add a figure?

REPLY:

Thank you for this comment. We have added some details about the Chen and Wei model used in case-study 1, as well as a comparison of results using the USGS Shakemap. For Case-Study 2, we have generated a stochastic seismic event set (100,000) using the OpenQuake hazard model. We have added details in section 5.2. While the purpose of the paper is not to produce new hazard information, we think this has nonetheless strengthened the paper, and enabled us to produce annual expected fatalities (accounting for the entire hazard curve) rather than fatalities for a specific hazard level.

CHANGES MADE:

- **In Section 5.1, 2nd paragraph, we added details of the Chen and Wei model used for case-study 1 (now in Lines 235-244)**

  The shaking intensity at the school sites during the 2015 Gorkha earthquake is obtained from the broadband ground-motion simulations produced by Chen and Wei (2019). This hazard model was selected because the location of sources of the high-frequency energy (strong-motion generation areas) is a critical factor in explaining the relatively low damage phenomenon observed in Kathmandu Valley during the 2015 Gorkha earthquake (Gallovicˇ, 2016; Koketsu et al., 2016), aside from effects of site conditions and rupture directivity (Dixit et al., 2015; Rajaure et al., 2017; Gallovicˇ, 2016; Koketsu et al., 2016). A map of the PGA values at the location of the retrofitted buildings is shown in Figure 4. With this hazard model, PGA values at the location of the retrofitted buildings range from 0.065 to 0.149 g, and come in a resolution of 0.0167 degrees, or around 1.85km. More details about the PGA data are summarised in Chen and Wei (2019) and its companion paper, Wei et al. (2018).

- **In Section 5.1, last paragraph, we added a comparison of results using USGS ShakeMap (now in Lines 259-268)**

  In an attempt to explore the sensitivity of the casualty estimates to different hazard models for the 2015 Gorkha earthquake, we repeated the analysis using a PGA map from the USGS ShakeMap (USGS ShakeMap, 2015; Wald and Allen, 2007). While using Chen and Wei (2019)'s hazard model results in 25 lives saved, using the USGS ShakeMap hazard model results in 68 lives saved (see Figure S1). The analysis using either model highlights the life-saving benefit of the school retrofitting program, but we believe that the fatality analysis using Chen and Wei (2019's model is more accurate in terms of representing the shaking during the 2015 Gorkha earthquake. Chen and Wei (2019)'s model better captures the amplification or attenuation of the seismic shaking as it accounts for the location of sources of the high-frequency energy (strong-motion generation areas), rupture directivity, and site conditions critical in understanding the relatively low damage phenomenon observed in Kathmandu Valley during the earthquake.

- **In Section 5.2, second paragraph, we added details of the hazard model used for case study 2 including generating stochastic seismic event set (100,000 simulations) - now in Lines 276-283**

  A probabilistic seismic hazard analysis (PSHA) was developed for the school building sites based on twenty-three independent seismic source zones for Nepal identified by (Ram and Wang, 2013) and adopted in Chaulagain et al. (2015)'s PSHA model. The ground motion prediction equation by Chio and Youngs (2014) for active shallow crust regions is used within a logic tree for an event-based probabilistic seismic hazard calculation in the OpenQuake-engine (Silva et al., 2014). To reach statistical convergence, 100,000 stochastic event sets with a 1-year time interval were generated (Silva , 2016). The result of the simulation is a large number of realisations of seismic events and corresponding shaking at the locations of the schools within a year. The resulting hazard curves for some selected schools in the database are shown in Figure 6.

