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# Evaluating HCLP Risk: Economic Loss Modelling for New Zealand's Earthquake-Prone Buildings System

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## ABSTRACT

This paper presents recently completed national cost–benefit analysis (CBA) for New Zealand's earthquake-prone building (EPB) system. The risk framework integrates displacement-based fragility curves and the 2022 National Seismic Hazard Model to evaluate seismic strengthening options for the 5,500 EPB buildings - from no action and targeted measures to the current regulatory minimum 34%NBS and up to 67%NBS. We compared a pseudo-scenario (deterministic) approach with a traditional CBA (probabilistic) approach, noting that the probabilistic lens alone tells only half the story, whereas using both provides complementary insights. Results indicate that traditional CBA often tends to support inaction on seismic resilience; the deterministic approach reveals new insights into high-consequence, low-probability (HCLP) earthquake scenarios, especially in lower-hazard zones. The findings of the study therefore recommend an approach which extends beyond traditional CBA to include pseudo-scenario analysis and incorporate other criteria such as socio-economic consequences and recovery potential in decision-making and framework reviews.

## 1 INTRODUCTION

### 1.1 Background

In New Zealand, the Building (Earthquake-prone Buildings) Amendment Act 2016 established the current earthquake-prone building system which is designed to manage seismic risk associated with existing buildings over time to protect people from the life-safety risk posed in earthquakes from the most vulnerable buildings in New Zealand.

In June 2024, the Ministry of Business, Innovation and Employment (MBIE) commenced a review of the management of seismic risk in earthquake-prone buildings in New Zealand. Building owners, as territorial authorities and officials raised concerns about the feasibility of meeting and enforcing the current earthquake-prone building deadlines. The purpose of the MBIE review is to understand whether seismic risk

in existing buildings is being managed in a way that is workable, equitable, financially sustainable, and proportionate. The recently completed review indicated that cost have led to less-than-complete compliance, many EPB not strengthened, and, in some cases, demolition by neglect. As a result, many buildings remain unstrengthened, which risks falling short of the intended objective of progressively reducing seismic risk over time. These challenges suggest that a reset of current risk settings may be required to achieve a more sustainable and effective system.

In response to the review, the government has initiated several studies, including an economic analysis and an evaluation of the risk implications of New Zealand's earthquake-prone building (EPB) system. This paper presents the findings of the economic analysis. The economic analysis employed a pseudo scenario, annual probability of exceedance (APoE) based approach and a traditional CBA approach to evaluate the costs and benefits of seismic strengthening. The analysis recognises the significant immediate and long-term impacts of low-likelihood, high-consequence strong earthquake events. The study focuses on comparisons between the status quo and retrofit options to improve life safety performance.

An initial focus was given to six locations: Auckland, Whanganui, Feilding, Wellington, Christchurch and Dunedin to give a spread of town/city size, variation in seismicity and geographical location. As a follow on scope of work the study was expanded to include the rest of the country. The focus of this paper is on the initial study results of the six centres.

These economic studies were intended to inform understanding of the risks associated with the status quo and also various options for changes to the EPB system.

## **1.2 Definition of the two methods adopted**

### **1.2.1 Pseudo-scenario (APoE) based approach**

APoE benefit cost ratios do not discount benefits over time and assumes the scenarios occur tomorrow which is of interest when dealing with low probability high consequence events. This analysis resulted in larger ratios that are not comparable to traditional CBAs. However, it offers useful insights into examining different levels of severity of the shaking and consequences. This approach is referred to as pseudo-scenario as they do not represent realistic earthquake scenarios.

### **1.2.2 Traditional CBA**

The traditional cost-benefit ratio is calculated as the sum of the benefits of six APoE shaking levels, annualised and weighted by their probability rates. These values are entered for every year and then discounted using the elected discount rate.

## **1.3 Other methods**

We acknowledge a number of other methods that have been employed internationally to model low-probability, high-consequence events. This study is a single-hazard (earthquake) assessment and is specifically not a scenario-based simulation. Scenario-based simulations traditionally focus on single hazards or deterministic chains. Previous papers have argued that such approaches underestimate extremes, because they ignore hazard interdependences and dynamic vulnerability and exposure.

