Cost-Benefit Analysis of a Building Code Change

Applying the NIBS 2019 methodology in New Zealand

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Ilan Noy and Tomas Uher

Te Herenga Waka – Victoria University of Wellington

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1 Introduction

This document proposes a cost-benefit analysis (CBA) method to assess a building code change for engineered buildings in Aotearoa New Zealand. The proposed methodology is based on the methodology used in the Natural Hazard Mitigation Saves 2019 Report (henceforth the NIBS report) by the United States' National Institute of Building Sciences (NIBS, 2019). New Zealand has recently completed its 2022 National Seismic Hazard Model (NSHM), and it suggests that it "will be used to inform regulations related to meeting Building Code requirements and for loss modelling needs in New Zealand." (Gerstenberger et al., 2022, p. 1). It seems inevitable that these building code requirements will be strengthened as the report finds "in general, over most of New Zealand and for most hazard metrics, the NSHM 2022 forecasts increased hazard when compared to the 2010 NSHM." (Gerstenberger et al., 2022, p. 101). This impending tightening of the building code is the impetus for this report's consideration of an up-to-date CBA assessment methodology for this type of policy change.

The NIBS Report was identified as the most comprehensive and detailed hazard-resistant building-code CBA that has been conducted to date and therefore its methodology was chosen for adaptation to the Aotearoa New Zealand context. While most of the instructions and suggestions herein are based on the original methodology of the NIBS report, some details have been changed to reflect the need to use the methodology in the different New Zealand hazard and data availability contexts. The material included here also reflects adjustments and considerations proposed during a 'Building Code CBA' workshop held in Wellington on 20th October 2022.

Section 2 contains a literature review of building code change CBAs, including studies that analyse specifically building code benefits or costs separately. Further sections describe the methodology to assess the cost-effectiveness of building code change.

2 Literature review

2.1 Hazard-resistant building code CBAs

Hazard-resistant building code CBAs employ deterministic or probabilistic methods to estimate disaster impacts. The relatively less common deterministic approach is used to analyse the costs and benefits of adopting seismic codes in the US in studies such as Litan et al. (1993) or Porter (2017). Litan et al. (1993) conducts a CBA of seismic code adoption and seismic retrofits and estimate a Benefit-Cost Ratio (BCR) given specific earthquake events. Porter (2017) quantifies the costs and benefits of constructing ordinary buildings with an earthquake importance factor of 1.5 using a hypothetical earthquake scenario.

More commonly, the disaster loss reduction associated with building code change is estimated probabilistically, considering the probabilities of different levels of hazard severity, as is mostly the case in the following literature. Cost-effectiveness of hurricane-resistant building codes is assessed in several studies focusing on Florida, as the Florida codes were revised following the significant damages brought about by the 1992 hurricane Andrew. Englehardt and Peng (1996) analyse the costs and benefits of adopted revisions to the South Florida Building Code using a hurricane vulnerability model based on expert opinion. ARA (2002) examines the costs and benefits of the later introduced Florida Building Code (FBC) for three related housing types and estimate avoided losses using the HURLOSS probabilistic hurricane model. A different approach is used in a CBA by Simmons et al. (2018) who assess the past loss reduction caused by FBC enactment using actual insured loss data rather than probabilistic loss estimates.

The tornado hazard is the focus of Sutter et al. (2009) and Simmons et al. (2015), who assess the costs and benefits of wind-resistant design of new buildings in Oklahoma. Since both studies lack detailed engineering estimates for damage reduction, Sutter et al. (2009) assess what minimum damage reduction would lead to a zero net present value. Simmons et al. (2015) analyse the loss reduction based on the authors' assumptions and expert opinions on which the building codes are based. Focusing on the flood hazard, Jones et al. (2006) and FEMA (2008) assess the cost-effectiveness of constructing buildings in flood hazard areas in the US above the minimum required elevation using the FEMA Mitigation CBA Toolkit. Porter et al. (2021) conducts a CBA of fire-resistant design of new buildings and building retrofits related to the recommendations from the National Guide for Wildland-Urban Interface Fires in Canada. Similarly to the NIBS report, this study considers a relatively wider range of benefit categories, including a reduction in deaths and injuries, post-traumatic stress disorder (PTSD) cases, indirect economic losses, and environmental costs (quantified using the cost of carbon released per burned house).

