SIMPLIFIED PBEE TO ESTIMATE ECONOMIC SEISMIC RISK FOR BUILDINGS

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ABSTRACT

A seismic risk assessment is often performed on behalf of a buyer of large commercial buildings in seismically active regions. One outcome of the assessment is that a probable maximum loss (*PML*) is computed. *PML* is of limited use to real-estate investors as it has no place in a standard financial analysis and reflects too long a planning period for what-if scenarios. We introduce an alternative to *PML* called probable frequent loss (*PFL*), defined as the mean loss resulting from an economic-basis earthquake such as shaking with 10% exceedance probability in 5 years. *PFL* is approximately related to expected annualized loss (*EAL*) through a site economic hazard coefficient (*H*) introduced here. *PFL* and *EAL* offer three advantages over *PML*: (1) meaningful planning period; (2) applicability in financial analysis (making seismic risk a potential market force); and (3) can be estimated by a rigorous but simplified PBEE method that relies on a single linear structural analysis. We illustrate using 15 example buildings, including a 7-story nonductile reinforced-concrete moment-frame building in Van Nuys, CA and 14 buildings from the CUREE-Caltech Woodframe Project.

Keywords: Simplified methods; loss estimation; seismic risk; real-estate investment.

1. INTRODUCTION: SEISMIC RISK IN REAL-ESTATE INVESTMENTS

Seismic risk enters into several important real-estate decision-making processes: performance-based design of new buildings, purchase of investment property, seismic retrofit of existing buildings, and the purchase of earthquake insurance. We focus on one of the more common of these: the purchase by real-estate investors of existing commercial property in seismic regions.

Every time a purchase in excess of about \$10 million in replacement value (roughly 50,000 to 100,000 sf) is to be financed by a commercial mortgage, the lender requires an assessment of the earthquake probable maximum loss (*PML*). The *PML* has no standard quantitative definition (Zadeh 2000), although working definitions involve the loss associated with a large, rare event. One definition is the 90th percentile of loss

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given shaking with mean recurrence time of 475 years. Lenders typically refuse to underwrite the mortgage if the *PML* exceeds 20% to 30% of the replacement cost of the building, unless the buyer purchases earthquake insurance—a costly requirement that often causes the investor to decide against bidding.

If the *PML* hurdle is passed, bidders typically proceed to ignore seismic risk, for good reasons: (1) they plan on the order of 5-10 yr, so an upper-bound loss associated with 500-yr shaking is largely meaningless for investment sensitivity studies; (2) *PML* cannot be used in a financial analysis of return on equity or other standard financial performance metrics; and (3) *PML* cannot be used to compare seismic retrofit benefits with costs. Thus, the main seismic risk metric in one of the most common seismic risk decision situations provides owners little value for risk-management decision-making.

Two potentially useful performance metrics are expected annualized loss (*EAL*), which measures the average yearly loss when one accounts for the frequency and severity of various levels of loss, and mean loss given shaking in a reasonable upper-bound event during the investor's planning period. We introduce such a metric and refer to it as probable frequent loss (*PFL*), to evoke *PML* with a briefer planning period. The bidder who knows *EAL* can include it as an operating expense in the financial analysis. *PFL* can be used in the sensitivity studies commonly performed during bidding. We present three increasingly simple performance-based earthquake engineering (PBEE) methods to estimate *EAL* and *PFL*.

2. THREE METHODS TO CALCULATE INVESTOR'S SEISMIC RISK

2.1 *EAL* Method 1: Integrate Vulnerability and Hazard at Several IM Values

Assuming independence of intensity and of loss between earthquakes, *EAL* can be calculated as

$$EAL = V \int_{s=0}^{\infty} y(s)\left|G'(s)\right| ds \qquad [1]$$

where V denotes the replacement cost of the building, s refers to the seismic intensity measure (*IM*), $y(s)$ is the mean seismic vulnerability function (defined here as the average repair cost as a fraction of V, given s), $G(s)$ is the mean annual frequency of exceeding shaking intensity s, and G'(s) is its first derivative with respect to s.

