RESETTING THE ECONOMICS OF SEISMIC STRENGTHENING IN AREAS OF LOWER SEISMICITY

T. Paret(1), G. Searer(2), K. Klaboe(3), H. Proctor(4)

(1) Senior Principal, Wiss, Janney, Elstner Associates, Inc., tparet@wje.com
(2) Principal, Wiss, Janney, Elstner Associates, Inc., gsearer@wje.com
(3) Senior Associate, Wiss, Janney, Elstner Associates, Inc., kklaboe@wje.com
(4) Associate II, Wiss, Janney, Elstner Associates, Inc., hproctor@wje.com

Abstract

Although balancing safety and economics has traditionally been at the core of all engineering, in earthquake engineering, the scales have recently been tipped heavily toward safety. This paper seeks to identify some of the reasons for this divergence and provides recommendations to re-establish the balance that has been lost.

While seismic design requirements throughout the United States (US) are ostensibly anchored to a 2,475-year return period event and design lateral forces are required to be computed as a fixed fraction of the accelerations associated with this event, the code is opaque regarding the fact that the code-computed design forces are actually associated with something other than the 2,475 event. In fact, the resultant return periods that are associated with code-computed design forces vary significantly on a regional basis, with structures in areas of lower seismicity being required to be designed for more rare earthquake events than similar structures in areas of higher seismicity. The economic burden of seismic strengthening has thereby become disproportionately greater and unreasonable in areas of lower seismicity. We develop and present herein the notion of an "effective return period" to illustrate these regionally-specific design return periods and to show that design lateral force procedures that require design forces to be computed as some fraction of a pre-defined earthquake return period have irrational and uneconomical consequences for both new design and for assessment and strengthening of existing buildings when the code method of quantifying seismic demands is used.

Where damaging earthquakes occur more frequently, existing structures are more likely to experience potentially damaging shaking during their remaining useful life than structures in areas of lower, infrequent, seismicity that may never experience any potentially damaging shaking before they are demolished. The decreased likelihood of intense shaking in regions of lower seismicity ought to influence how existing structures are treated there, but today's codes confoundingly require effectively longer-return-period, rarer events for seismic design of buildings in regions of lower seismicity than for buildings in regions of high seismicity because the code methodology does not adjust for regional differences in hazard curve shapes.

The single-minded focus on the assurance of good performance for a design event tilts the scale against economic reasonableness in other ways as well. Existing structures have some degree of inherent lateral resistance, regardless of their era of design, whether designed to conform to any of the US codes in the twentieth century, or whether they are pre-code. Most of these structures have adequate lateral resistance without intervention, despite that they assuredly do not comply with the seismic design requirements in recent codes. Direct evidence for this is abundant; the 2011 Mineral Virginia earthquake, among others, demonstrated the seismic adequacy of a wide variety of extant structure types and vintages throughout densely populated areas of lower seismicity regions of the US, meaning that economy is furthered when these inventories of structures are recognized as not being high priority subjects for wholesale upgrading.

Annualized economic loss estimates from the US Federal Emergency Management Agency (FEMA) also strongly support the modulation of wholesale strengthening in regions of lower seismicity and provide an economic basis for limiting strengthening to only the most vulnerable portions of the most vulnerable buildings in regions of lower seismicity, and not strengthening any buildings at all in some regions.

This paper presents the results of various studies that will help engineers and policymakers prioritize where seismic risk mitigation is cost-effective and where it is not.

Keywords: effective return period; annualized economic loss; strengthening triggers; IEBC

1. Introduction

The economics of seismic strengthening of buildings in regions of lower seismicity in the United States (US) have not been widely discussed or studied, though the presence of non-negligible seismic hazards throughout much of the country is generally recognized by the earthquake engineering community. Code development, policymaking, and engineering decision-making regarding risk reduction in regions of lower seismicity ought, however, to consider the economics of the problem. Three subtopics explored herein are especially relevant to this general subject. First, the code methodology for calculating seismic forces for design leads to inconsistent "effective return periods" that vary widely across the US, which is inconsistent with the notion that all seismic design in the US is predicated on a 2,475-year hazard. These inconsistencies penalize lower seismicity areas by requiring the design forces in those areas to be based on more rare events than in regions with greater seismicity. The authors believe that this is not generally understood by the engineering community. Second, FEMA's annualized economic loss estimates for cities around the US demonstrate that community-wide seismic strengthening does not "pay for itself" within the economic life of most existing structures, which by itself may undercut the rationale for strengthening many existing buildings. Third, empirical data from the 2011 Mineral earthquake—which subjected a huge inventory of existing pre-code and noncompliant buildings to design-level and maximum considered earthquake level (MCE-level) shaking—demonstrates that the inventory in these and similar regions is generally adequate to protect life-safety without any seismic improvements.