With respect to earthquake hazard, Porter et al. (2006) analyses the cost-effectiveness of enhanced seismic design for new wood frame buildings and building retrofits in California, USA, using the Assembly Based Vulnerability method. In Aotearoa New Zealand, Stanway and Curtain (2017) conduct a CBA of seismic restraints for non-structural elements in new non-residential buildings and use the FEMA P-58 methodology to estimate losses due to seismic damage of non-structural elements. To our knowledge, the largest CBA of seismic code adoption preceding the NIBS report was conducted by the National Earthquake Hazards Reduction Program Consultants Joint Venture in 2013 (NEHRP, 2013) and assessed the construction cost premiums and benefits of adopting the 2003 and the 2012 International Building Codes (I-Codes) as opposed to the 1999 Standard Building Code in Memphis, USA, based on six reference building types. They assess the benefits of enhanced seismic design with a quantitative, probabilistic approach using the FEMA P-58 methodology. The categories of benefits they assess include reduced potential for building collapse, averted repair costs for non-collapsed buildings, and casualties.

Finally, NIBS (2019) was identified as the most comprehensive and detailed CBA of building code change to date. The study updates and expands on NIBS (2005), which assessed cost-effectiveness of FEMA-funded building retrofits related to earthquake, wind, and flood hazards. Both NIBS (2005) and NIBS (2019) consider a relatively wider range of benefit categories compared to the other CBAs described above, including loss reduction associated with direct and indirect business interruption, emergency response costs and (for certain hazards) non-market effects such as environmental damage and damage to historical sites. The innovations of NIBS (2019) include a longer time-duration considered (75 years compared to 50 years), creating modified vulnerability functions to reflect modern building design, estimation of building impairment (collapse, red-tagging and yellow-tagging), and considering PTSD and pre-event insurance premium costs. NIBS (2019) analyses cost-effectiveness of five sets of mitigation strategies: (i) adopting the 2018 I-Codes; (ii) exceeding select provisions of the 2015 I-Codes; (iii) private building retrofits; (iv) utility and transportation lifeline mitigation and (v) federal mitigation grants. The benefits and costs are estimated across four types of natural hazards - riverine and coastal flooding, hurricanes, earthquakes, and fires at the wildland-urban interface.

2.2 Building code benefits

A subset of building-code-related studies focus solely on the benefits (typically expressed as avoided disaster losses) of building codes without considering the associated costs. Some examples include retrospective assessments of loss reduction attributed to building codes during the 1992 hurricane Andrew (Fronstin and Holtmann, 1994), the 2004 hurricane Charley (IBHS, 2004) or an estimation of hail damage reduction (Czajkowski and Simmons, 2014), all in the US. While AIR (2010) focusses mainly on the benefits and costs of hurricane retrofitting, the study also finds that buildings designed in accordance with newer building codes benefit from hurricane loss reduction.

To our knowledge, the most detailed study of this kind was completed by FEMA in 2020 (FEMA, 2020) and analysed disaster losses avoided due to adoption of I-Codes in the US since 2000. FEMA applied the HAZUS methodology on a parcel-level dataset of 18.1 million post-2000 buildings to quantify loss reduction with respect to floods, hurricanes, and earthquakes. Here, the considered benefits were limited to direct property and content damage, excluding other benefit categories such as reduced social, indirect, or environmental costs.

2.3 Building code costs

Some studies examine specifically the costs of building code change. For example, Listokin and Hattis (2005) review empirical studies related to building code impacts on housing costs and conclude that codes increase housing costs by up to 5 percent. The increased costs associated with adopting seismic provisions in building codes are discussed or analysed in studies such as Weber (1985), Olshansky et al. (1998) or Porter (2016). Yu et al. (2015) quantifies the cost premium of recovery-oriented enhanced seismic design.

3 Selection of building designs

In the following sections, we provide details about the data requirements, the availability of data, and the associated methodologies as they pertain to the application of the NIBS Report application for the NZ case. For the selection of building design codes to be assessed, the status quo is associated with the current building code design as this is the default design that would apply to new buildings (if they were to be constructed).

What we need to compare the status quo to, of course, is a new (to be proposed) building code design that will reflect the newly quantified risks as described in the 2022 NSHM. Since this new building code has not yet been formulated, what follows is a discussion of a hypothetical CBA, rather than one that can be immediately conducted.

4 Monetary quantification of social losses (deaths, injuries, and PTSD)

In the NIBS report, all future social losses associated with a disaster event (as distinct from monetary damages) are not discounted. In the October 2022 workshop we held, participants suggested that social losses should be discounted as the baseline scenario, similarly to all other types of losses. The precise discount rates to be used were not agreed (nor did we seek a consensus on them), but there was an agreement that discount rates for social losses should be positive (though a sensitivity analysis of a 0% discount rate can also be appropriate). The plausible range of discount rates to be used were 3% (as per advice from the Treasury), 0% (as in the NIBS Report), and 5% (usually viewed as an analogue to the long-term real interest rate).