In practice, $y(s)$ and $G(s)$ are evaluated at n+1 discrete intensity levels s_0, s_1, … s_n. We denote these by y_0, y_1, … y_n, and G_0, G_1, … G_n, respectively. We assume $G(s)$ varies exponentially between the discrete values of s, and that $y(s)$ varies linearly, i.e.,

$$G(s) = G_{i-1} \exp\left(m_i \left(s - s_{i-1}\right)\right) \quad \text{for } s_{i-1} < s < s_i \qquad [2]$$

$$y(s) = y_{i-1} + \Delta y_i / \Delta s_i \cdot \left(s - s_{i-1}\right) \quad \text{for } s_{i-1} < s < s_i \qquad [3]$$

$$m_i = \ln\left(G_i / G_{i-1}\right) / \Delta s_i \quad i = 1, 2, \ldots n \qquad [4]$$

$$\Delta s_i = s_i - s_{i-1} \quad i = 1, 2, \ldots n \qquad [5]$$

$$\Delta y_i = y_i - y_{i\text{-}1} \quad i = 1, 2, \ldots n \qquad [6]$$

One can show (Porter et al. 2004) that *EAL* is then given by

$$EAL = V \sum_{i=1}^{n} \left(y_{i-1} G_{i-1} \left(1 - \mathrm{e}^{m_i \Delta s_i}\right) - \frac{\Delta y_i}{\Delta s_i} G_{i-1} \left(\mathrm{e}^{m_i \Delta s_i} \left(\Delta s_i - \frac{1}{m_i} \right) + \frac{1}{m_i} \right) \right) + R \qquad [7]$$

where R is a remainder term for values of $s > s_n$, and has an upper bound of $VG(s_n)$ if $y(s) \leq 1$. We refer to the method of calculating *EAL* by Equation [7] as Method 1.

Information on $G(s)$ is increasingly available (e.g., Frankel and Leyendecker 2001). To determine $y(s)$ requires either (1) large quantities of empirical post-earthquake survey data (which for various reasons do not exist in reliable form); (2) the exercise of expert opinion; or (3) PBEE analysis along lines pursued by the Pacific Earthquake Engineering Research (PEER) Center.

To create $y(s)$, we employ a PBEE methodology called assembly-based vulnerability (ABV). ABV is described in detail elsewhere (e.g., Porter et al. 2001). It meets the two main criteria set out by Hamburger and Moehle (2000) for a second-generation PBEE methodology: system-level performance evaluation (e.g., economic loss, casualties, and repair duration, or "dollars, deaths, and downtime") and rigorous propagation of all important sources of uncertainty. In summary, ABV has six steps:

1. Facility definition. The facility is defined by its location and design, including site soil, structure and nonstructural assemblies. One creates an inventory of the damageable assemblies and identifies the structural-response parameter (interstory drift ratio, member force, etc.) that would cause damage to each assembly. By assembly, we mean a collection of components, assembled and in place, defined according to a standard taxonomic system, e.g., RS Means Co Inc. (1997).

2. Ground-motion selection. One selects a ground-motion time history and scales all of its accelerations by a constant to achieve the desired value of s. We measure s by spectral acceleration at the facility's small-amplitude fundamental period of vibration, $S_a(T_1)$, and limit scaling of recorded time histories to a factor of 2. The scaled ground-motion time history is denoted here by $a(t)$.

3. Structural analysis. One creates a structural model and performs a nonlinear time-history structural analysis to determine structural responses, referred to as engineering demand parameters (*EDP*). The structural model is stochastic, meaning that component masses, damping, and force-deformation behavior (denoted here by M, ζ, and *FD*) are treated as uncertain, having prescribed probability distributions.