2. Effective Return Period and the Myth of Uniform Hazard

With the adoption of the *International Building Code* (IBC) and ASCE 7-98 *Minimum Design Loads for Buildings and Other Structures*, but unbeknownst to most designers even today, seismic design requirements in the US transitioned away from the uniform hazard-based philosophy that had underlain the code for decades. That transition was subsumed under a more widely recognized change to the nation's seismic design requirement that these, and other contemporary publications, explicitly discuss; namely, a revision to the codified mapped seismic risk from earthquake ground motions having a probability of exceedance of 10 percent in 50 years (i.e., the 475-year return period event) to motions having a probability of exceedance of 2 percent in 50 years (i.e., the 2,475-year return period event, otherwise known as the maximum considered earthquake, or MCE). The revision to the return period was significant but relatively transparent compared to the less obvious transition that resulted from the introduction of a uniform scale factor of 2/3, which these documents mandated be applied to the 2,475-year spectral accelerations to derive accelerations for the design basis earthquake, otherwise known as the DBE. While we find that far-reaching practical consequences arose from the introduction of this scale factor, these consequences are not explicitly described in the IBC, ASCE 7, or other contemporary documents. The absence of any narrative describing this transition suggests that these consequences were inadvertent and were an unintended by-product of what the writers understand was an intent to maintain parity in the seismic design forces to be used in California before and after the adoption of the new criteria. Indeed, the results of our analysis of the codified seismic design requirements for major cities across the US reveals fundamentally haphazard outcomes with respect to what we term the "effective return period" for the design earthquake. The transition of import associated with the adoption of these documents is therefore one in which the US moved from a seismic design philosophy that utilized a relatively uniform hazard across the US to one in which the seismic hazard was merely articulated as a uniform hazard but was actually defined on a community-specific basis and is decidedly not uniform. If decision-making about seismic strengthening (e.g., whether to strengthen a building or inventory of buildings, and the level of strengthening that is appropriate to target) is to be based on rational principles, the difference is critical for design professionals and municipal authorities to understand.

The concept of an effective return period provides a useful method for comparing and understanding the seismic hazards that are required by the IBC and ASCE 7 in design. This study expands a previous study by the writers that evaluated the effects of transitioning to a 2,475-year return period event for five locations in the US [1]. In the current study, we define "effective return period" as an effective probability of exceedance over a specific duration of time. For this study, we derived effective return periods for nine locations in the US, representing areas of low, moderate, and high seismicity. Five of the locations selected for the current study were also evaluated in the previous study. Locations of low seismicity are assumed to have both relatively low design spectral response parameters and low frequency of damaging events, and locations of high seismicity are assumed to have both relatively high design spectral response parameters and high frequency of damaging events. Locations of moderate seismicity lie between these extremes.

Calculations of effective return periods were performed based on the hazard curves for each location, which were obtained using the USGS Unified Hazard Tool [2] and adjusting the geometric mean values to obtain maximum response. Specifically, the effective return period for each location was derived by plotting the hazard curve for that location, multiplying the 2,475-year return period values (i.e., MCE event) by 2/3 as has been required for design by US codes over the past two decades, and re-entering the hazard curve to obtain the return period associated with this reduced value. The procedure is depicted in Fig. 1 for the city of Charleston, South Carolina, which is located in an area of moderate seismicity. The figure demonstrates that the effective return period associated with the required design acceleration in this location (i.e., 2/3 times the 2,475-year earthquake spectral acceleration) is roughly 1,300 years. By repeating this simple operation for each of the nine cities whose hazard curves are depicted in Fig. 2, which itself emphasizes the differences in the shape of each curve, we derived the results in Table 1. The MCE values in the second column are based on ASCE 7-98 [3]. The MCE_R values in the fourth column were calculated in the current study and are based on ASCE 7-16 [4]. We performed these calculations for both the MCE and the MCE_R because the codes in the US evolved from reliance on the MCE to reliance on a risk-adjusted MCE, referred to as the MCE_R, beginning with the adoption of ASCE 7-10. Buildings throughout the US have been designed using one method or the other, depending on the code governing at the time of design. In both the second and the fourth columns, the effective probabilities of exceedance are also provided parenthetically after the effective return period. We note that only one deterministically capped location is included in Table 1: Oakland, California. The values in the third column were taken directly from the hazard curves.

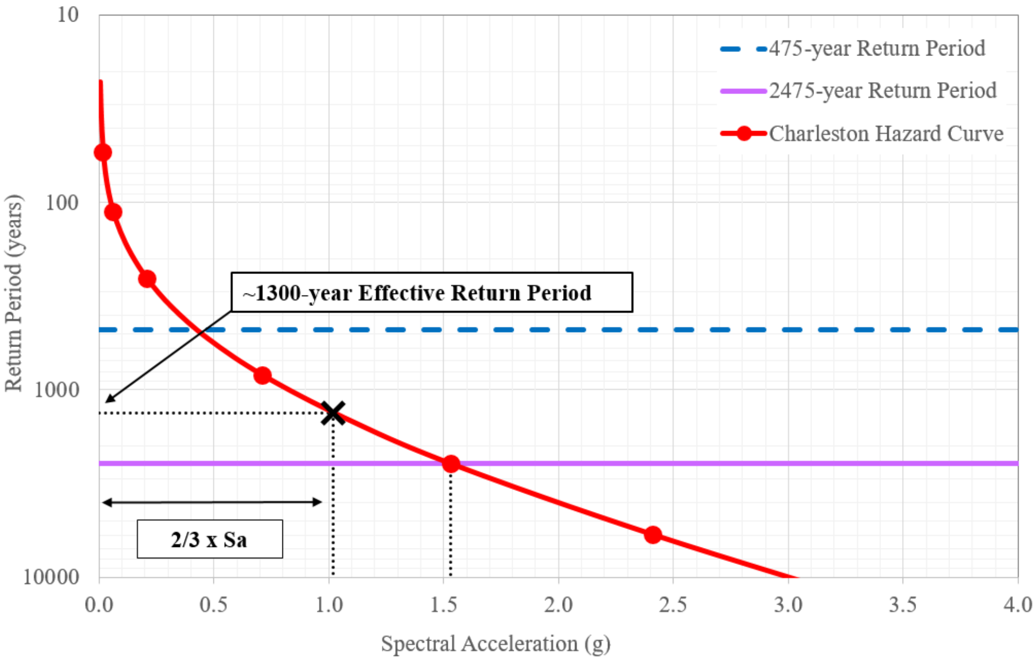

Fig. 1: Charleston, South Carolina hazard curve adjusted for maximum response. The spectral acceleration for the 2,475-year return period (1.53g) multiplied by 2/3, yields a spectral design acceleration of 1.02g, which is associated with a 1,300-year effective return period.

