Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

SAFE ENOUGH? HOW BUILDING CODES PROTECT OUR LIVES BUT NOT OUR CITIES

K. A. Porter[1]

ABSTRACT

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Porter KA. Safe enough? How building codes protect our lives but not our cities. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

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Introduction

Building codes have historically recognized that it is impossible to achieve perfect safety from overloading by gravity, snow, wind, earthquakes, etc. For earthquake loads in particular, probabilistic codes (those developed since the advent of load and resistance factor design) have also assumed it is impractical or uneconomical to achieve seismic resilience much greater than what is implicit in prior codes. A corollary to arguments about what is economical is that the public would be unwilling to pay for safer buildings, perhaps buildings that would be functional after very strong shaking. US codes have always specified design requirements that are blind to broader context, such as whether the building is in a big city or in an isolated community. While it is convenient and practical to do so, this approach cannot address concerns about the total number of buildings damaged or people killed in a single earthquake, only the per-building or per-person risk. Perhaps this approach is rooted in an unstated assumption that the per-building

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or per-person risk is the best measure of risk. Let us first review these assumptions in more detail, then consider some recent projects that undermine them.

Writing about whether it was practical to design water tanks and other structures to remain elastic under earthquake loading, Housner [1] speculated that "it would be quite costly to design for lateral forces of this magnitude, and it would probably be considered desirable to make a less strong structure and accept permanent deformations in the event of a severe earthquake." Housner and Jennings [2] state that "It is not economical to design every structure to resist the strongest possible earthquake without damage," and that therefore codes "permit yielding and structural damage in the event of very strong shaking." The authors of ATC-3-06 [3] were unable to provide figures on the probable costs to make buildings remain functional after a rare earthquake. Still, they codified the assumption that it is economically infeasible to do so and open the document with a philosophy of allowing structural damage in major earthquakes.

To say that it is uneconomical to provide greater seismic resistance is equivalent to saying that people would be unwilling to pay for it ("economical" being a subjective judgment, not necessarily measured in terms of, say, benefit-cost ratio). But in these sources and in others that underlie current code requirements there is no examination of the public's willingness to pay. (Unsurprisingly; codes are written largely by engineers and building professionals, while willingness-to-pay is the domain of economists and other social scientists.) Owners and tenants have generally not been asked to express their preferences and are typically absent from code committees. The authors of SP 577 [4] expressed the notion that the A58 standards committee (precursor to ASCE 7) represented "those substantially concerned with its [the standard's] scope and provisions." Though committee members included "a broad-spectrum group of professiona1s from the research community, building code groups, industry, professiona1 organizations and trade associations," it did not include representatives of owners or tenants. A recent effort to select performance measures for performance-based earthquake engineering [5], addressing current code philosophy, recognized that "public input was never sought," and that "engineers decided that this performance [structural damage being acceptable in a major earthquake] was appropriate." It would be easier to support judgments about what is economical or not if the public were asked what they would be willing to pay for greater seismic resilience.

Another apparently unexamined aspect of US building codes is that buildings are designed without regard to urban context. That is, conditioned on site seismic hazard and a building's planned use, it does not matter whether the building is in a megacity with a major influence on the world economy, or in a small isolated community. There are important consequences that have to do with what happens when a major earthquake occurs near that megacity, as opposed to the isolated community. The new building should offer equal safety to its occupants regardless of its location, but the economic risk to the region or the world can be very different, and the public reaction will likely be different. More on that point later.

Greater Seismic Resilience Can be Cost Effective

Let us consider a few projects that suggest that greater seismic resistance might not be so very costly, uneconomical, or impractical. As part of the CUREE-Caltech Woodframe project, the present author and colleagues [6] found that seismic retrofit of several of the project's so-called index buildings could be cost-effective, in the sense that the retrofit cost is exceeded by the expected present value of the future reduction in earthquake-related repair costs, across much of California. In some cases and locations the benefit-cost ratio (BCR) reached 8:1. Another project, a cost-benefit study performed for the US Congress of FEMA-funded seismic risk mitigation [7], showed that a broad portfolio of retrofit projects can be cost effective. The overall portfolio exhibited a BCR of 1.4 on average. Again, these were all retrofits, for which the BCR is generally lower than similar enhancements to new design (the "ounce of prevention" principle).

