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Benefit–Cost Analysis for Earthquake-Resilient Building Design and Retrofit: State of the Art and Future Research Needs

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Abstract: This paper reviews the state of the art in using benefit–cost analysis (BCA) to inform earthquake risk reduction decisions by building owners and policymakers. The goal is to provide a roadmap for the application and future development of BCA methods and tools for earthquake risk reduction. Our review covers three earthquake risk reduction measures: adopting up-to-date building codes for new construction, designing new buildings to exceed code requirements, and retrofitting deficient existing buildings. We highlight the factors that influence the cost-effectiveness of building design and retrofit, as well as tactics for increasing the cost-effectiveness of risk reduction strategies. We also present BCA results, methods, and data sources used in the literature to help researchers and practitioners design and conduct a reliable and robust BCA study. In the process, we develop a set of opportunities and challenges for applying BCA to new areas of research, as well as key gaps and limitations in current BCA approaches, including further investigation of above-code design, incorporation of code implementation and enforcement into BCA, quantification of environmental benefits of seismic retrofits, and optimization of seismic retrofits with energy upgrades. Overall, our review provides practical guidance and useful insights into BCA with the goal of increasing the earthquake resilience and economic efficiency of buildings in the United States. DOI: 10.1061/NHREFO.NHENG-1910.

Author keywords: Benefit–cost analysis (BCA); Earthquake risk reduction; Building codes; Seismic retrofit; Performance objectives.

Introduction

Benefit–cost analysis (BCA) is widely used in the engineering decision-making process for risk reduction. It evaluates future risk reduction benefits and compares the benefits to the investment costs. When the total benefit is greater than the total cost, the investment is considered cost-effective (FEMA 2009; Fung et al. 2022b). The evaluation criteria can be adjusted based on project needs and local policy requirements. In earthquake preparedness and mitigation practices, BCA has been utilized to determine the cost-effectiveness of adopting up-to-date building codes, designing buildings to exceed code requirements, and retrofitting deficient existing buildings, as illustrated in Fig. 1.

Building codes that reflect up-to-date construction methods and technologies can improve life safety and protect buildings from the effects of natural hazards (ICC 2022; FEMA 2020c). However, new codes can also lead to increased design, construction, and inspection costs, which may prevent state and local governments from implementing more stringent requirements (NEEP 2021; FEMA 1998). A recent study by the Federal Emergency Management Agency (FEMA 2020b) found that 65% of counties, cities, and towns in the United States have not adopted a modern building code [the 2015 and 2018 editions of the international codes (I-Codes)]. Compliance costs and mitigation savings are important considerations for code adoption (FEMA 2020a, b). Previous studies have examined whether compliance with new codes substantially increases construction costs compared to adherence to old codes (NAHB 2018), and whether the benefits of new codes outweigh the costs (NIBS 2019). These studies suggest that the value of adopting new codes in highly seismic regions is undisputed. However, there is a long-standing debate about the cost-effectiveness in regions with moderate seismic risk (Nikellis et al. 2019; Joyner and Sasani 2018; NEHRP 2013; Nordenson and Bell 2000).

Another area of research is the use of BCA to support above-code design. In the US, life safety represents the minimum code requirements that allow buildings to sustain extensive damage after an earthquake, as long as the buildings retain sufficient capacity to withstand aftershocks, and their nonstructural components do not pose a life-threatening hazard (ASCE 2017). However, in highly seismic regions, building codes cannot prevent costly repairs or loss of building functions and services after an earthquake (NIST 2021; Porter 2021; Sattar et al. 2018). This calls for above-code design to achieve higher performance objectives, such as functional recovery or immediate occupancy (Cook and Sattar 2022; Porter 2021;