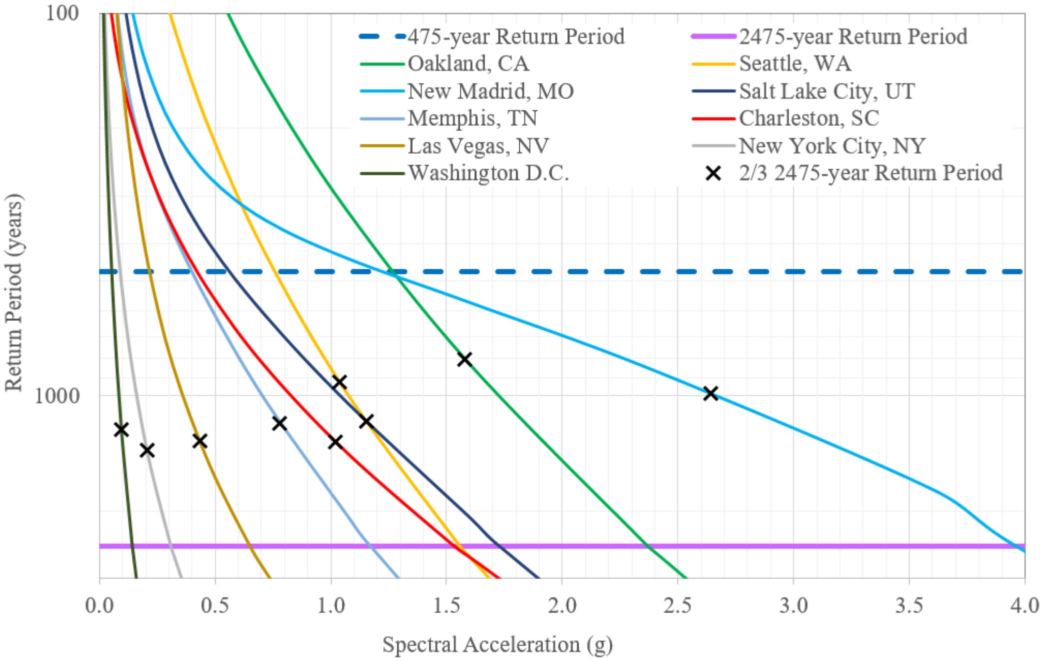

Fig. 2: Hazard curves for nine US cities adjusted for maximum response.

Table 1: Effective Design Return Periods and Probabilities of Exceedance in 50 years.

Location	Effective Design Return Periods and Probabilities of Exceedance in 50 Years			
	2/3 x MCE[1]	MCE_R[2]	2/3 x MCE_R[2]	1/2 x MCE_R
Oakland, CA[3]	600 (8% in 50yrs)	990 (5% in 50yrs)	380 (12% in 50yrs)	210 (21% in 50yrs)
Seattle, WA	1200 (4% in 50yrs)	1880 (3% in 50yrs)	730 (7% in 50yrs)	400 (12% in 50yrs)
New Madrid, MO	1600 (3% in 50yrs)	1330 (4% in 50yrs)	730 (7% in 50yrs)	560 (9% in 50yrs)
Salt Lake City, UT	1100 (4% in 50yrs)	1790 (3% in 50yrs)	930 (5% in 50yrs)	640 (8% in 50yrs)
Memphis, TN	-	1880 (3% in 50yrs)	960 (5% in 50yrs)	650 (7% in 50yrs)
Charleston, SC	1550 (3% in 50yrs)	1920 (3% in 50yrs)	1070 (5% in 50yrs)	750 (6% in 50yrs)
Las Vegas, NV	-	2080 (2% in 50yrs)	1120 (4% in 50yrs)	730 (7% in 50yrs)
New York City, NY	-	2240 (2% in 50yrs)	1270 (4% in 50yrs)	860 (6% in 50yrs)
Washington D.C.	-	2200 (2% in 50yrs)	1100 (4% in 50yrs)	680 (7% in 50yrs)

[1] Approximate effective return periods for the DBE at select locations based ASCE 7-98
[2] Effective return periods for the MCE_R and DBE at nine locations in the US based on ASCE 7-16
[3] The location selected as representative of Oakland, California was deterministically capped.

From the tabulated values, it is clear that the effective return periods for the DBEs that are required to be used for design vary widely by location. While the one deterministically capped effective return period is well below 475 years, the others range from slightly more than 700 years to almost 1300 years, with many well in excess of 1000 years. The effective probability of exceedance for these locales varies from 12 percent in 50 years to 4 percent in 50 years. It is therefore not accurate to describe seismic design across the US as uniform, either in terms of return period or hazard, and presumably not risk, although this paper is not directly addressing the writers' many concerns about the concept of "risk adjusting" of the MCE to obtain the MCE_R. The location-based disparity is a direct consequence of applying a scalar, in this case the 2/3 multiplier, to hazard curves having differing shapes (Fig. 2). It is also clear from the tabulated values that cities in lower seismicity areas are required to employ effective return periods that are longer than for cities in higher seismicity areas, meaning that, confoundingly, cities for which seismicity ought to be of less concern are actually required to design for less frequent, more rare, events, than cities with far more substantial seismic hazards, thus effectively penalizing locations of lower seismicity for having smaller hazards. We are unaware of any published justification for either the mentioned disparity or for this penalty and it seems unlikely that either resulted from a rational deliberative process, and yet this has been the law of the land in the US for two decades. Table 1 also illustrates that the evolution of the ASCE 7 design requirements from the MCE to the MCE_R did little to rectify this discrepancy.

