Scaling Ground Motions for Response-History Analysis of Tall Buildings

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SUMMARY
Next generation performance-based earthquake engineering involves the use of a probability framework, which incorporates the inherent uncertainty and variability in seismic hazard, structural and non-structural responses, damage states and economic and casualty losses. One key issue in seismic performance assessment is the scaling of ground motions for nonlinear response-history analysis. In this paper, the impact of five ground-motion scaling procedures, namely, 1) geometric-mean scaling of pairs of ground motions, 2) spectrum-matching of ground-motions, 3) first-mode-based scaling to a target spectral acceleration and 4) maximum-minimum orientation scaling, 5) pushover-based scaling method on the medians of and dispersions in peak floor acceleration and peak story drift responses in a sample 34-story building is investigated. The advantages and disadvantages of each method are discussed.

Keywords: Ground motion; scaling; tall building; performance assessment; response-history analysis

1. INTRODUCTION

The ATC-58 project (ATC 2011) in the United States is developing next-generation tools and guidelines for performance-based seismic design and assessment using a probability framework, which can incorporate the inherent uncertainty and variability in seismic hazard, structural and non-structural responses, damage states and repair costs in the assessment process. Performance levels are defined in terms of direct economic loss, casualties and downtime, and the procedures of the assessment involve the use of nonlinear response-history analysis.

One key issue in seismic performance assessment of buildings is the scaling of ground motions for nonlinear response-history analysis, which should 1) preserve the *distribution* (e.g., both median and dispersion) in the earthquake shaking for the selected characterization of the hazard for the site of interest; 2) enable losses to be computed for structural and nonstructural components and systems having different dynamic properties; and 3) be applicable across a wide range of earthquake shaking amplitudes since both structural and nonstructural components in a building may contribute significantly to seismic loss of the building (Huang et al. 2011).

A significant amount of research work has been carried out in the past for ground motion selection and scaling. Shome et al. (1998) suggested that the most efficient way to estimate the nonlinear response from a given event (magnitude (M), distance (R)) is to first estimate a median spectral acceleration, and then to scale the records from roughly the same magnitude to this spectral acceleration before carrying out the nonlinear analyses. They observed that the scaling of ground-motion records to the 5%-damped spectral acceleration at the fundamental frequency of the structure is best among the alternatives. Baker and Cornell (2005) considered Intensity Measure (IM) consisting of two parameters, spectral acceleration and epsilon (ε), at a given period to predict the response of a structure. They suggested consideration of ε when selecting ground motions as ε was found to be an indicator of spectral shape. Baker and Cornell (2006) proposed a spectrum, termed as conditional mean spectrum (CMS), considering ε (CMS-ε) that accounts for the magnitude (M), distance (R) and ε values likely to cause a given target ground motion intensity at a given site. A less conservative estimate of responses can be obtained by using CMS-ε conditioned on target Sa values at several periods, and taking the envelope (or some other combination) of responses estimated with records based on these spectra. They suggested using the uniform hazard spectrum (UHS) as a target spectrum if one is performing expensive analyses or experiments on a system with an unknown period or many sensitive periods and cannot run many tests, recognizing that the results may be quite conservative. Haselton et al. (2009) proposed an alternative simplified method which allows the analyst to use a general ground motion set, selected without regard to ε, to calculate an unadjusted building collapse capacity by using nonlinear dynamic analysis, and then to correct this capacity using an adjustment factor to reflect the expected $\varepsilon(T_1)$ for the building site and collapse hazard intensity, $S_{a,col}(T_1)$. This eliminates the necessity of considering $\varepsilon(T_1)$ in selection of the ground motion records. Jayaram et al. (2011) proposed a ground-motion selection algorithm which can match both the mean and variance in a target spectrum.

Huang et al. (2010) studied four scaling methods are studied, namely, 1) geometric mean scaling of pairs of ground motions, 2) spectrum matching of ground motions, 3) first-mode-period scaling to a target spectral acceleration and 4) scaling of ground motions per the distribution of spectral demands to see the impact of alternate ground-motion scaling procedures on the distribution of displacement responses in single-degree-of-freedom (SDOF) structural systems. Kalkan and Chopra (2010) have developed a modal-pushover-based scaling (MPS) method to scale ground motions for use in nonlinear response history analysis of buildings and bridges. The scaling method is based on their well-known modal-pushover static analysis and the determination of scale factors requires the use of nonlinear response-history analysis for single degree-of-freedom system.

