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SAFE DISTANCE BETWEEN ADJACENT BUILDINGS TO AVOID POUNDING IN EARTHQUAKES

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Abstract

We reexamine the required minimum permissible space between two adjacent buildings to preclude earthquake pounding damage. We examine several analytical approaches to estimate the minimum safe distance conditioned on the occurrence of risk-targeted maximum considered earthquake (MCE_R) shaking: 1) elastic spectral displacement response of the adjacent buildings at the top of the shorter building, accounting for mode shape and the height difference, 2) ASCE 7-10's equivalent lateral force procedure, and 3) multiple linear elastic dynamic structural analyses of the two adjacent buildings, factoring drift estimates by ASCE 7-10's C_d/R to approximate nonlinear response. We assume here that linear dynamic is the most accurate of the three and measure the safety of the others relative to it. Considering a suite of levels of MCE_R shaking and combinations of building heights and structural systems, both the more-approximate approaches appear to give modestly conservative estimates of safe separation distance. The spectral-response approach would be safe with 66% probability and the equivalent lateral force approach with 90% probability, assuming that multiple linear elastic structural analyses give a fairly accurate estimate of the true distribution of building motion. In other work we examine multiple nonlinear dynamic analysis and compare the first three with the fourth.

Keywords: seismic pounding; safe Structural Separation; adjacent buildings requirements

1. Introduction

Researchers have long examined earthquake-induced pounding between adjacent buildings because of the damage pounding has caused in past earthquakes. We reexamined safe separation distance because recent work on FEMA P-154 [1] suggested US practice is overly conservative.

Pounding tends to occur in dense urban areas because of the small separation distances there. Several authors have performed surveys of pounding damage after earthquakes. Rosenblueth and Meli [2] report on a damage survey after the 1985 Mexico City earthquake, performed by teams of engineering students, each team led by one or two experienced structural engineers. The teams performed mostly external (visual) inspection of 330 buildings that experienced severe damage or collapse, associated pounding with 40% of instances, and asserted that “in 15 percent of all cases [pounding] led to collapse.” The authors do not offer the teams’ basis for judgment, evidence, or any validation of the teams’ judgment is offered.

Kasai and Maison’s [3] survey of pounding damage after the 1989 Loma Prieta earthquake found that about 500 buildings were affected by about 200 instances of pounding, mostly involving older multistory masonry buildings, many with virtually no separation, and predominantly involving minor architectural or structural damage, although the authors warned of the potential for more serious damage in future, closer or larger earthquakes. Cole et al. [4] performed a similar survey of a portion of downtown Christchurch after the 2011 earthquake, most of which had no separation distance. Three notable findings: some buildings suffered partial collapse in part because of pounding; unreinforced masonry buildings were disproportionately likely to experience pounding damage, compared with concrete, timber, and steel; and the authors are not sure that pounding contributed to the complete collapse of any buildings.

Jeng et al. [5] used random-vibration theory to examine three approaches to estimate safe separation distance between single-degree-of-freedom systems subjected to white-noise excitation. (Actually they examined MDOF systems, but only elastic response in the first mode, so essentially SDOF). They recommend a double-difference combination (DDC) rule for building separation over either the sum of maximum displacements or the square root of the sum of the squares (SRSS); the recommended approach is like SRSS reduced by an amount related to the product of the maximum displacements and a correlation coefficient that varies with damping ratio and building periods.

Filiatrault and Cervantes [6], concerned that the separation distance prescribed by the 1990 National Building Code of Canada [7] was overly conservative (the sum of the maximum deflections at the top of the shorter building), performed nonlinear dynamic structural analysis of 5 realistic concrete shearwall buildings designed for each of 3 Canadian cities whose design base shears were generally in proportion 1:2:3 for a given building height. They use the estimates of structural response to support a method to estimate safe separation distance that involves equivalent lateral force (pseudostatic linear analysis) to estimate first-mode maximum response at the height of the top of the shorter building, and application of Jeng et al.’s DDC approach.

Lopez Garcia [8] provides a modified double difference combination (MDDC) approach similar to that of Jeng et al. but replacing the correlation coefficient with an empirical parameter that, he shows, provides consistent, modest conservatism and accounts for behavior of linear and nonlinear SDOF and MDOF systems. ASCE 7-10 [9] requires the separation distance to be at least the square root of the sum of squares of the two buildings' maximum response displacement by an equivalent lateral force approach that approximates inelastic response.