Although the IBC and ASCE 7 are specifically applicable to new structures and are specifically not applicable to existing structures, the requirements in these documents are also frequently employed for assessment and strengthening of existing structures. Underlying reasons for the application of these documents to existing structures vary widely. The writers are aware of instances when stakeholders or the authority having jurisdiction have required the structure to provide the same degree of seismic adequacy provided by new structures, as well as instances when designers simply default to applying these documents because they are already familiar with these documents from their day-to-day practice. In the US, however, alternatives to these documents exist when the subject of scrutiny is an existing structure. These alternatives include ASCE 41 and the *International Existing Building Code* (IEBC), both of which allow for a reduced level of seismic resistance. Rather than applying a scalar multiplier such as 2/3 to the MCE, ASCE 41 specifies that earthquakes with defined return periods of 225 years (20% in 50 years) and 975 years (5% in 50 years) be used for assessment and strengthening of existing buildings, the BSE-1E and the BSE-2E, respectively. By mandating consistency across all geographic regions, regardless of local seismicity, this approach avoids the pitfalls of applying the IBC and ASCE 7 to existing structures; however, ASCE 41 has its own problems, and even new buildings can have difficulty “passing” ASCE 41 checks. The IEBC is a document that is intended to be applied to existing structures that are undergoing alteration or damage repair. For structures requiring repair of structural damage that exceeds certain thresholds defined within the document, the current edition of the IEBC specifies lateral design forces that are three-quarters of the ASCE 7 design value, which equals one-half of the MCE_R (i.e., $3/4 \times 2/3 = 1/2$). The fifth column of Table 1 presents the effective return periods and effective probabilities of exceedance for this value, computed consistent with the methodology described above for the same nine cities. The effective return periods and probabilities of exceedance so computed range from roughly 200 years to more than 850 years and from 21 percent in 50 years to 6 percent in 50 years, respectively. Again, the slopes of the respective hazard curves and the application of a scalar to the 2,475-year return period value cause location-to-location variability that is irrational from the writers’ perspective.

3. FEMA Annualized Earthquake Loss

In the late 1990s, the US Federal Emergency Management Agency (FEMA) studied the economic risks posed by earthquakes in the US, with a primary focus of the study being to provide a method for comparing seismic risk across different regions in the country. The findings from FEMA’s initial study were published in the FEMA 366 report entitled, “HAZUS®99 Estimated Annualized Earthquake Losses for the United States” [5]. Since the publication of that report, FEMA has completed two additional studies that updated loss estimates nationwide, with the most recent study completed in 2017 and reported in FEMA P-366 [6]. Two primary risk indicators were included in the study:

- **Annualized Earthquake Loss (AEL)**: The AEL is defined as the estimated long-term cost of earthquake damage to the inventory of existing buildings in a specific geographic area (e.g., state or metropolitan area) on a per-year basis (i.e., annualized).
- **Annualized Earthquake Loss Ratio (AELR)**: The AELR is calculated as the AEL divided by the replacement value of the building inventory and expressed as a ratio of dollars of damage to dollars of inventory.

Risk indicators were calculated for all 50 US states (and some territories) in FEMA's study. Fig. 3 is a FEMA-generated map of the US that is color-coded to reflect the AELR for each state (or territory) in terms of annualized earthquake dollars of damage per million dollars of building inventory. It is important to recognize that the color-coded scale used in this figure is nonlinear and biased towards smaller AELRs, as the scale is not incremented uniformly. The use of a nonlinear color scale that is weighted towards smaller AELRs tends to obscure the relative hazard posed in each area and detracts from the meaningfulness of data.

To obtain a better understanding of the relative risk, we revised FEMA's map to reflect AELR based on a different color scale having five uniform increments, with each increment being 220 dollars of annualized damage per million dollars of building inventory, as shown in Fig. 4. The AELRs on this map are therefore plotted as a function of five uniformly divided ranges of AELR. Although the lowest increment of AELR plotted in Fig. 4—from $0/$1,000,000 to $220/$1,000,000—subsumes roughly 5.5 increments used by FEMA in Fig. 3, we view this increment as representing negligible overall economic risk. The resulting map demonstrates that the vast majority of the geography of the US has a negligible overall economic risk of damage from earthquakes, with only eight states and one territory having an AELR greater than $220 of annualized earthquake loss per $1,000,000 of construction.

