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Observations of Ground Motion Scaling Requirements in ASCE/SEI 7-22 Standard

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ABSTRACT

The seismic analysis and design of nuclear facilities require input ground motions that meet the specifications outlined in ASCE 4-98, ASCE/SEI 43-05, or Regulatory Guide 1.208. These standards aim to generate a suite of modified time histories that matches the design response spectra. However, in recent years, the use of recorded time histories with uniform scaling factors for building design has become increasingly prevalent and requested. The ASCE/SEI 7-22, which is the most widely used building code in various regions of the world, provides the input motion provisions for building structures, seismically isolated structures, and structures with damping systems. Despite having undergoing six revisions since ANSI/ASCE 7-95, certain provisions in ASCE/SEI 7-22 related to record selection and amplitude scaling still merit further discussion. This study aims to explore opportunities for improving the criteria of recorded ground motion selection and scaling as regulated in ASCE/SEI 7-22. The key issues under discussion include the definition of period range for scaling, the application of ground motions to structural model, and the number of input motions. Regarding future revisions of ASCE/SEI 7, we recommend incorporating equations for the upper and lower bounds periods. Additionally, consideration may be given to secondary scaling for ground motions representing a near-fault source to preserve the response spectrum formed by the pulse period. Further study is still needed to assess whether selecting 11 records adequately meets the requirements for sufficiency and efficiency in response history analysis.

INTRODUCTION AND OBJECTIVES

In recent years, with the emergence of new structural systems, extensive collection of earthquake data, advancements in the efficiency of analysis software/hardware, and the increasing demand for detailed seismic design requirements, nonlinear response history analysis based on recorded ground motions, has become the attractive option in seismic assessments and design of structures. This approach allows for a more comprehensive understanding of the actual dynamic behaviour of buildings under seismic conditions, contributing to an enhanced reliability in seismic structural design.

For design purpose, the fundamental goal of response history analysis is to predict the unbiased seismic demand with relatively limited variation in results. To develop input ground motions using real records for response history analysis, two primary procedures must be conducted: record selection and amplitude scaling. The criteria in this process vary depending on seismic hazard scenarios (site-specific), building types (structure-specific), and design purposes (project specific). These criteria generally relate to controlling earthquake, site condition, target spectrum, ground motion component, lower bound of recorded spectral value, spectral shape similarity, period range of interest, rotating of near-fault ground motion, and number of selected motions. In recently, many of national seismic building codes actively improved the requirements of input motion selection and modification, such as the New Zealand Standard (NZS 1170.5:2004-A1, 2016), the National Building Code of Canada (NBC 2020, 2022), and the U.S. building codes provided by the American Society of Civil Engineers (ASCE/SEI 7-22, 2022).

The objective of this study is to explore opportunities for improving the criteria related to recorded ground motion used in three-dimensional structure analysis, as regulated in ASCE/SEI 7-22. This standard is the broader used building code in various regions of the world and represents the latest edition of ASCE/SEI 7. This paper focuses on the three input motion issues for discussion, namely, the definition of period range for amplitude scaling, application of ground motions in structural analysis, and the number of input motions. The details are outlined below.

ISSUE 1: PERIOD RANGE FOR AMPLITUDE SCALING

The period range for assessing spectral shape and amplitude, crucial for capturing the dynamic response characteristics of structures, involves considering the fundamental period of the structure, the effect of period elongation associated with inelastic response, and the shorter period effect associated with higher modes response. In ASCE/SEI 7-22, this period range varies according to the type of structure, encompassing building structures, seismically isolated structures, and structures with damping systems. While ASCE/SEI 7-22 specify the upper and lower bounds of the period range, there are certain findings that warrant discussion, as outlined below:

- In the provision of Section 16.2.3.1, the period range for horizontal ground motion is defined as $0.2T$ to $1.5T$ - $2.0T$. For the lower bound period ($0.2T$), the T is defined as the largest first-mode period for the two principal horizontal directions of response. However, for the upper bound period ($1.5T$ - $2.0T$), the T is defined as the maximum of the fundamental periods in both translational directions and the fundamental torsional period. This definition is elaborated in the commentary but is not mentioned in the provision.