Our goal is to reexamine the required minimum permissible space between two adjacent buildings to preclude pounding, with some differences from prior studies. We employ 3 degrees of analysis up to linear dynamic structural analysis (later work will employ nonlinear dynamic analysis); 3 combinations of frame and shearwall buildings; 5 building heights between 2 and 26 stories; and 4 locations with degrees of seismicity in roughly equal increments corresponding to short-period mapped spectral acceleration response S_{MS} from 0.8 to 3.0g.

2. Research Methodology

The proposed procedure for this study can be summarized as follows:

2.1 Step 1: asset definition

To investigate both the effect of buildings seismic force-resisting systems and buildings fundamental periods of vibration on the minimum permissible space between two adjacent buildings, buildings with three combinations of seismic force-resisting systems (both wall, both frame, and mixed) and various fundamental periods of vibration are selected.

2.2 Step 2: hazard analysis and ground motions selection

To explore the effect of degree of seismicity on the safe distance between adjacent buildings, let us examine four locations with S_{MS} values (defined as in ASCE 7-10) between 0.8g and 3.0g. for each location, let us deaggregate the hazard to find the controlling source characteristics (modal magnitude M, distance R, and epsilon ε_0) associated with each location and its S_{MS}. Lastly, select suites of ground motions with approximately the same source characteristics and scale them to match the target S_{MS} for each location, attempting to limit the scaling factor (the constant that is multiplied by each acceleration to achieve the desired value of S_A(0.2 sec, 5%)) to 0.5 to 2.0, so as to keep the time histories realistic. For simplicity we do not comply with the requirements of ASCE 7-10 Sec 16.1.3.1, which requires scaling motions so that the that "the average value of the 5 percent damped response spectra for the suite of motions is not less than the design response spectrum for the site for periods ranging from 0.2T to 1.5T where T is the natural period of the structure in the fundamental mode for the direction of response being analyzed." In later research we compare results of our simple scaling method with scaling required by ASCE 7-10. We recognize that ASCE 7-10 requires at least 3 ground motions; we used 15 so as to better estimate the probability distribution of proximity.

2.3 Step 3: first approach, spectral displacement estimate of proximity

The minimum required safe distance according to this approach to avoid pounding can be estimated as the SRSS of the spectral displacement response of each pair of buildings, based solely on their estimated periods, heights, and the idealized design spectrum at the site of interest. This displacement spectrum is associated with the risk-targeted maximum considered earthquake (MCE_R) and characterized by ASCE 7-10's S_{MS} and S_{M1} parameters. Also, a triangular mode shape and the height of the shorter building for each building of the pair is considered as shown in Fig.1 and in accordance with Eq. (1). The approach requires very modest effort, with the disadvantage that it does not account for any building characteristics other than height and estimated period. SRSS represents almost the simplest approach possible (absolute sum having been shown to be overly conservative and DDC or MDDC requiring somewhat more effort and complexity).

$$d^{(SD)} = \sqrt{\left(S_{d1} \cdot \frac{h_2}{h_1}\right)^2 + \left(S_{d2}\right)^2} \tag{1}$$

where $d^{(SD)}$ denotes the spectral displacement estimate of proximity, S_{d1} and S_{d2} denotes the spectral displacement response for the taller and shorter buildings, respectively, using the idealized design spectrum, and h_1 and h_2 are the heights of the taller and shorter buildings, respectively.

