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CELEBRATING SUCCESSFUL EARTHQUAKE RISK REDUCTION THROUGH COUNTERFACTUAL PROBABILISTIC ANALYSIS

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Abstract

While thousands of lives are saved through effective earthquake risk reduction programs, very few opportunities exist to celebrate such successes. First, if the tangible benefits of such interventions are only felt in the advent of a large earthquake, there is often a large time-delay between the intervention and its benefits. Second, large earthquakes are rarely an appropriate time for celebration since even small losses cause suffering, and the argument that losses could have been worse had it not been for a successful risk reduction program is not particularly heartening for those who have nevertheless suffered. Therefore, we are calling for a more systematic assessment of probabilistic lives saved (or avoided losses) from earthquake risk reduction actions, and celebration of these successes before risk reduction programs demonstrate their benefits.

To address this challenge, this work presents a stochastic framework to estimate the mitigation effect of large-scale earthquake risk reduction measures in terms of probabilistic lives saved. The framework implements a counterfactual approach by analysing the probabilistic consequences of an earthquake had a certain risk reduction program not been implemented beforehand. Two main applications are presented: (1) Calculating the benefits of an earthquake risk mitigation action in an actual past earthquake, and (2) calculating probabilistic benefits over the lifetime of an intervention. For the former, probabilistic realizations of earthquake casualties without the risk intervention are modelled and compared with actual losses - a powerful representation of the success of a risk intervention. For the latter, probabilistic lives saved are calculated based on the hazard model rather than an actual past event. Since future risk is dynamic, we further make use of recently developed time-dependent exposure and vulnerability models to study long-term risk.

Ultimately, this study demonstrates the use of counterfactual probabilistic risk analysis as a method for assessing probabilistic benefits of disaster risk reduction actions, so that they may be celebrated. We hope that such methods could someday lead to a "Probabilistic Lives Saved Award," newspaper headlines highlighting disaster risk reduction successes, and ultimately reinforce more investments in such earthquake risk reduction policies and actions.

Keywords: earthquake risk assessment; probabilistic analysis; counterfactuals

1. Introduction

Measuring mitigation effects is a necessary component to improve disaster outcomes. Many current methods that attempt to quantify mitigation payoffs follow some form of cost-benefit analysis [1]. However, such efforts are limited by poor data and under-reporting of losses in disaster events. Meanwhile, monitoring and evaluation of risk reduction tends to be short term, tied to project cycles and focused on the outputs of initiatives (e.g., number of people trained in disaster planning), rather than their impact (the extent to which lives, assets and livelihoods are better protected during disasters). Efforts are being undertaken at various levels to improve data, and ultimately, improve disaster outcomes. Organizations such as the United Nations office for Disaster Risk Reduction through the Sendai Framework for Disaster Risk Reduction have called to establish risk auditing procedures as a way to measure and substantially reduce losses. In the Sendai Framework, 38 indicators have been identified, such as mortality, affected persons, and economic loss [2].

Rarely is a past mitigation intervention revisited for analysis after an event has occurred, but literature suggests that celebration of past successes can benefit disaster risk reduction. For instance, inspirational visions can be key components of transformations to sustainability or resilience [3] and can help shape the very reality they forecast or explain. We propose that focusing attention on these successes offers a novel way forward because it can help sustain and amplify efforts that already exist or desires people have for the future (e.g. [4]). This attention is crucial to the achievement of large-scale transformations [5]. Such celebration/information can be used to (1) understand the key characteristics and underlying values that worked; (2) appreciate the processes and conditions that make some initiatives, rather than others, emerge, grow, spread, and have large-scale impacts beyond localities and sectors.

We call for a consistent, systematic analysis of probabilistic lives saved of successful interventions in the aftermath of major earthquakes. The routine implementation of such analysis will provide the following benefits:

- Build a collection of case studies of past interventions that feature well-articulated, specific, implemented, and measured success towards a safer, more positive future.
- Provide elements of hope amidst an overall tragic or disastrous event.
- Give a quantitative measure that focuses on celebrating benefits of intervention, independent of the investment made often over a time frame of many years, and/or many years in the past.
- Improve quality and quantity of disaster data.
- Provide incentive to invest in additional mitigation in the future.
- Provide a means for crediting government and other officials for sound decisions, even if the benefits of these decisions are not felt till much after they were taken.