- For the vertical component, the lower bound period is defined as not be less than the larger of 0.1 seconds or the lowest period at which considerable vertical mass participation occurs. However, the upper bound period is unspecified defined.

- To enhance applicability, the definition of the upper and lower bound periods can be additionally expressed using equations.

Accordingly, the upper and lower bound periods for spectral scaling with different type of structure are formulated below:

$$T_{UB,H} \geq \begin{cases} \alpha \times \max\{\, T_{1X}, T_{1Y}, T_{1\theta} \,\}, \alpha{=}1.5{\sim}2.0 & ;\ \text{for building structures} \\ 1.25\ T_M & ;\ \text{for seismically isolated structures} \\ \alpha \times \max\{\, T_{1MX}, T_{1MY}, T_{1M\theta} \,\}, \alpha{=}1.5{\sim}2.0; & \text{for structures with damping systems} \end{cases} \tag{1}$$

$$T_{LB,H} \leq \begin{cases} \min\{\, T_{90X}, T_{90Y}, 0.2T_{1X}, 0.2T_{1Y} \,\} & ;\ \text{for building structures} \\ \min\{\, T_{90X}, T_{90Y}, T_{fbX}, T_{fbY} \,\} & ;\ \text{for seismically isolated structures} \\ \min\{\, T_{90X}, T_{90Y}, 0.2T_{1DX}, 0.2T_{1DY} \,\}; & \text{for structures with damping systems} \end{cases} \tag{2}$$

$$T_{UB,V} \geq \begin{cases} \alpha T_{1V}, \alpha{=}1.5{\sim}2.0; & \text{for building structures} \\ 1.25 T_{1V} & ;\ \text{for seismically isolated structures} \end{cases} \tag{3}$$

$$T_{LB,V} \leq \max\{\, 0.1\ s, T_{sV} \,\},\ \text{for building structures and seismically isolated structures} \tag{4}$$

where, $T_{UB,H}$, $T_{LB,H}$, $T_{UB,V}$, and $T_{LB,V}$ represent the upper and lower bound periods for horizontal ground motions, respectively; T_{1X} and T_{1Y} represent the fundamental periods in the X and Y principal horizontal orientations of building, respectively; $T_{1\theta}$ is the fundamental torsional period; T_{1V} is the fundamental vertical period; T_{sV} is the smallest vertical period at which considerable vertical mass participation occurs; T_{90} is the period corresponding to fulfil the condition of 90% modal mass participation; T_{fb} is the fundamental period of the superstructure with a fixed-base condition; T_M is effective period of the seismically isolated structure at the maximum displacement, determined using lower bound isolation system properties; T_{1D} and T_{1M} represent the effective fundamental mode periods of the structure equipped damping systems at the design and maximum displacements, respectively, determined using nominal damper properties.

The elongation factors (α=1.5~2.0; 1.25) applied in Equation 3 for $T_{UB,V}$ correspond to those utilized in Equation 1 for $T_{UB,H}$. The value of α is primarily set to 2.0 and is conditionally between 1.5 and 2.0; the latter should be justified by dynamic analysis under risk-targeted maximum considered earthquake ($\mathrm{MCE_R}$) ground motions.

For seismically isolated structures, considering the concern that the lower bound period may not sufficiently capture higher modes effect which strongly influence on floor spectra (as detailed in the commentary of Section C17.3.2), $T_{LB,H}$ may be redefined as follows:

$$T_{LB,H} \leq \min\{T_{90X}, T_{90Y}, 0.2T_{fbX}, 0.2T_{fbY}\};\ \text{for seismically isolated structures} \tag{5}$$

Here, $0.2T_{fbX}$ and $0.2T_{fbY}$ correspond to the basic definition of the lower bound period ($0.2T$).

ISSUE 2: APPLICATION OF GROUND MOTIONS IN STRUCTURAL ANALYSIS

In accordance with the provision of Section 16.2.3.2 and Section 16.2.4, the scale factor of the spectral amplitude for selected horizontal input motions shall satisfy the requirement that the mean of all the recorded response spectra shall not fall below 90% of the target response spectrum for any period within the period range of interest. Additionally, if ground motions represent as a distant fault source, the mean of these component spectra in each direction should be within ±10% of the mean of the component spectra of all records; if ground motions represent as a nearby fault source, their components should be rotated to the fault-normal and fault-parallel directions, and applied to corresponding orientations of the structure.