4. Damage analysis. Each damageable assembly has an uncertain capacity to resist damage. Damage is parameterized via an uncertain, discrete damage measure, denoted by $DM \in \{0, 1, \ldots N_{DM}\}$, where $DM = 0$ corresponds to no damage. Each level of *DM* is defined by prescribed repairs. For an assembly with $N_{DM} = 1$, one compares the *EDP* to which it is subjected with its uncertain capacity, denoted by *R*. If $R < EDP$, the assembly is damaged, otherwise not. For an assembly with $N_{DM} \geq 2$, the *DM* is the maximum value *dm* such that $R_{dm} < EDP$. If $N_{DM} \geq 2$, it is necessary to ensure that $R_{dm} \leq R_{dm+1}$ for $dm < N_{DM}$. A method to do so is shown in step 6. The result of the damage analysis is the number of damaged assemblies of each type (indexed by *j*) and level of damage (indexed by *dm*), denoted here by $N_{j,dm}$.

5. Loss analysis. Each assembly type and damage state has an associated uncertain repair cost, which we denote by $C_{j,dm}$. The total direct repair cost is the sum of the number of damaged assemblies of each type (*j*) and damage state (*dm*) times the unit cost to repair each. One adds the quantity of repainting required (the total painted area of each room, hallway, or other line of sight that has at least one damaged assembly that must be repainted) times the unit cost to repaint. To this subtotal is added contractor overhead and profit (denoted here by C_{OP}), treated here as a factor of the total direct repair cost. The result is the total repair cost. This is divided by the building replacement cost to produce a sample of the damage factor, *Y*:

$$Y = \frac{1}{V}\left(1 + C_{OP}\right)\sum_{j=1}^{N_j}\sum_{dm=1}^{N_{dm}} N_{j,dm} C_{j,dm} \qquad [8]$$

6. Propagate uncertainty. There are many uncertain parameters in the analysis. One way to propagate them is Monte Carlo simulation (MCS). In an MCS approach to ABV, each variable, denoted generically by *X*, has an associated cumulative distribution function (CDF), denoted by $F_x(x)$, which gives the probability that *X* will take on a value less than or equal to a particular value *x*. In a single loss simulation, one samples a value of each uncertain variable in steps 2 through 5 according to its CDF, and calculates a sample *Y*. One way to sample an *X* is to generate a sample *u* of a random number uniformly distributed between 0 and 1. The sample of *X* is given by

$$x = F_X^{-1}\left(u\right) \text{ where } u \sim U(0,1) \qquad [9]$$

The vector of uncertain variables is denoted here by $\underline{X} = [a(t), M, \zeta, FD, R, C, C_{OP}]^T$. Each component in the vector can itself have more than one component. Lacking a probabilistic model for $a(t)$, a suite of historical ground-motion time histories can be used and assigned equal probability. Each uncertain variable is simulated per Equation [9]. Steps 2-5 are performed, producing one sample of *Y*. The process is repeated many times at a given level of *s* to produce many samples of *Y*. The distribution of the samples is treated as the distribution of *Y*. One repeats this process at many levels of *s* to produce the uncertain seismic vulnerability function $Y(s)$.

Damage analysis for an assembly with $N_{DM} \geq 2$ requires more than simply simulating each capacity R_{dm} according to its distribution and comparing with *EDP*, owing to the necessity that $R_{dm} \leq R_{dm+1}$ for $dm < N_{DM}$. When $N_{DM} \geq 2$, one evaluates the CDF of *DM* for each assembly, conditioned on *EDP*, which we denote by $F_{DM|EDP=x}(dm)$. We denote the CDF of capacity R_{dm} by $F_{R,dm}(x)$ and calculate:

$$\begin{aligned} p\left[DM = dm \mid EDP = x\right] &= 1 - F_{R,(dm+1)}\left(x\right) && dm = 0 \\ &= F_{R,dm}\left(x\right) - F_{R,(dm+1)}\left(x\right) && 1 \leq dm < N_{DM} \\ &= F_{R,dm}\left(x\right) && dm = N_{DM} \end{aligned} \qquad [10]$$