The appropriate monetary values that can be used for deaths, injuries, and PTSD cases, as detailed in the NIBS Report, are described below in Section 4.1 and Section 4.2. An alternative source of values, possibly more appropriate to the NZ case, may be the Accident Compensation Corporation (ACC) – as the ACC compensates individuals for a large variety of injuries.

4.1 Deaths and injuries

The standard monetary measure of mortality is the value of statistical life (VSL). In the NZ case, the Ministry of Transport (MoT) set it to NZD 4,887,629 (Ministry of Transport, 2021; The Treasury New Zealand, 2021). Other government entities and (implicitly) policies use other values, but the MoT value is the most used one in policy analysis.

The costs of avoiding a statistical injury can be derived from the VSL and using fractions of VSL that are associated with different types of injury. This is implicitly the process that the World Health Organization uses when it calculates the burden of various diseases using Disability Adjusted Life Years (DALY) calculations. In this case, we can use the Riskscape casualty states that are presented in Table 1; these costs are based on the fractions of VSL for each AIS injury level adopted from Spicer and Miller (2010) and used by DOT (2021).

Table 1: Acceptable cost to avoid a statistical injury

Riskscape casualty state	Corresponding AIS level[(a)]	Fraction of VSL	Cost (NZD)
Minor	1	0.003	15,000
Moderate	2	0.047	230,000
Serious	3	0.105	513,000
Critical	4-5[(b)]	0.397	1,941,000
Dead	6	1.000	4,888,000

(a) AIS refers to the abbreviated injury scale created by the Association for the Advancement of Automotive Medicine (2001).

(b) The cost of a statistical incidence of a "critical" Riskscape casualty state is calculated using a geometric mean of the "fraction of VSL" values for AIS 4 and 5 (0.266 and 0.593, respectively).

4.2 Post-traumatic stress disorder (PTSD)

Possibly the most difficult to quantify injuries are the ones that refer to mental health. The NIBS Report highlights PTSD as a particular mental health consequence of disaster events. In the absence of more robust data about the prevalence of PTSD post-disasters, we suggest that in the NZ case, one sets the number of people who will experience PTSD as equal to the number of people who are estimated to experience "serious" Riskscape casualty state. We suggest that the overall acceptable cost to avoid a statistical incidence of PTSD (V_{PTSD}) to

NZD 140,000, following the NIBS report, but it is possible to arrive at a more locally relevant cost using data from the ACC.[1]

5 Time-element losses (residential displacement and business interruption)

In order to quantify time-element losses (those indirect losses that accrue over time, such as profit losses to businesses, there is a need to tabulate both the direct (V_{BI}) and indirect (Q) per day per occupant time-element loss for each occupancy class (residential and commercial) using the methods and values described in Sections 5.1 and 5.2. The total time-element losses can then be quantified by combining the estimates of direct and indirect per day per occupant losses for each occupancy class with the number of indoor occupants and the mean duration of loss of function (see the equation defining $PV_{MonetaryAgOcc}$ on page 15).

Workshop participants suggested some considerations regarding the mean duration of the loss of function (a duration that may be both sector-specific and location-specific, but different enough from the US considerations of the NIBS Report). It was also noted that using the duration of loss of function to proxy for business interruption costs is potentially misleading, as business recovery is often not dependent on the property reconstruction schedule A business can adapt by relocation, and resume services long before their property has been rebuilt, and equally can be interrupted for a longer duration if, for example, its customer base has not similarly recovered. Therefore, the possibility of using an alternative method of estimating business interruption costs may also be investigated.

Several items to consider when deciding on the duration of the recovery process, and thus on the time element, are:

- Should insurance cover and its role in recovery (particularly with respect to the duration of claim settlement) be considered in determining the duration of loss of function?
- Are there other important considerations in the context of New Zealand (e.g., resource constraints)?
- Is there a need to account for the fact that building functionality is highly dependent on infrastructure/utility availability?
- Should the possibility of a market breakdown and an associated step change or tipping point (as compared to a marginal change) be considered in the total business interruption losses and their duration? (An example of such a tipping point is a government decision to relocate out of Wellington, temporarily or permanently, after a local catastrophic event).
- Direct business interruption costs can be estimated using the operability functions from the MERIT model, which are derived based on survey data following the Canterbury earthquakes (Brown et al., 2019a; Kim et al., 2016). Are these estimates generalizable?[2]

[1] The value includes direct treatment costs and is based on the USD 90,000 value used in the NIBS report.

