Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses

C.B. Haselton
California State University, Chico, Chico, California, USA

A.S. Whittaker
State University of New York at Buffalo, Buffalo, New York, USA

A. Hortacsu
Applied Technology Council, Redwood City, California, USA

J.W. Baker
Stanford University, Stanford, California, USA

J. Bray
University of California at Berkeley, Berkeley, California, USA

D.N. Grant
Arup, Advanced Technology + Research, London, UK

SUMMARY:
The National Institute of Standards and Technology (NIST) funded a project to improve guidance to the earthquake engineering profession for selecting and scaling earthquake ground motions for the purpose of performing nonlinear response-history analysis. The project supported problem-focused studies related to defining target spectra for seismic design and performance assessment, response-spectrum matching, and near-fault ground motions. Recommendations are presented for target spectra, selection of seed ground motions, and scaling of motions to be consistent with different target spectra. Minimum numbers of sets of motions are recommended for computing mean component and systems responses, and distributions of responses. Guidance is provided on selection and scaling of ground motions per ASCE/SEI 7-10.

Keywords: ground motion, response-history, selection, scaling

1. INTRODUCTION

Seismic provisions in current model building codes and standards include rules for design of structures using nonlinear response-history analysis, which are based, in large part, on recommendations for analysis of seismically isolated structures from more than 20 years ago. Unfortunately, there is currently no consensus in the earthquake engineering community on how to appropriately select and scale earthquake ground motions for code-based design and seismic performance assessment of buildings using nonlinear response-history analysis.

This paper provides guidance to design professionals on selection and scaling of ground motions for the purpose of nonlinear response-history analysis. Specific recommendations for ASCE/SEI 7 (ASCE/SEI 2010) are also provided, along with a summary of future research needs. This effort was completed by the Applied Technology Council (ATC-82) and funded by the National Institute of Standards and Technology (NIST); this paper is based on the NIST GCR 11-917-15 report "Selecting and Scaling Earthquake Ground Motions for Performing Response-History Analyses" (NIST, 2011a).

2. GOALS AND USES OF RESPONSE-HISTORY ANALYSIS

Ground motions are selected and scaled to enable response-history analysis that supports either design or performance assessment. The analyst must have a clear understanding of the goals of analysis before choosing procedures to select and scale ground motions.

Nonlinear response-history analysis is performed for a number of reasons, including: (1) designing new buildings with non-conforming lateral force resisting systems; (2) designing new buildings equipped with seismic isolators or energy dissipation devices; (3) designing seismic upgrades of existing buildings per ASCE/SEI 41-06 (ASCE, 2007); and (4) assessing performance of new and existing buildings per ATC-58-1, *Seismic Performance Assessment of Buildings* (ATC, 2011).

ATC-58-1 identifies three types of performance assessment: intensity, scenario, and time-based. The best method for selecting and scaling ground motions will depend on the type of assessment being performed. Intensity-based assessments are the most common of the three types and compute the response of a building and its components for a specified intensity of ground shaking (this approach is the focus of this paper). A scenario-based assessment computes the response of a building to a user-specified earthquake event, which is typically defined by earthquake magnitude and the distance between the earthquake source and the building site. A risk-based (referred to as time-based assessment in ATC-58-1) assessment provides information on response over a period of time (e.g., annual rates). This is the most comprehensive type of assessment and involves a number of intensity-based assessments over the range of ground motion levels of interest.

The appropriate method for selecting and scaling ground motions will depend on the structural response parameter(s) of interest, whether record-to-record variability in structural response is to be predicted (in addition to mean response), and whether maximum responses or collapse responses are to be predicted. These are critical issues and are discussed in detail in Section 9.

3. LITERATURE REVIEW

Table 3.1 provides an overview of the steps involved in a response-history analysis and summarizes how the following documents handle each step of the analysis: Minimum Design Loads for Buildings and Other Structures, ASCE Standard 7-05 (ASCE/SEI, 2006), *Minimum Design Loads for Buildings and Other Structures*, ASCE Standard 7-10 (ASCE/SEI, 2010), *An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region*, 2008 Edition with Supplement #1, developed by the Los Angeles Tall Buildings Structural design Council (LATBSDC) (LATBSDC, 2008), and *Seismic Design Guidelines for Tall Buildings*, Developed by the Pacific Earthquake Engineering Research Center under its Tall Building Initiative (PEER, 2009).