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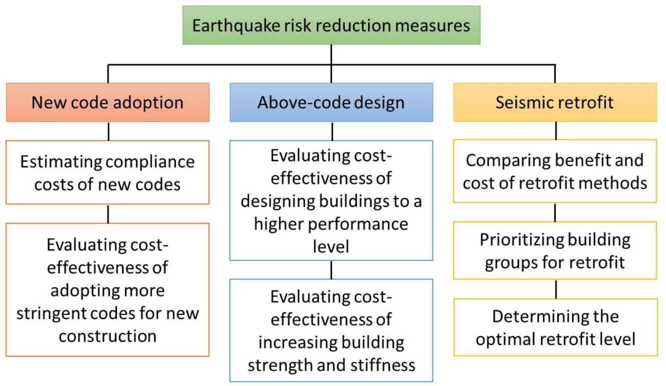

Fig. 1. Use of benefit–cost analysis in earthquake mitigation studies. White boxes enumerate example applications.

NIBS 2019; Kutanis and Boru 2014). Immediate occupancy means that a building remains safe for occupancy after an earthquake. Specifically, the structure retains its pre-earthquake strength and stiffness, and building access and life safety systems remain operational, but other nonstructural components may not function immediately (ASCE 2017). Functional recovery, which is under active development, is defined as "a post-earthquake performance state in which a building is maintained, or restored, to safely and adequately support the basic intended functions associated with its pre-earthquake use or occupancy" (NIST 2021). The key question addressed in the literature is whether designing buildings to exceed code requirements provides greater net benefits than conforming to existing codes (Fung et al. 2022a; NIBS 2019; Kutanis and Boru 2014; Porter et al. 2006). One of the themes that emerges from our review is that there are many gaps and research opportunities for the application of BCA to support investments in functional recovery design.

Furthermore, older buildings are more susceptible to earthquake damage due to structural deficiencies and deterioration (ATC 2010b). There is an extensive literature assessing the value of seismic retrofits in reducing casualties and building losses over the remaining life of the building or in the event of an unforeseeable large earthquake. The literature addresses questions such as: Is seismic retrofit more economical than demolition and replacement? Do currently available technologies allow older buildings to attain desired performance improvements at acceptable cost? Which strengthening method is most effective in terms of building performance and retrofit costs? Answering these questions helps inform policymaking and resilience planning for earthquake-prone communities (Paxton et al. 2017; Goettel 2016; Gibson et al. 2014). Another branch of research investigates the optimal level of retrofitting, either by minimizing life-cycle costs (e.g., Vitiello et al. 2017; Kappos and Dimitrakopoulos 2008) or by maximizing net present value (e.g., Galanis et al. 2018). The optimal level of retrofitting can be used to guide the design of cost-effective retrofits.

The objectives of this study are to (1) review the literature on BCA for building design and retrofits targeting different levels of seismic performance; (2) identify the factors that influence the cost-effectiveness of building design and retrofits; and (3) explore the opportunities and challenges of using BCA to support decision-making for earthquake-resilient buildings. To enhance the comprehensiveness of this review, we also include studies that delve into benefit analysis, cost estimation, or loss prediction, which are important components of BCA. Researchers may examine benefits or costs independently when significant uncertainties are associated with cost or benefit quantification (e.g., business interruption, community resilience, greenhouse gas emissions, indirect costs, and co-benefits) (Liel and Deierlein 2013; Hutt et al. 2016; Dong and Frangopol 2016; Haghpanah et al. 2017; ATC 2010a). On the other hand, when new design requirements are introduced to enhance life safety protection or secure emergency services, benefit analysis may be highly sensitive due to the incalculable value of human life and the immeasurable value of the services that save lives, and thus the focus shifts to the calculation of implementation costs and avoided casualty losses (Anagnos et al. 2016; Preston et al. 2019; Meade and Kulick 2007; DGS 2002). The goal of this review is to be comprehensive within the scope of our research questions, so there is no specific time period cutoff for publication.