The main objective of this study is to discuss the impact of ground-motion scaling procedures on the performance of tall structures. Bi-directional nonlinear response-history analysis is performed using a 34-story sample moment-resisting frame building with steel-concrete composite columns and steel beams, and ground motions scaled using different methods. The building is assumed to be located in Taiwan. Five ground-motion scaling procedures, including 1) geometric-mean scaling of pairs of ground motions, 2) spectrum-matching of ground-motions, 3) first-mode-based scaling to a target spectral acceleration, 4) maximum-minimum orientation and 5) modal-pushover-based scaling methods are studied. The impact of scaling on the seismic performance of buildings is discussed. The focus is not only on the peak inter-story drift, but also on peak floor acceleration. Both the median and dispersion values are discussed.

2. BUILDING DESCRIPTION AND SEED GROUND MOTION

Figure 1 presents the plan view of the sample thirty-four story building. The building has four (three) bays and is 35 (35) m wide in the X (Y) direction. It has a typical story height of 3.5m and consists of moment resisting frames with steel-concrete composite columns and steel beams. The column sections consist of high strength concrete core (compressive strength is 55 MPa). Steel box-sections are used as main reinforcement outside the concrete core. Steel plates are bonded to the inside concrete core section and the relatively low-strength out-side concrete (compressive strength is 20.5 MPa) through shear lugs.

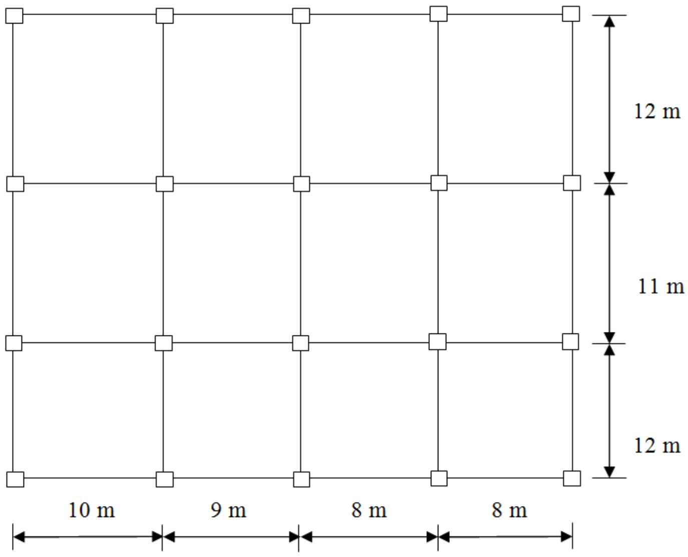


Figure 1. Plan view of the sample building

The sample building is modeled using SAP2000 (CSI 2009). The first three natural periods of the building in the X direction are 4.58, 1.63 and 0.94 seconds, respectively. The first three natural periods of the building in the Y direction are 4.90, 1.76 and 1.02 seconds, respectively. The period of the first torsional mode is 3.5 seconds.

According to the seismicity of the site of the sample building, the governing event is earthquake with moment magnitude of about 7 and site-to-fault distance about 7 to 9 km. Thirty pairs of seed ground motions were selected from PEER NGA ground motion database with moment magnitude between 6.7 and 7.6, closest site-to-source distance between 3 and 13 km and Site Classes of B and C per ASCE-7. Each pair of time series was rotated to be parallel and perpendicular to the orientation of GMRotI50, which is a rotated geometric-mean spectral demand independent of sensor orientation. The rotated time series were used as seed ground motions for this project.

3. GROUND MOTION SCALING METHODS

Six scaling methods studied in this project were summarized herein:

Method 1 is termed geometric-mean scaling method. It involves amplitude scaling a pair of seed motions by a single scaling factor to minimize the sum of the squared errors between the target spectral values and the geometric mean (square root of the product) of the spectral ordinates for the pair.

To study the impact of the degree of yielding on the seismic performance of the sample building, three sets of target spectral values were used: one corresponding to an earthquake return period of 475 years (a probability of exceedance of 10% in 50 years, see the solid line of Figure 2a), the second set corresponding to an earthquake return period of 2475 years (2%/50yr, see the solid line of Figure 2b) and the third set is 200% of the set corresponding to the set with earthquake return period of 2475 years. The seven spectral ordinates of each of the two spectra at periods of 1 to 7 seconds in increments of 1 second were used as the target spectral values to scale thirty pairs of seed ground motions. The period range of 1 through 7 seconds was selected to cover a range of $0.2T_1$ to $1.5\ T_1$, where T_1 is the fundamental period of the sample building.