The following sections of this paper provide more detailed discussion and recommendations regarding the ground motion selection and scaling steps shown in Table 3.1.

4. DEFINTION OF TARGET SPECTRA FOR SELECTING AND SCALING MOTIONS

4.1. Ground Motion Intensity Measures

There are many ground motion intensity measures and this section identifies only a few. The most widely used intensity measure is 5%-damped spectral acceleration, *Sa*, and this paper focuses on it, although it has many limitations and is not directly related to the nonlinear response of a building.

There are three primary types of horizontal spectral acceleration: (1) arbitrary component (Sa_{arb}); (2) geometric mean ($Sa_{g.m.}$); and (3) maximum direction (Sa_{maxDir}). These three definitions are discussed in the NIST report (NIST, 2011a). Any of these definitions can be used, and the performance prediction will not depend on the choice, but it is imperative that the procedure used to select and scale motions be consistent with the definition used for the target spectrum (Baker and Cornell, 2006b).

4.3. Uniform Hazard Target Spectrum

The Uniform Hazard Spectrum (UHS) has been used as the target spectrum in design practice for the

Table 3.1. Focused Literature Review

Steps for Response History Analysis	Design/Assessment Method: ASCE 7-05	ASCE7-10	LATBSDG (2008)	PEER TBI (2009)
Explicit Goals:	--	P[C] < 10% for MCE_R	Well-defined NL behav., func. for service motion, low P[C] for MCE.	Low risk of collapse, modest residual drift, no cladding failure.
Ground Motion Intensity Measure:	Sa_geoMean	Sa_maxDir	Sa_geoMean (by reference to ASCE7-05)	Sa_geoMean or Sa_maxDir (by ref. to ASCE7)
Ground Motion Level for Assessment:	2/3 MCE	2/3 MCE_R	MCE, service-level	MCE, service-level
Target Spectrum:	--	--	--	--
General approach	UHS	UHS with risk adjustment	UHS (by reference to ASCE7-05)	UHS or multiple CMS
Notes	Limited by deterministic cap.		Limited by deterministic cap.	Limited by deterministic cap.
Ground Motion Selection:	--	--	--	--
Number of motions	≥7 (or 3) pairs		≥7 pairs	≥7 pairs
Types of motions	Recorded and/or simulated		Rec. or sim. (ref. to ASCE7-05)	Recorded and/or simulated
Other	None		"Appropriate number" of motions with directivity effects.	Directivity if needed....
Scaling/Modification of Motions to Match Target Spectrum:	--	--	--	--
General approach	Scaling (spectral matching not mentioned).		Scaling or spectral matching	Scaling or spectral matching
Specific instructions for far-field sites	SRSS is above 1.17x target spec.	SRSS is above target spectrum	SRSS is above 1.17x target spectrum (by ref. to ASCE7-05)	"Match records to the target spectrum..."
Specific instructions for near-fault sites	None	Average of FN is above target.	None (by ref. to ASCE7-05)	None
Period range for matching	0.2T - 1.5T		0.2T - 1.5T (by ref. to ASCE7-05)	Not specified
Application of Ground Motions to Structural Model	--	--	--	--
Far-field sites	Just apply horizontal motions together; no rules for orientation.		Orient motions randomly; no need for multiple orientations of GMs.	"Apply along principle directions" (but no GM rotation mentioned).
Near-fault sites	No rules for orientation.	Apply in FN/FP directions if site > 5km from fault.	Apply in FN and FP directions.	Apply in FN and FP directions if directivity effects dominate.
Treatment of Vertical Ground Motion	Not considered		Not considered (ref. ASCE7-05)	Included in rare cases
Response Metrics and Acceptance Criteria (at MCE or 2/3 MCE):	--	--	--	--
Peak interstory drifts	μ < 1.25*limit		μ < 0.03	μ < 0.03, max < 0.045
Residual interstory drifts	No limit		No limit	μ < 0.01, max < 0.015
Deformations for deformation-controlled actions	μ < limit		μ < limit	No limit (except to keep within reliable analysis range).
Force for force-controlled actions (critical, well-defined mech.)	Maximum force is used for designs based on overstrength factor.		μ < limit	max(μ + 1.3σ, 1.2μ) ≤ $\varphi F_{n,e}$
Force for force-controlled actions (critical, no well-defined mech.)				1.5μ ≤ $\varphi F_{n,e}$
Force for force-controlled actions (non-critical)				μ ≤ Fn,e
Loss in story strength	No limit		No limit	Less than 20% loss.
Treatment of collapse cases	Unclear. Average drift limits suggest collapses are not allowed, but there is no consistent interpretation.		Not discussed. Average drift limits suggest collapses are not allowed.	Collapses are not allowed.
Other	None		None	Response in reliable analysis range
Notes	None		None	For the multiple CMS, use response envelope for the various anchor periods.
Other Design uses of Response History Analysis Predictions	--	--	--	--
Design of non-structural components	Not specified		Not specified	Not specified