[2] The model looks at the likely levels of productivity over time based on the disruption experienced during an earthquake (one of the contributing factors in the function is building damage). In this model, the ability to operate is not based on the loss of function duration but on the level of building damage.

5.1 V_{BI} for residential occupancies

For residential occupancy classes, the time-element displacement costs can be estimated using various publicly available data. To estimate a monthly house rental cost for each region one can use the equation below. The multiplier (1.667) is used in the NIBS report to account for higher costs associated with housing market shifts as the supply of housing is constrained post-event, and the higher costs associated with some households staying in hotels or other kinds of temporary shelters. The data for median monthly rent per territorial authority (TA) are publicly available (Tenancy Services, 2022).

$$Monthly\ house\ rental\ costs = Median\ monthly\ rent \times 1.667$$

For house contents, household furniture hire costs can be approximated as NZD 800/month (as in the NIBS Report) for all regions. Similarly to the NIBS Report, increased commuting costs can be approximated using data from the NZ Transport Agency; alternatively the NIBS Report uses a value of NZD 160/month. To account for the number of people who are displaced, the average household size is projected to be 2.6 people in the next two decades (StatsNZ, 2021).

Aggregating these, the total per day per occupant residential displacement cost V_{BI} for family dwellings occupancies can then be calculated for each region using the following equation:

$$V_{BI} = \frac{(monhly\ house\ rental\ cost +\ monthly\ furniture\ hire\ costs +\ commuting\ costs\ )}{average\ household\ size \times 30.4}$$

V_{BI} for temporary lodging occupancies

For temporary lodgings, we can assume losses that are equal to a typical average hotel cost (per night). This average per night hotel cost can be approximated as NZD 177, using the average daily rate value for hotels as reported for February 2022 (HCA, 2022).

V_{BI} for nursing homes

For residents of nursing homes, we can assume losses that are equal to the average daily cost of a private room in a nursing home. The maximum weekly cost for residential care in New Zealand varies for each TA and can be found in The New Zealand Gazette (2022). We can use these data (divided to reflect daily costs).

5.2 V_{BI} for non-residential occupancies

To obtain business interruption cost, we can calculate the direct per person economic sector business interruption cost using the following equation, data on industry-specific earnings, and the number of employees per industry (these are all publicly available from StatsNZ, 2022).

$$Direct\ loss\ (\$) = \frac{Wages\ and\ earnings\ in\ industry}{Number\ of\ employees\ in\ industry}$$

Once this direct loss per employee (for each sector) is convert to daily loss, we can map the different economic sectors to corresponding Riskscape non-residential occupancy classes; possibly based on the sector-occupancy classification mapping used in the NIBS report (Table 2).

Table 2: Mapping of economic sectors to Hazus occupancy classes

Code	Equivalent IO sector	Hazus occupancy
S1	Agriculture	AGR1
S2	Construction	IND6
S3	Other heavy industry	IND1
S4	Other light industry	IND2
S5	Food, drugs & chemicals	IND3
S6	Mining & metals/minerals processing & manufacturing	IND4
S7	High technology	IND5
S8	Wholesale trade	COM2
S9	Retail trade	COM1
S10	Banks & financial institutions	COM5
S11	Professional & technical services	COM4
S12	Education services	EDU1, EDU2
S13	Health services	COM6, COM7, RES6
S14	Entertainment & recreation	COM8, COM9
S15	Hotels	RES4
S16	Residential housing, other than hotels	RES1, RES2, RES3
S17	Other services	COM3, COM10
S18	Government & non-NAICS	GOV1, GOV2, REL1

5.3 Indirect output loss Q (indirect residential displacement/business interruption costs)

Calculating indirect losses associated with both residential displacement (5.1) and business interruption (5.2) is more challenging. One can potentially use Input-Output tables and analysis to calculate values of per dollar per person output loss Q for each occupancy class (as is done in the NIBS Report). These tables, however, are updated infrequently, and it remains unclear whether they are appropriate for use in a post-disaster situation when many supply chains and business relationships get reoriented to account for the associated dislocation.

6 Additional benefit/cost categories

This section details several possible additional categories which might be useful to quantify, as mentioned by participants of the October workshop.

6.1 Embodied carbon

The existing building stock includes an associated embodied carbon that was used in its construction. Calculations of these embodied carbon are available, and in principle one can associate costs with that. One possibility is calculating the embodied carbon in a building (to account for its possible destruction) and the carbon that might be required to fix a damaged building. One can then use the Emission Trading Scheme price of carbon (as of November 2022; that was about NZD 85 per ton of CO_2).