We conducted a case study utilizing a seismically isolated building to explore the issue of spectral scaling. The critical parameters for the target building use to define the period range for spectral scaling are listed in Table 1. Both $T_{LB,H}$ and $T_{UB,H}$ are determined as 0.056 s (=min$\{T_{90X}, T_{90Y}, T_{fbX}, T_{fbY}\}$) and 6.64 s (=$1.25\times T_M\times\sqrt{1/(1-\lambda)}$). A suit of 11 selected ground motions includes eight indicated as a distant fault source and three as a nearby fault source. The scaled response spectra representing a distant fault source and a nearby fault source are shown in Figure 1 and Figure 2, respectively. The findings and suggestions that can be discussed are as follows:

- After a careful selection of recorded ground motions representing a distant fault source, the mean N-S or E-W component spectrum still slightly falls outside the "±10%" criteria at two periods around 0.15 s (over 0.4%) and 1.42 s (over 1.8%).

  To address this issue, adding an exception may be a more practical approach compared to rotating ground motions. For example, stating that the number of spectral periods exceeding the "±10%" criteria shall be less than 10% of the total number of spectral periods within the period range. Following this method, the two outliers are less than 10% of the 35 periods within the period range between 0.056 s and 6.64 s.

Table 1: The structural and isolator parameters for the inter-story isolated building in the study.

T_{90X}	T_{90Y}	T_{fbX}	T_{fbY}	T_M	λ^*
0.056 s	0.058 s	2.0 s	1.9 s	4.6 s	25%

* variation of the nominal isolator properties

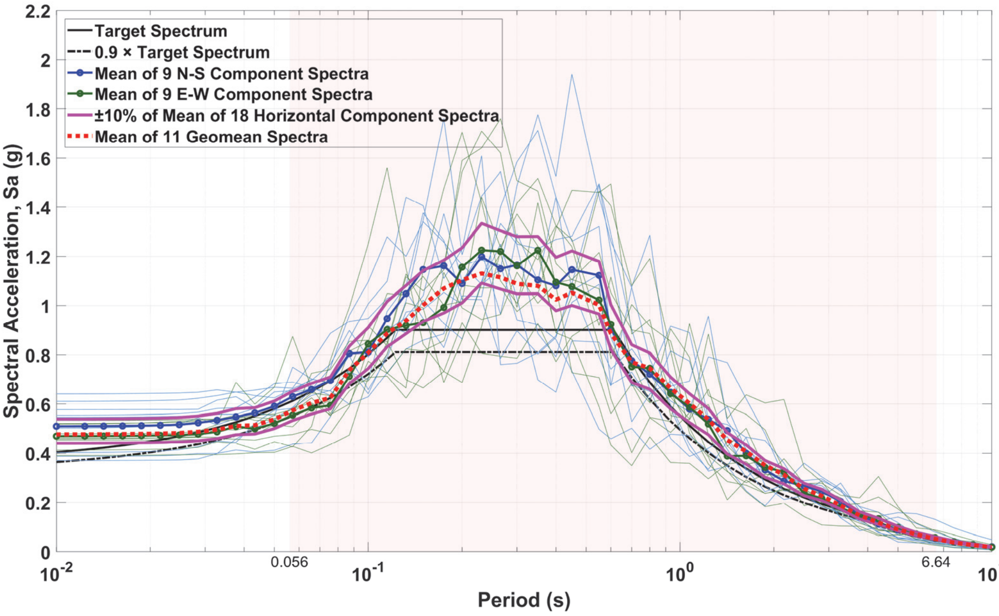

Figure 1. The mean of scaled N-S (blue line) and E-W (green line) component spectra representing a distant fault source.

- The results presented in Figure 2 reveal that the CHY064 and CHY067 strong-motion stations captured significant velocity pulse ground motions around 1 second in the E-W component during the 2016 Meinong earthquake in Taiwan. The scale factors applied to the ground motions representing a nearby fault source are determined based on the mean of all 11 recorded response spectra. However, this scale factor calculated with a broader period range may lead to an underestimation of the pulse-like characteristics in the spectral shape representing a nearby fault source, as illustrated by the CHY064 response spectra in Figure 2 (depicted by the blue-dashed line with circles).