More to the point for new seismic design, Reitherman and Cobeen [8], who created the CUREE-Caltech Woodframe Project's index buildings, also present variants with above-code performance. One building was designed to remain immediately occupiable (IO) after design-level shaking and had a marginal cost of 3% over that of the conventional variant ($229,000 versus $221,000 in 2002 USD). Another example comes from the use of buckling-restrained braced frames. The Broad Center for the Biological Sciences on the campus of the California Institute of Technology in Pasadena, a 120,000 sf, $47 million science building, was the second new US building to include unbonded braced frames in its lateral force resisting system. According to an Arup engineer involved in the design (Zekioglu, pers. comm. 2002), the braces added approximately 2% to the construction cost over other code-compliant alternatives. He estimated that the facades, clad in travertine and stainless steel, added 10% to the construction cost. The braces allow the building to remain elastic nearly to design-level shaking (i.e., before applying an R-factor for ductility). While it may be costly to make some structural systems remain elastic near design-level shaking, it does not appear to be the case for all systems.

The Public Is Sometimes Willing To Pay for an Earthquake Resistant Building Stock

As part of the San Francisco Community Action Plan for Seismic Safety (CAPSS), a public advisory committee was formed comprising self-selected volunteers representing neighborhood groups, landlords, tenants, affordable housing advocates, and others. One of their roles was to consider the risk to high-occupancy woodframe residential dwellings with soft-story conditions. When CAPSS engineers (the present author among them) provided the committee with risk estimates in terms that they had asked for—especially number of red, yellow, and green tags—along with costs to reduce that risk, the committee strongly recommended a mandatory retrofit program [9]. Landlords and tenants agreed to share the burden of paying for evaluation and mitigation. The engineers offered three levels of seismic retrofit and the committee recommended the strongest, not the least-expensive one. The recommendation became a mandatory retrofit ordinance enacted into law in 2013 [10]. Under at least some circumstances, the public is willing to pay for an earthquake-resistant building stock.

Total Numbers Matter to the Public More than Per-person or Per-building Risk

As noted earlier, "costly" and "cost effective" are subjective. The people making the call about what is cost effective have generally not been the people paying for the buildings. Because the pubic has not been asked what they would be willing to pay to reduce their risk, it is not entirely clear how the public prefers to think about seismic risk: how to measure it and therefore on what basis to decide how to measure the benefit of greater construction cost.

The authors of ATC-58-1 [5] discussed among a group of 26 engineers, architects, economists, and a few representatives of building owners how they preferred to measure the benefits of life-safety enhancements to a particular building: as a percentage of occupants' fatalities avoided, as a counting number of fatalities avoided, or as a counting number of non-fatal injuries avoided. The strong preference was counting numbers of people, not percentages. Similarly it was the aggregate number of soft-story dwellings that would collapse or be red-tagged, rather than the fraction of them, that most interested the CAPSS public advisory committee. This suggests that it is aggregate numbers rather than an arbitrary individual's life-safety risk that mattered to these participants. The public's interest in aggregate numbers agrees with observations by Slovic et al. [11], who found that that the magnitude of a catastrophe—the total number of people potentially harmed in a disaster—is one of the 3 leading influences on the public's perception of the risk posed by a peril. Neither of the other two is per-person fatality rate. This finding also agrees with the present author's observations from the US Geological Survey's Science Application for Risk Reduction (SAFRR) disaster scenarios ShakeOut [12], ARkStorm [13], and Tsunami Scenario [14]. In discussions with the public and in presentations by public officials, it has been the total numbers of people killed, injured, displaced, and the total numbers of buildings damaged or destroyed that seem to resonate with the public and with public officials. Nobody seems to ask about per-person risk or repeat the statistics offered about the fraction of buildings damaged.

By contrast, the code focuses on per-building risk. ASCE 7-10 [15] states that "The probabilistic [design] accelerations shall be taken as the … acceleration that is expected to achieve a 1 percent probability of collapse within a 50-year period." The authors of FEMA P-695 [16] estimate that for modern, code-compliant buildings, "The probability of collapse due to [2500-year] ground motions … is limited to 10%, on average…. The probability of collapse for individual archetypes is limited to 20%...." The most recent code addresses risk on the basis on the probability that a new building will collapse during its design life, which relates to per-person risk, not aggregate quantities. Prior probabilistic codes address the probability that a new building will collapse given design-level shaking, again a per-building (and thus per-person) risk measure. The current philosophy is blind to the magnitude of a potential catastrophe, but it is disaster potential that matters more to owners and occupants. See Fig. 1.