Low-probability-high-consequence events underscore the limitations when relying solely on severe, but plausible scenarios for risk practitioners and policy makers. Noting that some risks are mitigated through preventative measures, while others are neglected due to perceived futility or low likelihood. This underscores the need for structured approaches that systematically address cascading impacts and vulnerabilities across systems.

This study addresses the perceived short fall of only focusing on extreme events and models a range of earthquake magnitude scenarios which can be compared across both the pseudo-scenario and traditional CBA methods.

1.4 Key takeaways of the economic analysis

- Improving high vulnerability buildings yields high life-safety benefits.
- Dunedin shows elevated risk despite fewer EPBs than Christchurch due to both an increased hazard and high vulnerability.
- Traditional CBA tends to support inaction in seismic resilience, underplaying intangible benefits such as reducing fatalities in low-probability, high-consequence events, as shown for Auckland.
- A step change of losses in low seismicity areas for the very rare, high return period events (1-in-2500).
- For Wellington, the study showed that losses do not increase with an increase in shaking levels (higher return periods), suggesting that many EPBs may not have survived lower shaking. As the study was based on the 2022 seismic hazard update, a retrofit level above 34%NBS (per NZS 1170.5:2004 loadings) was indicated for Wellington to obtain sufficient benefit under the increased hazard.

2 METHODOLOGY

The loss estimation considers risk as the intersection of three factors: hazard, exposure and vulnerability.

- Hazard is based on the expected ground shaking as indicated by the latest NSHM 2022.
- Exposure is based on the estimated number of people inside and outside buildings, differentiated for both smaller towns and larger cities.
- Seismic vulnerability of the different types of buildings and the expected damage predicted by the assigned fragility functions.

This is shown diagrammatically in Figure 1 below.

The first step was to develop a comprehensive inventory of EPBs and building types, followed by creating fragility functions, estimating retrofit costs for 34%NBS and 67%NBS compliance, and developing fragility and consequence models to evaluate damage as well as people and economic impacts. These components were then integrated into a dashboard to support pseudo-scenario-based cost-benefit analyses with sensitivity checks. The pseudo-scenario approach is completed prior to undertaking the traditional CBA.