past two decades. The Uniform Hazard Spectrum is created for a given hazard level by enveloping the results of seismic hazard analysis (for a given probability of exceedance) for each period. The probability of observing all of those spectral amplitudes in any single ground motion is unknown. Accordingly, it will generally be a conservative target spectrum, especially for large and rare ground motion, unless the structure responds elastically in only its first translational mode. This inherent conservatism comes from the fact that the spectral values at each period are not likely to all occur in a single ground motion. This limitation of the Uniform Hazard Spectrum has been noted for many years (e.g., Bommer et al., 2000; Naeim and Lew, 1995; Reiter, 1990).

4.4. Conditional Mean Target Spectra

The Conditional Mean Spectrum (CMS) (and the Conditional Spectrum in the next section) is an alternative target spectrum to the Uniform Hazard Spectrum and can be used as a target for ground motion selection in performance-based engineering (Baker, 2011). To address the above mention problem with the Uniform Hazard Spectrum, the Conditional Mean Spectrum instead conditions the spectrum calculation on spectral acceleration at a single period, and then computes the mean (or distribution of) spectral acceleration values at all other periods. This conditional calculation ensures that the resulting spectrum is reasonably likely to occur, and that ground motions selected to match the spectrum have appropriate properties of naturally occurring ground motions for the site of interest. The calculation is no more difficult than calculation of a Uniform Hazard Spectrum, and is arguably more appropriate for use as a ground motion selection target in risk assessment applications. The spectrum calculation requires disaggregation information, making it a site-specific calculation that is difficult to generalize for use as a standard building code target spectrum. It is also period-specific, in that the response spectrum is conditioned on spectral acceleration at a specified period. The spectrum also changes as the spectral amplitude changes (even when the site and period are fixed).

Figure 4.1 provides examples of the Conditional Mean Spectrum for an example site in Palo Alto, California, USA, anchored at four different periods relating to the 20-story example building. The Uniform Hazard Spectrum for this example site is also provided for comparison.

4.5. Conditional Target Spectra

The CMS was initially proposed with an emphasis on the mean spectrum and less attention was paid to the variability in the spectrum. A comparable target spectrum that also considers variability is termed the "Scenario Spectrum" or "Conditional Spectrum" (CS). Another recent extension of the approach has been to consider conditional values of any ground motion properties (e.g., duration), rather than just response spectral values (Bradley, 2010). Figure 4.2 provides an example of a ground motion set selected and scaled based on the Conditional Spectrum, anchored at the 2.6 seconds fundamental period of the 20-story example building.

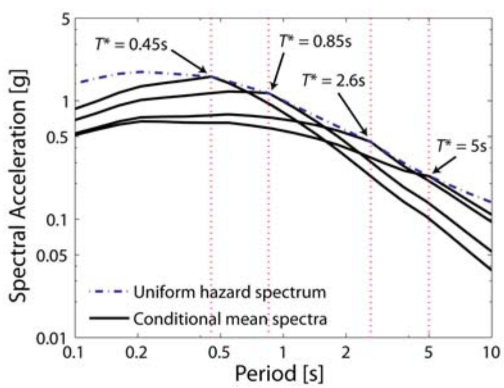

Figure 4.1. Example Conditional Mean Spectra for the Palo Alto site anchored for 2% in 50-year motion at $T = 0.45$s, 0.85s, 2.6s (fundamental mode), and 5s. (NIST, 2011a)