Our review reveals that the key drivers of the cost-effectiveness of earthquake risk reduction are the building occupancy class (e.g., hospital, school, or residential and commercial), the location (e.g., high or moderate seismic hazard risk), and the performance target (e.g., life safety, immediate occupancy). In particular, decision makers often face a trade-off between the benefits and costs of a risk reduction measure, which increase with the performance target, and thus the highest level of performance is not always optimal in terms of benefits. Moreover, BCA results appear to be sensitive to other input assumptions, including the discount rate, planning horizon, and assumed cost of an earthquake risk reduction measure. Our review culminates in a series of identified opportunities and challenges for research. We discuss the need for methods, data, and validation for building-level BCA, regional BCA, and the allocation of benefits and costs among building stakeholders. Moreover, we highlight the importance and underutilization of uncertainty quantification, including sensitivity analysis, uncertainty propagation, and stochastic methods. We also identify four understudied areas of high potential and impact: BCA for above-code design, BCA for code implementation, environmental benefits of seismic retrofits, and optimization of seismic retrofits with energy upgrades. An important lesson from our review is that while BCA helps to enhance risk reduction decisions, final decisions should be made in a holistic context. The Unreinforced Policy Committee of Seattle (UPC 2017) stated that BCA provides valuable information for making policy recommendations. However, this analysis is not able to provide exact predictions of actual damage, nor provide exact estimates of benefits. Given these limitations, policy recommendations should be made based on all available information and within the context of the community rather than on a single analysis or model. Distributed BCA, which we identify as a research need, has the potential to support policy design by identifying potential equity issues arising from earthquake risk reduction. As with other available economic evaluation tools (Fung et al. 2022b), BCA has its strengths and weaknesses, and particular attention should be paid to the assumptions made to ensure the accuracy and reliability of such an analysis.

The next section describes the basic steps for performing a BCA. The section that follows presents our review of BCA for earthquake risk reduction, with a focus on analysis results, methods, and data sources. We then delineate the limitations of existing BCA approaches and research needs to improve the approaches for better accuracy and credibility. Our main contributions are presented in the following two sections, "New Methods and Research Needs" and "New Focus Areas and Research Needs," which elaborate opportunities and challenges in the application of BCA for earthquake risk reduction. Finally, we conclude with a summary of lessons learned and practical recommendations for the implementation of BCA.

Procedure for Benefit–Cost Analysis

Step 0: Set Analysis Parameters

Discount rate (r) is the rate of return used to discount future cash flows back to the present value. A typical discount rate is between 2% and 10% (Gibson et al. 2014). Planning horizon (T) is the future time period in years over which benefits and costs are counted. Planning horizon is typically between 50 and 75 years for new buildings (NIBS 2019) and 30 years for existing buildings after seismic retrofit (FEMA 2009).

The process of economic discounting for future damage (e.g., discount rate) tends to prioritize the well-being of individuals living today over those who will exist in the future (Lind 2007). From an equity perspective, all individuals should be treated as equals, regardless of whether they are currently alive or yet to be born (Lenton et al. 2023). Therefore, when the strategy being evaluated has long-term impacts on life and health, such as climate change mitigation, it is recommended to use nonconstant discount rates for analysis periods that extend beyond the planning horizon (Lind 2007), utilize distinct discount rates to adjust long-term benefits and investment costs (Welsh-Huggins and Liel 2018), or refrain from translating benefits into monetary terms (Lenton et al. 2023). Because earthquake risk reduction measures are effective within the relatively short planning horizon of buildings, applying the same discount rate to life-saving benefits and investment costs is preferable as indicated by many studies (Pate-Cornell 1984; Liel and Deierlein 2013; NIBS 2019).