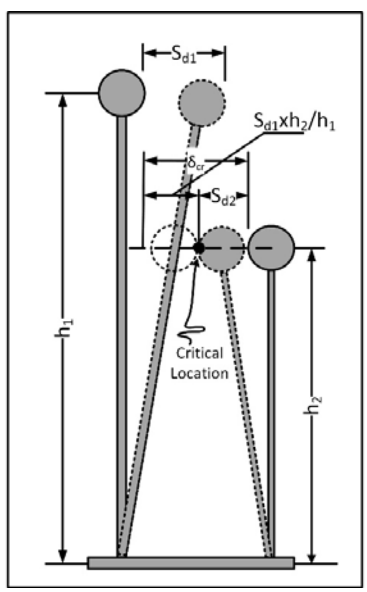

Fig. 1 – Approach 1, the spectral estimate of proximity model

2.4 Step 4: second approach, equivalent lateral force

Our second approach is to follow the equivalent lateral force procedure (ELF) specified in section 12.8 of ASCE 7-10, omitting the 2/3 factor of ASCE 7-10 equations 11.4-3 and 11.4-4 so as to measure proximity at MCE_R shaking, rather than at 2/3 that value, i.e., according to Eq. (2), which combines by SRSS the estimated maximum inelastic deformation of the two buildings at the top of the shorter building. Fig.2 illustrates the model. The second approach takes advantage of prior work to estimate the response modification factor *R* and the deflection amplification factor C_d—that is, it approximately accounts for lateral force resisting system—but it requires structural analysis of both buildings.

$$d^{(ELF)} = \sqrt{\delta_{M1}^2 + \delta_{M2}^2} \tag{2}$$

$$\delta_M = \frac{\delta_{Max} C_d}{I_e} \tag{3}$$

where

$d^{(ELF)}$ = equivalent lateral force estimate of proximity
δ_{Max} = maximum elastic displacement at the critical location (the top of the shorter building) under loading $S_{MT} \cdot I_e / R$
S_{MT} = soil-amplified spectral acceleration response in the idealized design spectrum and the appropriate period under risk-targeted maximum considered earthquake shaking,
R = response modification factor in ASCE 7-10 table 12.2-1
C_d = deflection amplification factor from ASCE 7-10 table 12.2-1
I_e = importance factor from ASCE 7-10 section 11.5-1

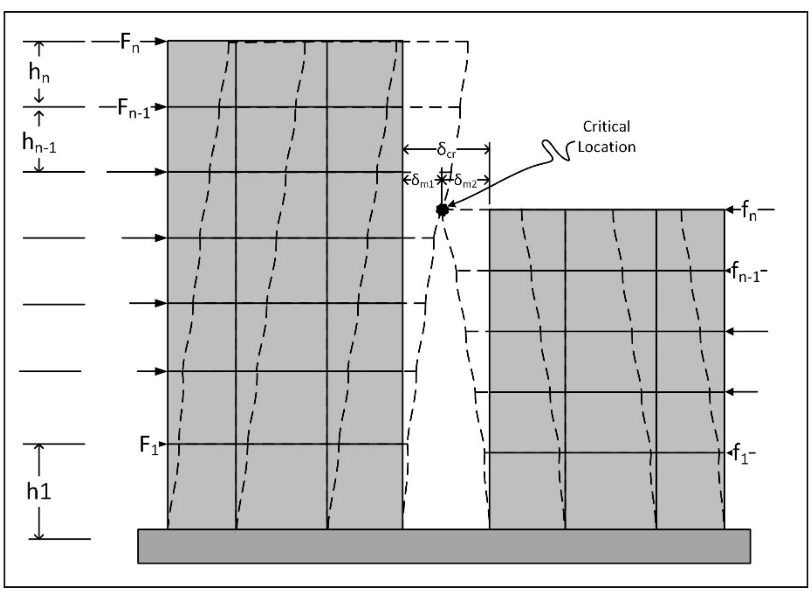

Fig. 2 – Approach 2, equivalent lateral force estimate of proximity

2.5 Step 5: third approach, multiple linear dynamic analyses

In this approach, one estimates the minimum safe distance at the critical location by modeling in linear dynamic analysis the pair of buildings as if they were adjacent, connected by a flexible link at the top of the shorter building. One subjects the building pair to suites of ground motions as described in step 2, records the time-maximum shortening of the flexible link, and calculates its cumulative distribution function conditioned on building pair and location. To comply with the requirements of ASCE 7-10 Section 16.1, we multiplied drift by C_d/R, which takes on a value of 0.83 for special reinforced concrete shearwalls and 0.69 for steel special moment frames. In contrast to ASCE 7-10 however, we examine drifts at MCE_R shaking level rather than 2/3 of the MCE_R, because our initial motivation was to inform FEMA P-154, which screens buildings for collapse hazard at MCE_R shaking, not 2/3 MCE_R. Fig.3 illustrates the model assembly.