To address this challenge, this work presents a stochastic framework to estimate the mitigation effect of large-scale earthquake risk reduction measures in terms of probabilistic lives saved. In Section 2, we present our framework to implement a counterfactual approach by analysing the probabilistic consequences of an earthquake, had a certain risk reduction program not been implemented beforehand. Probabilistic realizations of earthquake casualties without the risk intervention are modelled and compared with probabilistic realizations with the risk intervention (as well as with actual losses) in order to build a powerful representation of the success of a risk intervention. We exercise this framework in Section 3 on a case study of the School Earthquake Safety Program in Nepal, established in 1997 and subsequently tested during the major Gorkha Earthquake in 2015. In Section 4, we discuss the framework and case study results, and suggestions for future work. Finally, in Section 5, we present a call to action for the earthquake risk reduction community.

2. Background

2.1 Celebrating interventions through counterfactual analysis of earthquake events

To address the lack of a system for celebrating successful interventions, we present a framework for calculating *lives saved* through implemented interventions that builds on existing counterfactual risk analysis research.

Counterfactual thinking is the exercise of exploring what could have been realized in a past event. According to counterfactual research in the psychology field, downward counterfactual thinking (where one imagines an outcome worse than what actually transpired) is more challenging to engage in than upward counterfactual thinking (where one imagines a better outcome than what the past resulted in) [6]. In risk analysis, counterfactual analysis has thus far been used to provide a way to capture the range of outcomes due to highly uncertain and random variables in a small but growing variety of applications including seismic hazards [7, 8], climate change [9], terrorism and cyber security [10, 11], and volcanic eruptions [12].

In previous seismic applications, counterfactual changes on parameters such as time of day, location, or exact magnitude or rupture behavior of an earthquake have shown that randomness in any of these variables can result in a wide range of impacts [8, 13]. Understanding these ranges can help inform policy decisions moving forward or provide realistic yet extreme scenarios for training and preparedness exercises. So far in the literature, downward counterfactual risk analysis has been used primarily to point out how much worse things could have been for the purpose of insurance, preparedness, or future mitigation [e.g., 8, 12, 13]. This is the first time it is applied to quantify improvement (relative to a certain point in time) or celebrate past successes: this marks a fundamental shift in the application of downward counterfactuals in risk analysis.

This framework focuses instead on a specific downward counterfactual change to explore: the *removal* of mitigating (a preventive action or human decision) rather than a random variable such as time of day. By focusing on counterfactual human decision making, counterfactual analysis can empower us to celebrate decisions and subsequent actions, such as retrofit schemes to improve a building stock or implementing training drills and preparedness exercises. This framework is an analysis between the world as it is — with actions to be celebrated — and a counterfactual world in which those actions never came to fruition.

We present one approach for calculating counterfactual probabilistic lives saved from an existing intervention that has been put to the test in a past earthquake (Section 2.1). We also propose a second approach for calculating probabilistic lives saved for an intervention regardless of whether a major earthquake event has occurred (Section 4).

2.2 Existing counterfactual risk analysis framework

In the existing counterfactual framework [e.g., 8], the first step is to identify a factual, historic event. This event roots the rest of the analysis in reality, and provides a starting point for unraveling the story of a catastrophic counterfactual event. Second, this past event is modeled as it occurred (e.g., Eq. (1) represents the past event, where I is the impact of interest, as a function of parameters time (t), magnitude (M), etc.).

$$I = f(t, M, \ldots) \tag{1}$$

At this point, modeling assumptions and historic parameters (e.g., time of day or location) are relaxed (e.g., time is changed by quantity Δ in Eq. (2)) to reveal an event that challenges the historic record and perceived risk levels -- when an event that is more consequential than the factual event is found (e.g., $I_{counterfactual} > I$), this is accepted as a downward counterfactual event. The last step may be repeated over multiple variables or varying increments.

$$I_{counterfactual} = f(t + \Delta, M, \ldots) \tag{2}$$

2.3 Proposed application of counterfactual risk analysis framework to calculate lives saved

Building collapses are the main contributor to total earthquake fatalities worldwide [14], thus this case study is focused on quantifying the benefits of interventions aimed to save lives from earthquake-induced building collapse.

Using the counterfactual risk analysis framework, we use an actual earthquake event as a starting point and go towards a more consequential realization – a scenario where the implemented risk intervention did not happen. Assuming that the risk intervention had been beneficial, removing the effects of the intervention becomes the driving element which challenges the historic risk levels, thus driving a downward counterfactual event.