Step 1: Estimate the Benefit, B_i, of Action i

This step requires first identifying assets that are sensitive to earthquakes and then estimating the relationship between the severity of expected losses and the level of ground shaking hazard. Benefits are estimated from the avoided losses under action i relative to the status quo

$$B_i = [EAL_0 - EAL_i] \sum_{t=1}^{T} (1 + r)^{-t} \tag{1}$$

where t = time starting from the year that a mitigation action is taken; and EAL_j = expected annual losses under action j, for $j = 0, \ldots, I$; where I is the set of actions, and is calculated as follows:

$$EAL_i = \int_0^{\infty} l|dp(l)| \tag{2}$$

where $p(l)$ = annual rate of exceedance for the loss l, given as follows (Krawinkler et al. 2006):

$$p(l) = \int_{dm} \int_{edp} \int_{im} p(l|dm)dp(dm|edp)dp(edp|im)dp(im) \tag{3}$$

where $p(x|y)$ = exceedance probability of x given y (e.g., survival function, the complementary cumulative distribution function); dm = damage measure (e.g., damage state); edp = engineering demand parameters (e.g., maximum drift); im = intensity measure (e.g., peak ground acceleration); and $p(im)$ = expected rate of return of the ground shaking hazard (e.g., hazard curve).

Direct benefits include avoided damage to buildings and contents, and avoided deaths and injuries. Indirect benefits may be economic or related to community resilience, social equity, and environmental sustainability, including avoided displacement and debris removal, loss of business or rental income, loss of life quality, loss of productivity, loss of customers, supply chain delays, reduction in employment, tax base, and affordable housing, among others (Fung et al. 2022b).

Step 2: Estimate the Cost, C_i, of Action i

The cost for alternative design is estimated as the difference in initial construction cost or life-cycle cost relative to the baseline. Initial construction cost may include material, labor, equipment costs, and contractor overhead and profits. Life-cycle cost is the total cost associated with building design and construction, building operation and maintenance, and building disposal at the end of the life cycle. The cost for seismic retrofit is a combination of structural and nonstructural improvement costs and may also include changes in maintenance costs (FEMA 2009; Fung et al. 2022b).

Step 3: Compare Benefits and Costs

Given estimates from Steps 1 and 2, one can distribute benefits and costs across stakeholders to obtain tiers of impacts (NIBS 2019; Fung et al. 2022a). Benefits and costs are compared using two metrics: benefit–cost ratio (BCR) and net present value (NPV)

$$\text{BCR}_i = B_i / C_i \tag{4}$$

$$\text{NPV}_i = B_i - C_i \tag{5}$$

where a $\text{BCR}_i > 1$ or $\text{NPV}_i > 0$ implies that the benefit of the action outweighs the cost.

Sensitivity analysis can be applied to examine whether the BCR shifts dramatically when inputs vary due to uncertainties in a building's useful life, inflation rate, benefit and cost assumptions, hazard level, and model simulations. It is often helpful to determine the sensitivity range for each input and identify the inputs most important to BCR estimation (Gibson et al. 2014; Fung et al. 2022a).

Use of Benefit–Cost Analysis in Earthquake Risk Reduction Studies

This section provides an overview of the methodologies employed in BCA studies and a summary of findings concerning the primary drivers of cost-effectiveness of earthquake risk reduction measures: code adoption, above-code design, and seismic retrofits. The literature selected here represents a collection of studies that share fundamental assumptions and research approaches and is not intended to be comprehensive. The conclusions about cost-effectiveness should be carefully interpreted because they depend on the assumptions made for benefit and cost estimation, the methods used to predict direct and indirect losses, and the reference cases. We especially encourage cautious interpretation of results from non-peer-reviewed studies.

Building Code Adoption

For new buildings, studies are regularly conducted to analyze the economic impacts of code changes. The economic impacts include reduced probabilities of property loss, death, and injury, population displacement, and business interruption in future earthquakes. Table 1 summarizes the literature on BCA for adopting new code requirements. At the national level, FEMA evaluated annual avoided losses for post-2000 buildings conforming to 2000 I-Codes (FEMA 2020a). The seismic requirements of 2000 I-Codes are equivalent to that of 1997 Uniform Building Code. The study combined damage functions from Hazus [a free geographic information

Table 1. Benefit–cost analysis methods for adopting or exceeding requirements of seismic codes