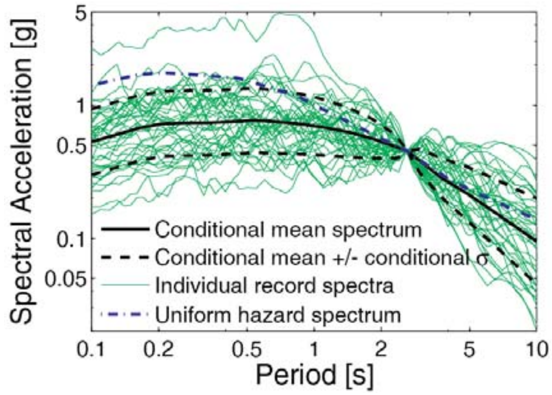

Figure 4.2. Conditional Spectra for the Palo Alto site for the 2% in 50-year motion anchored at $T = 2.6$s. (NIST, 2011a)

5. GROUND MOTION SELECTION

Ground motions must be either selected from previous recorded earthquake events or supplemented by physics-based simulations where there is a lack of appropriate recordings, such as for large magnitude earthquakes at short site-to-source distances. Recorded motions are selected from a bin of recorded motions such as the PEER NGA database (http://peer.berkeley.edu/peer_ground_motion_database), COSMOS (http://db.cosmos-eq.org/scripts/default.plx), or K-NET (http://www.k-net.bosai.go.jp). A bin of ground motion records containing pulses is presented in Appendix C of the parent report (NIST, 2011a). The seismic hazard at the site should be disaggregated before selecting seed motions.

Regarding the number of ground motions, typical practice in structural design is to use seven motions, but the appropriate number of motions is still a topic of needed research. The appropriate number of ground motions is dependent on the application, such as which structural response(s) are to be predicted, whether mean values or distributions of responses is desired, the required accuracy of the estimated values of mean and variance, the possible prediction of maximum responses or collapse responses, and the expected degree of inelastic response.

For distant sites (not near-field), the most important factor in selecting ground motions for scaling to a target spectrum is spectral shape over the period range of interest (currently $0.2T_1$ to $1.5T_1$ in ASCE/SEI 7-10, where T_1 is the first mode translational period). Secondary considerations are the earthquake magnitude, site-to-source distance, and ε that dominate the hazard curve at period $\overline{T}$, and local site conditions. Selecting pairs of motions whose spectral shapes are similar to the target spectrum minimizes the need for scaling and modification.

For near-field sites, the two most important factors in selecting ground motions for scaling to a target spectrum are spectral shape and the possible presence of velocity pulses. Selecting pairs of motions whose spectral shapes are similar to the target spectrum minimizes the need for scaling and modification. Velocity pulses are present in many near-fault ground motion recordings, especially in the forward directivity region. Alavi and Krawinkler (2000), Somerville et al. (2004), Mavroedis and Papageorgiou (2003), Bray and Rodriguez-Marek (2004), Fu and Menun (2004), Baker (2007), Shahi and Baker (2011) have all observed and quantified a relationship between pulse period and earthquake magnitude. A relationship is proposed for estimating the appropriate number of pulse motions in a suite of design motions in Appendix C of the parent report (NIST, 2011a). Disaggregation of the seismic hazard curve will identify the combinations of earthquake magnitude, site-to-source distance, and ε that dominate the hazard around the period of the building; this can aid the selection of pulse periods and thus seed ground motions for later scaling.

6. GROUND MOTION SCALING OR FREQUENCY MODIFICATION

This section provides recommendations for scaling pairs of horizontal ground motions to each type of spectrum, noting that the UHS and CMS are used when mean or average estimates of responses are sought, and the CS is used when distributions of response are sought.

A period range or interval must be specified when scaling ground motions consistent with a UHS or CMS. The recommended interval is ($0.2T_{1,min}$, $3T_{1,max}$) for moment-frame buildings and ($0.2T_{1,min}$, $2T_{1,max}$) for shear-wall or braced frame buildings, where $T_{1,min}$ ($T_{1,max}$) is the lesser (greater) of the first mode translational periods along the two horizontal axes of the building.