To be able to quantify the benefits of this risk intervention, the first step is to understand the risk parameters of each of the two scenarios: (1) the actual past earthquake event on a site with implemented risk intervention and (2) the counterfactual scenario (Fig. 1). The risk parameters are composed of three main components: (A) the hazard intensity at the time of event, (B) the exposure which can be described by the building stock composition with associated occupancy, and (C) the vulnerability represented by structure-specific collapse fragility functions defined in terms of the units of hazard intensity.

Earthquake risk interventions target either the exposure or vulnerability. Since the occurrence and intensity of earthquake events are beyond our control, the hazard component remains unchanged. Risk interventions such as limiting urban development in hazardous areas reduce exposure, and improved construction practices make the built environment less vulnerable. Therefore, part of the process is identifying which risk component the risk intervention affects and to what extent.

Three common and distinct approaches are used for estimating earthquake casualties, namely empirical, analytical, and hybrid (or semi-empirical) approaches [15]. Since earthquake events almost always have a reliable count of casualties sometime after the event, this casualty record can be compared to the output of any casualty model simulating the actual event. This presents an opportunity to communicate how much uncertainty the model brings when it is used to estimate casualty for another scenario.

The selected casualty estimation approach utilises the hazard intensity and structure-specific fragility data to estimate building collapse. This collapse estimate is then integrated with occupancy rates associated with each building category and a fatality rate given structural collapse. The approach is implemented to the counterfactual scenario to get a distribution of probabilistic lives lost. By comparing the counterfactual lives lost to actual number of casualties, this procedure lets us estimate the probabilistic lives saved by the risk intervention. In the next section, we demonstrate this approach to quantify benefits of a school earthquake safety intervention in the 2015 Gorkha Earthquake in Nepal.

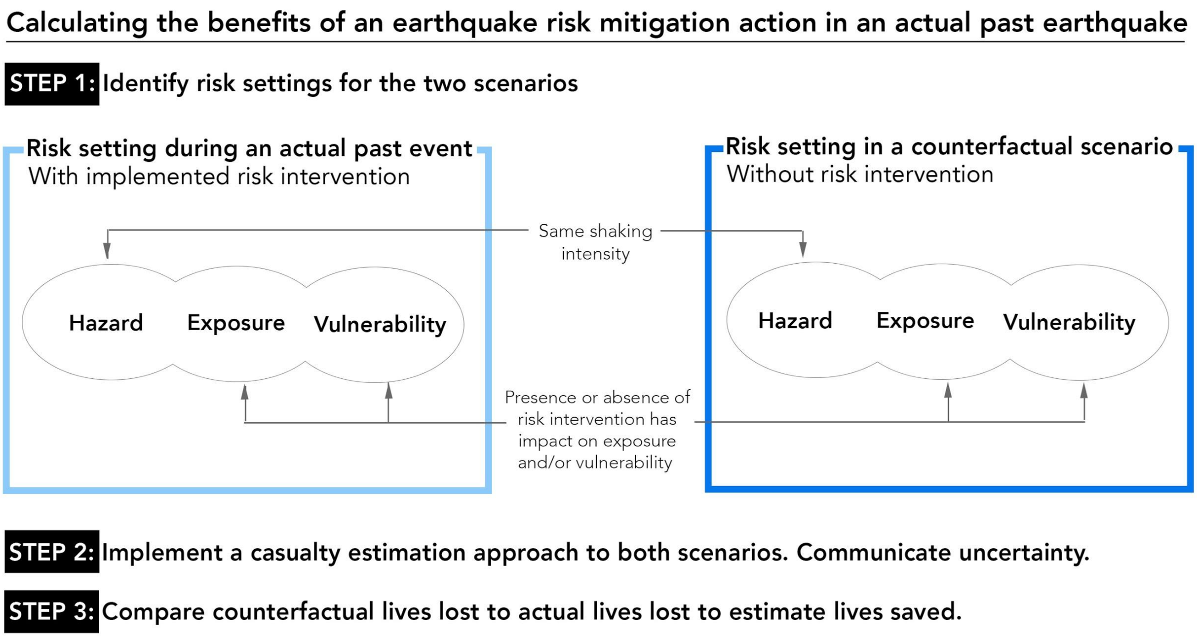

Fig. 1 – Procedural framework for calculating the benefits of an earthquake risk mitigation action in an actual past earthquake in terms of lives saved. Details of each step discussed in Section 2.3

3. Case study: Celebrating the Nepal Schools Retrofit

3.1. Seismic risk in Nepal and the 2015 Ghorka Earthquake

Nepal is subject to high seismic activity, and according to the Bureau of Crisis Prevention and Recovery of the United Nations Development Programme, Nepal is the 11th most vulnerable country in the world when ranked for seismic risk [16]. Kathmandu Valley, the most populated and developed place in Nepal, is considered the world's most at-risk urban area [17]. The high seismic hazard is compounded by earthquake-prone building construction often in remote, rural locations. Additionally, many schools and government buildings have not been designed in accordance with the most recent seismic design codes [18].

