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

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REVIEWER 1

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 presented in two categories that follow Reviewer 1's supporting PDF file:

(1) "Comments on the Text" and

(2) "Comments on the Figures".

We'd like to note that, based on the comments from another reviewer, we have restructured the paper as shown below. 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.

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

1. COMMENTS ON THE TEXT

1.1. *Abstract: The abstract should also mention the second case study using the 10% in 50 year PGA values, to more accurately reflect the scope of the work.*

REPLY:

Thank you for the recommendation. In fact, we have updated the analysis for the second case study by generating a stochastic event set (100,000 simulations) representing the seismic hazard in Kathmandu Valley, Nepal. This enables us to calculate the annual expected fatalities for the retrofitted and non-retrofitted scenarios. This metric is more directly informative and actionable than the 10% in 50-year fatality estimates. To reflect this new analysis, we have updated the abstract and a paragraph in the Introduction describing the scope of the paper. Details of the hazard model developed are added in Section 5.2.

CHANGES MADE:

- **In the Abstract, Line 14, the following lines are inserted:**

  Using a school building database for Kathmandu Valley, Nepal, we present two applications: (1) the quantification of lives saved during the Gorkha earthquake as a result of the retrofitting of schools in Kathmandu Valley since 1999, (2) quantification of the annual expected lives saved if the pilot retrofitting program was extended to all school buildings in Kathmandu Valley based on a probabilistic seismic hazard model.

- **In the Introduction, Line 80, we updated the paper's outline to reflect the 2nd case study.**

  From:
  The second application calculates future probabilistic lives saved by the retrofitting program based on a probabilistic seismic hazard model for Kathmandu Valley.

  Changed to: (now in Line 92)
  The second application calculates the annual expected lives saved upon retrofitting all the school buildings in our database based on a probabilistic seismic hazard model we generated for Kathmandu Valley, Nepal.

- **In Section 5.2, we describe the updated analysis for the 2nd case study, and the probabilistic seismic hazard model we generated for study. We also added Figure 7 to show the results of the 2nd case study (see changes made for comment #1.8).**

1.2. *Line 43: I think the term "downward counterfactual" should be explained here, for readers that may be unfamiliar with the term*

REPLY:

Thank you for the suggestion. We added an explanation of the term *downward counterfactual* in this line. Aside from *downward counterfactual,* other terms such as *realised, counterfactual, and probabilistic downward counterfactual analysis* were also mentioned for the first time in this part of the text. To explain all these terminologies, we have reworded the paragraph.

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. Two applications are presented to model how the consequences of a hazard event would be made worse by the absence of a risk reduction intervention (i.e. downward counterfactual).

  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.

1.3. *Line 100: "that conducted" – it would be more appropriate for this to be replaced by "that led to".*

REPLY:

We revised the line based on this suggestion.

CHANGES MADE:

- **From Lines 99-100:**
  Specifically, we focus on one of the most significant risk interventions **in the recent years that conducted** improved construction practices - the seismic retrofitting of school buildings in Nepal.

  Changed to: (now in Line 124)
  Specifically, we focus on one of the most significant risk interventions **in recent years that led to** improved construction practices - the seismic retrofitting of school buildings in Nepal.

1.4. *Equation 3: This equation suggests negative benefits because the impacts from the counterfactual will be higher than those from the realized case. I would suggest the authors reverse the right-hand side of the equation, to make the benefits positive if the realized impacts are less than those of the counterfactual – it would also better reflect the calculations conducted in the case studies of the manuscript. You can find a similar comment on Figure 1 below. To better reflect the calculations conducted in the case studies of the manuscript, it might be better to write this equation in terms of expected values of impacts.*

REPLY:

We agree -- thank you for the suggestion. Equation 3 is now revised to better reflect the calculations in the case studies. We have reversed the right-hand side of the equation to make the benefits positive. The impacts are also now expressed as expected values. These changes are consistent with a related comment about Figure 1 (Comment #2.1).

CHANGES MADE:

- **From Lines 96-97 and Equation 3:**

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

$$B = I_{realised} - I_{counterfactual} \quad (3)$$

  Changed to: (now in Line 119)

  The expected benefits *(B)* of effective risk mitigation is then calculated as the difference between the expected value or the mean of impacts of the realised event $E(I_{realised})$ and the counterfactual event $E(I_{counterfactual})$ (see Equation 3 and Figure 1). Assuming the realised impacts are less than those of the counterfactual, *(B)* is expected to be a positive value in Equation 3.

$$B = E(I_{counterfactual}) - E(I_{realised}) \quad (3)$$

1.5.a. *Section 4: Why use only 70 retrofitted buildings if 300 had been retrofitted (as mentioned in line 117)?*

REPLY:

There were a total of 300 schools retrofitted across Nepal, 160 of which were in Kathmandu Valley (the focus of our study), but our database contained information on 70. We added clarifying sentences in the discussion of the scope of the first case study.

CHANGES MADE:

- **In Section 5.1, first paragraph, we added the following lines: (now in Lines 230-233)**

  While there were a total of 160 schools retrofitted in Kathmandu Valley at the time of the 2015 Gorkha earthquake (Marasini, 2019), our database contained information on 70. Hence while the focus of our analysis is on the life-saving benefit of the retrofit of the 70 schools in our data, the true reduction in fatalities due to the earthquake retrofitting program is much greater.