- **Added hazard curves for three locations (Figure 6)**

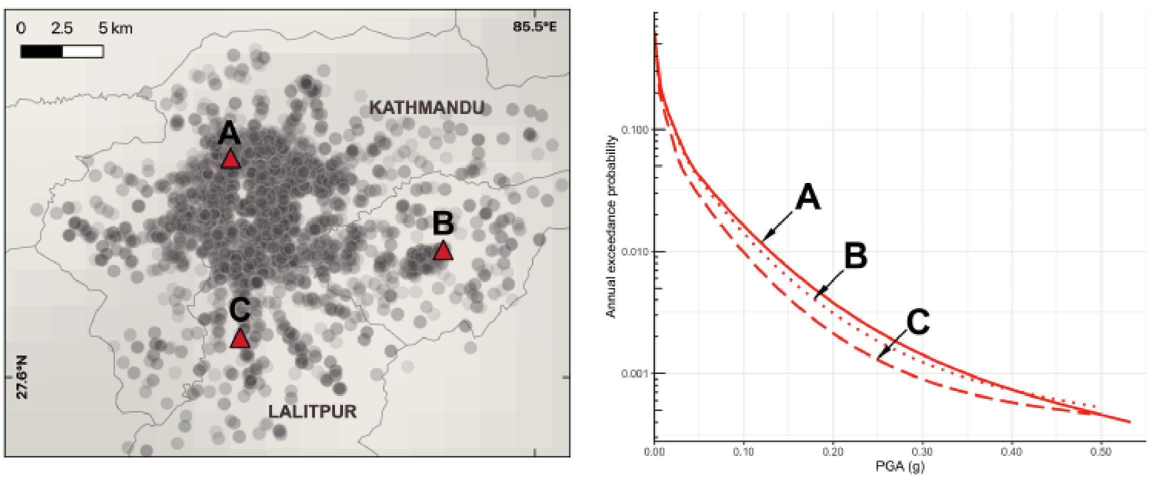

Figure 6. Hazard curves for three sample school building locations in the analysis.

- **We added Figure 7 to show the results of the 2nd case study, using annual expected lives saved as the metric.**

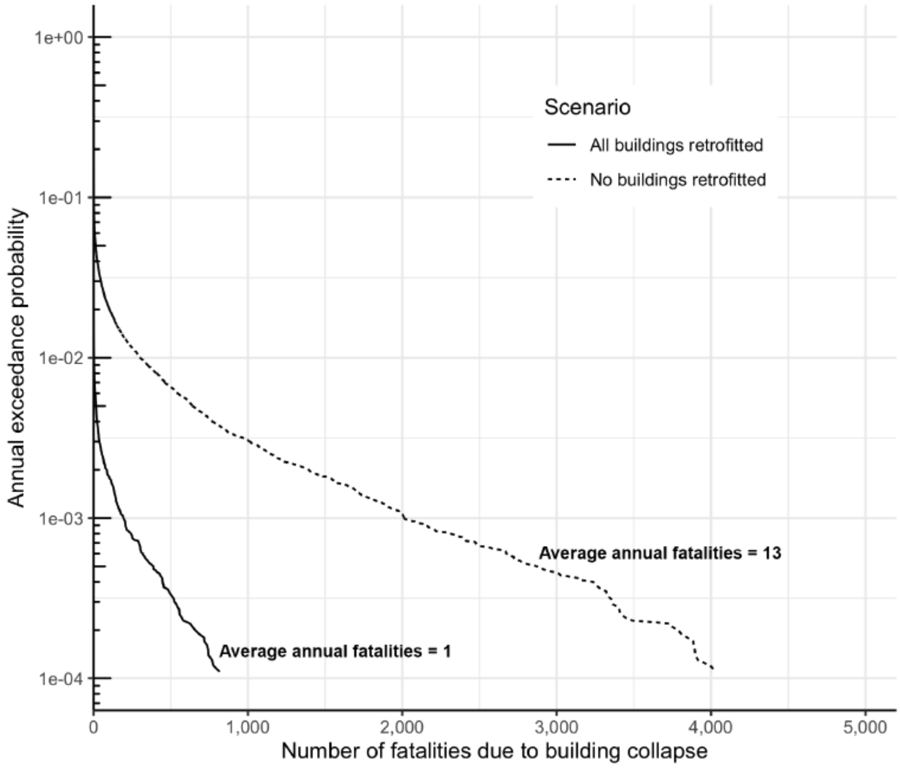

Figure 7. Benefits of extending Nepal's school retrofit program to 5029 schools in the database in terms of the shift in the fatality exceedance curve.

2.7. Line 167-168:

"More details about the PGA data are summarized in Chen and Wei (2019) and its companion paper, Wei et al. (2018).

So, if I understand well, Authors have used the PGA data generated by other authors. Is it right?

REPLY:

Thank you for this comment. We have reworded the paragraph to highlight that we used PGA data generated by authors Chen and Wei for the first case study. The references to the authors' paper are introduced earlier in the paragraphs. We also added more explanation on why we specifically chose the PGA data generated by Chen and Wei.

CHANGES MADE:

- **See the first change made for Comment #2.6**

2.8. Line 175 - 176:

"Including site effects, the school buildings are expected to have a 10% probability of exceeding shaking of 0.506 to 0.649g in any 50 year period."

Can the authors include a figure of the hazard curves? Or also here they used values made by other authors?

REPLY:

We have included a figure of a hazard curve at a few school building sites in the study area.

CHANGES MADE:

- **Added a figure of with hazard curves for 3 school sites (see the 3rd change made for 2.6)**

2.9. Line 188 - 191:

"A Monte Carlo simulation of Bernoulli trials then generates a distribution of number of collapsed buildings in the realised case and counterfactual case. We can estimate the number of avoided building collapse by comparing the building collapse between the realised and counterfactual scenario."

It is not clear how the method was used.

REPLY:

We have added an equation (Equation 4) to clarify the method of calculating the expected number of fatalities (due to earthquake-induced building collapse) for each scenario.