On Saturday, April 25, 2015 at 11:56am local time, a M7.8 earthquake occurred 3km east of Khudi, Nepal, about 80km northwest of Kathmandu, the capital of Nepal [19]. This is often referred to as the Gorkha earthquake. It was also followed by numerous aftershocks. According to the Nepali Government Post-Disaster Needs Assessment report, the Ghorka earthquake resulted in 8,790 casualties, 22,300 injuries, and over 8 million impacted persons (about one-third of the population of Nepal) in 31 districts [20]. Fourteen of these districts were declared "crisis-hit" [20]. 8,242 public schools were affected by the earthquake [20]. Specifically, 25,134 classrooms were fully destroyed; 22,097 additional classrooms were partially damaged [20]. The total direct economic loss is estimated at 7 billion USD. The effects of the earthquake exacerbated inequalities in Nepali society. Poorer, rural areas were more affected than towns and cities; more women and girls were affected than men and boys, in part because of gender roles that tend to assign indoor work to women [21, 22].

3.2. Description of the Seismic Intervention

In this work, we illustrate one way to celebrate and calculate lives saved by highlighting the timely intervention in Nepal of the School Earthquake Safety Program (SESP), initiated in 1997 by the National Society for Earthquake Technology (NSET) and continued through the Nepal Safer Schools Projects (NSSP) by the Department of Education [23]. Through structural assessment of schools in the Kathmandu Valley, NSET reported [24] to have found that a majority of public schools were built via typical Nepali construction techniques, including earthquake-prone materials such as adobe, stone rubble in mud mortar, and brick in mud mortar. This is particularly relevant because public schools in Nepal are centers of social and cultural life. In post-disaster times, public school buildings can serve as emergency shelters, and playgrounds are often used for shelter tents and emergency medical services [21]. Furthermore, psychological impacts to members of the community from the collapse of a school building can be particularly intense [21]. Returning to school also provides a sense of normalcy after a disaster in recovery [21].

The primary aim of this program was to raise earthquake safety awareness in Nepal through outreach and capacity building amongst teachers, students, and parents, and to strengthen school buildings. Its three primary activities included:

1. Outreach and training of local masons
2. Training of teachers, parents, and students on earthquake preparedness and preparedness planning
3. Seismic retrofit or earthquake-resistant reconstruction of public-school buildings, with the engagement of local masons and assistance of NSET to implement construction. [25]

The first seismic retrofitted school was completed in 1999. As of April 2015, at the time of the Gorkha earthquake, NSET reported to have retrofitted 300 schools, with 160 of those schools in affected districts (78 specifically in Kathmandu). Following the Gorkha earthquake, among the schools that had been retrofitted in the affected districts, 125 reported no damage, with 35 reporting hairline cracks on plaster. None of the retrofitted schools collapsed or needed major repairs [23].

In a document published by USAID [26] after the April 2015 earthquake, the headline reads: "Success story: School Earthquake Safety Program Saves Lives in Nepal." The numbers and information that follow emphasize the number of schools and classrooms that had been retrofitted as a result of the program; an estimation for the number of lives saved, though prominent in the title, is absent from the document.

3.3 Datasets for risk parameter identification at the time of the earthquake

Retrofitting buildings directly impacts the physical vulnerability of the built environment. Thus, to compare the lives lost from the actual event and a counterfactual scenario where retrofitting of the school buildings was not done, we followed the procedure in Figure 1, and used the following data:

1. Peak ground accelerations experienced by each school building.
   Data on shaking intensity is derived from ShakeMap of the 2015 Gorkha Earthquake, created by United States Geological Survey (USGS) [27]. The USGS Global ShakeMap system produces shaking hazard maps focused on ground shaking (e.g. peak accelerations, Modified Mercalli intensity) accounting for local rock and soil conditions [28].