Not-Very-Rare Shaking Can Lead to a Catastrophe in a Code-Compliant Building Stock

What if we continue to design buildings to be unusable after rare shaking? Let us first focus on a code-compliant building stock. If California is lucky, a large earthquake—the Big One—will not occur until the bulk of the building stock complies with current code objectives. Let us consider the Big One to be something like the Mw 7.8 ShakeOut scenario [12] or an Mw 7.9 repeat of the 1906 San Francisco earthquake. These are not very rare events. Under the Uniform California Earthquake Rupture Forecast version 3 (Field et al. [17]), there is a 5% chance *each year* that California will experience an earthquake of at least Mw 7.8. Loosely speaking, an earthquake like the ShakeOut on the southern San Andreas Fault has a mean recurrence interval on the order of 150 years (and it has been 300 years since the last one). What will happen in such an event? Rather than relying on computer models of building vulnerability, let us assume that the outcome is exactly what FEMA P-695 aims for, namely an average 10% collapse rate in code-compliant stock when subjected to 2500-year shaking (more precisely, shaking with 2% exceedance probability in 50 years).

(a) (b)

Figure 1. (a) What the code sees, (b) What society sees

In the ShakeOut or a repeat of the 1906 earthquake, small areas will be shaken very strongly, with shaking reaching MCE_G-level (2500-year) recurrence. (The subscript G is used here to distinguish 2500-year motion from risk-targeted ground motion). In these small areas, approximately 10% of the building stock will collapse, according to FEMA P-695. Some number of buildings will be damaged to the extent that they would be red-tagged, that is, rendered unsafe to enter or occupy, without collapsing. The authors of FEMA P-695 do not estimate the ratio. Let us rely on California earthquake history (acknowledging that that history does not reflect a code-compliant stock). In the 1994 Northridge earthquake, 2,290 buildings were red tagged in Los Angeles County, according to EQE and OES [18], and approximately 200 soft-story woodframe buildings and 15 hillside houses "collapsed or came close." An unknown number of unreinforced masonry buildings and reinforced concrete buildings collapsed. Suppose the latter number was in the low 10s, so something like 10 non-collapsed buildings were red-tagged for every collapse. In the 1989 Loma Prieta earthquake, there were 40 to 50 red-tagged buildings in the San Francisco Marina district, and 4 collapses, again 10:1. This suggests that in past earthquakes, 10 non-collapsed California buildings were red-tagged for every collapse. Again, while this ratio is for a non-compliant stock, absent better estimates let us assume it holds for a compliant stock as well.

What about yellow-tagged (limited-use) buildings? The 1994 Northridge earthquake resulted in 9,445 yellow tags in Los Angeles (versus 2,290 red). So let us assume that the yellow-to-red ratio in the future Big One would be 4 yellow per 1 red tag. The implications for the small area with 2500-year shaking are summarized in Table 1. The first column lists the three conditions considered here: collapsed, red tagged, and yellow tagged. Column 2 recaps the basis for estimating the fraction of the building stock in each condition. Column 3 presents the estimate of the fraction of the building stock in each condition. Of course, the figures in Column 3 are for a code-compliant stock. If the Big One occurred tomorrow, the collapse rate would probably be greater, because the existing building stock will presumably perform worse than buildings that all comply with current code.

The Big One does not produce MCE_G shaking over the entire region. Shaking varies by site, and is generally lower the farther from the rupture and the firmer the soil. What kind of shaking occurs over a large area? Fig. 2a compares estimated 5%-damped, 0.3-sec spectral acceleration response the hypothetical Southern California ShakeOut scenario with MCE_G S_S

shaking in ASCE 7-05, shown in Fig. 2b. Figs. 2c and 2d offer a similar comparison between 5%-damped, 1.0-sec spectral acceleration response in a repeat of the 1906 earthquake, versus ASCE 7-05's map of S_1. Though the ASCE 7 maps do not reflect site amplification (the parameters F_A and F_V), the two figures show that shaking in the Big One is generally 0.5 to 1.0 times MCE shaking across much of the greater Los Angeles or San Francisco Bay Areas, i.e., over an area on the order of 10,000 km^2. Los Angeles County has a population density of 810 per km^2 and the San Francisco Bay Area population density is roughly the same, so 10,000 km^2 in either region contains millions of residents and hundreds of thousands of businesses (there are about 11 people per business in California according to the US Census: http://quickfacts.census.gov/qfd/states/06000.html).