Response-spectrum matching of a pair of horizontal ground motions is acceptable if the target spectrum is either a UHS or a CMS, if the scaled pair of motions will not include velocity pulses, and if the goal of the analysis is to calculate mean responses and not distributions of responses. Guidance regarding selection of ground motions for spectrum matching can be found in the parent report (NIST, 2011a). When using spectral matching, the ground motions should be matched in pairs (Grant, 2011).

7. APPLICATION OF GROUND MOTIONS TO THE STRUCTURAL MODEL

The manner in which the two horizontal ground motion are oriented when being applied to the structural model is critically important and there is both little and inconsistent guidance for how this should be done. The debates about the appropriateness of various ground motion intensity measures (Sa_{arb}, $Sa_{g.m.}$, or Sa_{maxDir}) arguably hinge on how the ground motions are oriented when being applied to the structural model. As was previously stated in Section 4.1, the structural response predictions should not depend on what type of spectral acceleration definition is being used to quantify the ground motion (e.g. Sa_{arb}, $Sa_{g.m.}$, or Sa_{maxDir}), provided that each step of the process is completed in a manner that is consistent with the chosen spectral acceleration definition (selection, scaling, application to the structural model, and interpretation of response predictions).

At distant (or “far-field”) sites, the guidance given in recent design and assessment documents is both limited and inconsistent (see Section 3). When the geometric mean spectral acceleration value (Sa_{gm} or the similar $Sa_{GMRotI50}$) is being used to describe the ground motion intensity, there is no implied directional dependence to the ground motion, so the pair of horizontal ground motion components should be applied to the structural model in a random orientation. If the maximum direction spectrum (Sa_{maxDir}) is being used to describe the ground motion intensity, there is a perceived directional dependence to the ground motion. However, the direction (or azimuth) in which the Sa_{maxDir} value occurs is random in the far-field (Huang et al., 2008) and does not necessarily align with a principal direction of the building. Accordingly, for the response-history analysis to result in an unbiased prediction of structural response, the ground motions should still be applied to the structure in a random orientation. On the surface, this may seem inconsistent with how the ground motions were scaled but there is no inconsistency in this process and the application of randomly-oriented pairs of motions is necessary to avoid causing a biased prediction of structural response.

For near-fault sites, the scaled motions should be applied in the same orientations as the corresponding seed motions were recorded with respect to the strike of the causative fault.

In response-history analysis, it is not uncommon to apply the horizontal ground motion pair in one orientation and then apply the same pair of ground motions in a second orientation (typically 90 degrees from the original orientation). These additional analyses are considered to be unnecessary.

For application of ground motions over the subterranean levels of the structure, the recent PEER TBI guidelines (PEER TBI, 2009) and the recommendations contained in the NIST GCR 11-917-14 report (NIST, 2011b) both state that the subterranean levels of the building should be included in the structural model and related guidance are provided in those documents.

8. INTERPRETATION OF STRUCTURAL RESPONSE PREDICTIONS

This report focuses on guidance for ground motion selection and scaling for response-history analysis. The acceptance criteria used to determine the acceptability of the structural responses are outside the scope of this study (e.g. allowable interstory drift limits, allowable inelastic deformations in structural members, etc.). Even so, the manner in which the structural responses are interpreted (e.g. mean responses versus also utilizing response variability) has critical impact on how the ground motions should be selected and scaled, so this warrants a careful discussion. Such discussion is provided in this section, with a focus on the intensity-based assessment approach.

8.1. Structural Responses

Ground motions must be selected and scaled with an understanding of what responses are being sought because this can affect the recommended selection and scaling approach. For example, prediction of floor spectra may require ground motions with a wider band of frequency content as compared with predicting peak story drifts. This paper focuses on prediction of typical response like peak story drifts and more research is needed to ensure that these recommendations apply to other types of structural responses.

8.2. Mean and Median Structural Responses

For intensity-based assessments (which include code-based component checking), mean values are generally sought for each response quantity (demand parameter) of interest. This is the basis for the acceptance criteria of the current ASCE 7-10 Standard (ASCE/SEI, 2010) and is typically accomplished using a set of seven ground motion records. For the prediction of mean response, the Conditional Mean Spectrum (CMS), Conditional Spectrum (CS), or the Uniform Hazard Spectrum (UHS), can be used as the basis for analysis. Ground motions can be scaled to match (or exceed) the target spectrum or be spectrally-matched to the target spectrum.