2. Database of school buildings in Kathmandu Valley

   For demonstration purposes, we used surveyed data of 5143 school buildings in the Kathmandu Valley, which is only a subset of all school buildings affected by the Nepal earthquake. The dataset came from the Open Data for Resilience Initiative (OpenDRI) in partnership with the Government of Nepal in 2012, along with support from Kathmandu Living Lab to understand the seismic risk of Nepal [29]. Of these schools, 70 were retrofitted for earthquake resilience under the "Nepal Safer Schools Project". Note that this is also a subset of the 78 retrofitted schools surveyed by NSET in Kathmandu [23]. From the Kathmandu Valley school building database, we extracted the 70 retrofitted schools, and used the key attributes of each school building shown in Table 1 for the purpose of this work.

Table 1 – Key attributes for each school in the database (Data source: [29])

Building attribute	**Description**
Coordinates	Point location of school in terms of latitude and longitude
Usage	Buildings are tagged either as schools, universities, college, or kindergarten
Number of occupants	Observed occupants for each building during a typical school day. During the day, all schools under study have a combined capacity of 14,144 people. Occupancy numbers range from 3 to 424 with an average of 202.
Number of floors	Of the 70 school buildings, 65 have 1-3 floors, and the rest have 3-5 floors.
Structure type	Buildings were categorized as: Brick wall (either in cement mortar, mud mortar, or mixed) and reinforced concrete frame (either engineered or non-engineered).

3. Fragility curves

   To estimate the vulnerability of the school buildings to collapse before they were retrofitted – the counterfactual case scenario – fragility curves were adopted from a study by Japan International Cooperation Agency (JICA) on earthquake mitigation in Kathmandu Valley before the Gorkha Earthquake [30]. Each building typology found in the school dataset from OpenDRI [29] was matched to the fragility curve corresponding to the collapse damage state of that building typology without seismic reinforcement. We use these curves (Fig. 2a) for the counterfactual case scenario had all the 70 school buildings were not retrofitted.

   On the other hand, to represent the vulnerability of the school buildings as it occurred in reality – all school buildings were retrofitted – we again utilise information from JICA [30]. In the absence of fragility curves for the retrofitted building typologies, we assume that retrofitted buildings will be associated with a collapse fragility curve corresponding to a specially designed reinforced concrete (RC) building (Building type C3 in Table 2 and Fig. 2b). With this simplifying assumption for the non-retrofitted case, we apply this fragility curve (Fig. 2b) to all 70 buildings to represent their vulnerability after they were retrofitted.

   The collapse fragility curves describe the probability of collapse given an intensity measure (*IM*), by following a generalized linear model formulation as described by Eq. (3). The descriptions of the building typologies as well as parameters α and β are summarized in Table 2.

$$P(Collapse|IM) = \Phi(\alpha + \beta log(IM)) \quad (3)$$

Table 2 – Building typologies of the 70 schools and fragility curve parameters. (Data source: [29, 30])

Building type	Description	Structural state of building	Fragility curve parameters	
			α	β
B	Buildings with mud mortar, ordinary brick, large blocks, natural dressed stone with height up to 1 storey, or with cement mortar in brick masonry and height up to 3 storeys.	Un-retrofitted	1.066	0.858
B-	B-type rural buildings with traditional materials and height up to three storeys, or with cement mortar in brick masonry and height up to five storeys	Un-retrofitted	1.129	0.790
C2	RC buildings designed for normal load only, or mason designed 3 storey RC buildings	Un-retrofitted	-0.137	0.772
K5	Mason-designed 5 storey RC buildings	Un-retrofitted	1.118	1.246
C3	Specially designed RC buildings	Retrofitted	-0.758	0.445