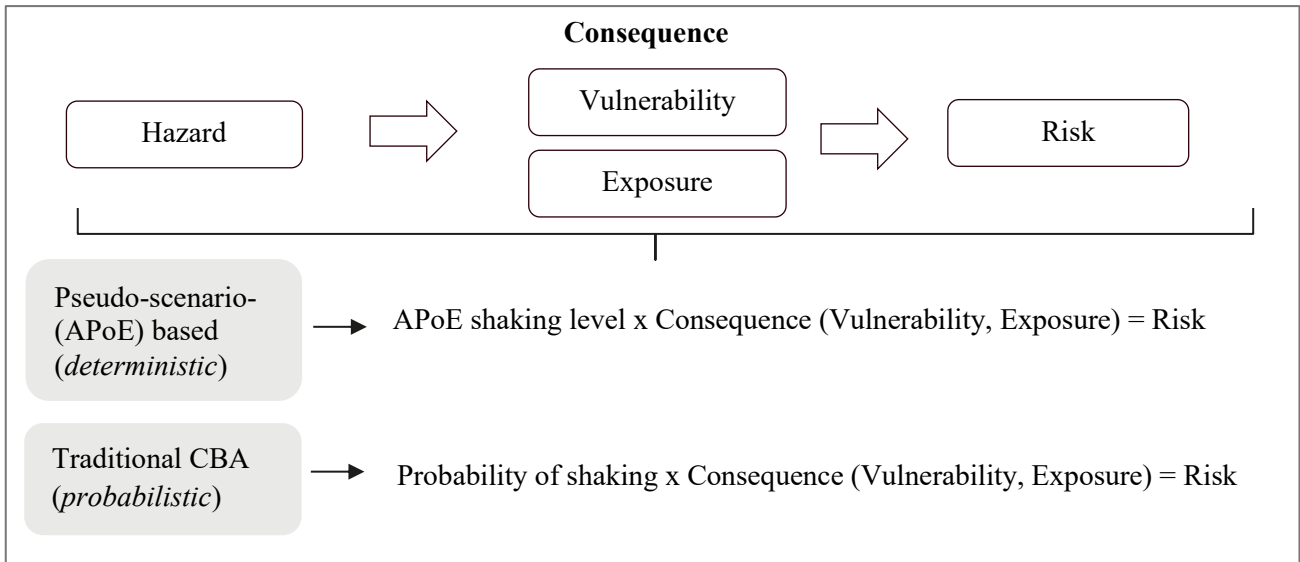


Figure 1: Risk assessment methodology of EPB's system

## 2.1 Inventory and Vulnerability

The building inventory included in the study comprised approximately 2,570 EPBs (later expanded to a national stock of approximately 5,500), compiled from the national EPB register and territorial authority records from the six representative centres. The buildings were then categorised into one of ten groups, representing a reasonable distribution of material attributes and their primary lateral load-resisting system. Each building type accounts for between 5% and 20% of the total number of buildings. The list of ten types was established through a review of the building inventory to identify trends in the data, an examination of relevant research papers on typical structural vulnerabilities, and engineering experience with these buildings. The distribution of building types for the six centres is shown in Figure 2 below.

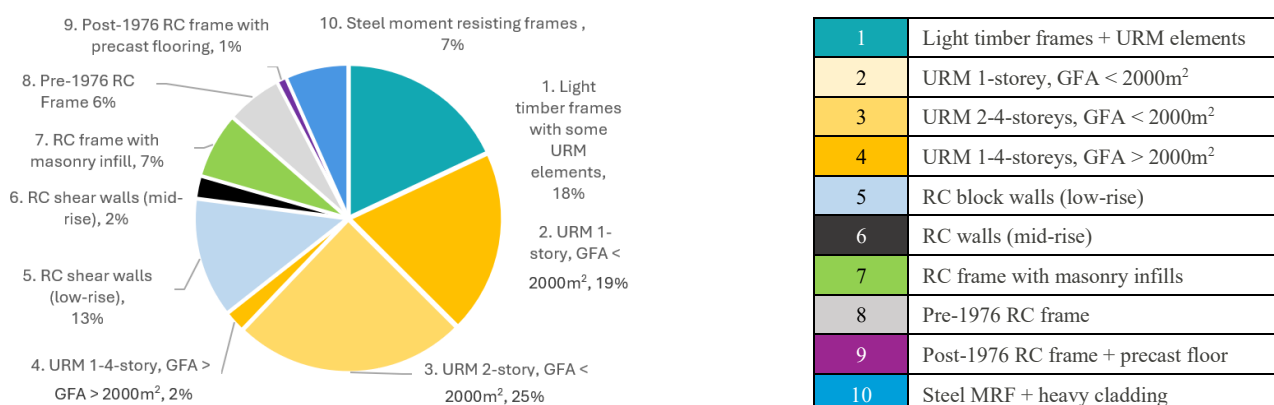


Figure 2: Distribution of building types over all six centres

The inventory is predominantly unreinforced masonry (URM) and reinforced concrete (RC) buildings. URM buildings account for more than 50% of the EPB register, with vulnerabilities including façade and parapet instability (elevating pedestrian risk), weak out-of-plane wall behaviour, and poor diaphragm connectivity.

The second largest cohort is RC buildings, with typical vulnerabilities including inadequate detailing to suppress brittle failure mechanisms, displacement incompatibilities, diaphragms and plan and vertical irregularities.

The remainder of the building stock are low-rise light-timber frame or steel frame buildings and are generally considered less vulnerable. Some of these buildings appear to be on the current EPB register due to the vulnerability of heavy parts.

The lists of EPB buildings are not necessarily complete for all centres in medium and low seismicity areas as the regulatory timeframes for identifying these buildings in these areas has not necessarily passed.