1.5.b. *Section 4: Please justify your designation of the retrofitted buildings as specially designed reinforced concrete buildings (Building Class C3)*

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.**

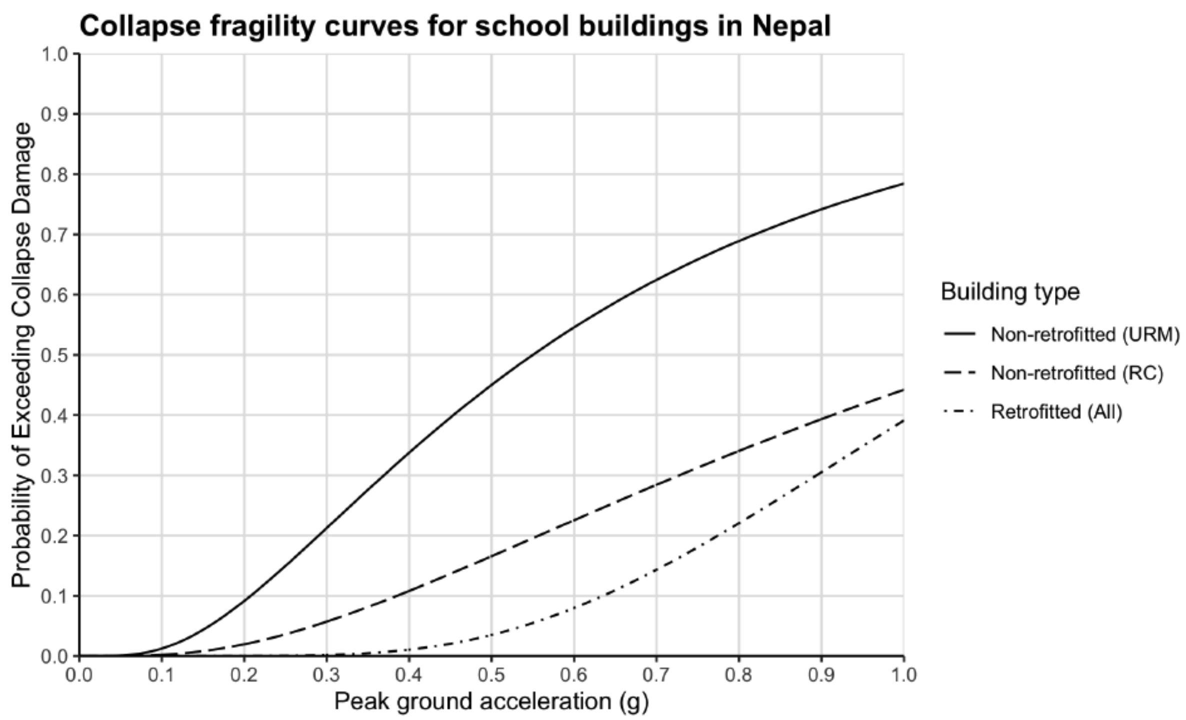

Figure 3. Collapse fragility curves adopted in the analysis.

- **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 4. 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.**

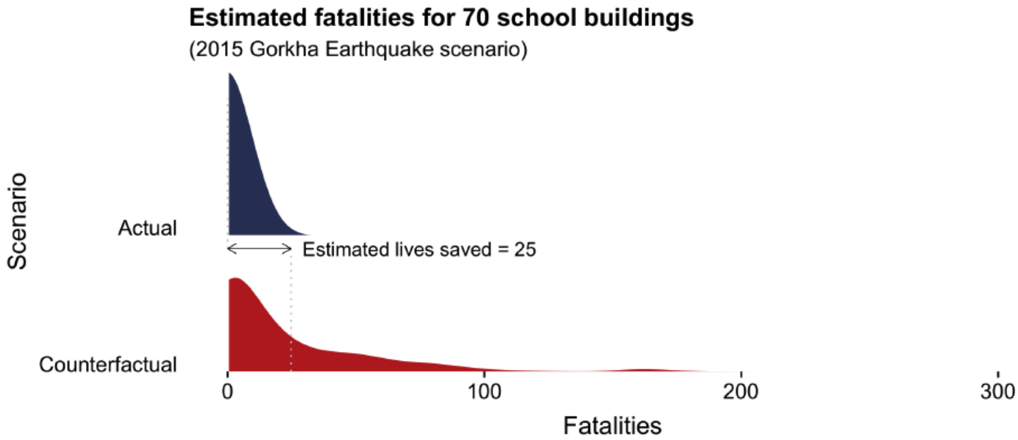

Figure 5. Distribution of estimated fatalities from the 2015 M_w 7.8 Gorkha earthquake based on earthquake intensity values from Chen and Wei (2019). Two scenarios are shown: the actual scenario where all 70 school buildings were retrofitted prior to the 2015 Gorkha earthquake, and a counterfactual scenario 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

1.5.c. ***Section 4: One thing that is not quite clear to me is how building classes are assigned to the retrofitted buildings in the counterfactual case. Was the required information obtained from a particular source or was it assumed based on the distribution of building classes of non-retrofitted buildings?***

<u>REPLY:</u>

See response 1.5.b.

<u>CHANGES MADE:</u>

See response 1.5.b.

1.6.a. ***Section 5: The first paragraph of this section is a bit confusing. The first sentence seems to suggest that the counterfactual considers a school day and therefore a different exposure to the original case. However, the last sentence of the paragraph seems to suggest that the exposure remains the same. The authors should clarify this apparent contradiction.***

REPLY:

Thank you for the recommendation. We have reworded the paragraph to clarify.

CHANGES MADE:

- **From Lines 178-184**

  This case study imagines the scenario: What if the 2015 Gorkha earthquake happened on a school day, and the seismic retrofitting program had not been implemented? With the counterfactual risk framework, we estimate the building collapse for a realised case where the 70 school buildings were retrofitted and a counterfactual case where these buildings are not retrofitted using the data shown in Figure 2. To explore the impact of reduced fragility from the program to the final risk results, the hazard and exposure footprint.