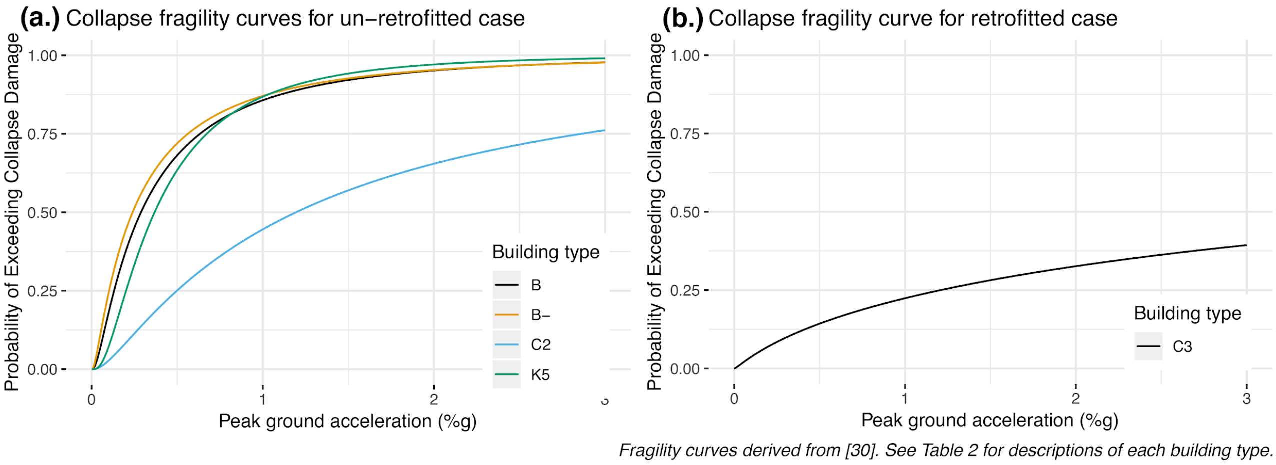

Fig. 2 – Collapse fragility curves corresponding to the building typologies in the school database at their un-retrofitted state (left) were adopted from a study on earthquake mitigation in Kathmandu Valley [30]. In this work, we assumed that after retrofits, buildings will be associated with a collapse fragility curve corresponding to a specially designed RC building (right) with parameters derived from JICA's study [30]. Descriptions of each building type and fragility curve parameters shown in Table 2.

3.4 Methods

Here we apply a simple probabilistic approach to estimate building collapse for two scenarios: (1) actual case where all 70 school buildings of interest were retrofitted, and (2) a counterfactual case where the school buildings are not retrofitted. For each school point location, PGA values were extracted from ShakeMap. Accounting for the building typology and whether the school is a single-story or a multi-story, these PGA values were matched with the corresponding probability of exceeding a collapse damage state using the fragility curves in Fig. 2. Upon obtaining a value of probability of exceedance of collapse for each building, a Monte Carlo approach is then implemented. For the portfolio of all school buildings, we generated 30,000 realizations of Bernoulli trials based on exceedance probabilities defined from their respective fragility curves and the PGA at their location. To obtain a distribution of probabilistic fatalities, the total number of occupants on a typical school day for the collapsed buildings was multiplied by a 20% fatality rate consistent with NSET's calculations for masonry and RC buildings [31, 24]. For the first scenario, we use fragility curves corresponding to a retrofitted building, whereas for the second scenario, we assume that the whole building stock consists of un-retrofitted buildings and thus use associated fragility curves for buildings that are not retrofitted.

3.5 Results

This section presents results for our case study celebrating the School Earthquake Safety Program in Nepal, which began in 1997 and was put to the test in the 2015 Gorkha Earthquake. Prior to the earthquake, 300 schools had been retrofitted through this program; of those 300 retrofitted schools, 160 were in the Kathmandu Valley, and 78 of these schools are specifically in the Kathmandu district. Of the 78 schools, our analysis includes 70 of the retrofitted schools based on available data.

After we generate 30,000 realizations of Bernoulli trials, we determine the distributions of possible number of collapsed buildings in the retrofitted case (Fig. 3 green histogram), and the counterfactual, non-retrofitted case (Fig. 3 red histogram). In the case of the retrofitted case, 7 out of the 70 school buildings on average were predicted to collapse (10% collapse rate), whereas for the counterfactual case, 33 out of the 70 school buildings were predicted to collapse on average (47% collapse rate). Fig. 4 shows the estimated number of fatalities after multiplying the distribution of collapsed buildings to the corresponding number of occupants of each building on a typical school day to a 20% fatality rate recommended by NSET [24]. Based on the counterfactual analysis of this event *without* the SESP intervention, we estimate that the lives of approximately 1014 students and teachers were saved in Kathmandu by the retrofit of just these 70 schools in this single event. This was obtained by comparing the estimated mean casualties for the real retrofitted case (289) and the much higher mean casualty estimate for the counterfactual case (1303). This exact value is not to be taken as conclusive, rather a demonstration of how the framework works. It is important to note the assumptions and limitations associated with this estimate which are discussed in the next section.

4. Discussion

Counterfactual probabilistic risk analysis can assess probabilistic benefits of disaster risk reduction actions, so that they may be celebrated. This framework for calculating the counterfactual probabilistic lives saved pushes the analysis beyond exploring changes in random variables. Counterfactual change of time on the scales of hours or days, typical of the random variable changes have been explored in the counterfactual risk analysis literature.