$$\begin{aligned} F_{DM|EDP=x}\left(dm\right) &= 1 - F_{R,dm+1}, && 0 \leq dm < N_{DM} \\ &= 1 && dm = N_{DM} \end{aligned} \qquad [11]$$

$$dm = F_{DM|EDP=x}^{-1}\left(u\right);\ u \sim U(0,1) \qquad [12]$$

where $p[A|B]$ denotes the probability of A given B. For many assembly types and damage states, it is reasonable to take $F_{R,dm}(x)$ as a cumulative lognormal distribution,

$$F_{R,dm}\left(x\right) = \Phi\left(\ln\left(x/\hat{x}\right)/\beta\right) \qquad [13]$$

where Φ is the cumulative standard normal distribution and $\hat{x}$ and β are the median and logarithmic standard deviation of capacity, which vary by assembly type and damage state. See Porter et al. (2001) and Beck et al. (2002) for examples.

Latin hypercube simulation (LHS). To enhance step 6, replace Equation [9] by

$$x = F_X^{-1}\left(u_1/N + u_2/N\right) \qquad [14]$$

where N is the number of samples desired, u_1 is sampled from $\{0, 1, \ldots N\text{-}1\}$ with equal probability and without replacement, and $u_2 \sim U(0,1)$. Replace Equation [12] by

$$dm = F_{DM|EDP=x}^{-1}\left(u_3/N + u_4/N\right) \qquad [15]$$

where u_3 is sampled from $\{0, 1, \ldots N\text{-}1\}$ with equal probability and without replacement and $u_4 \sim U(0,1)$. LHS ensures that the simulations produce samples from the tails of each distribution as well as the body.

2.2 EAL Method 2: Use Probable Frequent Loss

One can simplify method 1 by evaluating $G(s)$ and $y(s)$ at only two points, taking

$$G\left(s\right) = G\left(s_{NZ}\right)\exp\left(m\left(s - s_{NZ}\right)\right) \qquad [16]$$

$$\begin{aligned} y\left(s\right) &= 0 && s < s_{NZ} \\ &= a\left(s - s_{NZ}\right) && s_{NZ} \leq s \leq s_U \\ &= y_U && s_U < s \end{aligned} \qquad [17]$$

where s_{NZ} is defined such that $y(s_{NZ}) = 0+$, i.e., the value of s where loss first becomes nonzero, and s_U denotes the value of s where y reaches an upper-bound y_U such as 1.0.

Given a value of s_{NZ} such as $S_a(T_1) = 0.05$g, one can determine a by calculating the mean seismic vulnerability function at some value $s_{NZ} \leq s_{EBE} \leq s_U$, where s_{EBE} denotes the site shaking intensity in an event referred to here as the *economic-basis earthquake* (EBE), named to evoke the design-basis earthquake (DBE) of older codes, with a hazard level more relevant to repair costs than to life safety. We refer to mean loss given the EBE as the *probable frequent loss* (*PFL*), in imitation of and contrast with the *PML*. One can define the EBE as the event causing a level of shaking with 10% exceedance probability in 5 yr, although other moderate shaking levels also produce reasonable results. The shaking level s_{EBE} can be calculated, e.g., using Frankel and Leyendecker (2001), adjusting for site classification by using F_a or F_v, as appropriate, from the International Building Code (International Code Council 2000).

There is good reason to define EBE this way. To test the life-safety of a structural design, engineers have historically considered upper-bound shaking (10% exceedance probability) during the building's design life (e.g., 50 years), referring to this level of shaking as the DBE. To examine an upper-bound economic loss during the owner's planning period, it is consistent to use the same exceedance probability (10%) during that planning period (5 yr). We could define EBE as the event causing the site shaking intensity with 50% exceedance probability in 50 years, an event treated by FEMA 356 (ASCE 2000) that would be only slightly stronger than the 10%/5-yr event, but favor the suggested definition for its value to risk communication. EBE is defined for meaning to the investor, for whom 50 years is too long a planning period and 50% exceedance probability does not suggest an upper-bound intensity. Our 10%/5-yr definition of EBE more directly addresses the concerns of the investor.