## 2.2 Seismic Retrofit Schemes

The improvement in building performance through retrofit was captured within the fragility curves as described below. To capture the costs associated with the retrofit and to reflect variation in seismicity, concept designs were developed for all ten building types to 34%NBS and 67%NBS across the six locations based on the NZS1170.5:2004 loadings. This required a representative building for each building type to be assigned, which was defined through analysis of the inventory data for typical features, such as gross floor area and number of storeys.

A number of resources were used to establish “typical” retrofit schemes for each of the building types. Cost estimates were prepared by a quantity surveyor with appropriate contingencies taken into account for the conceptual nature of the schemes, as well as taking into account regional variations affecting cost.

Providing high-level cost estimates for seismic strengthening projects comes with inherent limitations due to the complex and variable nature of such undertakings. Factors like the unique structural characteristics of each building, varying site conditions, and evolving regulatory requirements can significantly impact on cost.

## 2.3 Fragility Functions

As part of the vulnerability model, displacement-based fragility curves are derived from building vulnerability to characterise the probability of reaching specified damage states under a given shaking intensity measure.

The fragility functions are defined by four damage states (DS), for each of the ten building typologies, with thresholds of inter-storey drift for structural behaviour and peak floor acceleration for non-structural components. The DS are defined as: DS1: Slight, DS2: Moderate, DS3: Extensive and DS4: Complete damage. Typology-specific fragility sets were developed using displacement-based procedures and benchmarked against HAZUS to ensure plausible behaviour across the intensity range. The chosen intensity measure is consistent with the hazard model at each building’s characteristic period, maintaining alignment between hazard input and structural response. Fragilities were produced for each retrofit option; retrofitting systematically shifts the curves to lower probabilities of damage at a given intensity. The building level consequence model specifies loss rates conditional on the realised damage state and provides the basis for estimating expected loss.

To adjust the final fragility curves to collapse margin (Damage state DS4 -complete collapse), an adjustment factor was required. In New Zealand, assessments of existing buildings are framed around life safety at the Ultimate Limit State (ULS) and expressed as %NBS, whereas fatality risk is governed by collapse performance. Accordingly, when normalising fragilities, the model applies a collapse margin adjustment represented by a study specific Inherent Capacity Factor (ICF) which was applied to the backbone curves for these existing structures.

## 2.4 Exposure

Exposure comprises people potentially affected, inside and outside buildings. Density differences between rural towns and urban centres were accounted for. The per-building occupancy follows the FEMA Hazus Earthquake Model Technical Manual version 6.1 Table 11-1 (HAZUS) classes by use type for day and night-time (e.g., office daytime peaks; residential evening peaks). Reporting occupancy for representative day and night events ensures consistent inputs to casualty modelling and enables sensitivity testing of the exposure variations. Final reporting for a day and night event in line with other international reporting, derived from peak and average occupancy rates. For a 1,000 m<sup>2</sup> metropolitan office building, it was assumed there are approximately 80 occupants in the morning (about 90% of peak) and 8 occupants at night (about 10% of peak) during a workweek; lower baseline occupancies are expected in New Zealand’s regional towns due to lower population density. Adjacent pedestrian count was assumed to average 2-3 persons at any time, with diurnal peaks, and higher number of pedestrians for buildings along main urban thoroughfares, and near public transport nodes (e.g., bus stops and rail stations). The lack of credible occupancy and pedestrian data required us to apply some judgement to these numbers and compare these to pedestrian count data by Wellington City Council. This is an area that warrants further research.

## 2.5 Hazard

Seismic hazard inputs were taken from the 2022 National Seismic Hazard Model. For the pseudo-scenario based approach mean uniform hazard spectra were used to derive spectral acceleration  $S_a(T)$  at each

building's period, for each APoE level, with site effects represented by estimated  $V_{s(30)}$ . Limitations include uncertainty in  $V_{s,30}$  and the methodology. Because APoE shaking levels are used, hazard is assumed uniform across each centre, varying only by the soil shear wave  $V_{s,30}$  - unlike real earthquakes, where shaking varies spatially (e.g. attenuation with distance from the epicentre). Relative hazard differs nationally: APoE 1:500 in Wellington is broadly comparable to 1:625 in Feilding, 1:1,250 in Whanganui, 1:2,500 in Christchurch, 1:5,000 in Dunedin, and at least 1:10,000 in Auckland.