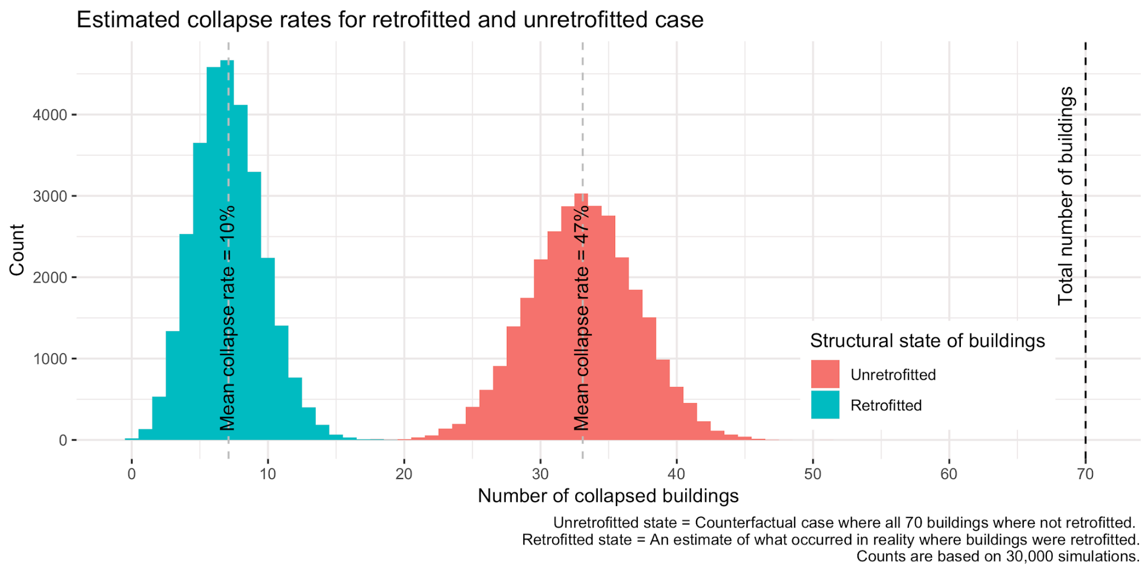

Fig. 3 – Estimated collapse rates for retrofitted and non-retrofitted cases.

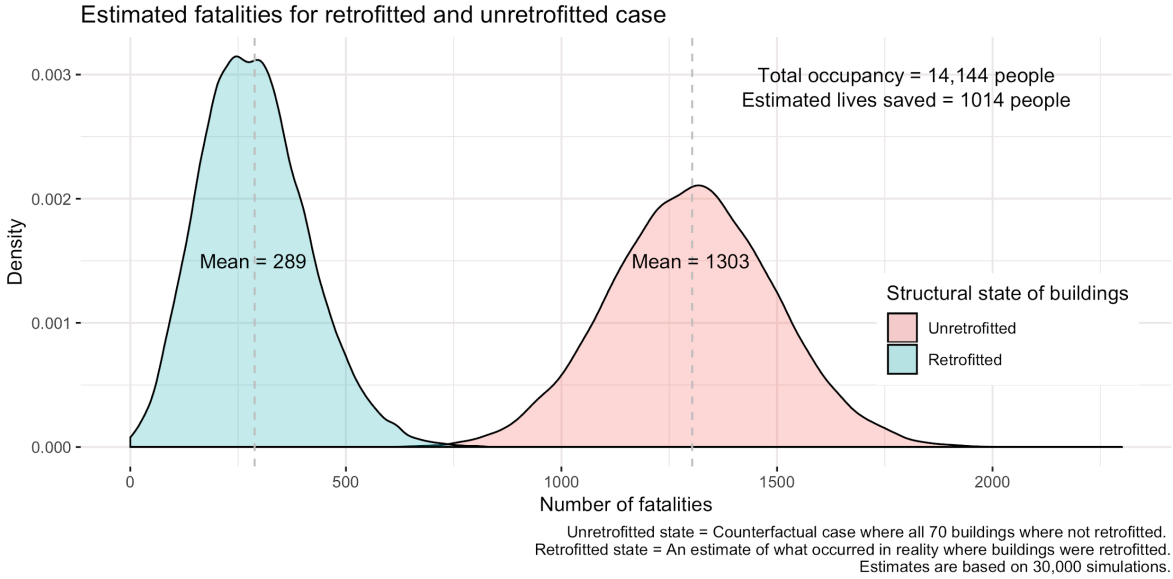

Fig. 4 – Estimated fatalities for retrofitted and non-retrofitted cases.