Returning to *EAL*, we denote the mean annual frequencies of a site exceeding s_{NZ}, s_{EBE}, and s_U by G_{NZ}, G_{EBE}, and G_U, respectively. Then

$$a = PFL \Big/ \left[V \cdot \left(s_{EBE} - s_{NZ} \right) \right] \qquad [18]$$

$$m = \ln\left(G_{EBE} / G_{NZ} \right) \Big/ \left(s_{EBE} - s_{NZ} \right) \qquad [19]$$

$$\begin{aligned} s_U &= s_{NZ} + y_U / a \\ &= s_{NZ} + y_U V \left(s_{EBE} - s_{NZ} \right) \Big/ PFL \end{aligned} \qquad [20]$$

One can show (Porter et al. 2004a) that substituting [16] through [20] into [1] leads to

$$EAL = PFL \cdot \left[\left(G_{NZ} - G_U \right) \Big/ \ln\left(G_{NZ} / G_{EBE} \right) \right] \qquad [21]$$

If $s_U >> s_{NZ}$, as expected, then $G_U << G_{NZ}$, leading to:

$$EAL \approx PFL \cdot H \qquad [22]$$

where

$$H \equiv G_{NZ} \Big/ \ln\left(G_{NZ} / G_{EBE} \right) \qquad [23]$$

We refer to H as the *site economic hazard coefficient*. It can be mapped as a scalar for a given fundamental period, site classification, and s_{NZ}. Its units are yr^{-1}. Equation

[22] still requires that one estimate *PFL* somehow. One can use Method 1 with one the intensity level s_{EBE}, which requires multiple PBEE simulations. This is Method 2.

2.3 *EAL* Method 3: PFL and Linear ABV

We further simplify the analysis by noting that at moderate s, around s_{EBE}, the structural response may be adequately modeled using linear spectral analysis. Further, since only mean loss at s_{EBE} is required, we can avoid some aspects of ABV that are intended to quantify damage and uncertainty. Method 3 employs a simplified PBEE approach called linear assembly-based vulnerability (LABV). It has four steps:

1. Facility definition. Same as in Methods 1 and 2.

2. Hazard analysis. Determine s_{EBE} as in Method 2.

3. Structural analysis. Calculate *EDPs* using the first-mode spectral response. We denote by ϕ_1, L_1 and M_1, the building's fundamental mode shape, modal excitation, and modal mass, respectively. For example, considering one frame direction, the *EDP* for a segment of wallboard partition on the m^{th} story would be the interstory drift along that column line, estimated as

$$EDP \approx \frac{s_{EBE}}{\omega_1^2}\left(\frac{\phi_{1(m+1)} - \phi_{1m}}{h_m}\right)\frac{L_1}{M_1} \qquad [24]$$

where $\omega_1 = 2\pi/T_1$, ϕ_{1m} is the component of the fundamental mode shape at floor m, and h_m refers to the height of story m.

4. Damage and loss analysis. Let c_{dm} denote the mean cost to restore an assembly from damage state dm; it can be calculated by standard cost-estimation principles. We denote by $c(x)$ the mean cost to repair one assembly given that it has been exposed to $EDP = x$. We refer to $c(x)$ as the mean assembly vulnerability function, calculated by

$$c(x) = \sum_{dm=1}^{N_{DM}} c_{dm}\, p\left[DM = dm \mid EDP = x\right] \qquad [25]$$

where $p[DM=dm|EDP=x]$ is given by Equation [10]. Mean assembly vulnerability functions can be created and archived for later use. See Porter et al. (2004) for examples. This is not a new idea. Czarnecki (1973) proposed several, as did Kustu et al. (1982), who normalized by the assembly replacement cost. Because construction contractors estimate repairs in terms of labor hours and dollar amounts, we find it simpler to deal with c_{dm} directly (i.e., not normalized). Introducing subscript k to index particular assemblies and c_{OP} to denote the mean value of C_{OP}, *PFL* is given by

$$PFL = \left(1 + c_{OP}\right)\sum_{k=1}^{N} c_k\left(x_k\right) \qquad [26]$$

where N is the number of building assemblies. *EAL* is then given by Equation [22].