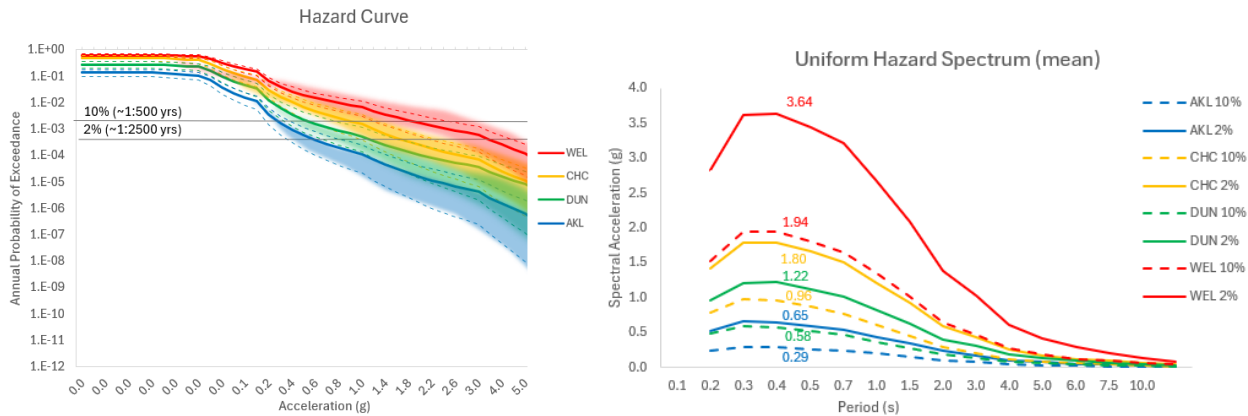


Figure 3: Left: Hazard curve for  $V_{s30}=350\text{m/s}$ . Right: Uniform hazard spectrum. The bold lines indicated 2% PoE in 50 years (1:2500 years) and the dotted line 10% in 50 years (~1:500 years). Source: NSHM 2022, Earth Science NZ (GNS)

## 2.6 Consequences

The consequence model covers three outcomes: casualties (injuries and deaths), damage (damage ratio—fraction of replacement cost and carbon emissions), and downtime (days of reduced functionality conditioned on damage). For each damage state and building type, there are estimated rates assigned consequence models for casualty state, building damage and repair cost and business disruption. For example, a URM building with extensive damage (DS3) is assumed to have an estimated rate (the ratio of total building population at the specific time of the day) 7% with moderate injury, 3.5% with serious injury, 0.7% with critical injury and 10% fatalities. Injuries inside the building are mainly due to being hit by non-structural items or contents or falls and strains from strong shaking. For each building, using fragility sets for strengthened and unstrengthened states, consequences were computed for the relevant shaking intensities. The fragility curves provide the probability of the structure's response meeting or exceeding the specified damage state (along vertical Y-axis) at a certain intensity measure and spectral acceleration (along horizontal X-axis). For the consequence model confidence bounds (upper and lower) were introduced to allow sensitivity testing of the risk model.

## 2.7 Final Risk model

A final risk model was developed to evaluate mitigation options and to investigate cost-benefit relationships, informing decisions on the earthquake-prone building policy and methodology. Options ranged from do-nothing and targeted securing works to 34%NBS (status quo) and 67%NBS strengthening based on the Engineering Assessment Guidelines 2017 and loadings from NZS1170.5:2004. In total, 2,750 buildings were analysed, testing combinations of targeted mitigation: applying or withholding mitigation in lower human-exposure contexts (e.g. small towns), including or excluding low-seismic zones, or applying retrofit only to highly vulnerable types, such as URM and high-risk three-plus-storey concrete. The consequence model was applied across four damage stages for each building type. Results covered people-related losses (injuries and deaths), business disruption, and property damage for day and night events across the required

APoE levels. The results of this step has then been applied for both the pseudo scenario approach and traditional CBA.