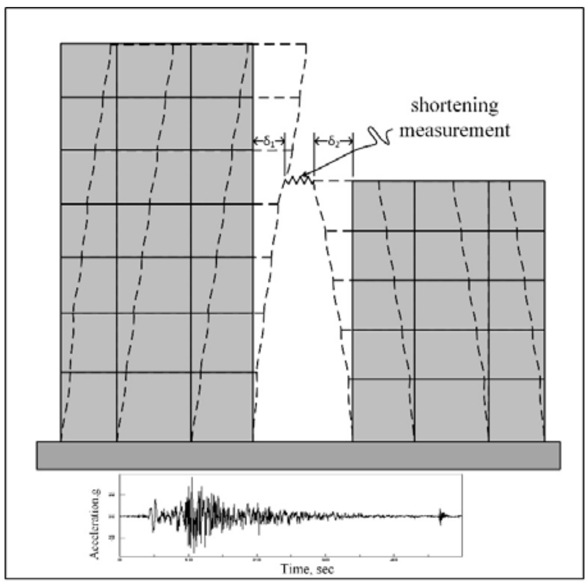

Fig. 3 – The Linear Dynamic Estimate of Proximity

2.6 Step 6: iterate to characterize probabilistic structural response

One iterates steps 2 through 5 for each of many combinations of frame and shearwall buildings, several building heights, and several locations with degrees of seismicity in roughly equal increments corresponding to the range of S_{MS} values in the United States that correspond to ASCE 7-10 risk category D, i.e., 0.8g ≤ S_{MS} ≤ 3.0g.

2.7 Step 7: comparisons

Finally, one examines how safe are approaches 1 and 2 versus 3? Assuming that approach-3 produces an approximately accurate probability distribution of the reduction in proximity of two buildings considering record-to-record variability and nonlinear response, with what probability would the actual reduction in distance between two buildings in a particular earthquake with MCE_R shaking be less than or equal to the safe distance calculated by either simpler approach? Idealizing the reduction in proximity under the 3rd approach with a lognormal cumulative distribution function, one can use Eq. (3) to estimate the probability that a pair of buildings subjected to an earthquake with MCE_R shaking would experience a reduction in proximity less than or equal to the safe separation distance *d* calculated using an approximate approach (1 or 2):

$$p = \Phi\left(\frac{\ln\left(d/\theta\right)}{\beta}\right) \tag{4}$$

where Φ denotes the standard normal cumulative distribution function, *d* is either $d^{(SD)}$ or $d^{(ELF)}$, i.e., the safe separation distance calculated for a given building and geographic location by approach 1 or 2, θ is the median safe separation distance calculated for the same building and location using approach 3 (i.e., the median considering the various ground motion time histories), and β is the standard deviation of the natural logarithm of safe separation distance considering the various ground motion time histories. One can calculate *p* for each combination of building pair and location, and do so for approaches 1 and 2. (In later study will treat nonlinear dynamic analysis as the best estimate of true separation distance, and compare the first three with the fourth.)

3. Case studies

3.1 Asset definition

We investigated pounding within and between two seismic force-resisting systems: steel special moment frames and special reinforced concrete shear walls. To sample steel special moment frames, we used the 3-story, 9-story, and 20-story models provided to the SAC Steel project by Gupta and Krawinkler [10], plus the 6- and 12-story steel-frame building models examples offered by BSSC to illustrate the 2009 NEHRP Provisions [11]. For the special reinforced concrete shear wall buildings, we idealized the lateral systems of five buildings (2-, 6-, 11-, 13, and 26 stories) as cantilever columns. Shearwall building plan dimensions and fundamental periods were estimated to match mean observations regressed from or offered by Goel and Chopra [12]. We estimated shearwall building dead loads based on the mass of a 6-in normal-weight concrete slab of the given plan dimensions factored up by 20% to account for shearwalls, columns, architectural finishes, and mechanical, electrical, and plumbing systems. We estimated realistic shearwall cross-section dimensions using the same source. Table 1 summarizes our 10 sample buildings: their fundamental period of vibration T, height H, and stories. Table 2 presents the combinations we examined: FF denotes adjacent steel-frame buildings; WW denotes two adjacent shearwall buildings, and WF denotes a shearwall next to a steel frame.