  Changed to: (now in Lines 225-234)

  In order to quantify the reduced fatalities from the school retrofit program in Kathmandu Valley, we estimate the fatalities during the 2015 Gorkha earthquake in the 70 retrofitted school buildings in our database as well as in the counterfactual scenario where these are not retrofitted. By chance, the earthquake occurred during a school holiday, during which occupancy was very low. For both re-analysis scenarios (current retrofit and counterfactual non-retrofit schools), we analyse fatalities for the expected occupancy during the school day. While there were a total of 160 schools retrofitted in Kathmandu Valley at the time of the 2015 Gorkha earthquake (Marasini, 2019), our database contained information on 70. Hence while the focus of our analysis is on the life-saving benefit of the retrofit of the 70 schools in our data, the true reduction in fatalities due to the earthquake retrofitting program is much greater. A map of the 70 retrofitted school buildings used in this analysis is shown in Figure 4.

1.6.b. ***Section 5: Line 186: How does daytime occupancy affect the probability of exceeding a school building's collapse damage state?***

REPLY:

The daytime occupancy does not impact the probability of collapse and we have corrected the corresponding sentence. However, it impacts the expected fatalities given building collapse. We added Equation 4 to clarify this. In Equation 4, we use O_i as daytime occupancy of school buildings based on our dataset. Section 4.3's second paragraph explains Equation 4 in detail. We have also added information on the integration of daytime occupancy into the case 2 probabilistic analysis in section 5.2.
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:

- **From Lines 185-187**

The probability of exceeding a school building's collapse damage state is estimated based on the peak ground acceleration (PGA) at the site, daytime occupancy, building class based on construction typology, and collapse fragility curves.

Changed to: (now in Section 4.3's second paragraph, 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

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

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.

- **In Section 5.2, we added the following sentences (now in Lines 285-290)**

In the fatality calculation of each event, we incorporate the probability distribution of school building occupancy. In Nepal, schools are open and run 220 days a year, and each school day lasts for 6 hours (Government of Nepal, 2009). This means that out of the 8760 hours in a year, 1320 (15%) are school hours in Nepal. To account for this, we simulate a large number of Bernoulli trials for each event that takes a 15% probability of occurring during school hours. The resulting annual exceedance probability curves for two different retrofitting scenarios is shown in Figure 7.

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

1.6.c. *Line 193: The authors should clarify that the fatality rate is conditional on building collapse.*

REPLY:

We added Equation 4 to clarify how the fatality rate is being used to calculate fatalities due to the collapse of buildings. Building collapses are the main contributor to total earthquake fatalities worldwide, therefore the paper focuses on fatalities from earthquake-induced building collapse. We added a sentence and a reference that clarifies this.

CHANGES MADE:

- **Added Equation 4 (see the first change made for comment #1.6.b)**

- **In Section 4.3's first paragraph, we insert the following sentences: (now in Lines 196-198)**
  A vast majority of earthquake fatalities worldwide are due to building collapse (Spence, 2007). Therefore, this paper focuses on quantifying the fatalities from earthquake-induced building collapse, and how much effective interventions have reduced and will reduce such fatalities.

- **Added a Reference entry:**
  Spence, R. (2007). Saving lives in earthquakes: successes and failures in seismic protection since 1960. Bulletin of Earthquake Engineering 5, 139–251

1.6.d. ***Section 5.1: This section should also detail how uncertainty in the daytime occupancy is captured in the analyses, both in the realized and counterfactual scenarios. Reference to the violin plots provided in Figures 2 and 3 could help to clarify these calculations.***

REPLY:

Thank you for this advice. For the first case, we assume the event occurred during school hours and have clarified this in the paper. For the 2nd case, we have conducted a full probabilistic seismic hazard analysis, as well as a simulation of the time of the event in order to capture the probability distribution of school building occupancy. We have added a description in section 5.2.

CHANGES MADE:

- **In Section 5.2, third paragraph, we added the following sentences: (now in Lines 285-290)**

> In the fatality calculation of each event, we incorporate the probability distribution of school building occupancy. In Nepal, schools are open and run 220 days a year, and each school day lasts for 6 hours (Government of Nepal, 2009). This means that out of the 8760 hours in a year, 1320 (15%) are school hours in Nepal. To account for this, we simulate a large number of Bernoulli trials for each event that takes a 15% probability of occurring during school hours. The resulting annual exceedance probability curves for two different retrofitting scenarios is shown in Figure 7.

1.6.e. ***Line 221 to 222: "meaning…its occupants do not change". Are the authors referring to a distribution of building occupancy here or a discrete number? This should be clarified in the text.***

REPLY:

We use a discrete occupancy value for each building based on the database (reference). To clarify this in the text, we added Equation 4 to describe how occupancy values from the database were used to calculate the fatalities.

CHANGES MADE:

- **See response to comment 1.6.b.**
- **Added Equation 4 (see the first change made for comment #1.6.b)**

1.7. ***Section 7: Line 295: The authors should comment on how the number of lives saved for this analysis compares to the number of lives saved using the main PGA map.***

REPLY:

Thank you for the recommendation. We added sentences that compare the number of lives saved between the main PGA map (from Chen and Wei) and the ShakeMap. We have also updated the analysis results using the new fragility curves (see response to Comment #1.5.b)

CHANGES MADE:

- **From Line 293-297**

In an attempt to explore how different the casualty estimates would be for different hazard models for the 2015 Gorkha earthquake, we repeated the analysis in Section 5.1 using a PGA map from the USGS ShakeMap (Wald and Allen, 2007). Looking at the results in Figure S3, using ShakeMap results to 355 lives saved. This is only a simple exploration using a different hazard model, and not a full sensitivity analysis.

Changed to: (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.

1.8. ***General Note: The authors describe the second application of the framework as an estimation of the lives saved "throughout the program's lifetime". I am not comfortable with this description for two reasons:***

a. The authors investigate the number of lives saved assuming all buildings have been retrofitted, and are therefore technically investigating the number of lives saved at the end of the program's lifetime.

b. The authors investigate the number of lives saved based on just one point on the hazard curve, whereas the word "lifetime" seems to suggest a time-based hazard assessment that considers multiple points on the hazard curve.