Study	Strategy	Performance objective[a]	Benefit	Cost	Analysis period	Method and data source
NIBS (2019)	Designing for 2018 I-Codes or exceeding 2015 I-Codes, compared with 1990s codes	LS and above	Avoided property loss, deaths, and injuries, direct and indirect business interruption, search and rescue	Assuming a 1% increase in cost with a 50% increase in strength and stiffness (Porter 2016)	75 years (2019–2094)	Hazus software, modified Hazus tabulated vulnerability functions, RSMeans cost data
NAHB (2018)	Designing for 2018 I-Codes, compared with 2015 I-Codes	LS	Not assessed	Added construction cost	Initial costs	RSMeans cost data, Census data, Bureau of Labor Statistics data, distributors' or retailers' websites
Nikellis et al. (2019)	Designing for ASCE 7-16 and AISC 341-10, compared with the criteria lower than ASCE 7-16	LS	Avoided structural and nonstructural damage	Added construction cost	50 years (2019–2069)	OpenSees software, PBEE approach, costs data from consulting firms and other studies
NEHRP (2013)	Designing for 2012 IBC, compared with 1999 SBC	LS	Reduced repair costs, fatalities, injuries, probability of collapse	Added construction cost	Annualized benefits; initial costs	PBEE approach, PACT software
Ryu et al. (2010)	Designing for 2009 NEHRP provisions, 2006 IBC, or 2003 IBC, compared with 1999 SBC	LS	Avoided structural and nonstructural damage	Not assessed	Annualized benefits	Memphis urban and adjusted national hazard curves, Hazus data
FEMA (2020a)	Designing for 2000 I-Codes (equivalent to 1997 UBC), compared with 1994 UBC	LS	Avoided physical and contents damage	Not assessed	Annualized benefits	Hazus software, CoreLogic parcel database, Microsoft footprint data
Kutanis and Boru (2014)	Designing for IO, compared with LS specified by Turkish seismic code TSC-07	IO	Annual losses (assuming no losses when buildings are designed for IO)	Added construction cost	Initial costs	Probina Orion software, Turkish governmental unit cost document

Note: LS = life safety; IO = immediate occupancy; NIBS = National Institute of Building Sciences; NAHB = National Association of Home Builders; I-Codes = the international codes; IBC = International Building Code; SBC = Standard Building Code; UBC = Uniform Building Code; NEHRP = National Earthquake Hazard Reduction Program; and PBEE = Performance-Based Earthquake Engineering.
[a]The performance objective applies to a building (group) under the design earthquake if no further specification.