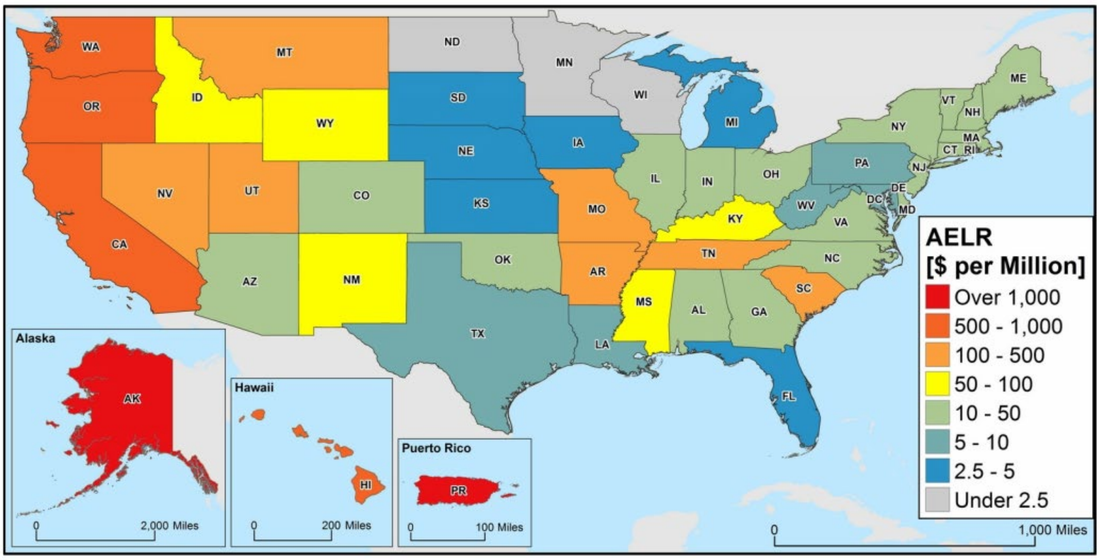

Fig. 3. Annualized Earthquake Loss Ratios by State [6]

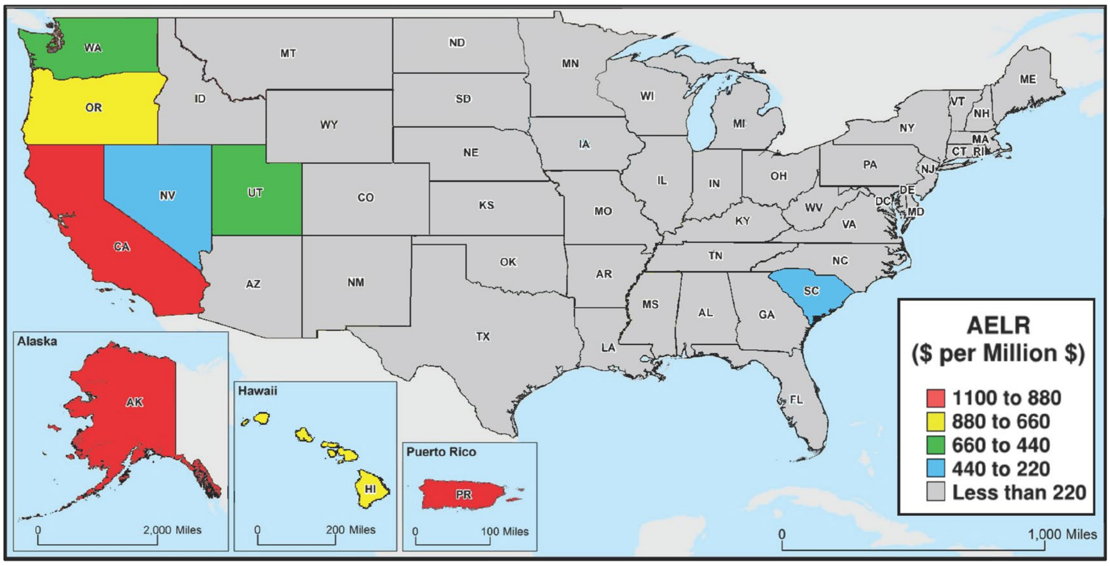

Fig. 4. Recolored Annualized Earthquake Loss Ratios by State (modified from FEMA P-366 [6])

3.1 What Does Annualized Estimated Loss Ratio Mean with Respect to Larger Buildings?

Although there are some limitations to doing so, the hazards posed by earthquakes can also be visualized on a per-building basis; these limitations are similar to those associated with using HAZUS-type models to generate probable maximum loss estimates. Using AELR values, which FEMA has also reported by metropolitan area, we studied the potential economic exposure for an "average" building, say an office building, with a replacement value of $20 million in the nine selected cities in the study. Using the AELR for each of the selected metropolitan areas, we computed the average annualized loss for the "average" building by multiplying the AELR by the value of the building, which produces an estimate of the average annualized economic loss for that building, with the annualized economic loss stemming from physical damage, and not, for example, business interruption. We based our calculations on an assumption that an "average" existing property may have about 20 years remaining in its life until it is either demolished or undergoes a significant renovation. Understanding that 20 years may overstate or understate the actual remaining life of any particular building, but based on a 20-year assumption, we also computed a cumulative loss estimate for that period of time by multiplying the average annualized loss by this 20-year exposure period. Table 2 shows the results of this analysis.

Table 2: Economic Risk Posed by Earthquakes for Nine Selected Cities.

Location	AELR [$ per Million]	Average Annualized Loss Estimate	Average 20-year Loss Estimate
Oakland, California	$1,437	$28,740	$574,800
Charleston, South Carolina	$977	$19,540	$390,800
Seattle, Washington	$704	$14,080	$281,600
Salt Lake City, Utah	$633	$12,660	$253,200
New Madrid, Missouri	$631	$12,620	$252,400
Memphis, Tennessee	$434	$8,680	$173,600
Las Vegas, Nevada	$182	$3,640	$72,800
New York, New York	$29	$580	$11,600
Washington D.C.	$8	$160	$3,200

From the table, an average $20 million office building in Oakland, which has the highest tabulated AELR, would have an annualized loss of about $29,000, or 0.15 percent. Over a 20-year exposure period, the average cumulative risk to the average $20 million office building from earthquake damage is about $575,000, or 2.9 percent of replacement cost. In fact, FEMA represents that Oakland has one of the highest economic risks of any metropolitan area in the US. A similar average $20 million office building located in the middle hazard range occupied by the Seattle, Salt Lake City, and the New Madrid areas, would have an annualized loss of about $13,000, or 0.07 percent and a cumulative economic risk of physical damage of only $260,000, or 1.3 percent of replacement cost. In our experience, this risk would be considered quite low, bordering on negligible. Similar buildings in cities with the lowest hazard in this study, New York City and Washington D.C., for example would have an annualized loss on the order of only a few hundred dollars, or 0.003 percent, and have a 20-year cumulative loss of less than $12,000, or 0.05 percent of replacement value – a negligible risk by any standard.