I therefore think that the authors should modify their description of the second application accordingly (including in Section 7).

REPLY:

Thank you for these comments. (a) Indeed the counterfactual scenario assumes all school-buildings are retrofitted. We have clarified this in the text. (b) We have also updated the analysis by generating a stochastic event set (100,000 simulations) representing the seismic hazard in Kathmandu Valley, Nepal. This enables us to calculate fatalities and reduced fatalities for the entire hazard curve. We thank the reviewer for highlighting this, and we think that the new metrics of reduced fatalities on the basis of the entire hazard curve are more informative and actionable. We have changed the section title to better reflect this.

CHANGES MADE:

- **From the section title for the 2nd case study (Section 6.2)**
  "Lives saved throughout the program's lifetime"

  Changed to: (now in Section 5.2)
  "Annual expected lives saved through scaling the retrofit programs to all schools in Kathmandu Valley"

- **In Section 5.1, first paragraph, we added sentences that describe why the authors chose the case study: (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.

- **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) - 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.

- **In Section 5.2, third and fourth paragraph, we added explanations on how we calculate the fatalities for the entire hazard curve: - Lines 284-295**

For every event generated, the number of fatalities in the building portfolio due to collapse is estimated using Equation 4. In the fatality calculation of each event, we incorporate the probability distribution of school building occupancy. In Nepal, schools are open and run 220 days a year, and each school day lasts for 6 hours (Government of Nepal, 2009). This means that out of the 8760 hours in a year, 1320 (15%) are school hours in Nepal. To account for this, we simulate a large number of Bernoulli trials for each event that takes a 15% probability of occurring during school hours. The resulting annual fatality exceedance probability curves for two different retrofitting scenarios are shown in Figure 7.

The average annual fatalities are obtained by integrating the hazard curve. For the scenario in which none of the 5029 school buildings is retrofitted, we estimate 13 average annual fatalities, whereas when the retrofitting program is extended to all buildings, we estimate an average of 1 annual fatality. In this probabilistic analysis, we calculate an average of 12 annual lives saved from scaling the retrofit program in all of Kathmandu Valley.

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

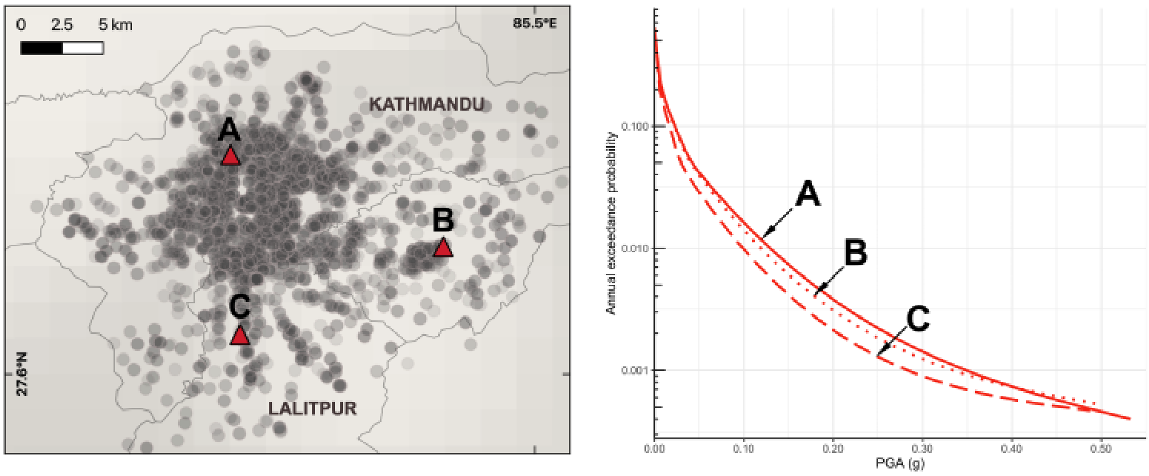

Figure 6. Hazard curves for three sample school building locations in the analysis.

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

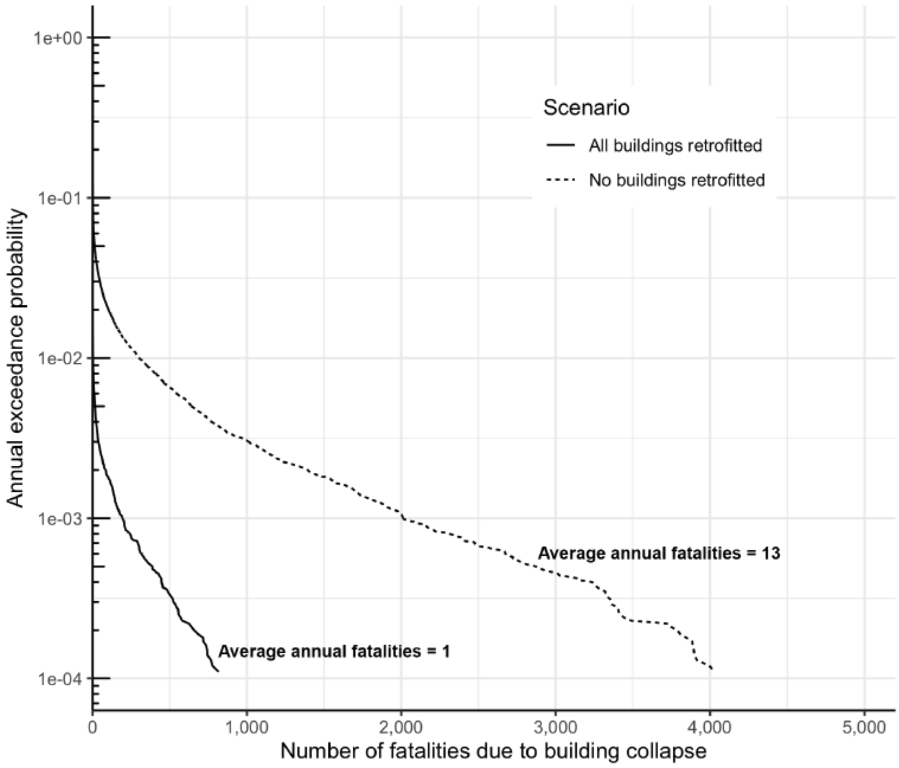

Figure 7. Benefits of extending Nepal's school retrofit program to 5029 schools in the database in terms of the shift in the fatality exceedance curve.