In the Methods section (Section 4.3), we also added more detail on how the Monte Carlo simulation of Bernoulli trials are executed. In order to generate the entire probability distribution of fatalities, we generate 10,000 Bernoulli trials for collapse given a shaking intensity at each building location and for each building class for both the realised and counterfactual scenario.

A link to all code is also provided in the text and in the data availability section.

Having added Equation 4 and clarifications that the paper focuses on fatalities as a metric, we removed the Supplementary material that shows the distributions of building collapse.

CHANGES MADE:

- **Added Equation 4 in Section 4.3 second paragraph, with explanations: (now in Lines 205-211)**

  In this study, we calculate the total estimated fatalities $E[I]$ for a given building portfolio having a total number of m buildings from a single earthquake event. Each building i in the portfolio has a known structure type k_i. Using the empirical casualty model, we can write $E[I]$ as

$$E[i] \approx \sum_{i=1}^{m} O_i \cdot FR_i(k_i) \cdot C_i(im_i, k_i) \qquad (4)$$

  where O_i is the total exposed population inside building i at the time of the earthquake, $FR_i(k_i)$ is the fatality rate associated with the collapse of building i based on its structure type k_i, and $C_i(im_i, k_i)$ is the probability of collapse of building i given the earthquake intensity at its location im_i and its structure type k_i.

- **From Lines 40 - 43:**
  A Monte Carlo simulation of Bernoulli trials then generates a distribution of number of collapsed buildings in the realised case and counterfactual case. We can estimate the number of avoided building collapse by comparing the building collapse between the realised and counterfactual scenario.

  Changed to: (now in Section 4.3 last paragraph) now in Lines 219-222)
  In order to generate the entire probability distribution of fatalities we conduct Bernoulli simulations (10,000) for collapse given a shaking intensity $C_i(im_i, k_i)$ at each building location and for each building class k_i for both the realised and counterfactual scenario. The complete source code is available at https://github.com/ntu-dasl-sg/frontiers2021-PLS.

- **Removed Supplementary material showing number of collapsed buildings (Figures S1 and S2).**

2.10. Line 187:

Change:	***The realised scenario …***
To:	***The real-case scenario …***

REPLY:

In the literature of counterfactual analysis, the term ‘realised’ is used in juxtaposition to counterfactual. In addition, ‘realised value’ or ‘realisation’ is also used in the literature of probability when referring to a value that is observed in reality. To clarify, we added a sentence in the Introduction where ‘realised’ is first mentioned.

CHANGES MADE:

- **From Lines 40 - 43:**
  In this paper, we propose to address this bias through the use of probabilistic downward counterfactual analysis and highlight effective risk reduction activities in terms of probabilistic lives saved.

  Changed to: - now in Lines 44-53
  To address outcome bias, we propose a *probabilistic downward counterfactual analysis* approach. It relies on comparing the outcome of a realised event in which a risk reduction was implemented, to an alternative branch of history (i.e. *counterfactual*) in which the disaster risk reduction intervention was not implemented. Throughout the paper, we use the term *realised* to refer to events or outcomes that transpired (in juxtaposition to counterfactual), in alignment with prior literature on probability and counterfactual analysis (Roese, 1997). An imagined scenario where an intervention is absent is considered a *downward counterfactual* because the assumed outcome is worse than what was observed in reality (Roese, 1997). This is in contrast with an *upward counterfactual* where the assumed outcome is better. Probabilistic downward counterfactual analysis is *probabilistic* in that it follows probabilistic risk analysis procedures to propagate and account for uncertainties in events and outcomes.

---

3. GRAMMATICAL COMMENTS

Thank you for noting the grammatical errors in the PDF as enumerated below. We followed and made changes accordingly for all of them. We also read through the whole paper to ensure that there are no further grammatical errors made.

3.1. Line 30-31:

From: ***"Another challenge is to recognize successful interventions if the hazard they were designed for have not yet occurred."***

Changed to: ***"Another challenge is to recognize successful interventions if the hazard they were designed for has not yet occurred."***

3.2. Line 96-97:

From: ***"The benefits (B) of effective risk mitigation are obtained by comparing the distribution of counterfactual impacts to the realised impacts (Equation 3 and Figure 1)."***

Changed to: ***"The benefits (B) of effective risk mitigation is obtained by comparing the distribution of counterfactual impacts and the realised impacts (Equation 3 and Figure 1)."***

3.3. Line 133 - 134:

From: ***"The 70 retrofitted schools in the dataset is part of the 78 retrofitted schools surveyed by NSET in Kathmandu Valley's affected areas (Marasini, 2019)."***

Changed to: ***"The 70 retrofitted schools in the dataset are part of the 78 retrofitted schools surveyed by NSET in Kathmandu Valley's affected areas (Marasini, 2019)."***