While more sophisticated numerical analysis methods can be applied, we opted to use these values to render qualitative judgments about the economic reasonableness of seismically strengthening the average $20 million office building in these metropolitan areas. Given that in Oakland, cumulative 20-year risk is $590,000 while the cost of strengthening of the same hypothetical building could easily cost several million dollars, seismic strengthening of this building likely makes little economic sense unless the building is highly likely to perform significantly worse than an average building.

In areas of moderate seismicity like Seattle or Salt Lake City, with an average cumulative economic risk of only about $260,000 for that same $20 million office building, it would be difficult to justify seismic strengthening from a purely ‘cost of physical damage’ perspective when an upgrade is likely to cost an order of magnitude greater than the cumulative loss. In these areas, perhaps focusing on strengthening only the most vulnerable parts of the most vulnerable buildings make sense.

In areas of low seismicity like New York City and Washington D.C., with a 20-year cumulative exposure of $12,000 or less for the average $20 million office building, it appears unreasonable for seismic strengthening of such buildings even to be in the discussion since most seismic strengthening activities—except perhaps strengthening only the most vulnerable parts of the most vulnerable buildings—will never come close to paying for itself. In fact, with the exception of Charleston, South Carolina, the entire eastern seaboard of the US—including Baltimore, Maryland; Boston, Massachusetts; Jacksonville, Florida; Miami, Florida; New Haven, Connecticut; New York, New York; Philadelphia, Pennsylvania; Portland, Maine; Richmond, Virginia; Washington, D.C.; and Wilmington, North Carolina—has minimal to no economic justification for seismically strengthening anything but the most vulnerable parts of the most vulnerable buildings. In these areas, a building would need to have highly unique characteristics for seismic strengthening to be economically justifiable. Empirical evidence derived from the 2011 Mineral earthquake, presented below, confirms the validity of this conclusion.

To further emphasize the point, it is important to note that comparing the cost of seismic strengthening with the average cumulative risk of physical damage loss as we have done in the prior examples overemphasizes the beneficial results from seismic strengthening, since it is incorrect to equate seismic strengthening with elimination of all damage. In reality, seismically strengthened buildings are still likely to experience significant repair costs from large earthquakes, even if in the best case those repairs are limited to nonstructural elements. Therefore, the time needed to recoup the cost of a seismic strengthening project is likely much longer than the cost of strengthening divided by the average annual risk.

3.2 What Does Annualized Estimated Loss Ratio Mean with Respect to Single-Family Homes?

We also used the AELR to evaluate the risk to single-family houses, and the economic argument for or against strengthening them. California overall has one of the highest AELRs—$971 per $1,000,000 in value. At the time of writing this paper, the median price of a home in California is about $600,000 USD [7]. Assuming that about half of that price is the cost of the land and half is the cost of the structure, then the cost of the average home structure in California is in the range of about $300,000. With an AELR of $971, the average annual loss is only $291 for the average home in California. The cost of having a contractor seismically strengthening just the crawlspace of a home built prior to the Northridge earthquake, however, can easily be $7,000 to $10,000, so the house would need to be owned for more than 37 years before seismic strengthening would “pay off” *on average*. As was mentioned in the discussion above for office buildings, these comparative costs are biased in that retrofitting of a crawlspace is highly unlikely to preclude all damage in the remainder of the structure, meaning that the calculated pay-off time frame is unrealistically low.

That said, relying on AELRs for making decisions about strengthening any individual home is problematic, because an individual home is likely to represent a significant portion of a homeowner’s assets, and significant damage to any particular home could be financially ruinous. In California, earthquake insurance is often discussed as a way to reduce that risk.

In California, earthquake insurance costs an average of about $800 per year and has deductible of 5 to 25 percent [8]. With a 15-percent deductible, for example, the damage for the average home structure discussed above would have to exceed $45,000 before the policy would cover any losses. While the writers doubt that California homeowners are relying on the AELR and performing calculations like these, there appears to be a general perception that earthquake insurance is not cost-effective, potentially explaining why only about one million Californian homes have earthquake insurance and eleven million do not [8].

3.3 Use of Annualized Estimated Loss Ratio for Large Inventories of Buildings

While using AELRs for making decisions about seismic strengthening on a per-property basis can be problematic, FEMA AELRs ought to be a primary factor in discussions about the economic reasonableness of community-wide mandates for seismic strengthening, public policy decisions, and building code requirements pertaining to seismic strengthening. With this in mind, we wonder what the justification is for provisions in codes like the IEBC that set forth triggers for seismic strengthening in the event of, say, significant fire damage. FEMA's AELRs would seem to speak loudly against such triggers, and against public policy that targets all buildings in areas of moderate and high seismicity as appropriate targets for seismic strengthening.

4. Case Study: 2011 Mineral, Virginia Earthquake

The process for assessing whether a building ought to be seismically improved commonly involves quantitative engineering evaluations to establish whether the building already has inherent resistance mechanisms and load paths with adequate strength and/or ductility capacity to protect occupant safety against collapse with reasonable assurance. This general methodology, however, is unworkable for large inventories of buildings both because quantitative assessment of large inventories of buildings is unmanageably burdensome and because buildings with lateral systems that have been demonstrated to provide reasonable levels of protection of life safety commonly fail modern-day prescriptive and performance-based engineering tests. It would not be unreasonable, for example, to expect that most older buildings in areas of lower seismicity throughout the eastern portion of the US—a great many of which rely on unreinforced masonry for lateral strength and stiffness and were either constructed prior to the era of modern building codes or prior to the incorporation of any express design criteria for lateral loading into the building code—would not come close to satisfying either the seismic design requirements of the IBC or the quantitative performance measures of ASCE 41.