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2. COMMENTS ON THE FIGURES

2.1. ***Figure 1: This plot implicitly assumes that a risk intervention can only influence the vulnerability component of risk. But risk interventions can also influence the two other components of risk, as well-detailed by the authors in Section 7.4 and as implied by equation 2. On this basis, I suggest the authors either make it clear in the caption that the figure is only one demonstration of how counterfactual risk analysis can be conducted or else they also shift hazard and exposure in the counterfactual section of the figure. Furthermore, I think the figure would be more intuitively laid out if the counterfactual was presented first, because the subtraction sign in front of the counterfactual implies that the risk benefit is negative.***

REPLY:

Thank you. We have updated Figure 1's caption to clarify the purpose of the figure. We also arranged the individual graphics to make the risk benefit a positive value. We have also renamed 'risk benefit' to 'risk reduction benefit' to further improve the clarity of the figure.

CHANGES MADE:

- **From Figure 1:**

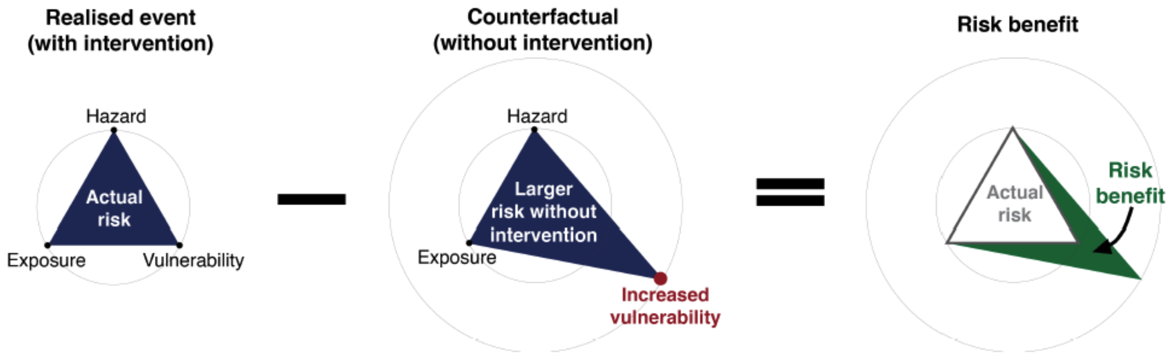


Figure 1. The concept of the counterfactual risk analysis framework for quantifying the probabilistic benefits of effective risk reduction

Changed to:

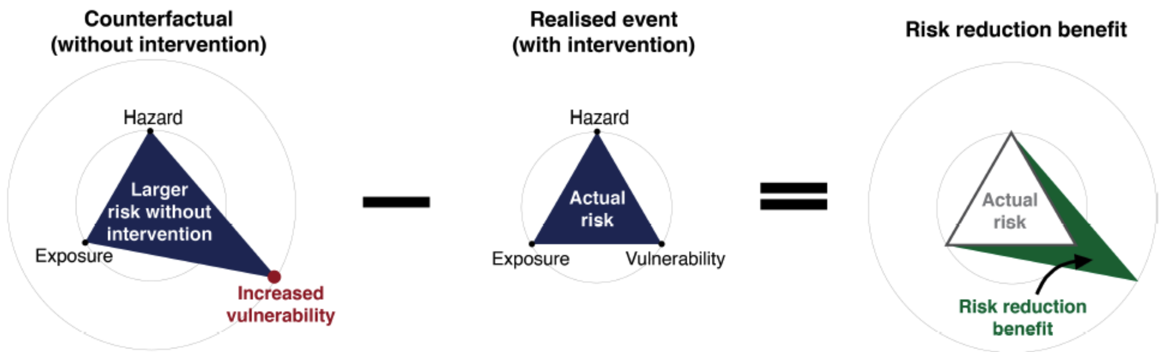


Figure 1. The concept of the counterfactual risk analysis framework for quantifying the probabilistic benefits of effective risk reduction. This graphic serves as a demonstration of the framework that is specific for a risk intervention that reduces vulnerability.

- **From Figure 1's caption:**

  Figure 1. The concept of the counterfactual risk analysis framework for quantifying the probabilistic benefits of effective risk reduction.

  Changed to:

  Figure 1. The concept of the counterfactual risk analysis framework for quantifying the probabilistic benefits of effective risk reduction. This graphic serves as a demonstration of the framework that is specific for a risk intervention that reduces vulnerability.

2.2. ***Figure 2: The violin plot of daytime occupants is an excellent visualization tool. Does this daytime occupancy encompass all days of the week or only days in which school is in session? Furthermore, what times of the day are captured by the plot? It would be useful to provide this information in the caption and in the relevant position of the text. Same comment applies to Figure 3.***

REPLY:

The violin plot shows the distribution of daytime occupancy (while school is in session) of all the 5029 schools in the database. It demonstrates the very wide distribution of school size. We have in fact removed this from the figure, as it suggests the change in occupancy throughout the day rather than the distribution of daytime occupancy for all schools in the database. We have added summary statistics in the paper text (Section 4.1). In addition, the annual expected fatality analysis accounts for the variation in occupancy based on school session hours and day of the week. We have added an explanation of this in Section 5.2.