Table 1: Performance of a code-compliant building stock in a small area with MCE shaking

Condition	**Basis for estimating**	**Fraction of building stock**
Collapse	10% of stock (FEMA P-695)	10%
Red & not collapsed	10 red per collapse (Loma Prieta and Northridge)	Most of the rest
Yellow	4 yellow tags per red tag (Northridge earthquake)	Most of the rest
Total		Virtually all

Assuming a reasonable value of the uncertainty in the collapse capacity (a logarithmic standard deviation of 0.6), the collapse probability at 0.5 times MCE_G is on the order of 1%. Using the same ratios as before (10 red tag per collapse, 4 yellow per red), the area experiencing ½ MCE_G shaking would experience 1% of its code-compliant stock collapsed, 10% red-tagged, and 40% yellow tagged. That is to say, half the building stock would be impaired (Fig. 3). Since shaking is stronger closer to the fault, we can infer that more than half the code-compliant building stock would be destroyed or impaired over an area on the order of 10,000 km^2, given an earthquake with a mean recurrence interval on the order of 150 years.

This is the rosy outcome, with the Big One occurring decades from now when most of the older buildings are replaced. Fig. 4 shows that currently, approximately 70% of the highrises at 75% of dwellings predate 1980, which one might take as a reasonable breakpoint between modern and less-modern buildings (except for steel moment frames, whose breakpoint is more like 1994). A growth and replacement rate of 25% in 30 years corresponds with an annual growth and replacement rate of approximately r = 0.95%, or about 1% per year. That is, $1 - (1 - r)^t = 0.25$ when t = 30 years. At that rate, it will take approximately 168 years to replace 80% of the building stock with code-compliant buildings. That is, $1 - (1 - r)^{168} = 0.80$. This simple model suggests that it will be many decades, perhaps a century or more, before the majority of California's building stock complies with modern codes.

Where do people live and work after the Big One? In 2012, Los Angeles residential vacancy rates were 2-5%; commercial, on the order of 11%; industrial, 5%. More than half the vacant space would be impaired along with the rest of the building stock, so there will be insufficient space to accommodate the displaced homes and workplaces. If half the yellow-tagged space were still usable (yellow tag means limited use), then perhaps 25% to 50% of households and businesses in a 10,000 km^2 area would move away, out of the metropolitan area.