However, that pre-code buildings in areas of lower seismicity in the US are generally adequate to resist design level shaking within expected norms is readily demonstrable. With limited exception, these buildings do not generally require seismic improvements to prevent structural collapse or even to protect against structural damage. Powerful empirical evidence supporting this thesis was revealed by the response of the built environment during the Magnitude 5.8 Mineral, Virginia earthquake in 2011 (Mineral). While in-depth discussion of all this evidence is beyond the scope of this paper, the main points from which this conclusion is drawn are summarized herein.

Mineral provides a unique opportunity to assess the economic reasonableness of pursuing inventory-wide seismic strengthening of existing buildings in areas of lower seismicity because it exposed a very large inventory of buildings—presumably numbering in the hundreds of thousands—to design-level or MCE-level ground shaking. In both rural and urban areas, much of the building inventory that was shaken most strongly was older pre-code, or at least pre-modern code, unreinforced brick masonry construction and was representative of construction up and down the eastern seaboard. Moreover, the shaking intensity was similar to the design- or MCE-level shaking that is postulated by the USGS in many other areas of the East Coast. For example, ground motion spectra from various locations in and around Washington D.C. during Mineral, both measured and calculated, as well as the USGS MCE_R spectrum for the National Mall in Washington, roughly 130 kilometers from the Mineral epicenter, are shown in Fig. 5. Based on this figure, and given that the vast majority of buildings in the Washington D.C. metropolitan area are low rise, they likely experienced ground shaking that exceeds the design basis earthquake, in some cases by a significant margin. From the USGS ShakeMap for Mineral, the densely populated area in and around Washington D.C. experienced instrumental intensities of I_{mm} V to I_{mm} VI. The epicentral region, which is quite rural, was exposed to I_{mm}

VII shaking. No lives were lost as a result of the earthquake and the dollar value of the earthquake-caused damage has been estimated to total only about \$200 to \$300 million USD [9].

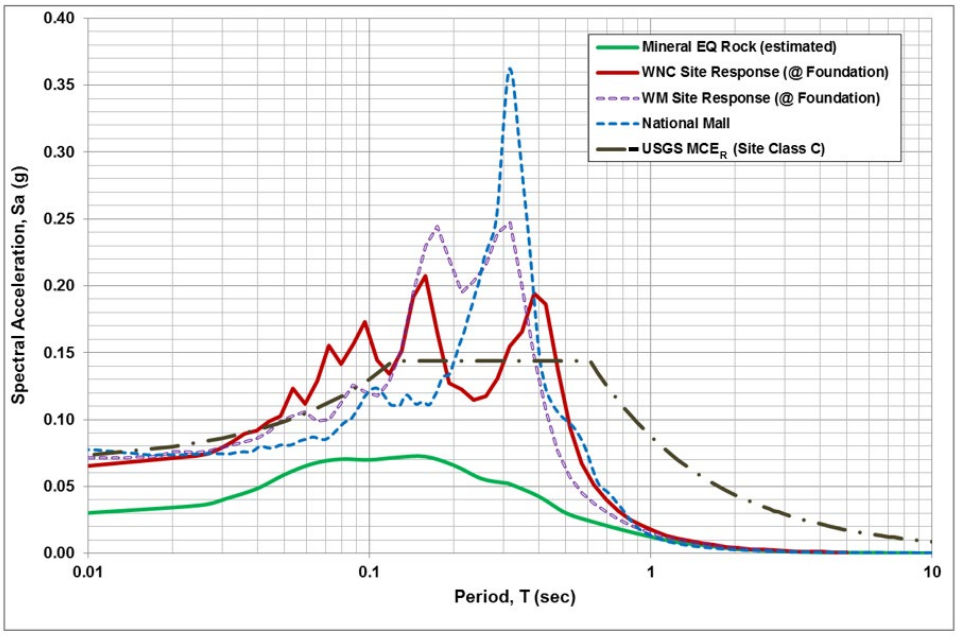

Fig. 5. Plot comparing spectral accelerations recorded in and computed for Washington DC with USGS MCE$_R$. Figure adapted from the study by Wells, et. al. (2015) [10]

Fig. 6 depicts post-earthquake damage survey results from the Virginia Department of Mines Minerals and Energy (VDMME) from the immediate epicentral region [11]. That survey found that the shaking destroyed up to seven houses and caused major damage to 120 houses, and that beyond 3 km from the epicenter, the damage distribution had moderated such that while many residences had damage, only few residences had major damage. Two buildings collapsed in the town of Mineral, Virginia, with minor damage to several other buildings. Whatever the definition of “destroyed” used by VDMME, no lives were lost in these buildings. While the significance of this damage for the individuals whose property was affected should not be downplayed, the post-earthquake survey results demonstrate that buildings in the community at-large performed well within the intent of the code for new construction.