CHANGES MADE:

- **Complete update of Figure 2 and Figure 3 (now Figure 4). Removed violin plots.**

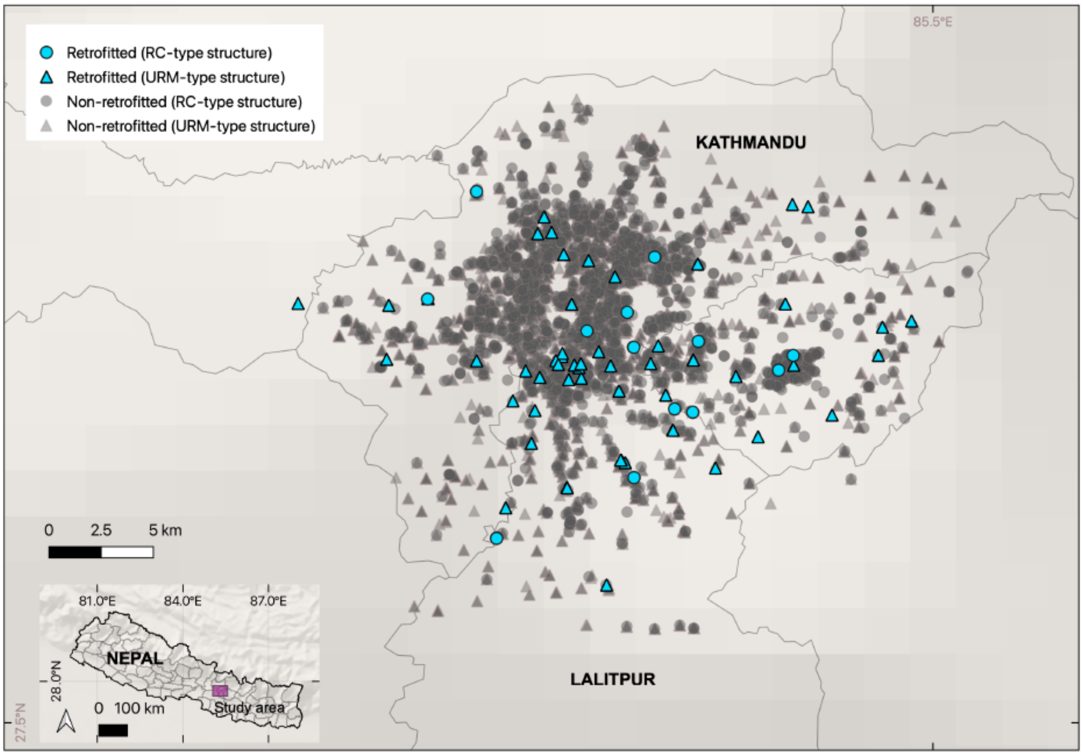


Figure 2. A map of the building database used in the analysis showing distribution of schools retrofitted and non-retrofitted as well as structure type.

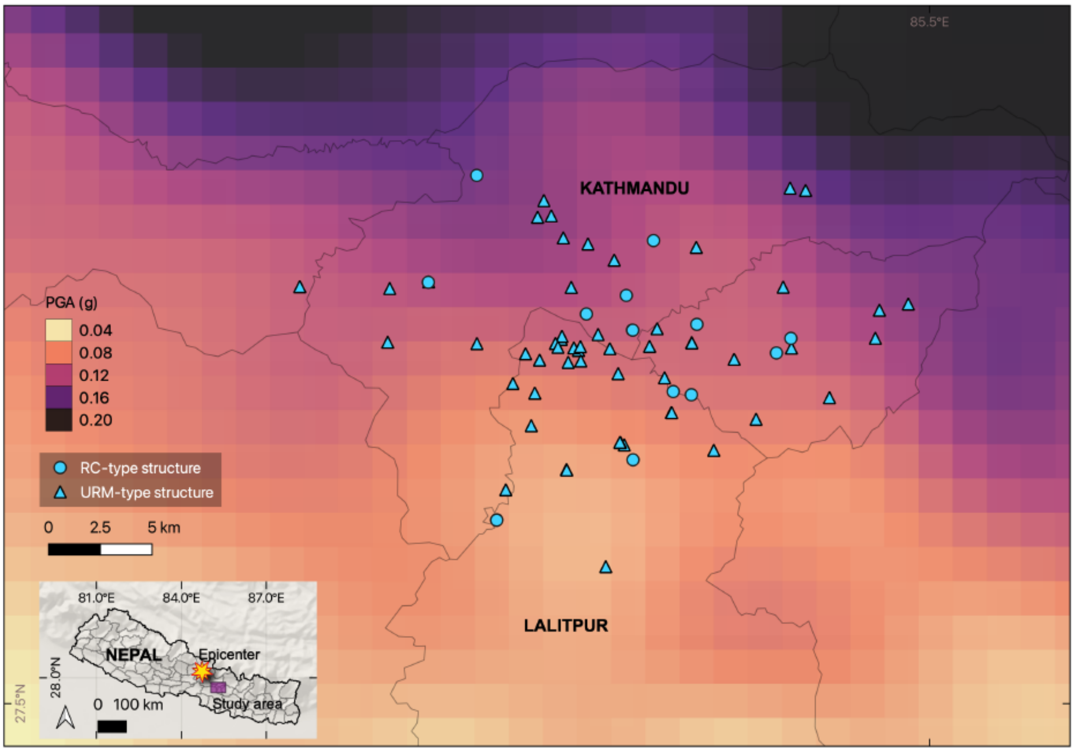


Figure 4. A map of the 70 retrofitted schools and their corresponding structure type used in the analysis described in Section 5.1. The basemap shows the hazard model developed by Chen and Wei (2019) for the 2015 Gorkha earthquake in terms of peak ground acceleration (in g-units).

- **Section 4.1, 2nd paragraph (now in Lines 159-161) - Added summary statistics of the building occupancy in the paper text**

  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.