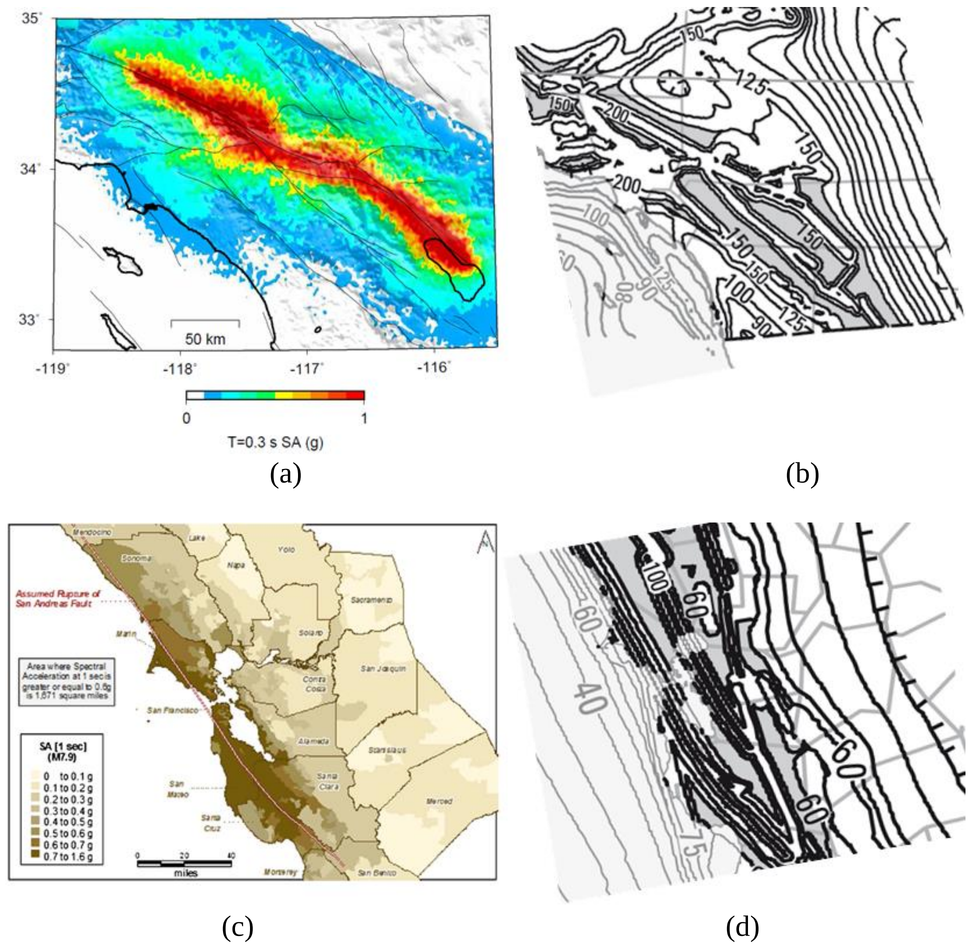

Figure 2. (a) ShakeOut Sa(0.3 sec, 5%) compared with (b) S_S from ASCE 7-05. Similarly (c) estimated Sa(1.0 sec, 5%) in a repeat of the 1906 earthquake, compared with (d) S_1 from ASCE 7-05. In both cases shaking exceeds $0.5 \cdot MCE_G$ shaking over roughly 10,000 km^2.

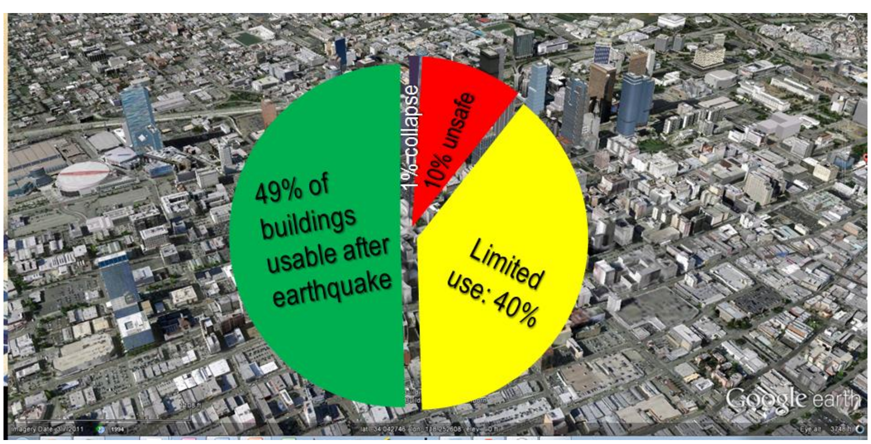

Figure 3. What happens in the Big One, assuming 100% code-compliant building stock

The loss of 25% to 50% of the population represents a catastrophic change, a nearly existential threat to a region's economy and character, and a profound shock to the people affected. It will have far more damaging effects on the state and national economy when it happens in a metropolitan area compared with a rural community. Remember: all of this follows from current code objectives, the best models of shaking, and recent experience with the ratio of red tags to collapses and yellow tags to red tags. These catastrophes are baked into the code. They are what the code is aiming for, even if nobody deliberately chose the target.

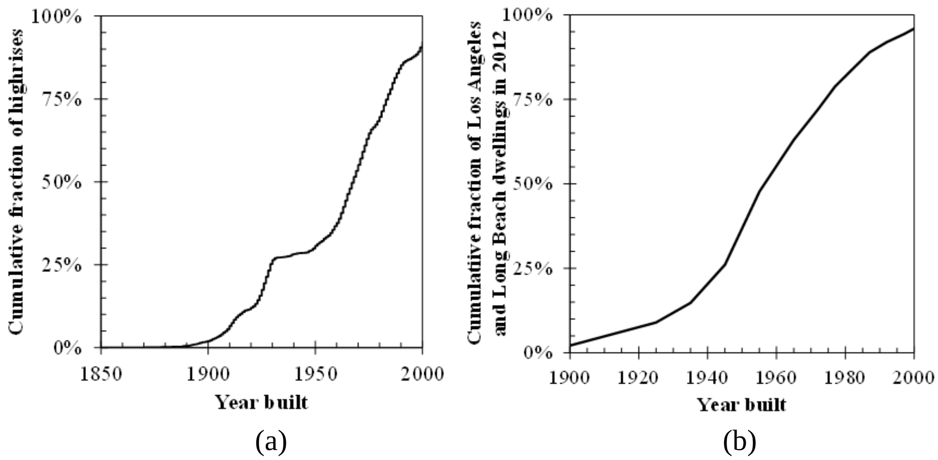

Figure 4. Cumulative fraction by year built of (a) California highrises (data from [19]) and (b) dwellings in Los Angeles and Long Beach (data from [20]).