Table 1 – Sample buildings

Building ID	T, sec	H, ft	Stories	Building system
SMF-1	3.77	265.0	20	SMF
SMF-2	2.93	155.5	12	SMF
SMF-3	2.51	122.0	9	SMF
SMF-4	2.07	77.5	6	SMF
SMF-5	0.93	39.0	3	SMF
SW-1	1.8	258.1	26	SW
SW-2	1.0	134.3	13	SW
SW-3	0.9	119.4	11	SW
SW-4	0.5	62.1	6	SW
SW-5	0.2	22.4	2	SW
SMF: steel special moment frames structure SW : special reinforced concrete shear wall structure				

Table 2 – Building Combinations

Frame-frame		
Case #	Left	Right
FF-1	SMF-1	SMF-2
FF-2	SMF-1	SMF-3
FF-3	SMF-1	SMF-4
FF-4	SMF-1	SMF-5
FF-5	SMF-2	SMF-3
FF-6	SMF-2	SMF-4
FF-7	SMF-2	SMF-5
FF-8	SMF-3	SMF-4
FF-9	SMF-3	SMF-5
FF-10	SMF-4	SMF-5

Wall-wall		
Case #	Left	Right
WW-1	SW-1	SW-2
WW-2	SW-1	SW-3
WW-3	SW-1	SW-4
WW-4	SW-1	SW-5
WW-5	SW-2	SW-3
WW-6	SW-2	SW-4
WW-7	SW-2	SW-5
WW-8	SW-3	SW-4
WW-9	SW-3	SW-5
WW-10	SW-4	SW-5

Wall-frame		
Case #	Left	Right
WF-1	SW-1	SMF-1
WF-2	SW-1	SMF-3
WF-3	SW-1	SMF-5
WF-4	SW-2	SMF-4
WF-5	SW-3	SMF-1
WF-6	SW-3	SMF-2
WF-7	SW-3	SMF-3
WF-8	SW-5	SMF-1
WF-9	SW-5	SMF-2
WF-10	SW-5	SMF-3

3.2 Hazard analysis and ground motion selection

We explored the effect seismicity by examining four locations: Sacramento CA (ASCE 7-10 [9] S_{MS} = 0.8g), eastern San Francisco (S_{MS} = 1.5g), western San Francisco (S_{MS} = 2.3g), and northwestern Tennessee (S_{MS} = 3.0g, which is near the highest value of S_{MS} in the United States). We estimated Vs30 using Wills and Clahan's [13] map for the California sites and Wald and Allen's [14] map for the Tennessee site. We used the USGS's probabilistic seismic hazard deaggregation tool [http://geohazards.usgs.gov/deaggint/2008/] to estimate source characteristics (modal magnitude M, distance R, and epsilon ε_0) associated with S_{MS} at each location. We selected suites of 15 ground motions corresponding to the modal source characteristics and scaled them to match S_{MS} for each location. We selected records whose scaling factors were closest to 1.0 using the tools of the Pacific Earthquake Engineering Research (PEER) Center at http://ngawest2.berkeley.edu.

3.3 Results

Table 3 summarizes the statistics of safe distances under the three approaches. The column labeled "case group" indicates the building combinations: WW denotes all the cases with two adjacent shearwall buildings, WF denotes all the cases with a shearwall building adjacent to a moment frame, etc. S_{MS} denotes the hazard level in terms of risk-targeted site-soil adjusted, mapped 5%-damped short-period spectral acceleration response at the location of interest: 0.80 g indicates the Sacramento, California location, 1.5g indicates eastern San Francisco, 2.3g indicates western San Francisco, and 3.0g indicates northwestern Tennessee.

The subsequent columns give statistics of safe separation distance as a fraction of the height of the shorter building, averaging over all particular building combinations in the given case and hazard level: μ denotes average, δ denotes coefficient of variation, averaging over all the building combinations in the group. In the case of the 3rd approach, we averaged over all the ground motion time histories as well. The column labeled $\hat{\beta}_{RTR}$ measures record-to-record variability. To be precise, one calculates the natural logarithm of separation distance in each pair of buildings, S_{MS} value, and ground motion time history. There are 15 such distances per combination of building pair and S_{MS} value, one for ground motion time history. The standard deviation of those natural logarithms measures the record-to-record variability in separation distance. There are 10 such standard deviations for each case group and S_{MS} value, one for each of 10 building pairs. The record-to-record variability varies among the 10 cases; the value shown in the table is the average of those 10. The columns labeled $p^{(1)}$ and $p^{(2)}$ give the probability (averaging over all 10 cases in the group) that an actual earthquake with MCE_R shaking will produce a smaller reduction in separation distance than the value of *d* calculated by approach-1 or approach-2, respectively.