The use of the Conditional Mean Spectrum has been shown to provide unbiased predictions of mean response, with the use of the Uniform Hazard Spectrum being shown to lead to conservatively biased predictions of mean response (Haselton et al., 2009). The Uniform Hazard Spectrum is still a viable but conservative tool for ground motion selection and scaling approach, specifically if conservatism is sought and/or when the additional steps associated with generating the Conditional Mean Spectrum (or Conditional Spectrum) are undesirable.

8.3. Variability in Structural Responses

It is often desirable to predict the variability in structural response (e.g., the standard deviation, σ) to help judge margins against undesirable performance. For example, the PEER TBI guidelines use the variability in the element force demands to help provide a greater level of conservatism in the design of critical force-controlled elements (some are designed for the $\mu + 1.3\sigma$ force demand). Even though predicting the variability in structural response is desirable for intensity-based assessment, it is also extremely difficult to accomplish in any statistically meaningful manner. Of the ground motion selection and scaling approaches summarized in this paper, only the Conditional Spectrum approach provides a mechanism to support the calculation of structural response variability. Even when the Conditional Spectrum is employed, a large number of ground motions are necessary to have reasonable confidence in the estimated variability (on the order of 30+). The other ground motion selection and scaling approaches, such as Uniform Hazard Spectrum and Conditional Mean Spectrum, are based only on a mean target spectrum with no defined variability in the spectral values. When such approaches are used for ground motion selection and scaling, the prediction of structural response variability is statistically meaningless and will depend entirely on how the ground motions were selected and scaled (or modified) to match the target spectrum. Even when the Conditional Spectrum approach is used, it is still not known at this time how many ground motions are needed to establish stable distributions of structural responses; this is still a needed topic for future study.

8.4. Maximum Structural Responses and Treatment of Structural Collapse Cases

In some instances it is also desirable to predict the maximum structural response from a set of ground motions or to predict the percentage of ground motions that cause structural collapse in a ground motion set (or some large undesirable, or non-converged, structural response). For example, the PEER TBI guidelines (PEER, 2009) acceptance criteria place a limit on the maximum story drift for any ground motion in the record set, which effectively disallows any occurrences of structural collapse for any ground motion in the record set. Similarly to the prediction of response variability, it is extremely difficult (even more difficult) to predict the maximum response or the proportion of collapse cases in any statistically meaningful manner. As with the prediction of variability, the only possible approach is the Conditional Spectrum approach and a large number of ground motions would be required (on the order of 30–40+). If the Uniform Hazard Spectrum or the Conditional Mean Spectrum methods are utilized, then the observance of collapse cases (or, conversely, the observance of no collapse cases) is statistically meaningless and will depend entirely on how the ground motions were selected and scaled (or modified) to match the target spectrum. With this difficulty in the reliable prediction of structural collapse cases (or maximum response), this leave a large open question for how to interpret the meaning of collapse cases in the response-history analysis results. Even though occurrence of collapse cases is statistically meaningless (per the above discussion), a conscientious structural designer will be concerned about such occurrence (and should be) and the occurrences of such collapse cases may arguably provide the designer with some insight into a possible weakness in the structural design (albeit not in a statistically significant manner).

The treatment of structural collapse and the related issues of ground motion selection and scaling is a major gap in the knowledge and requires further research, especially for intensity-based assessments.

9. SPECIFIC RECOMMENDATIONS FOR ASCE/SEI 7

Based on the findings of this research (NIST, 2011a), it is recommended that the following changes be considered for the ASCE/SEI 7 Standard (ASCE/SEI, 2010).