  To preserve these pulse-like characteristics, a secondary amplitude scaling may be implemented to this ground motion. For instance, each ground motion representing a nearby fault source shall not fall below the 90% of the target response spectrum for any period within the period range of constant spectral acceleration. Following this approach, the scale factors for CHY064 and CHY067 ground motions would increase from 3.0 to 3.13 and from 2.81 to 3.63, respectively.

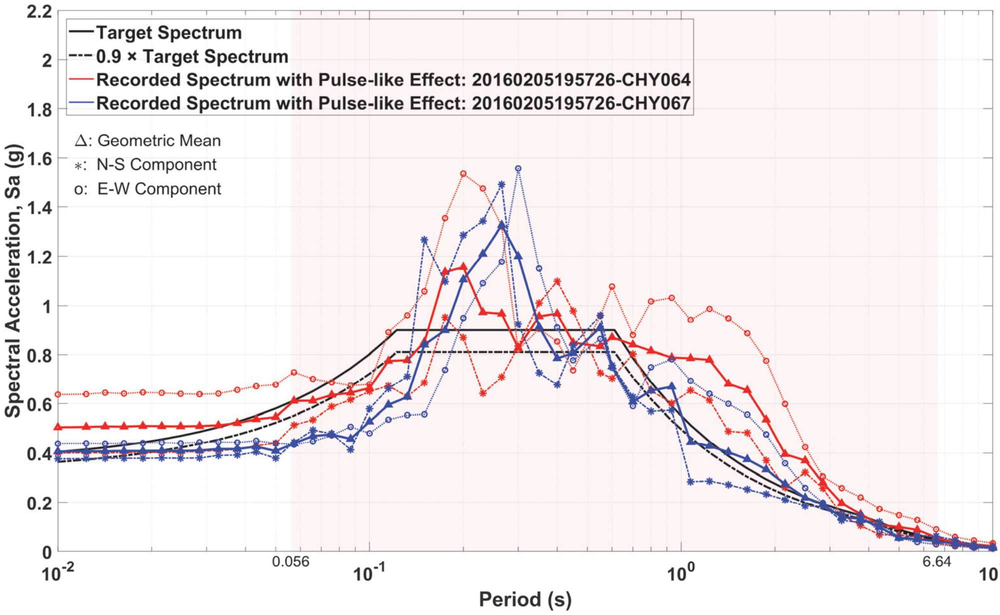

Figure 2. The scaled and rotated component spectra representing a near-fault source.

ISSUE 3: NUMBER OF INPUT GROUND MOTIONS

Traditionally, the number of input ground motions for dynamic analysis is typically 3 or 7. When using 3 ground motions, the maximum response is analyzed for design, and when using 7 ground motions, the average response is considered for design. However, with well-developed ground motion databases and growing importance of seismic reliability, ASCE/SEI 7-22 now requires a minimum of 11 input ground motions for all types of structures.

To explore the efficiency and sufficiency of using a suit of 11 ground motions in seismic assessment, a series of nonlinear response history analysis was performed on a 24-story reinforced concrete (RC) building. The objective of this study is to investigate the relationship between the error of inter-story drift ratio and the number of input motions. Despite the fundamental period of the symmetrically regular structure being 2.9 s, the period range for spectral scaling is set between 0.01 s to 8.0 s to ensure comprehensive coverage all structural responses subjected to high seismic intensity (MCE level). Figure 3 displays a suit of 50 scaled ground motions devoid of pulse-like characteristics for dynamic analysis. It's worth noting that the minimum record-to-target ratio not meet the regulated value of 0.9, given the seismic assessment objectives in this case study.