- **Section 5.2, 3rd paragraph (now in Lines 285-290) - Added further description of analysis including occupancy**

  In the fatality calculation of each event, we incorporate the probability distribution of school building occupancy. In Nepal, schools are open and run 220 days a year, and each school day lasts for 6 hours (Government of Nepal, 2009). This means that out of the 8760 hours in a year, 1320 (15%) are school hours in Nepal. To account for this, we simulate a large number of Bernoulli trials for each event that takes a 15% probability of occurring during school hours. The resulting annual exceedance probability curves for two different retrofitting scenarios is shown in Figure 7.

2.3. ***Figure 3: Figure 3 is referred to in the text at Line 153, but the caption of Figure 3 suggests that the figure is only relevant for the 10% in 50-year analysis. I think the connection between the text and the figure needs to be made stronger here.***

REPLY:

We have restructured the paper so that all the information relevant to each case-study (including data, figures, tables) is within the same section. The new Figure 2 now shows a map of all buildings and building types in the database (relevant for both case-studies), while Figure 6 (previously Figure 3) shows a map of all the buildings along with hazard curves at three locations (since we are no longer using the 10% in 50 year hazard).

CHANGES MADE:

- **Added Figure 2**

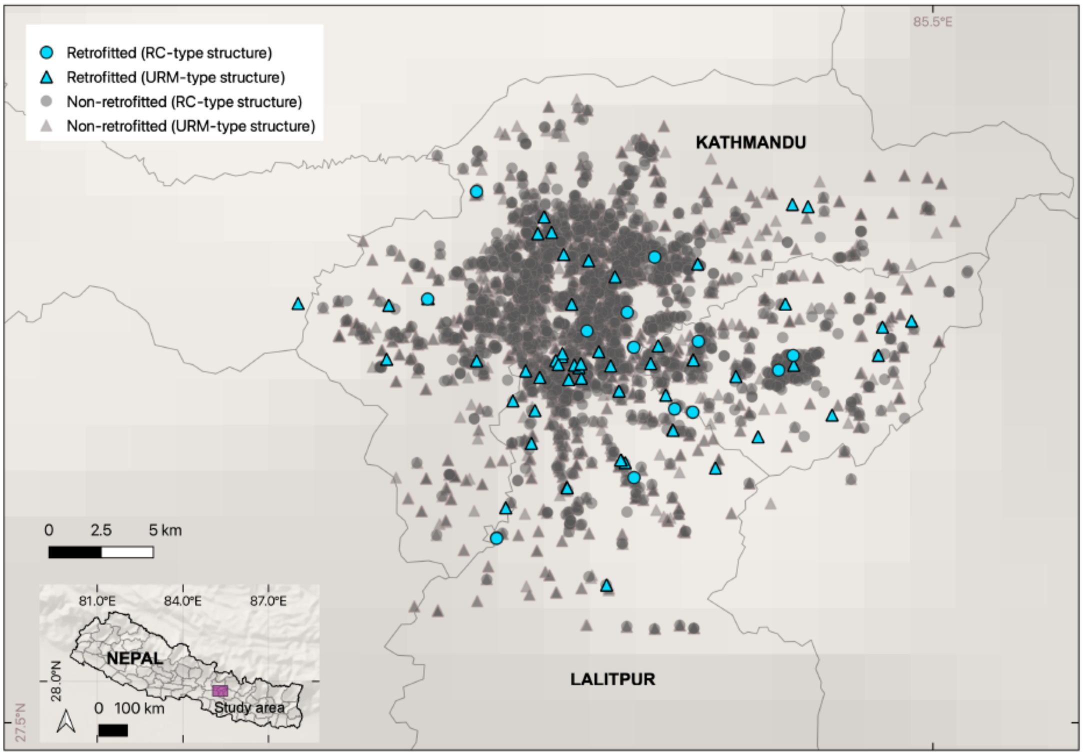


Figure 2. A map of the building database used in the analysis showing distribution of schools retrofitted and non-retrofitted as well as structure type.

- **Added Figure 6**

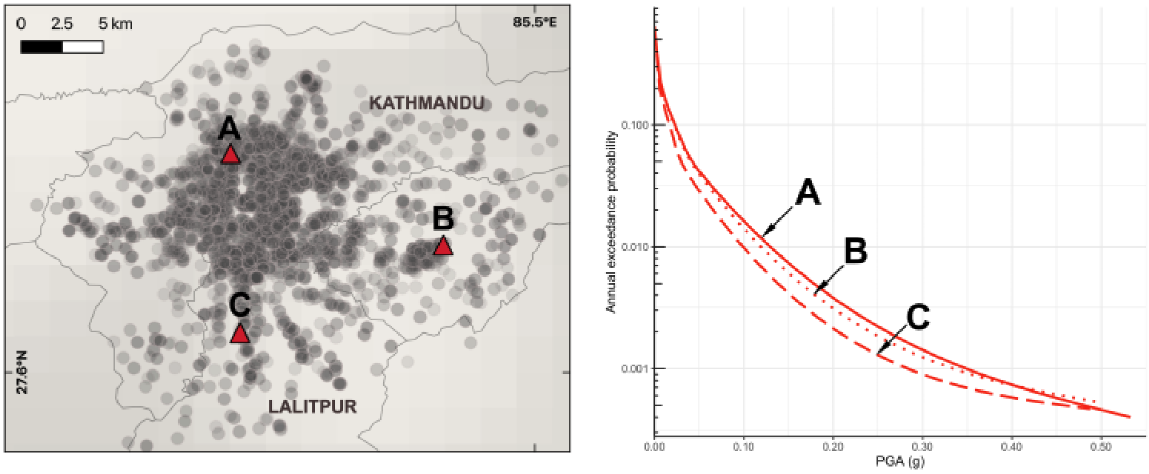


Figure 6. Hazard curves for three sample school building locations in the analysis.