6.2 Demolition or waste management costs

Other environmental costs, other than greenhouse gas emissions, might also be considered. In particular, one can quantify the demolition waste management costs; especially as the quantity of waste from demolished building that cannot be recycled is quite large.

6.3 Implications for existing buildings

A further consideration should be what impact the new construction code change will have on the existing building stock. There are probably several ways in which a code change affects the way existing buildings are viewed. Should this be taken into consideration is an open question, as many of these buildings are privately owned, and the potential impact will mostly be on their value rather than their economic function.

6.4 Other

There may be other potential benefits and costs that may be even harder to quantify (e.g., avoiding out migrations, maintaining social cohesion, and other mental health costs). Some of these are described in Brown et al. (2022) and Brown et al. (2019b). As we see no easy way of quantifying them, several might be considered qualitatively rather than explicitly included in the associated CBA.

7 Estimating the hazard

This section describes the NIBS Report's original methodology as it relates to estimating the seismic hazard. The application in New Zealand will most likely rely on the 2022 revision of the National Seismic Hazard Model as it requires the use of the most up to date seismic hazard information available. The NIBS Report considers only ground shaking, excluding effects such as liquefaction, (dry) landslides or fault offsets. We are unsure whether the new NSHM includes enough granular information to include some of these in the analysis as well.

The NIBS Report uses the following hazard measure (the NIBS report uses data from 2015 NEHRP Recommended Provisions as in FEMA (2015):

- Sa(0.2 sec, 5%), g or Sa(1.0 sec, 5%), g,
- Vs30 (mean shearwave velocity in the upper 30 meters of soil) (the NIBS report uses OpenSHA.org site data app at tract geographic centroid)
- F_V (site coefficient)

They create gridded seismic hazard curves, showing probability in 1 year of shaking exceeding each of 20 levels of spectral acceleration response from less than 0.01 g to more than 5.0 g in logarithmic increments. They then calculate the hazard curves for site conditions with average shearwave velocity in the upper 30 meters of soil (Vs30) equal to 760 m/s, corresponding to the boundary between NEHRP site classes B and C. They address site amplifications using NEHRP site classes; mapping from Vs30 to NEHRP site class based on the 2015 NEHRP Recommended Seismic Provisions (FEMA, 2015) (to calculate design parameters S_{MS} and S_{M1}) and boundary soil types (BC, DE, CD etc.) (to calculate the hazard to which buildings are subjected).

To estimate hazard spatially, at census-tract (roughly equivalent to Territorial Authorities) centroids, they extract hazard curves from the gridded seismic hazard data, interpolate exceedance frequency at each of the many levels of ground motion available to them, and then adjust the interpolated hazard curve to account for each site's local conditions (subject to information availability). This results in spatially explicit hazard curves (for each TA).

8 Estimating exposure

To estimate exposure, much of the NZ data is available from Riskscape and StatsNZ for each TA[3]:

- Building replacement value of new buildings that will be built in the next year (V_b), separately for each aggregate occupancy class.
- Building content replacement value of new buildings that will be built in the next year) (V_c), for each aggregate occupancy class.
- Total number of indoor occupants in new buildings (that will be built in the next year) at 2:00 AM, 2:00 PM and 5:00 PM (N_{OccH}), for each aggregate occupancy class.
- Total building area (for calculating weighted-average vulnerability functions).
- Building area for each building type/occupancy class associated with recent construction (for calculating weighted-average vulnerability functions).

The building replacement value of new buildings can be estimated as a fraction of the total value of building replacement of the existing buildings (the NIBS report uses 1%); if that is the case, the content replacement value, and the number of indoor occupants in the new buildings can be estimated using the same fraction of total values.

9 Estimating seismic vulnerability

The NIBS Report uses the capacity-spectrum method of structural analysis to estimate the acceleration and displacement of the buildings. In the NIBS report, new vulnerability functions were created[4] (with design strength based on design for site-specific hazard and response modification coefficient based on model building types of recent vintage, using the method from Porter (2009a; 2009b), for the entire building stock.

For the Aotearoa New Zealand case, it was suggested that the analysis may require developing new fragility functions, for the current and proposed building codes, as there were some doubts about the applicability of the functions developed in the US context. The new functions should be developed using a consistent approach for both the current and proposed building design codes. In particular, workshop participants highlighted the following:

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[3] The NIBS report uses statewide weighted-average residential and nonresidential vulnerability functions for each state to avoid having to generate hundreds of combinations of building types and occupancy classes. Some instructions (e.g., using aggregate occupancy classes rather than each combination of occupancy class and building type separately) in the this and further sections assume that the weighted-average vulnerability functions are used. The average vulnerability functions are described in more detail in Section 9.2.