Three sets thirty pairs of scaled ground motions were developed using Method 1. The median of the thirty spectra of ground motions scaled using Method 1 is presented in Figure 2b, using a red dash line, for earthquake return period of 2475 years. That for earthquake return period of 475 years is presented in Figure 2a, also using a red dash line. The median spectra match reasonably well to their target in the period range between 1 and 7 seconds.

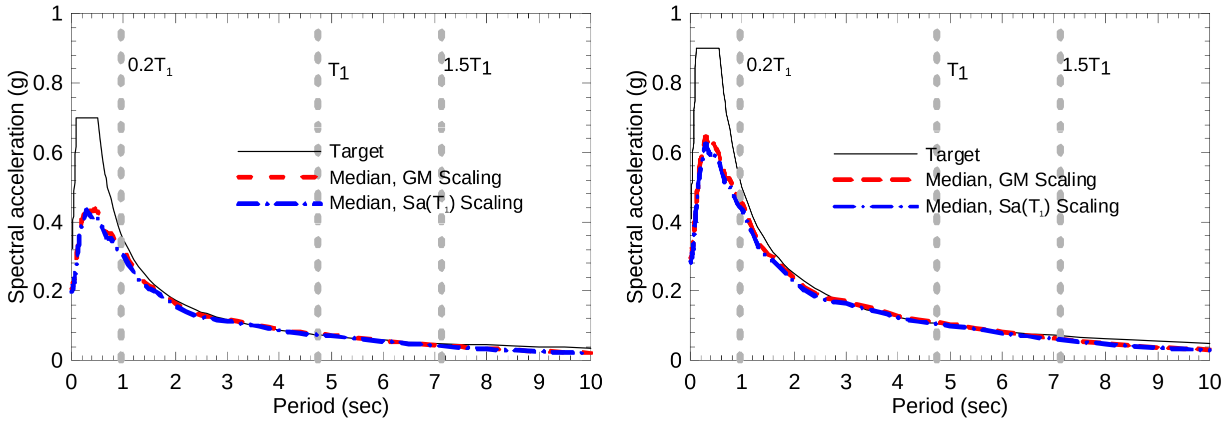


Figure 2. Target design spectra for the sample site and the median spectra of the ground motions scaled using Methods 1 and 3.

Method 2 is termed spectrum-matching method. Spectrally matched ground motions have been widely used for seismic design of structures. To judge the utility of spectrum-matched ground motions for predicting the response of the building, the thirty pairs of seed ground motions used in this project were modified to match the median spectrum of the ground motions obtained using Method 1. Three sets of scaled ground motions were obtained using Method 2: two corresponding to an earthquake return period of 475 years and 2475 years respectively, and the third set is 200% of the set corresponding to the earthquake return period of 2475 years.

Method 3 is termed $S_a(T_1)$ scaling method. It involves amplitude scaling of ground motion records to a specified acceleration at the first mode period of the structure. The seed ground motions of this study were scaled to match the median spectral acceleration of the scaled ground motions for Method 1 at a period of 4.75 seconds. The median of the thirty spectra of ground motions scaled using Method 3 is presented in Figure 2a (Figure 2b), using a blue dash-dot line, for earthquake return period of 475 (2475) years. The median spectra match reasonably well to their target. The dispersion in spectral accelerations of ground motions scaled using Method 3 in the short and mid period ranges is much greater than that using Method 1.

Method 4 is termed maximum-demand scaling method. Huang et al. (2009) used an orientation-dependent parameter, $\bar{R}_{S_a}(\theta)$, to investigate the orientation of maximum elastic spectral demands for near-fault ground motions. The upper bound on $\bar{R}_{S_a}(\theta)$, equal to 1, occurs when the spectral demands for a given orientation are equal to the maximum demands at all periods considered. The maximum value of $\bar{R}_{S_a}(\theta)$ was termed $\bar{R}_{S_a,\max}$. In Method 4, the two components of each pair of seed ground motions were first rotated to the orientations parallel and perpendicular to the orientation associated with $\bar{R}_{S_a,\max}$. The rotated seed ground motions were then scaled using Method1. The resultant ground motions were used in the analysis for Method 4.

For Methods 4 and 5, two sets of target spectral values were used: one corresponding to an earthquake return period of 2475 years (the solid line of Figure 2b) and the other set is corresponding to 200% of the set corresponding to the earthquake return period of 2475 years.

Note that the values of the seismic design parameters reported in the 2010 Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10), the 2009 NEHRP Recommended Seismic Provisions for New Buildings and Other Structures (FEMA P-750), and the 2012 International Building Code have been set to be identical. Both the probabilistic and deterministic values of the design parameters are defined in terms of maximum spectral demand rather than geometric-mean demand.