- **Level of Ground Motion.** The fundamental goal of ASCE/SEI 7-10 is to ensure a collapse probability of 10% for the MCE_R ground motion level (Chapter C1 of ASCE/SEI 7-10, 2010). To directly evaluate collapse probability, it is the position of the project team that ground motions should be anchored to the MCE_R spectrum and not 2/3 of the MCE_R spectrum.
- **Definition of the Target Spectrum.** The target spectrum requirements of ASCE/SEI 7 should be revised to permit the use of a target "Scenario Spectrum" or "Conditional Spectrum." Such an approach would be similar to what is already done for nuclear facilities in the ASCE 43-05 Standard (Section 2.3 of ASCE, 2005), the Department of Energy Standard 1024-92 (Appendix B of DOE, 1996), and the US Nuclear Regulatory Commission Regulatory Guide 1.165 (Appendix F of USNRC, 1997). If this option was added to ASCE/SEI 7, a mean target spectrum would be sufficient (e.g., a Conditional Mean Spectrum) and there would be no needed to match the variability in the response spectral values (the Conditional Spectrum); this is sufficient because ASCE/SEI 7 focus on prediction of mean structural response and does not attempt to quantify the variability in the response. The inclusion of this "Scenario Spectrum" option in ASCE/SEI 7 would need to be augmented by guidance regarding proper use (see parent report). It is recommended that this new target spectrum approach be included as an option and not as a replacement for the current ASCE 7-10 approach, because the current UHS-based approach still has useful applications when simplicity and conservatism are desired.
- **Period Range for Scaling Ground Motions.** The recommended interval is ($0.2T_{1,min}$, $3T_{1,max}$) for moment-frame buildings and ($0.2T_{1,min}$, $2T_{1,max}$) for shear-wall or braced frame buildings, where $T_{1,min}$ ($T_{1,max}$) is the lesser (greater) of the first mode translational periods in the two directions.
- **Ground Motion Scaling Method.** For sites in far-field regions, the current scaling approach involves computing a square-root-of-sum-of-squares (SRSS) spectrum for each pair of ground motions and scaling the motions such that the average Sa_{SRSS} values exceed the target spectrum within the period range of interest. It is recommended that a more direct scaling method be

developed, which is based on scaling the maximum direction spectral values (Sa_{maxDir}) to meet or exceed the target Sa_{maxDir} spectral values.

- **Spectral Matching.** Spectral matching is a commonly used approach and is not currently mentioned in ASCE/SEI 7-10. It is recommended that a statement be added to ASCE/SEI 7 to clarify that spectral matching is an allowable scaling (modification) method for all far field sites and near-field sites for ground motions that do not include velocity pulses, and related guidance and/or limitations should be developed on the use of spectral matching.
- **Orientation of Ground Motion Components.** For sites in far-field regions, there is currently no guidance given for how the ground motions should be oriented when they are applied to the structural model. It is recommended that language be added to ASCE/SEI 7 regarding how this should be done. It is recommended that the new requirements specify the ground motions being oriented randomly when being applied to the structural model. It is recommended that a statement be added to clarify that it is not required to apply each ground motion pair in multiple orientations.
- **Treatment of Structural Collapse Cases.** This paper has discussed the difficulties in interpreting the meaning of structural collapse cases (or cases where a ground motion causes a large and undesirable structural response). The current ASCE/SEI 7-10 requirements are silent on how to handle these cases. It is recommended that research be dedicated to this topic and that the ASCE/SEI 7 Standard ultimately take a clear position on how to handle the occurrences of structural collapse within the acceptance criteria.

10. RECOMMENDATIONS FOR FUTURE STUDY

This paper provides guidance to design professionals on selection and scaling of ground motions for the purpose of nonlinear response-history analysis. In the process of this project, gaps in the current knowledge related to selecting and scaling ground motions for seismic design and performance assessment were identified. The key gaps identify the need for:

- Extending the conditional spectra approaches to address two horizontal components of ground motion and for the use of maximum direction Sa (Sa_{maxDir})as the intensity measure,
- A technical basis for the number of sets of ground motions necessary to compute mean values of responses and distributions of responses,
- Assessing the adequacy of a design if one or more analyses indicates either a collapse or a large undesirable (or non-converged) response,
- Assessing the adequacy of a design where the response distributions are not lognormal or normal,
- Incorporation of forward-directivity in probabilistic seismic hazard analysis and target spectra,
- Characteristics of ground motions in a record set that include velocity pulses,
- Scaling motions containing single-sided (fling step) and double-sided pulses to a target spectrum,
- Increased strong motion instrumentation is needed to capture future ground motions with small site-to-source distances and future ground motions in the Central and Eastern United States (the latter also need to be augmented by physics-based simulations).

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