### 3 RESULTS OF THE STUDY

This project has been a risk investigation to provide the means to enable others to understand the implications of the current EPB settings and to provide the ability to “test” the implications of potential future policy changes. A condensed summary of observations is presented below.

#### 3.1 Location

Retrofitting the unreinforced masonry (URM) buildings and the high-risk concrete three-plus-storey buildings alone, even to the minimum 34%NBS, provides the greatest contribution to potentially saving thousands of lives.

Dunedin is historically considered a low seismicity zone; however, this study highlights that the increased hazard due to nearby fault lines that are triggered for the rare, higher return period shaking levels, combined with brittle masonry buildings, significantly elevates the city’s vulnerability. Wellington is the highest-hazard area – five times higher than other centres and exhibits the greatest people-related losses at APoE 1:500. In Wellington, losses saturate by the 500-year return period; earthquake-prone buildings have already collapsed at that level, so the 2,500-year event does not increase total loss. In Auckland, the HCLP events reveal a step change in the benefits of strengthening buildings to 34%NBS, primarily due to the impact of business disruption costs.

#### 3.2 Pseudo-scenario (APoE) Approach

There was a significant step change for rare earthquake events (1:2500 year) compared with 1:500 year where people-related losses increased three to four-fold in Auckland. For Wellington’s population of EPB, the Benefit-Cost-Ratios did not rise to the same extent with longer return periods, contrary to expectations, because many EPB buildings were found not able to survive lower shaking levels.

#### 3.3 Mitigation - a balance of cost versus life safety

Across most centres, achieving the minimum mitigation level of 34%NBS was found to reduce losses by at least two-thirds. The exception was Wellington where a higher level of strengthening beyond 34%NBS would be required to achieve a reduction in losses. The cost for 67% vs 34%NBS mitigation is double but the effect on loss reduction is four times. In Figure 4, results are plotted for mitigation options ranging from do-nothing to status quo—showing both residual life-safety risk and regulated retrofit cost.

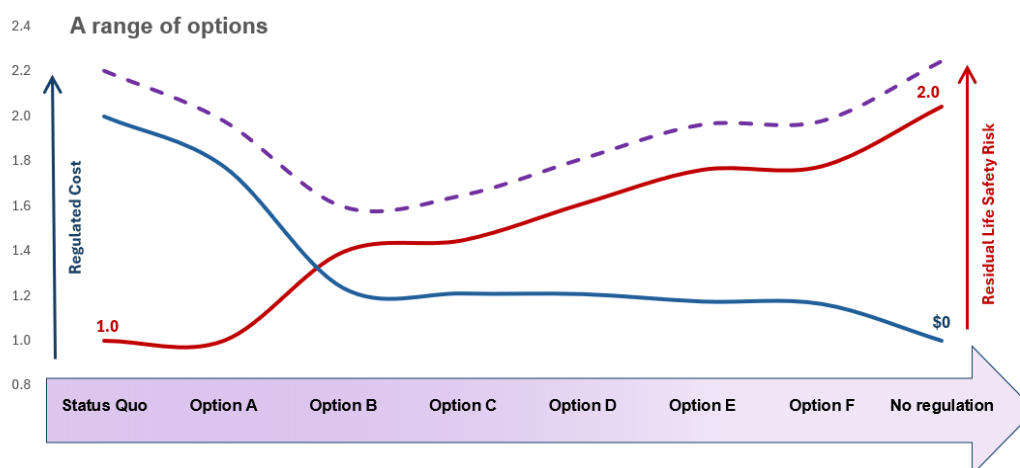


Figure 4: Retrofit cost to residual life safety risk for various mitigation options

Figure 5 shows a step change for Auckland at larger return periods (2500 years). This step change is only visible in the pseudo-scenario approach, and not in the traditional BCR which shows a BCR of less than 1.0, indicating cost exceeds benefits.