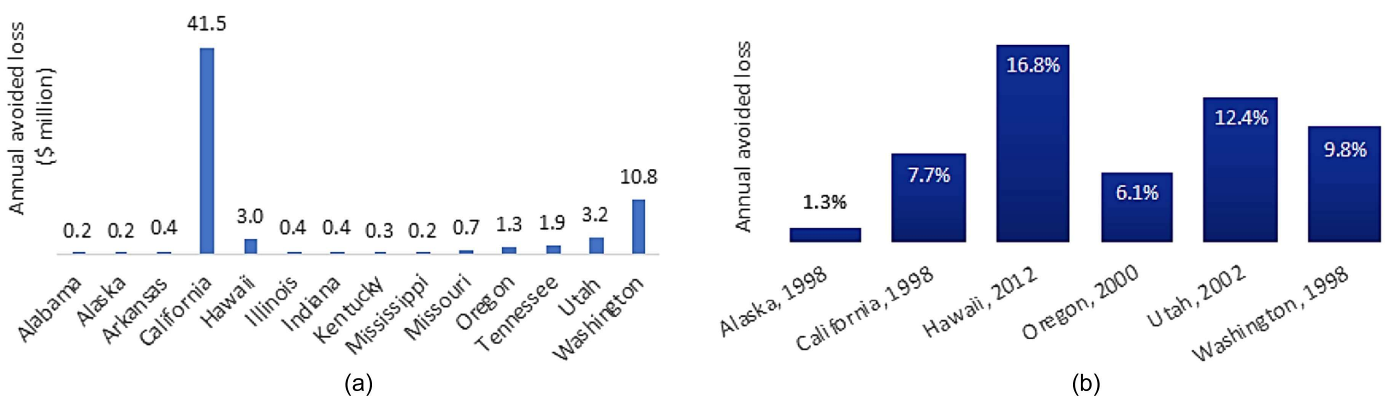

Fig. 2. Benefit and cost for adopting new seismic codes relative to 1990s codes: (a) benefit of adopting 2000 I-Codes in 14 earthquake-prone states; and (b) impact of adoption year for 2000 I-Codes on annual avoided loss, relative to the baseline replacement value. (Data from FEMA 2020a, 2017.)

system–based risk assessment tool developed by FEMA (2012)], parcel and building footprint data from multiple sources, and input from experts in building performance and building code history to develop detailed spatial loss estimates. The results show that annual avoided losses are significant for US states with high to moderate seismicity [Fig. 2(a)]. In highly seismic regions (Alaska, California, Hawaii, Oregon, Utah, and Washington states), an average 8% reduction in annual losses can be expected. The avoided losses are more pronounced in regions with higher seismic hazard (California), lower seismic design requirements (Hawaii), or both (Utah), as illustrated in Fig. 2(b). Similarly, the Multi-Hazard Mitigation Council (NIBS 2019) found that adopting the 2018 I-Codes for new construction in the 48 contiguous United States can result in a BCR of 12 compared to 1990s seismic codes. Specifically, implementing the 2018 I-Code requirements for earthquake can prevent annual property losses of $1,500 per building in 2018 US dollars, reduce annual deaths, injuries, and trauma-related losses by $800 per building, and lower annual business interruption losses by $2,000 per building (NIBS 2019). Other national-level studies focus on evaluating compliance costs. The goal of such studies is to demonstrate that the marginal cost of complying with the newer code is not very large relative to an earlier code (e.g., NAHB 2018). Such studies naturally raise the question of the need to adopt new seismic standards in regions of moderate seismic risk. For instance, the middle Mississippi River Valley region experienced very large earthquakes in the past but no damaging earthquakes in recent decades (NEHRP 2013; Nordenson and Bell 2000). The National Earthquake Hazards Reduction Program (NEHRP 2013) assessed the benefits and costs of adopting the 2012 International Building Code (IBC) in Memphis, Tennessee, relative to the 1999 Standard Building Code (SBC). A major conclusion of their study is that the compliance costs are low, but the benefits associated with the improved design are significant. However, Stein et al. (2003) estimated that the total compliance cost for the 2000 IBC ($200 million=year in 2001 US dollars) is an order of magnitude greater than the total benefit ($17 million=year) and argued that buildings in Memphis should not be designed to the same level as in California because of lower seismic hazard. Ryu et al. (2010) also showed that designing new commercial buildings in Memphis to the 2003 IBC, 2006 IBC, or 2009 NEHRP provisions has little effect on expected annual losses (EALs) relative to the 1999 SBC. The controversy between NEHRP (2013) and the two studies is due to different versions of seismic hazard maps used, building types analyzed, and benefit elements considered. Similar debates exist in Charleston, South Carolina, and Boston, where recent seismic activity is minor but magnitude 7 or larger earthquakes struck the regions in the past (Nordenson and Bell 2000; Nikellis et al. 2019; Joyner and Sasani 2018).

A potential gap in such studies is the absence of co-benefits, which accrue even in the absence of a hazard event during the planning period (Fung and Helgeson 2017). A few studies have evaluated the co-benefit of seismic codes on wind mitigation. Nikellis et al. (2019) analyzed steel moment frame (SMF) office buildings in two US cities and found that ignoring wind-induced losses in Los Angeles can lead to a 32%–62% underestimation of EAL for 40-story buildings. Ignoring earthquake-induced losses in Charleston, South Carolina, can result in a 33% and 29% underestimation of EAL for 30-story and 40-story buildings, respectively. However, Joyner and Sasani (2018) indicated that the co-benefit is negligible in earthquake or wind-controlled regions. Wind damage accounts for 5% of the total EAL for a 7-story concrete building in San Francisco (earthquake-controlled). Earthquake damage accounts for 1% of the total EAL for a 7-story concrete building in Boston (wind-controlled). The controversy between the two studies is mainly due to different building heights and structural types analyzed, and further research is needed.