For example, despite the already significant loss of life, the Post Disaster Needs Assessment [32] notes that the time and day of the main earthquake likely saved thousands of lives, considering that the event occurred on a Saturday, the one day of the week when schools are not in session in Nepal. When considering that nearly 7,000 schools were completely or significantly damaged, the death toll specifically of young people could have been much higher than the reported 200 deaths of students and teachers in school buildings across Nepal [33].

Instead, the analysis in this paper assesses the counterfactual changes of deliberate human actions that affect seismic risk in order to celebrate the probabilistic lives saved by an intervention when encountering a real earthquake. With this, we can quantify the claims made by organizations and newspapers that such an action saved lives (for example, the USAID headline "Success story: School Earthquake Safety Program Saves Lives in Nepal" [26] mentioned in Section 3.2.

Celebrating benefits of SESP intervention using counterfactual analysis serves as a proof of concept rather than prediction of actual lives saved. This case study is presented as a way to illustrate the proposed framework to celebrate probabilistic lives saved in the event of a major earthquake. The current calculations for this case study have a number of limitations and assumptions that should be noted for future work:

- Exclusion of fatalities from partially collapsed buildings (eg., NSET's survey on seismic vulnerability of school buildings in Kathmandu Valley suggests including 10% fatality rate from heavily damaged buildings [24])
- Generalization of retrofitted buildings' vulnerability to a single fragility curve
- Dataset for schools not complete (contains 70 out of the 78 schools in Kathmandu)
- Does not account for uncertainty in PGA at each site
- Does not account for distribution of occupancy rates between times of day (school hours vs. non-school hours) and days of the week (weekly holiday vs. school day)

It should also be noted that in modeling fatalities *with* the intervention (e.g., recreating the past event), we modeled much higher fatalities (mean of 289) than what was observed in reality. Across Nepal, there were 200 deaths of students and teachers in collapsed school buildings [33], wherein Kathmandu was much less damaged than expected. Although there was no actual count of the fatalities specifically associated with the

70 schools under study, it was reported that none of the retrofitted schools collapsed after the earthquake [23]. High levels of collapse or fatalities in the simulated results is likely due to inaccurate shaking intensity measurements.

Given these limitations, the exact number of lives saved is not conclusive. However, the framework to calculate the lives saved is illustrated by this case study, and our preliminary analysis provides a step towards quantifying the benefits of life-saving interventions, and celebrating them accordingly.

By providing a framework to quantify the probabilistic lives saved, we can provide measurable markers of success for past interventions. The current example measures success based on a counterfactual exploration of an actual past event. In the absence of an actual earthquake event as scenario of calculation, the framework could be extended to calculate probabilistic lives saved based on a probabilistic hazard model rather than an actual past event.

5. Call to action

Effective earthquake risk reduction programs have saved, and/or will continue to save, thousands of lives worldwide. Unfortunately, there are few opportunities to celebrate these successes, as such benefits from interventions are usually marked by what did not happen (e.g., a building that does not collapse). In addition, the benefits of seismic risk reduction interventions often arise only many years after their implementation. Furthermore, large earthquakes are rarely an appropriate time for celebration since any loss of life causes pain to individuals and the community, and the argument that losses could have been worse had it not been for a successful risk reduction program is not particularly heartening for those who have nevertheless suffered.

Imagine a future where there might exist a "Probabilistic Lives Saved Award" or “Earthquake Risk Reduction Award” celebrated each year, and awarded in two categories: one for an event that occured in the previous year (ie., analogous to the calculation in this study), and one for a new intervention that has just been implemented (ie., the proposed future work). We submit this work as a first step towards systematic recognition and celebration of successful DRR efforts within the earthquake engineering and seismic risk community.

This study demonstrates the use of counterfactual probabilistic risk analysis as a method for assessing probabilistic benefits of disaster risk reduction actions so that they may be *celebrated*. In doing so, we are calling for a more systematic assessment of probabilistic lives saved (or avoided losses) from earthquake risk reduction actions in order to enable the celebration of these successes, particularly after such programs have been through a major earthquake event. This is a concrete way to lift up the iterative, long-term, dedicated actions required of most seismic interventions. Furthermore, by highlighting successful interventions, we can continue to build the case for additional interventions in more communities world-wide.

We hope this shift in use of counterfactual thinking and risk analysis can encourage the opportunities for future newspaper headlines highlighting disaster risk reduction successes, and reinforce more investments and institutional support in such earthquake risk reduction policies and actions.

6. Acknowledgements

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