3. CASE STUDIES

Van Nuys Hotel Building. To compare the three methods, we begin with an actual highrise hotel building located in Van Nuys, CA. It is a seven-story, eight-by-three-bay, nonductile reinforced-concrete moment-frame building built in 1966. It suffered earthquake damage in 1971 and 1994, after which it was seismically upgraded. We analyzed the building in its pre-1994 condition. See Beck et al. (2002) and Porter et al. (2002a) for details of the hazard model, structural model, component capacity distributions and unit repair costs. We performed 20 simulations at each of 20 levels of *IM*: S_a(1.5 sec, 5%) = 0.1, 0.2, … 2.0g, producing 400 simulated values of Y.

We took masses as perfectly correlated, normally distributed, with coefficient of variation (COV) equal to 0.10, per Ellingwood et al. (1980). We took damping as normally distributed with mean value of 5% and coefficient of variation of 0.40, as derived in Beck et al. (2002). Structural members were taken as having deterministic stiffnesses (including post-yield, unloading, etc.) but with yield and ultimate force and deformations that are perfectly correlated, normally distributed, with COV of 0.08, per Ellingwood et al. (1980). We took component capacities and unit repair costs as lognormally distributed; see Beck et al. (2002) for damage states, repair efforts, and parameters of the lognormal capacity distributions. We took C_{OP} as uniformly distributed between 15% and 20%. A professional cost estimator provided all costs.

Figure 1(a) shows the resulting vulnerability function; Figure 1(b) shows the site seismic hazard function. Each circle in Figure 1(a) represents one simulation. The jagged line shows mean loss at each S_a level. The smooth curve is a polynomial fit to the data. Each simulation includes one nonlinear time-history structural analysis using one simulation of the building's uncertain mass, damping, and force-deformation characteristics, one simulation of the capacity of each of 1,233 structural and nonstructural components, and one simulation of the unit-repair cost for each of 9 combinations of component type and damage state. The structural analyses took approximately 12 hours of computer time; the loss analysis took an hour. The most time-consuming portion of the analysis was creating the structural model. Figure 1 shows that, for S_a up to about 0.5g, a linear approximation for $y(s)$ is reasonable; and that beyond 0.5g, G'(s) is so small that the integrand of Equation [1] makes little contribution, supporting the approximation for $y(s)$ in Equation [17].

We applied Methods 1, 2, and 3 to this case-study building, producing the results shown in Table 1. Note that *PFL* for Method 2 was taken from the Method-1 analysis at $s = s_{EBE}$. Agreement between the methods is reasonable: Methods 2 and 3 produce *EAL* estimates within about 30% of that of Method 1. That Method 3 produces a reasonable estimate is particularly promising: at least in this case, one need not create a nonlinear structural model to get a reasonable estimate of *PFL* and *EAL*.