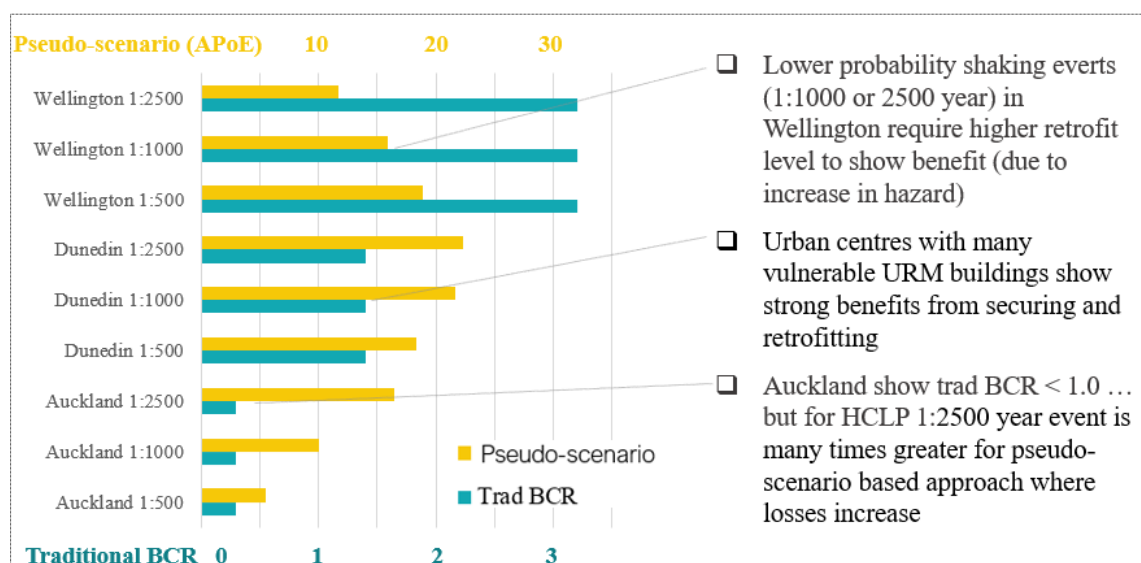


Figure 5: Comparison of Traditional BCR vs pseudo-scenario based BCR for strengthening to 34%NBS

### 3.4 Limitations and Uncertainties

The study provides high-level trends for policy and planning, not asset-level predictions. Results are indicative due to several constraints: they rely on existing data and broad assumptions; are limited to registered EPBs; use generalised retrofit concepts and scaled costs introducing uncertainty when applied to individual buildings; and fragility models simplify complex behaviours. During real earthquakes, not all buildings are similarly affected, and they do not all perform the same. Additionally, socio-economic, cultural, and heritage impacts were not quantified or only partially considered. Future studies should be considered that align with social-science research to address disproportionate impacts and recovery potential on marginalised communities.

## 4 CONCLUSIONS

The economic study described in this paper indicated that in Wellington, larger shaking events (1,000–2,500-year) generally require higher retrofit levels to demonstrate benefit, given the increased hazard, while many retrofitted and unretrofitted EPB buildings may not survive lower-intensity shaking. Urban centres with a substantial URM building stock, such as Dunedin and Whanganui, showed strong benefits from securing and targeted retrofitting. In Auckland, traditional Benefit-Cost-Ratios are below 1, indicating low retrofit benefit; however, under the pseudo-scenario-based approach, rare but high-impact events (e.g., 2,500-year) showed a significant step change, with people-related losses increasing approximately three- to four-fold. These consequences were not visible in the traditional CBA approach due to likelihood-based averaging, which is why this method often supports inaction in seismic resilience. The pseudo-scenario-based (deterministic) approach makes these consequences explicit.

Traditional CBA applies likelihood reduction factors and discount rates to estimate average expected loss over time, which is useful for budgeting and insurance but is less reflective of the potential impacts for low probability, high consequence events.

A dual-framework approach is recommended when considering low-probability high consequence situations: using traditional CBA to assess expected-loss reduction and affordability, and pseudo scenarios to not lose sight of low probability life-safety implications.

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