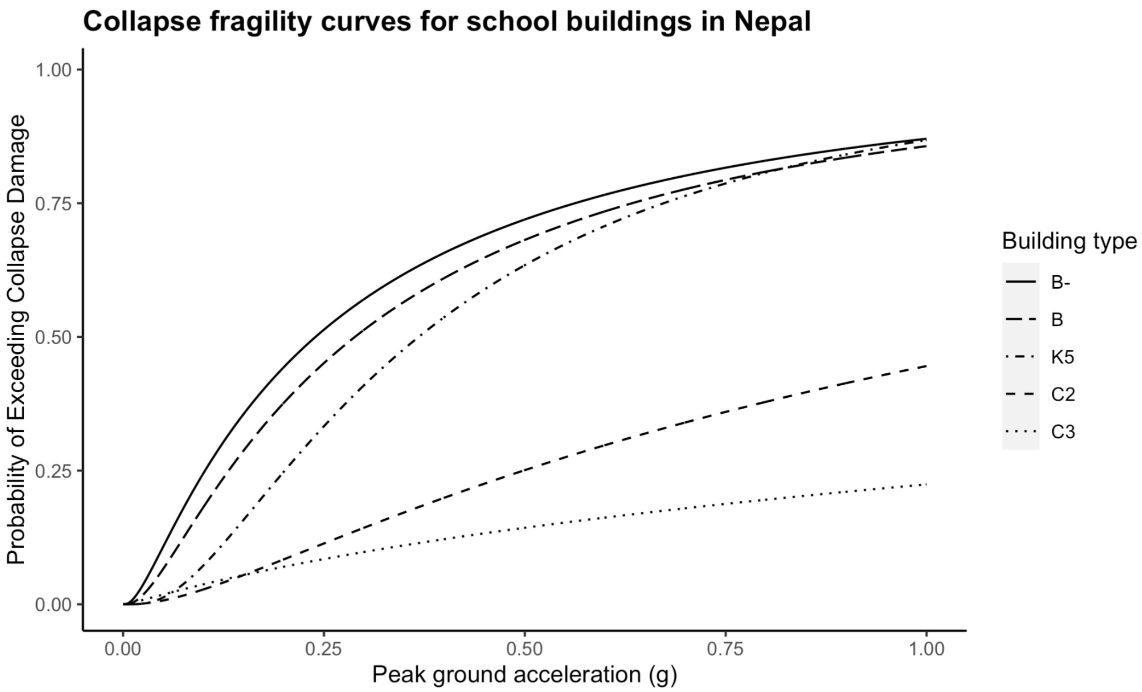
2.4. ***Figure 4: I think it would improve readability of the figure if both the x- and y-axes started at 0.***

REPLY:

Thank you for the recommendation. We have moved the plot's x- and y- origin to 0.

CHANGES MADE:

- **From Figure 4: (Plot origin not at 0)**



Changed to: (Plot origin now starts at 0), now Figure 3

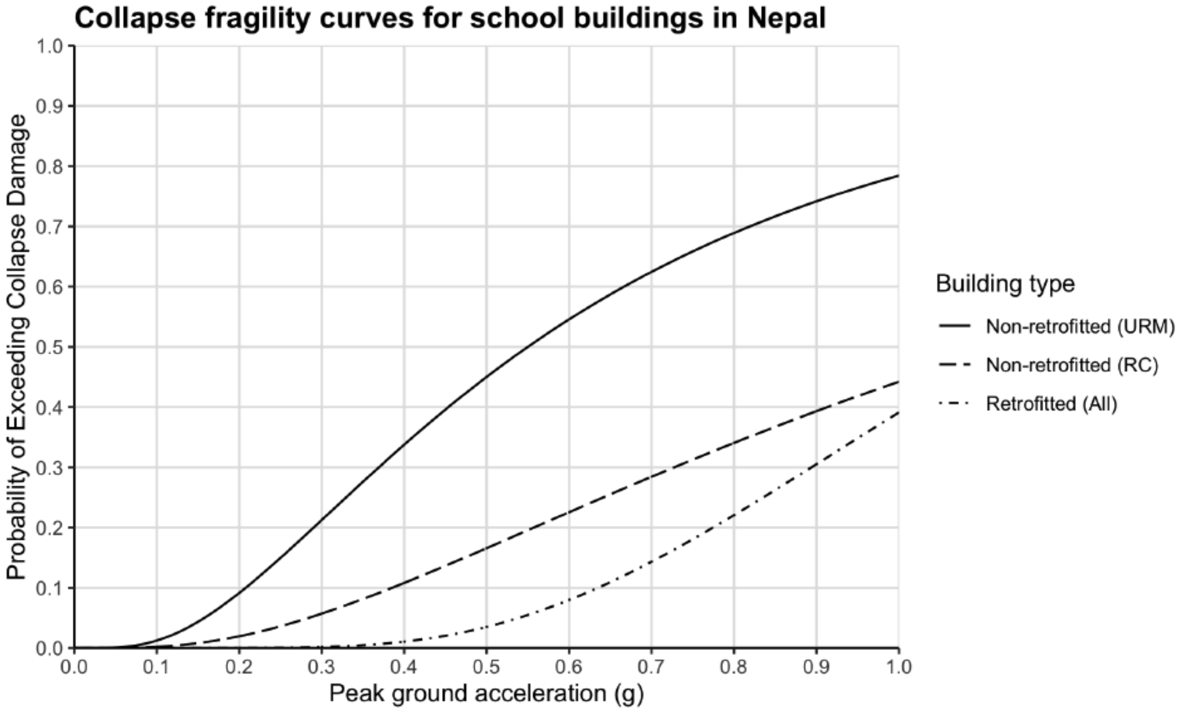


Figure 3. Collapse fragility curves adopted in the analysis.