Method 5 also uses spectrum-matching method, but the seed ground motions were matched to the entire code-compliant spectrum, rather than the median spectrum of the ground motions obtained using Method 1. The code-compliant spectrum has higher demand in the short-period range than the median spectrum of the ground motions for Method 1. The purpose for Method 5 is to investigate the contribution of higher modes to structural responses of tall buildings. The spectrally-matched ground motions were developed using the computer code RSPMATCH (Abrahamson 1998).

Method 6 is modal-pushover-based scaling method developed by Kalkan and Chopra (2010). The method involves several steps, including 1) developing the pushover curve of the sample building, 2) developing a single degree-of-freedom (SDOF) system based on the pushover curve of the sample building, and 3) scaling the seed ground motions so that the nonlinear displacement of the SDOF system subjected to the scaled ground motions is equal to a target value. Only the analyses using ground motions corresponding to 200% of the earthquake return period of 2475 years were performed for Method 6.

Figure 3 presents the median spectral accelerations for ground motions scaled using Methods 1 through 6 for target spectral accelerations corresponding to 200% of the earthquake return period of 2475 years.

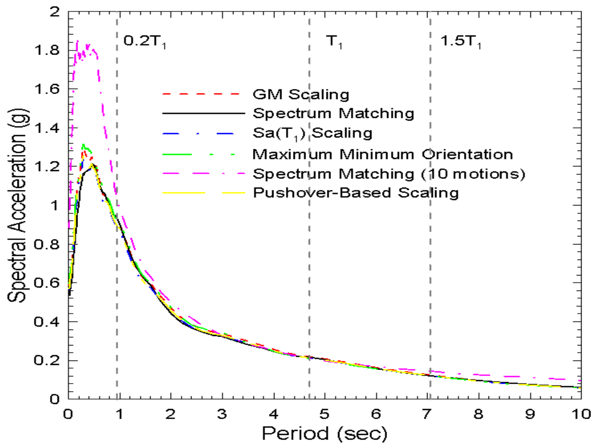
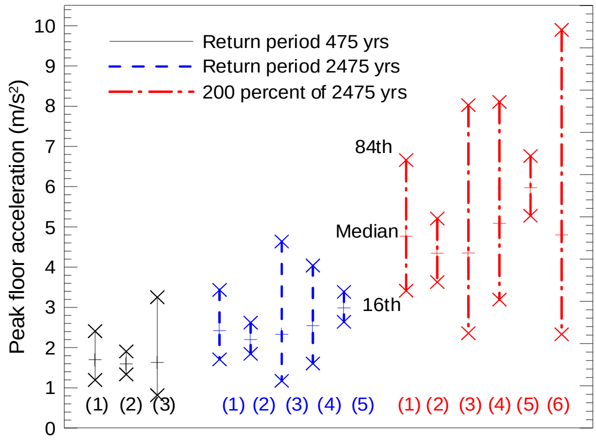


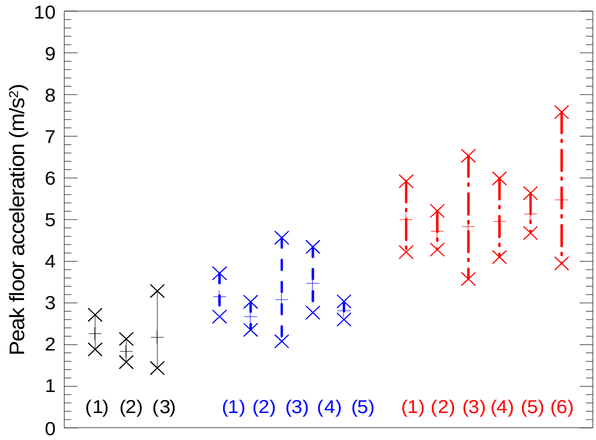
Figure 3. Median spectral accelerations for ground motions scaled using Methods 1 through 6 for 200% of the earthquake return period of 2475 years

4. ANALYSIS RESULTS

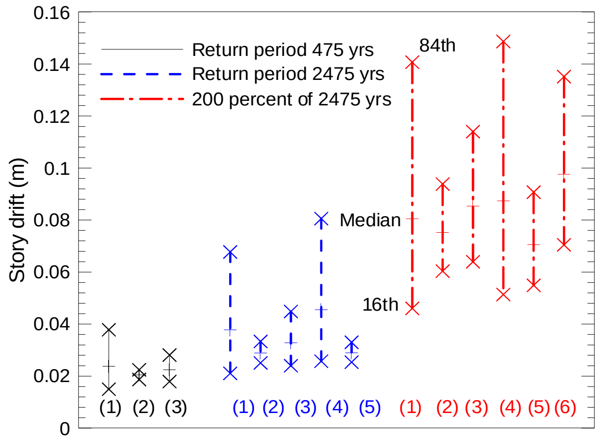
Panels a and b (c and d) of Figure 4 present median, 84th and 16th percentiles of peak floor accelerations (story drifts) at the 1[st] and 34[th] floors for Methods 1 through 6. Results are presented at ground-motion intensity levels corresponding to earthquakes with return periods of 475 and 2475 years and 200% of the intensity for the return period of 2475 years.