[4] The NIBS report uses new high-code vulnerability functions because the HAZUS vulnerability functions cannot be used in conjunction with modern seismic hazard information and do not reflect modern design for site-specific hazard.

- The need to develop functions based on strength, stiffness, and displacement parameters.
- Damage to both structural and non-structural elements needs to be modelled in these functions.
- Either the capacity-spectrum method or FEMA P-58 methodology could be used for this purpose.
- Simplified fragility functions, similar to those considered in ongoing research in Auckland, could be used.
- If possible, a more rigorous assessment similar to the FEMA P-58 methodology could be used for representative buildings, with designs costed for the old versus new code design solutions.
- If possible, the simplified NIBS approach of using average vulnerability functions should not be adopted.

10 The NIBS methodology for creating vulnerability functions

10.1 Creating local vulnerability functions

The process for creating vulnerability curves is described in the NIBS report as follows:

- Create capacity curves.
- Calculate input motion for each point on the curve.
- Estimate the probability of damage (0-4) for each point on the curve.
- Calculate loss measures for all combinations of earthquake intensities (each point on the capacity curve – parametrized by pairs of S_d and S_a), building type, occupancy class, C_S and I_E levels. Use these to calculate collapse probability, and fraction of red-tagged and yellow-tagged buildings.
- Tabulate vulnerability functions, for each building type, occupancy class, C_S, I_e, and each level of SA02 from 0.00g to 4.00g (401 values of SA02).

Resulting tabulated vulnerability functions:

$y_b(x)$ = mean building repair cost as a fraction of the replacement cost given SA02 = x

$y_c(x)$ = mean content repair cost as a fraction of the replacement cost given SA02 = x

$y_{i1}(x)$ = mean fraction of indoor occupants in injury severity level 1 given SA02 = x

$y_{i2}(x)$ = mean fraction of indoor occupants in injury severity level 2 given SA02 = x

$y_{i3}(x)$ = mean fraction of indoor occupants in injury severity level 3 given SA02 = x

$y_{i4}(x)$ = mean fraction of indoor occupants in injury severity level 4 given SA02 = x

$y_{i5}(x)$ = mean fraction of indoor occupants in injury severity level 5 given SA02 = x

$y_T(x)$ = mean duration of loss of function, in days, given SA02 = x

$y_{tc}(x)$ = fraction of indoor occupants trapped in collapsed buildings, given SA02 = x

10.2 Creating TA-level weighted-average vulnerability functions

If the analysis needs to be aggregated, TA-level weighted-average vulnerability functions can be generated using a weighted-average of the common building types in each TA, with weights that reflect the area's recent construction practice (using building area for each building type and occupancy class). This step was done in the NIBS Report but may not be necessary in the local case.

In the NIBS approach, the aggregation was conducted separately for residential and non-residential average building type. When calculating the residential average building type, the algorithm uses zero weight for non-residential occupancy classes and vice versa.

11 Estimating construction costs

In order to estimate the construction cost increases (e.g., per unit of earthquake importance factor I_E) as a percentage of total replacement cost of new buildings (C), the NIBS report uses 2% per unit of I_E –> C = 0.02). Workshop participants indicated that:

- There is a possible nonlinear effects of a significant cost increase if the event is large enough, and this may need to be accounted for (especially in a capacity constrained small country like NZ).
- Worker upskilling costs can be ignored in the NZ context.

The cost (c) of adopting the new building code for a given TA is defined in the following equation:

$$c = V_b \times C \times (I_e - 1)$$

Where,

V_b = total replacement cost of new buildings in TA.

C = construction cost increase per unit of I_E as a percentage of total replacement cost of new buildings.

I_e = earthquake importance factor.

12 Calculating BCR

The instructions below assume that weighted-average vulnerability functions are used (as in the NIBS Report). If they are not used, the present value of losses has to be calculated for each combination of building type and occupancy class separately.

12.1 A summary of the required data

Exposure data:

- V_b = total replacement cost of new buildings, in TA, in aggregate occupancy class.

- V_c = total replacement cost of building contents in new buildings, in TA, in aggregate occupancy class.

- N_{OccH} = total number of indoor occupants in new buildings at time h (2AM, 2PM, 5PM), in TA, in occupancy class.

- N_{AgOccH} = total number of indoor occupants in new buildings at time h (2AM, 2PM, 5PM), in TA, in aggregate occupancy class.