Society can probably afford greater seismic resilience. The public is sometimes willing to pay the increased costs of greater seismic resilience, even for seismic retrofit. (Not always; many California cities for example declined to enact mandatory retrofit of unreinforced masonry buildings mandatory after the passage of the 1986 URM Law [21].) In light of the threat our current design philosophy poses to our cities, perhaps it is time for a thorough review of what we want from the seismic provisions of our building codes.

An Overdue Conversation

It seems unlikely that we will have that conversation if we continue to develop codes as we have since 1980. In drafting SP 577, Ellingwood et al. [4] stated that "The new probability-based load criterion should lead to designs which are essentially the same [level of safety]… as those obtained using current acceptable practice." That is, code objectives were calibrated to prior safety goals that were implicit but never deliberately chosen. The 2009 International Building Code (IBC) aims to be "consistent with the expected performance expressed in the Commentary of the 2003 NEHRP Provisions, namely that 'if a structure experiences a level of ground motion 1.5 times the design level [i.e., if it experiences the 2500-year ground motion level], the structure should have a likelihood of collapse… [of] 10%.'" The 2012 IBC employs new risk-targeted ground-motion maps that aim to ensure 1% collapse probability in 50 years, considering all levels of shaking that could happen and their various likelihoods. However, the adjustment factor (called the risk coefficient) relative to 2%/50-year shaking is on average 0.9 (for S_1) and has a standard deviation of 0.06. The new map is very similar to the old one and slightly lower on an average geographic basis. In each case the update involved calibration to a prior code, not reconsideration of whether the prior code provided the right performance.

Ellingwood et al. [4] were concerned that seismic and wind reliability indices in SP 577 were “relatively low when compared to that for gravity loads,” and called for “a profession-wide debate” over whether wind and seismic loads ought to have similar reliability as that inherent in gravity loads. That debate did not occur. In 2008 discussions over setting the goal for new design to be 10% collapse probability in 2500-year shaking, one discussant was “shocked that there was literally no debate” over whether the goal was reasonable or the right measure. In discussions in BSSC Project ‘07 (reassessment of seismic design procedures), there “May have been a little discussion” about measuring societal impacts, but no formal deliberation of the topic (Luco, pers. comm. 2012). Whatever we are doing now as we modernize US codes, we are doing it oblivious to the preferences of building owners and occupants and to the catastrophe the code guarantees.

Conclusions

US code philosophy since 1980 guarantees an urban catastrophe capable of displacing millions of people and hundreds of thousands of businesses. Considering buildings in isolation and allowing collapse rates of 10% in rare shaking ensures that 50% or more dwellings and businesses over an area on the order of 10,000 km^2 will be at least partially impaired: at least 40% yellow tagged, 10% red tagged, at 1% collapsed, in a code-compliant building stock.

It does not have to be this way. With the advent of 2nd generation performance-based earthquake engineering as exemplified by FEMA P-58 [22] and using modern earthquake scenarios like ShakeOut, we are capable of measuring earthquake risk in terms of dollars, deaths, and downtime. We can make apples-to-apples comparisons of the cost for stronger buildings and the benefits in terms of reduced future losses. The comparison can be made both at the single-building level (for design professionals) and at the societal level (which SAFRR and other projects show the public seems to care more about). As CAPSS showed, the public can express its preferences for balancing risk and cost if we ask. The engineering and building professions do not need to make those decisions in isolation, let alone without any debate at all.

If we are to act as faithful trustees of the public’s safety, health, and welfare, we should involve the public in deciding what its interests are, how to measure its risk, and what it is willing to pay for a seismically resilient society. That dialog can be part of a thorough review of what we want our building codes to provide, how to achieve the desired ends, how cost-effectively to enhance society’s safety, and how to avoid catastrophe.

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