Figure 4 shows the relationship between the mean error of inter-story drift ratio (IDR) and the number of input motions. Figure 5 illustrates the IDR profile by the 50 input motions. The ranking shown in Figure 4 and Figure 5 corresponds to the mean-squared errors (MSE) between target spectrum and scaled recorded spectra. A lower rank number means a smaller MSE, indicating a more similar spectral shape between the target spectrum and the recorded spectrum. In Figure 4, the individual IDR mean error of a ranked input motion for N-S and E-W components is represented as grey dot and circle, respectively; the average IDR mean error of input motions form the first to a certain rank number for N-S and E-W components is represented as red dot and circle, respectively. The observations are as follows:

- As illustrated by the distribution of red dots in Figure 4, despite using a broader period range and ranking by spectral shape similarity, 11 input motions appears insufficient to achieve the stable average structural response. This outcome persists even when increasing the number of input motions.

- As illustrated by the distribution of grey dots in Figure 4, an input motion with a similar spectral shape does not necessarily result in a structural response close to the median estimation. The top 11 input motions for the N-S component with the smaller IDR mean errors are ranked as follows: 5, 18, 4, 11, 12, 40, 21, 23, 1, 25, and 2.

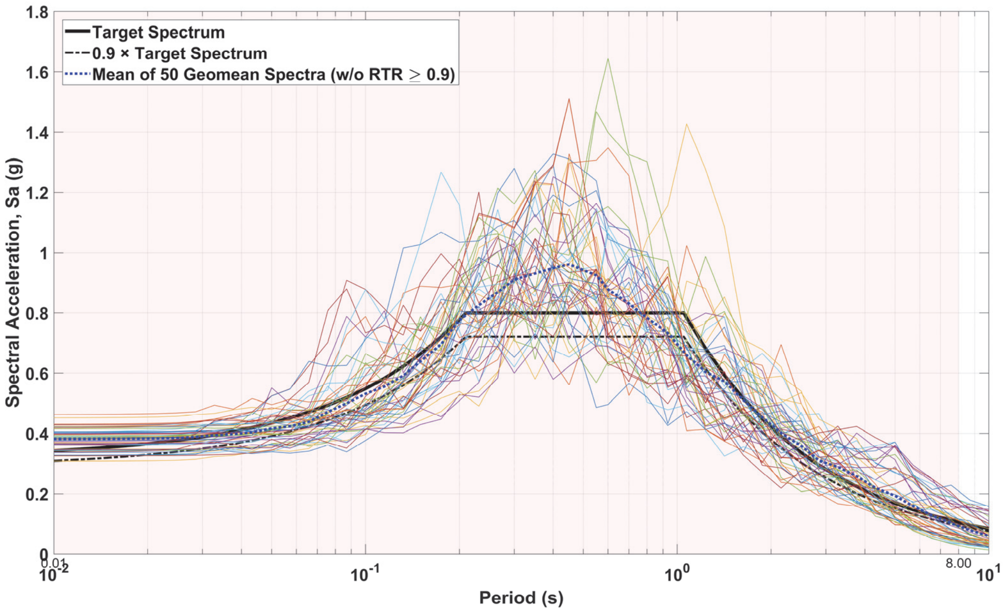

Figure 3. The 50 scaled response spectra for nonlinear response history analysis.

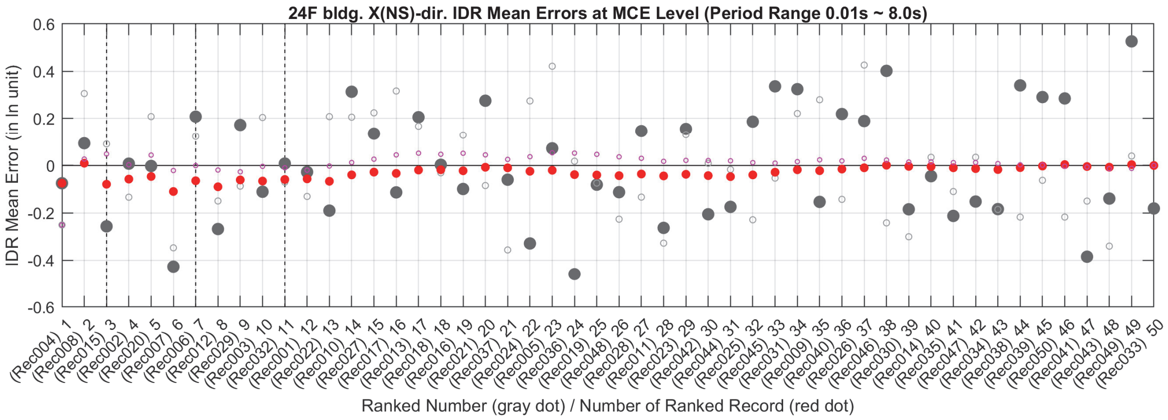

Figure 4. Relationship between mean errors of inter-story drift ratio and number of input motions.