- N_{AgOcc} = average total number of indoor occupants in new buildings, in TA, in aggregate occupancy class.

$$N_{AgOcc} = \frac{98}{168} N_{AgOcc2am} + \frac{40}{168} N_{AgOcc2pm} + \frac{30}{168} N_{AgOcc5pm}$$

Vulnerability data:

- y(x) – weighted-average vulnerability functions (building repair cost $y_b(x)$, content repair cost $y_c(x)$, mean duration of loss $y_T(x)$, fraction of injured occupants for injury severity level 1-5 $y_{ij}(x)$, fraction of occupants trapped in collapsed buildings $y_{tc}(x)$).

Hazard data:

- G(x) - mean frequency (events per year) of earthquakes causing shaking SA02 ≥ x, by TA

Other data:

- V_{ij} = cost to avoid injury severity level j (see Table 1)

- V_{PTSD} = cost to avoid a case of PTSD = NZD 140,000

- V_{usar} = urban search and rescue cost to extricate 1 trapped victim = NZD 16,000[5]

- V_{BI} = output loss (residential displacement cost or direct business interruption loss) per-person per-day, by occupancy class (see Section 5.1)

- Q = per-person per-dollar indirect output loss resulting from $1.00 of direct time-element loss, by occupancy class

- t = time-duration considered = 75 years

12.2 Calculating the present value of losses

The present value of monetary losses

EAD_b = expected annualized damage factor for building repairs, e.g., the expected value of the annual cost to repair new buildings, as a fraction of replacement cost new.

[5] The value is based on the USD 10,000 value used in the NIBS report.

$$EAD_b = \int_{x=0}^{\infty} y_b(x) \left|\frac{dG(x)}{dx}\right| dx$$

The integral can be evaluated numerically:

$$I = \int_0^{\infty} y(x) \left|\frac{dG(x)}{dx}\right| dx$$

$$I = \sum_{i=1}^{n} (y_{i-1}\, G_{i-1}(1 - \exp(m_i \Delta x_i)) - \frac{\Delta y_i}{\Delta x_i} G_{i-1}(\exp(m_i \Delta x_i)\left(\Delta x_i - \frac{1}{m_i}\right) + \frac{1}{m_i}))$$
$$= \sum_{i=1}^{n} (y_{i-1} a_i - \Delta y_i b_i)$$

$$\Delta x_i = x_i - x_{i-1}$$

$$\Delta y_i = y_i - y_{i-1}$$

$$m_i = \frac{ln(G_i/G_{i-1})}{\Delta x_i} \text{ for i = 1, 2, … n}$$

$$a_i = G_{i-1}(1 - \exp(m_i \Delta x_i))$$

$$b_i = \frac{G_{i-1}}{\Delta x_i}(\exp(m_i \Delta x_i)\left(\Delta x_i - \frac{1}{m_i}\right) + \frac{1}{m_i})$$

The equation gives an exact solution when y(x) and ln(G(x)) are linear between values of x

EAL_b = expected annualized building repair cost of new buildings

$$EAL_b = V_b \times EAD_b$$

EAL_c = expected annualized content repair cost in new buildings

$$EAL_c = V_c \times \int_{x=0}^{\infty} y_c(x) \left|\frac{dG(x)}{dx}\right| dx$$

EAN_{tc} = expected annualized number of occupants of new buildings who are trapped in collapsed buildings

$$EAN_{tc} = N_{AgOcc} \times \int_{x=0}^{\infty} y_{tc}(x) \left|\frac{dG(x)}{dx}\right| dx$$

EAL_{tc} = expected annualized cost of urban search and rescue efforts

EAN_{i5} = expected annualized number of people in new buildings in Riskscape casualty state "Dead"; the equation to calculate EAN_{ij} is shown in Section 11.2.2

$$EAL_{tc} = (EAN_{tc} + EAN_{i5}) \times V_{usar}$$

EAD_T = expected annualized number of days required to restore new buildings to functionality.

EAL_{BIOcc}= expected annualized time-element loss (both direct and indirect), by occupancy class; because values for direct and indirect output loss (V_{BI} and Q) vary by occupancy class.

EAL_{BIOcc} has to be calculated for each occupancy class separately and then aggregated separately for all residential and all non-residential occupancy classes using the equations below (aggregation of total present value of losses for residential and non-residential occupancy classes is done below).

$$EAD_T = \int_{x=0}^{\infty} y_T(x) \left|\frac{dG(x)}{dx}\right| dx$$

$$EAL_{BIOcc} = EAD_T \times \max\left(N_{Occ2am}, N_{Occ2pm}\right) \times V_{BI} \times (1 + Q)$$

$$EAL_{BIResOcc} = \sum_{ResOccs} EAL_{BIOcc}$$

$$EAL_{BINonresOcc} = \sum_{NonresOccs} EAL_{BIOcc}$$

$PV_{MonetaryAgOcc}$ = total present value of monetary losses in aggregate occupancy class

$$PV_{MonetaryAgOcc} = (EAL_b + EAL_c + EAL_{tc} + EAL_{BI}) \times \left(\frac{1 - \exp(-rt)}{r}\right)$$