Table 3 – Summary statistics

Case group	S_{MS} (g)	1^{ST} approach		2^{nd} approach		3^{rd} approach			$p^{(1)}$	$p^{(2)}$
		μ	δ	μ	δ	μ	δ	$\hat{\beta}_{RTR}$		
WW	0.80	0.004	0.14	0.006	0.34	0.003	0.56	0.38	0.79	0.98
WW	1.50	0.007	0.14	0.011	0.34	0.005	0.46	0.29	0.84	1.00
WW	2.30	0.012	0.16	0.019	0.37	0.010	0.51	0.33	0.74	0.97
WW	3.00	0.014	0.14	0.022	0.33	0.012	0.55	0.37	0.69	0.95
WF	0.80	0.009	0.30	0.012	0.27	0.008	0.48	0.34	0.64	0.90
WF	1.50	0.015	0.30	0.021	0.27	0.016	0.48	0.35	0.54	0.83
WF	2.30	0.026	0.30	0.036	0.27	0.027	0.52	0.40	0.57	0.82
WF	3.00	0.029	0.30	0.040	0.27	0.030	0.53	0.39	0.56	0.81
FF	0.80	0.013	0.13	0.019	0.31	0.011	0.43	0.31	0.68	0.93
FF	1.50	0.023	0.13	0.034	0.31	0.022	0.50	0.41	0.60	0.85
FF	2.30	0.040	0.13	0.060	0.31	0.037	0.52	0.46	0.62	0.85
FF	3.00	0.044	0.13	0.065	0.31	0.041	0.54	0.46	0.63	0.85

Some general observations of the summary statistics in Table 3:

- All three use linear elastic structural analysis, so average and median values tend to be proportional to S_{MS}. The third approach uses ground motions appropriate to the particular locations—Sacramento has different modal magnitude, distance, etc. than eastern San Francisco, so the ground motions for the two differ—but average and medians under the 3^{rd} approach vary little from proportionality with S_{MS}.
- Wall-wall combinations have the smallest safe separation distances, wall-frame combinations have safe separation distances roughly twice that of wall-wall, and frame-frame roughly 3 times that of wall-wall.
- Average values for the 1^{st} approach are slightly larger (within 20%) than those of the 3^{rd}.
- Average values for the 2^{nd} approach range from 1.5 to 2 times those of the 3^{rd}.
- Variability in the 1^{st} and 2^{nd} approaches are much smaller than those of the 3^{rd}, as measured by the coefficients of variation (δ). That observation should surprise nobody because only the 3^{rd} approach reflects record-to-record variability.
- Record-to-record variability in safe separation distance ranges between 0.3 and 0.5, averaging 0.4. Approaches 1 and 2 both give modestly conservative estimates of safe separation distance. Approach 1 would produce a safe distance with an average 66% probability, approach 2, approximately 90%.

4. Conclusions

We examined three relatively simple approaches to estimate safe separation distance to avoid pounding at MCE_R shaking: (1) SRSS of 5% damped elastic spectral displacement response at the top of the shorter building;

(2) ASCE 7-10's equivalent lateral force procedure; and (3) multiple linear elastic dynamic structural analyses, with drift results multiplied by C_d/R to approximate nonlinear response. We varied seismicity (four levels of S_{MS} from 0.8g to 3.0g), combinations of seismic force-resisting systems (shearwall and steel moment frame), building heights (2 to 26 stories), and fundamental periods of vibration (0.2 sec to 2.8 sec). We estimated safe separation distance as a fraction of the height of the shorter building and as a function of S_{MS}, system combination, and analytical method. Both the spectral displacement approach and the equivalent lateral force procedure appear to give modestly conservative estimates of safe separation distance. The former would be safe with 66% probability, the latter with 90% probability, assuming that the third approach (multiple linear elastic structural analyses with drifts factored by C_d/R to approximate nonlinear response) gives a fairly accurate estimate of the true distribution of building motion. In later work we will examine multiple nonlinear dynamic analysis and compare the first three with the fourth.

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