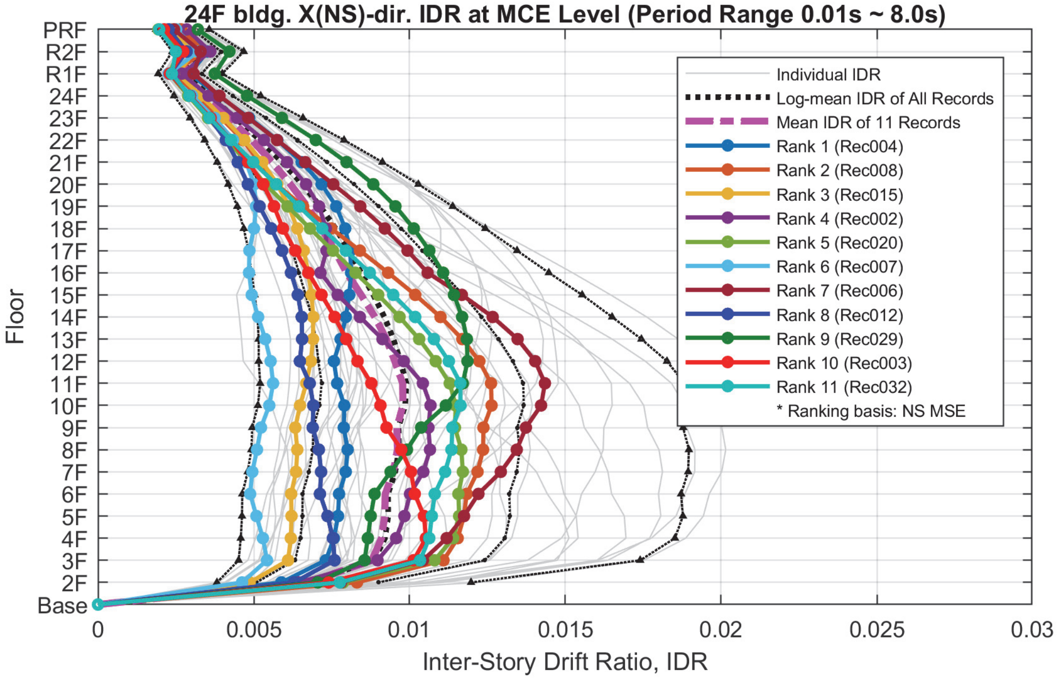

Figure 5. Inter-story drift ratio profile for the 24-story building.

CONCLUSIONS

This study explored the three key aspects concerning ground motion selection and scaling for response history analysis, as regulated in ASCE/SEI 7-22. The investigated issues include the definition of period range for amplitude scaling, application of ground motions in structural analysis, and the number of input ground motions. The findings and insights from this study may serve as a reference for future revision of ASCE/SEI 7 Standard. The conclusions of this study are outlined below:

- The period ranges for spectral scaling, detailed in Equation 1 to Equation 4, systematically formulate upper and lower bound periods. These periods were categorized according to horizontal and vertical components, as well as specific structural types, such as building structures, seismically isolated structures, and structures with damping systems. For seismically isolated structures, Equation 5 is recommended for determining the lower bound period, considering the acknowledged concerns related to higher mode effect.

- A secondary scaling may consider for the ground motions representing a nearby fault source to preserve the response spectrum formed by pulse period. This scaling method may be as follows: each ground motion representing a nearby fault source shall not fall below the 90% of the target response spectrum for any period within the period range of constant spectral acceleration.

- A nonlinear response history analysis using 50 input ground motions was performed on a 24-story RC building. The relationship between the mean error of inter-story drift ratio and the number of ground motions shows that 11 input motions appears insufficient to achieve the stable average structural response. However, further study is still needed to assess whether selecting 11 records adequately meets the requirements for sufficiency and efficiency in response history analysis.

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