The present value of human losses

EAN_{ij} = expected annualized number of people in new buildings with injury severity j

$$EAN_{ij} = N_{AgOcc} \times \int_{x=0}^{\infty} y_{ij}(x) \left|\frac{dG(x)}{dx}\right| dx$$

EAL_{ij} = expected annualized value of avoiding injuries of severity j

$$EAL_{ij} = EAN_{ij} \times V_{ij}$$

EAL_{PTSD} = expected annualized loss associated with PTSD

$$EAL_{PTSD} = EAN_{i3} \times V_{PTSD}$$

$PV_{HumanAgOcc}$= total value of deaths, injuries and PTSD in aggregate occupancy class

$$PV_{HumanAgOcc} = (EAL_{i1} + EAL_{i2} + EAL_{i3} + EAL_{i4} + EAL_{i5} + EAL_{PTSD}) \times t$$

12.3 TA-level benefits

PV_{AgOcc} = total present value of losses in aggregate occupancy class

$$PV_{AgOcc} = PV_{MonetaryAgOcc} + PV_{HumanAgOcc}$$

PV = total present value of losses in TA

$$PV = PV_{RES} + PV_{NONRES}$$

b_{TA} = total benefit (accumulated over the time duration t) associated with adopting the new building code for a year in a TA

$$b_{TA} = PV_{oldBC} - PV_{newBC}$$

12.4 TA-level costs

c_{TA} = marginal construction cost associated with constructing new buildings based on the new building code in a TA.

I_E = earthquake importance factor.

C_S = seismic response coefficient (design strength).

C = construction cost increase (per unit of I_E) as a percentage of total replacement cost of new buildings (the NIBS report uses 2% per unit of I_E above 1.0, or 2% for a 100% increase in strength and stiffness C_S –> C = 0.02).

$$c_{TA} = V_b \times C \times (I_e - 1)$$

$$c_{TA} = V_b \times C \times \frac{C_S' - C_S}{C_S}$$

12.5 TA-level BCR

$$BCR_{TA} = \frac{b_{TA}}{c_{TA}}$$

12.6 National-level BCR

$$B_{National} = \sum_{TAs} b_{TA}$$

$$C_{National} = \sum_{TAs} c_{TA}$$

$$BCR_{National} = \frac{B_{National}}{C_{National}}$$

13 Sensitivity tests

The NIBS Report conducts several sensitivity tests using the following parameters:

- Changing the discount rate – the proposed rates therein are 0% and 5% (with 3% as the baseline 3%).
- Varying the assumed economic life of a building – proposed for 50 and 100 years (with baseline 75 years).
- Varying the building replacement costs to 67% and 150% of baseline value.
- Adjusting vulnerability, similarly to 67% and 150% of baseline value.
- Assuming a construction cost increase of 67% and 150% of the baseline cost increase value.
- Probability at MCE_R level of shaking = 2 %.

Table 3 shows the outcomes of the NIBS report's sensitivity analysis related to designing to exceed 2015 I-Code requirements for earthquake and the BCR ranges associated with each tested parameter. As can easily be seen, the vulnerability and construction cost parameters were associated with the highest BCR ranges of 1.1, indicating that prioritizing acquisition of high-quality data for estimation of these parameters may be beneficial.

Table 3: BCR ranges associated with tested parameters in the NIBS report

Parameter	Values (baseline; lower; upper)	BCR range
Vulnerability (multiple of baseline value)	1.00; 0.67; 1.50	1.1
Construction cost (multiple of baseline value)	1.00; 0.67; 1.50	1.1
Discount rate	varies; 3%; 7%	0.9
Replacement cost (multiple of baseline value)	1.00; 0.67; 1.50	0.8
Economic life (years)	75; 50; 100	0.3

14 Conclusion

This report attempts to suggest a path for adopting the NIBS 2019 Report's methodology for assessing code changes, as they relate to higher standards for disaster risk reduction. While the NIBS Report analysed several hazards, we suggested an application that is specific to the new National Seismic Hazard Model changes (introduced in 2022) and their implications for building codes throughout Aotearoa New Zealand.

Significant pieces of the inputs required – specifically the vulnerability curves – are still not available for the local case, so we consider these lacunae as high priority for future research. Many of the other associated parameters and functions can be approximated well enough using the available data, or alternatively the NIBS parameterization may be appropriate by themselves.

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