Farther from the epicenter, but remaining within about 10km, Louisa County, with a population of around 36,000, experienced \$80 million USD in damage, accounting for between 25 and 40 percent of the total estimated damage from the earthquake, and had 65 homes with major damage [12]. Only \$15M of that was associated with residential structures, with the balance concentrated in a small number of school facilities. In general, masonry construction including bearing walls and veneer fared worse than other types of construction, with some of the masonry damage associated with pre-code structures from the 19th century. The per capita economic value of reported earthquake damage was low especially considering that the shaking during Mineral was likely approaching MCE-level in Louisa County via extrapolation from data from the Washington D.C. area. Beyond this region, as the distance from the epicenter increased, the intensity of damage continued to diminish, with sporadic damage to chimneys, veneer, and parapets remaining predominant rather than damage to primary structural components in masonry buildings, and with the vast majority of masonry and other structures incurring no damage at all. Despite Washington D.C. proper experiencing MCE-level shaking during Mineral, little damage occurred to the many thousands of older masonry bearing wall residential and commercial buildings, and where damage was noted, it was again typically limited to minor cracking of nonstructural unreinforced masonry features. Notable exceptions occurred in a relatively limited number of very unique historic masonry structures including the Washington Monument, the Washington National Cathedral, Smithsonian Castle and the Armed Forces Retirement Home, which were significantly damaged, though primarily to facade ornaments and appendages.

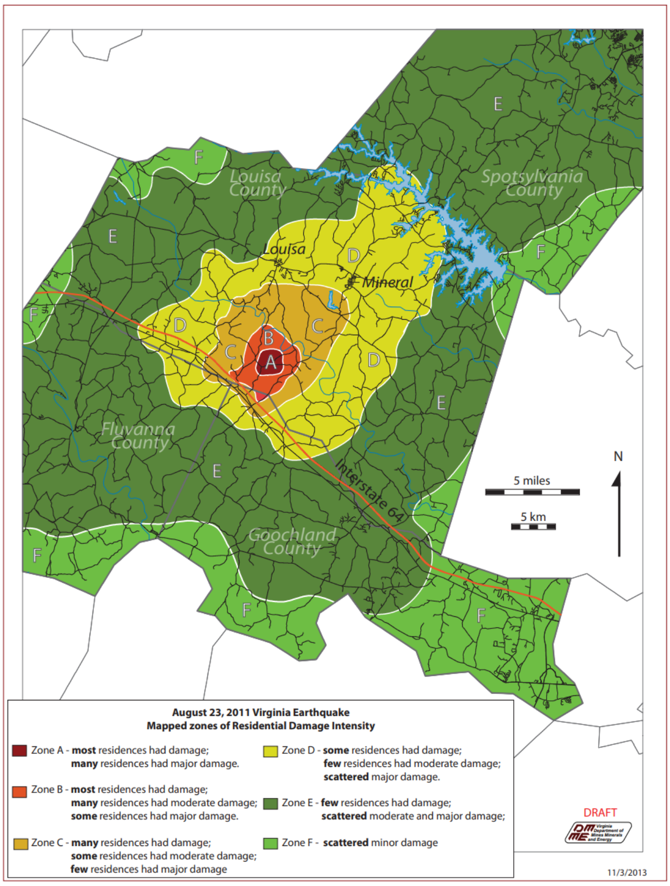

Fig. 6. The qualitative distribution of damage to residential structures in the Mineral epicentral zone [11]

Together with the representation that a widespread region experienced roughly MCE-level shaking, this empirical evidence amply demonstrates the folly of promoting seismic strengthening on a community-wide basis in the low-seismicity Washington D.C. area, and likely throughout the low-seismicity mid-Atlantic states, and perhaps throughout much of the eastern seaboard—at least insofar as the engineering profession ought to be considering economic factors in their recommendations. Given the empirical evidence that the very large inventory of existing buildings in the Washington D.C. area was exposed to MCE level shaking without the occurrence of structural collapses—despite that much of the as-built inventory of buildings throughout much of the East Coast is pre-code and never explicitly considered seismic forces in their design, it would be unreasonable to conclude that the inventory is seismically inadequate as a whole and poses a substantial threat to the residents of this and similar areas of lower seismicity with similar inventories of buildings. If seismic strengthening has any notable merit in these areas, it is with respect to unique heritage structures. For more typical buildings, however, our focus should be on mitigating demonstrable risks such as unreinforced masonry chimneys, appurtenances, ornaments, and veneer rather than wholesale upgrading.

5. Conclusion

Current code provisions in the US require scaling the 2,475-year earthquake by 2/3 for new design. This scalar causes the effective return period for the calculated DBE to vary significantly by geographic location, with code requirements in areas of lower seismicity requiring design for much longer effective return period earthquakes than are required in areas of higher seismicity. This is counterintuitive because it results in relatively less investment in seismic force resisting systems in areas of high seismicity and relatively greater investment in areas of lower seismicity. For existing buildings, where the engineer may have more control over seismic design criteria, more thought should be given to choosing a return period that makes sense for the project rather than using a certain percentage of the requirement for new construction. Return periods should also be chosen commensurate with the expected remaining life of the structure. The writers argue that economics and risk are both necessary considerations in strengthening decisions. Based on studies by FEMA, it appears that earthquakes pose little to no risk of costly earthquake damage across most of the US. Evidence from the 2011 Mineral earthquake strongly support this thesis, as relatively minor economic impacts were observed from DBE and MCE level shaking across a broad region. In areas of high seismicity, it may make sense to strengthen only more vulnerable types of buildings. In areas of moderate seismicity, it may make more sense to strengthen just the most vulnerable components of the most vulnerable types of buildings. In areas of lower seismicity, it may make sense to not invest in seismic strengthening, or to only strengthen elements that are extremely vulnerable, such as unreinforced masonry parapets, unreinforced appendages and ornaments, unreinforced masonry chimneys, and poorly anchored veneer. Engineering, at its core, should always remain a balance of safety and economics, with the impact of our engineering decisions balanced by the potential economic impact on society.

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