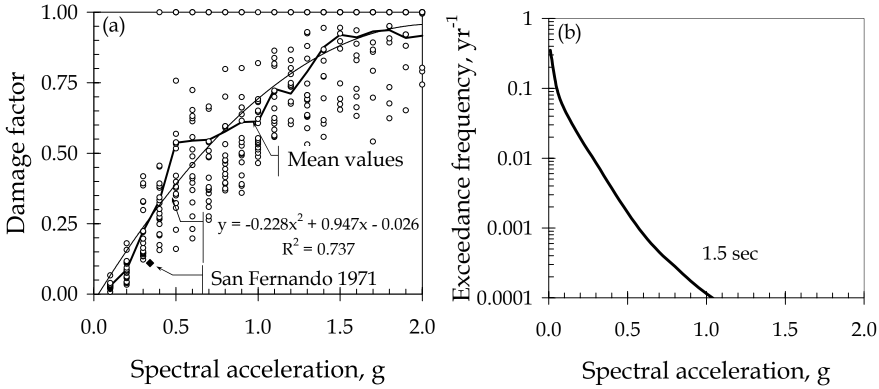

Figure 1. (a) Seismic vulnerability and (b) site hazard for Van Nuys building

Table 1. Approximation of seismic risk for Van Nuys case study

	Method 1	**Method 2**	**Method 3**
s_{NZ}	N/A	0.05g	0.05g
s_{EBE}	N/A	0.20g	0.20g
$G(s_{NZ})$, yr^{-1}	N/A	0.1026	0.1026
$G(s_{EBE})$, yr^{-1}	N/A	0.0195	0.0195
H, yr^{-1}	N/A	0.0617	0.0617
PFL	N/A	$613,000	$930,000
EAL	$53,600	$37,800	$57,400

We performed three additional tests. First, we evaluated Equation [7] at each of $n = 1, 2, \ldots 20$, for $\Delta s = 0.1$g. Figure 2 shows the result: the *EAL* considering only $S_a \leq 0.1$g, then $S_a \leq 0.2$g, etc. Figure 2(a) plots the results against S_a; Figure 2(b), against mean recurrence time. They show that only about 15% of cumulative economic loss comes from events with *PML*-level shaking or greater ($S_a > 0.5$g). As important as the 500-year earthquake is for life safety, it is largely irrelevant for cost. About half the *EAL* for this building results from events with $S_a \leq 0.25$g, whose mean recurrence time is 85 years or less. About 35% of loss is due to $S_a \leq s_{EBE}$. Ideally, loss from $S_a \leq s_{EBE}$ would be near 50% of *EAL*, making s_{EBE} is a good representative scenario shaking level, but the fraction will likely vary between buildings, so a cumulative *EAL* fraction of 35% at the s_{EBE} defined this way seems acceptable.

CUREE-Caltech Woodframe Project Buildings. As a second test, we compared Methods 1 and 2 using 14 hypothetical but completely designed buildings from the CUREE-Caltech Woodframe Project (Porter et al. 2002b). The buildings are variants of four basic designs referred to as index buildings (Reitherman and Cobeen 2003).

They include a small house (single story, 1,200 sf, stucco walls, no structural sheathing), a large house (two stories, 2,400 sf, some walls with structural sheathing, stucco exterior finish), a three-unit townhouse (two stories, 6,000 sf total, some walls with structural sheathing, stucco exterior finish), and an apartment building (three stories, 13,700 sf, 10 dwelling units, and tuck-under parking). Each index building included four or more variants: poor-, typical-, and superior-quality versions, and one or more retrofits or above-code or alternative designs. We considered these woodframe buildings located at an arbitrary site in Los Angeles, CA, at 33.9°N, 118.2°W. Using Frankel and Leyendecker (2001) to determine site hazard and adjusting for NEHRP site classification D, we find s_{EBE} = 0.4g. Of the 19 buildings examined in Porter et al. (2002b), 14 have nonzero mean loss at s_{EBE}.

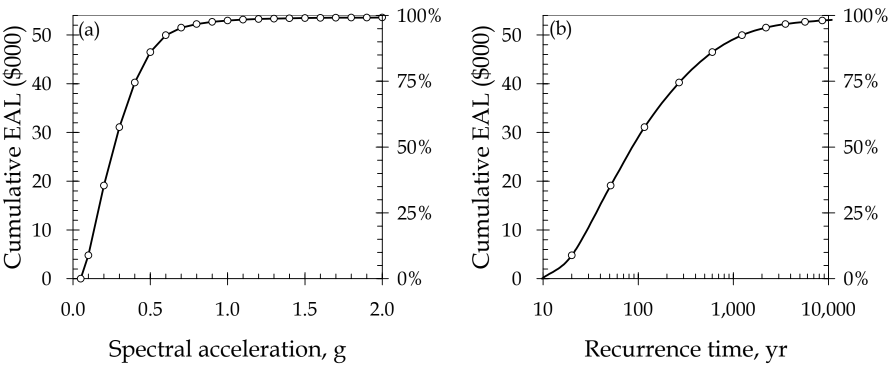

Figure 2. Dominance of frequent events in EAL for Van Nuys building

Figure 3 shows *EAL* for the Van Nuys and 14 woodframe buildings calculated by Method 1 (referred to in the figure as "exact") and by Method 2 (referred to as "approximate"). We denote Method-1 *EAL* by EAL_1, define estimation error as