Unlike many studies that assess benefits based on predicted building performance, a few studies have used historical insurance data to evaluate avoided losses due to the implementation of a building code (e.g., Simmons et al. 2020, 2018). This approach compares paid insured losses before and after code implementation, facilitating regional-level impact assessment. A caveat is that buildings built after the enactment of the code are assumed to comply with the code, whereas in practice, buildings may be built to lower or higher standards, depending on code enforcement, quality control, and owner requirements for safety and resilience. Moreover, this method is more suitable for frequent natural hazard events such as hurricanes because it requires comparable events in intensity or magnitude before and after code implementation.

Above-Code Seismic Design

Several studies have assessed the benefits and costs of above-code seismic design (Table 1) and found it to be a cost-effective option (NIBS 2019; Kutanis and Boru 2014). Specifically, the Multi-Hazard Mitigation Council (NIBS 2019) estimated that buildings above the 2015 IBC requirements could result in a national average BCR of 4, relative to 1990s seismic codes, meaning that $4 can be saved for every $1 spent to make new buildings stronger and stiffer. To achieve greater building strength than required by the 2015 IBC, the Multi-Hazard Mitigation Council assigned the buildings a higher importance factor than specified by the 2015 IBC. The vulnerability functions used in Hazus were also modified to reflect the increased strength and stiffness of the buildings. Likewise, Kutanis and Boru (2014) recommended adjusting the performance target of residential buildings to immediate occupancy in Turkey, where 71% of the land is located in high seismicity zones. Kutanis and Boru (2014) designed six benchmark residential buildings of three heights and two structural systems (infilled frame and dual system), and estimated that construction costs could increase by 4.2%–11.2% for 3-story buildings, 21.2%–28.8% for 6-story buildings, and 20.7%–27.4% for 10-story buildings built to the immediate occupancy level relative to the life safety level. The expected annual cost increase for new construction is comparable to the historical annual loss from earthquakes, meaning that the BCR is greater than 1, assuming no loss in the immediate occupancy scenario.

Seismic Retrofits for Older Buildings

There is an extensive literature on evaluating the economic value of seismic retrofits for existing buildings. A major focus is on bringing existing residential and commercial buildings up to the life safety standard. Another focus is on improving the performance of hospitals and schools to the immediate occupancy level in the event of a major earthquake. Given that much of the variation is across structural systems and risk categories, we present our review by building type. Table 2 summarizes the methods employed in the literature for evaluating retrofit strategies applicable to hospitals, schools, and residential and commercial buildings.

Hospitals (Risk Category IV)

Following the 1994 Northridge earthquake, California passed Senate Bill (SB) 1953, which required that the state's hospitals not only maintain structural integrity but also continue operations after an earthquake. Meade and Kulick (2007) estimated that the cost for 2,484 hospitals to comply with SB 1953 could be as high as $41.7 billion in 2006 US dollars. Preston et al. (2019) updated the cost analysis with respect to the 2030 deadline for ensuring post-earthquake operational performance. The estimated compliance costs are still outstanding between $34 billion and $143 billion in 2019 US dollars. These figures demonstrate that improving the performance of existing hospitals to the immediate occupancy level can incur significant costs. However, investing in higher performance can shorten payback periods and increase the overall benefit of risk mitigation. Ghesquiere et al. (2006) estimated that for hospitals in Bogota DC, Colombia, the annual rate of return could be 19.1% for basic structural reinforcement, but 32.8% for comprehensive mitigation that enables hospitals to remain functional during and immediately after a seismic event. Notably, the avoided deaths due to retrofits include not only patients and staff at the hospital but also lives saved because hospitals are able to

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