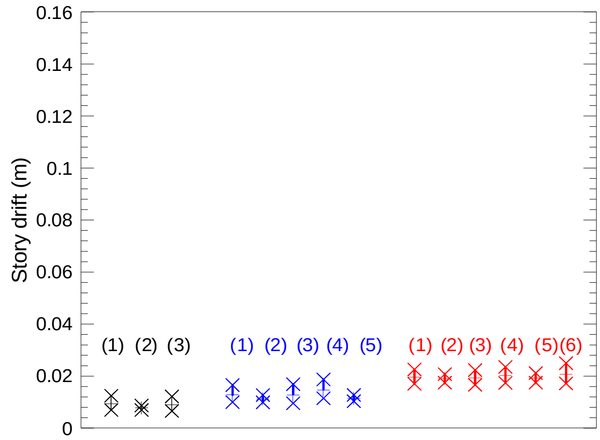
a) 1st floor, peak floor acceleration



b) 34th floor, peak foor acceleration



c) 1st story, peak story drift



d) 34th story, peak story drift

Figure 4. Median, 84th and 16th percentile values of peak floor acceleration and peak story drift at the 1st and 34th floors in the X direction for Methods 1 through 6

Major observations of Figure 4 include:

1. Methods 1 and 3 generally provide similar prediction in median responses.
2. Method 2 moderately underestimates the median response quantities compared to the other methods.
3. Method 4 provides higher median response quantities compared to Method 1, 2 and 3 in maximum direction.
4. Method 5 provides higher median values for peak floor acceleration and average floor spectral acceleration responses at lower floors compared to the other methods due to higher spectral demand in the short period range. For peak inter-story drift response, Method 5 provides similar median values as Method 2 and smaller median values than Method 1.

5. The median responses for Method 6 are similar to or slightly higher than those for Methods 1 and 3.
6. Dispersions in all the response quantities are very different for Methods 1 through 6. Methods 2 and 5 provide lowest dispersions in all the response quantities. Dispersions are similar for Methods 2 and 5.
7. Methods 3 and 6 provide very high dispersions in peak floor acceleration, especially in the lower floors, compared to Methods 1 and 4. This is due to the higher mode effect. Dispersions in story drift for Method 6 are smaller than those for Method 1. Note that Method 6 produces smaller dispersion in spectral demand at the fundamental period of the sample building than Method 1, but higher dispersion in the short period range.

5. CONCLUSION

From this investigation it is found that to predict median and dispersions in peak floor acceleration response in high-rise building structures first mode as well as higher modes are important. For peak inter-story drift responses, contribution from the modes in the short period range is usually much lower than those in the mid and long period range for tall buildings.

Maximum-demand scaling method (Method 4) can be used to scale ground motions to avoid unconservative estimate on structural responses. If the dynamic property of the building is different in the two horizontal directions, the components of each ground-motion set should be rotated 90 degrees to create another set of ground motions for analysis.

Spectrum-matching scaling method can cover the target design spectrum for a wide period range but need to be used with care. The user should keep in mind that the dispersion in the structural response will be significantly underestimated using the procedure.

The distribution of spectral demands for modal-pushover-based scaling method (Method 6) is similar to that for Method 3. Therefore, it (comparing to Method 1) tends to overestimate the dispersion in floor acceleration and underestimate that in story drift.

The dispersions in structural responses are critical to the results of seismic performance assessment of buildings. From this investigation, it is also observed that the dispersions in response quantities are very much dependent on the dispersions in spectral ordinates for the scaled ground motions. The target seismic hazard for performance assessment of a high-rise building should be defined for both median magnitude and dispersion and the scaled ground motions should appropriately represent both the median magnitude of and dispersion in the spectral acceleration demand of ground motions.

ACKNOWLEDGEMENT

This research is supported by a grant (Code# ’09 R&D A01) from Cutting-edge Urban Development Program funded by Ministry of Land, Transport and Maritime Affairs of Korean government. The authors gratefully acknowledge the support.

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