$$\varepsilon \equiv \left(EAL_2 - EAL_1\right)/EAL_1 \qquad [27]$$

and take the error for each case-study building as a sample of ε. We find the sample mean and sample standard deviation of this error are $\overline{\varepsilon}$ = 0.12 and s_ε = 0.52, respectively. Thus, for these 15 buildings, the use of s_{EBE} defined as the shaking with 10% exceedance probability in 5 yr produces a fairly modest (12%) error in the estimate of *EAL*, relative to the exact method, which requires analysis of the complete seismic vulnerability function.

As a final test, we calculated the error if one defines s_{EBE} as shaking with 50% exceedance probability in 50 yr, and found $\overline{\varepsilon}$ = 0.06 and s_ε = 0.47. Defining EBE this way produces slightly more accurate results for the case-study buildings than using shaking intensity with 10% exceedance probability in 5 yr (as we have done), although at a the cost of meaningful risk communication.

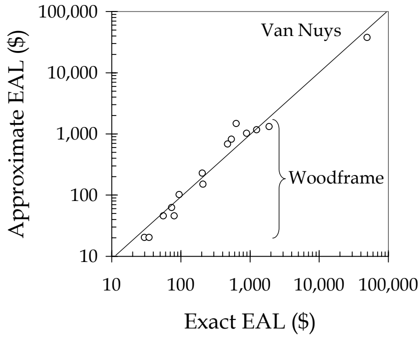

Figure 3. Comparing *EAL* by methods 1 and 2 for 15 sample buildings

The *EAL* values shown in Figure 3 might be quite meaningful to the real-estate investor. In the case of the Van Nuys building, whose replacement cost is approximately $7.0M and whose annual net operating income is on the order of $1M, an *EAL* of $54,000 represents a significant expense. The *EAL*s for the poorer-performing woodframe buildings can exceed $1,000. This would be a significant expected annual expense for a small investor, of the same order as homeowner insurance (Insurance Information Institute 2003).

4. CONCLUSIONS

Through a case study of a nonductile reinforced-concrete moment-frame building, we show that repair costs can be dominated by small, frequent events, rather than rare, *PML*-level losses. Using this example and that of 14 woodframe buildings, we show that expected annualized loss (*EAL*) is approximately proportional to a scenario loss referred to as the probable frequent loss (*PFL*). The constant of proportionality, referred to as the site economic hazard coefficient (*H*), can be mapped or tabulated for use by engineers or investors. *PFL* can be defined as the mean loss conditioned on the occurrence of shaking with 10% exceedance probability in 5 years. This is the economic-basis earthquake, EBE, named in imitation of the design-basis earthquake (DBE) of older codes. An approach called linear assembly-based vulnerability (LABV) can reasonably estimate *PFL* and *EAL* with one simplified PBEE analysis.

This methodology can inform a common opportunity for seismic risk-management: the purchase of commercial buildings in seismically active regions. Current practice produces little information to help investors consider seismic risk. Consequently, the opportunity for risk-management is usually missed. The problem might be alleviated by using *PFL* rather than (or in addition to) *PML*. *PFL* offers several advantages as a performance metric: (1) it better reflects upper-bound loss during an investor's planning period than does *PML*; (2) it can be multiplied by *H* to estimate *EAL*, which can be used as an operating expense, thereby making seismic risk more of a market force; (3) it can be readily calculated by a single, simplified PBEE simulation using linear structural analysis; and (4) by this method, PBEE can bring rigor to the most-common seismic risk-management opportunity for commercial buildings.

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