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Response History Analysis for the Design of New Buildings in the NEHRP Provisions and ASCE/SEI 7 Standard: Part I - Overview and Specification of Ground Motions

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This manuscript, the first in a four-part series, describes the response history analysis approach developed for Chapter 16 of the ASCE/SEI 7 Standard and critical issues related to the specification of ground motions. Our approach provides new procedures for demonstrating adherence to collapse safety goals for new buildings (≤10% collapse probability at the MCE_R shaking level), creating nonlinear structural models, selecting and applying ground motions to the structural model, interpreting computed structural responses, and enforcing acceptance criteria to achieve the collapse safety goal. The ground motion provisions provide the option of using target spectra having more realistic spectral shapes than traditional uniform hazard spectra. Ground motions are developed using a two-stage procedure emphasizing spectral shape in their selection, followed by scaling or matching them to the target, with a modest penalty for matching. Horizontal component motions are applied to the structural model with random components to avoid bias associated with the maximum-component definition of the target spectrum.

INTRODUCTION

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This paper is the first of four companion papers presenting the results of a multi-year effort to rewrite Chapter 16, *Seismic Response History Procedures,* of the ASCE/SEI 7-10 Standard (ASCE 2010) to include detailed, consensus-based procedures for using nonlinear dynamic analysis in the performance assessment and design of new buildings. The new Chapter 16 replaces earlier versions that effectively date from 1997, when the response history analysis (RHA) approach was introduced to the National Earthquake Hazard Reduction Program (NEHRP) Provisions.

The Building Seismic Safety Council (BSSC) Provisions Update Committee (PUC) initiated this effort in 2005 as part of the 2009 National Earthquake Hazard Reduction Program (NEHRP) Recommended Provisions (BSSC 2009) update, resulting in a modified version of Chapter 16 that was published in Part III of the 2009 NEHRP Provisions. The 2009 NEHRP Provisions were published in three parts: Part I comprised recommended changes to ASCE 7-05; Part II comprised commentary to ASCE 7-05; and, Part III recommended improvements that did not achieve sufficient consensus to be included in Part I. By custom, the ASCE 7 committee formally considers all Part I materials for inclusion in the next edition of the standard while Part III materials may or may not be considered at the committee's discretion. The Part III Chapter 16 materials were not adopted by the ASCE 7-10 Standard. In 2010, the PUC formed an Issue Team with the specific mandate of finalizing the revision to Chapter 16. This paper and its companions document the results of this work. The revised Chapter 16 is published in Part I of the 2015 NEHRP Provisions and has also been adopted into the ASCE 7-16 Standard.

In this paper, we describe the general approach taken in developing the new Chapter 16 procedures and differentiate our approach from other guidelines and code documents. We also describe the ground motion procedures, and the rationale behind their development, in some detail. Paper II in this series (Haselton et al. 2016) focuses on structural modeling and acceptance criteria in Chapter 16. Paper III (Zimmerman et al. 2016) provides three design examples. Paper IV (Jarrett et al. 2016) documents a study of several assumptions in the Chapter 16 requirements.

We begin by explaining the goals of response history analysis in ASCE 7. We then present a focused literature review covering recent ASCE Standards and other code and resource documents, followed by a summary of the new Chapter 16 framework for building design using

RHA. Next, we discuss the selection and modification of ground motions. Finally, a brief review of modeling procedures related to soil-structure interaction is provided.

GOALS OF EVALUATION PROCESS IN ASCE/SEI 7

ASCE 7-10 establishes expected performance in the form of acceptable probabilities of collapse based on the occurrence of risk-targeted maximum considered earthquake (MCE_R) shaking. Table 1 indicates these goals.

Table 1. Performance Goals in ASCE/SEI 7-10 (Table C.1.3.1b).

Risk Category	Tolerable Probability of Total or Partial Structural Collapse	Tolerable Probability of Individual Life Endangerment	Ground Motion Level
I or II	10%	25%	MCE_R
III	6%	15%	MCE_R
IV	3%	10%	MCE_R

The 10% collapse probability threshold for Risk Category I and II structures has a long history. Commentary contained in FEMA-273/274 (1997) suggests that one out of ten structures designed in accordance with the guidelines might experience worse performance than targeted by the design. The design guidance contained in FEMA-350 (2000) targeted 90% confidence of not greater than a 10% probability of collapse, conditioned on the occurrence of maximum considered earthquake (MCE) shaking. In the FEMA-350 procedures, confidence was determined considering random (aleatory) uncertainties while probability of collapse was determined considering both lack-of-knowledge-based (epistemic) uncertainties and aleatory variability. More recently, the FEMA P-695 project (FEMA 2009) condensed these two forms of uncertainty and developed the simpler performance goal of a 10% conditional probability of collapse given MCE shaking. The ASCE 7 committee adopted this goal and selected the 6% and 3% thresholds for Risk Categories III and IV structures by assuming that the historic seismic importance factors (I_e) of 1.25 and 1.50, would reduce typical building collapse fragilities.

In addition, ASCE 7-10 established the concept that buildings designed according to its provisions would have a *1% chance of collapse over a 50-year time period* and set the ground motion level so as to achieve this objective. This redefined shaking was designated as “risk-targeted MCE shaking” or MCE_R. Were the MCE_R ground motion to occur at the site, the objective is a 10% probability of collapse. Commentary to the 2009 NEHRP Provisions (BSSC

2009) documents this approach, and Luco et al. (2015) provide further details. While the collapse probability goals shown in Table 1 apply to all building types and all sites, the 1% in 50-year collapse goal applies only to Risk Category I and II structures located on sites with probabilistically determined motions. Sites near active faults have $\mathrm{MCE_R}$ shaking defined by an alternative deterministic calculation (ASCE 2010, section 21.2.2) and this produces a higher level of risk at those sites. The scope of this Chapter 16 effort, and the related discussion in this paper, did not include revisiting the definition of the $\mathrm{MCE_R}$ design ground motion, as introduced in BSSC (2009) and described in Luco et al. (2015). There is some concern about the $\mathrm{MCE_R}$ definition of design ground motion and this is being addressed in currently the BSSC Project 17 effort (BSSC 2016).

While those performance goals are specified outside of the Chapter 16 scope that was the responsibility of this effort, they are mentioned here as they provide targets that the Chapter 16 procedures should aim to verify. It is conceptually desirable for the Chapter 16 RHA performance assessment process to allow for *explicit* evaluation of collapse probabilities so as to fulfill performance goals. However, as described in FEMA P-695 (FEMA 2009), to realistically achieve this goal requires: (a) a structural model that can simulate collapse, (b) use of many (perhaps hundreds) of nonlinear response history analyses, and (c) explicit treatment of many types of uncertainties. While this process is too complex and lengthy for routine use in design, the explicit approach is nonetheless permitted by Section 1.3.1.3 of ASCE 7-10. An example of such an explicit approach is the Appendix F methodology provided in the FEMA P-695 document (2009).

In lieu of the relatively complex explicit approach, the updated Chapter 16 maintains a simpler approach of *implicitly* demonstrating adequate performance through a prescribed set of analysis rules and acceptance criteria. This approach checks that buildings have predictable and stable responses under $\mathrm{MCE_R}$ ground motions, that deformation and strength demands on elements are in the range of modeling validity and acceptable behavior, and that story drifts are within specified limits. Such checks do not explicitly verify that a building meets the collapse goals (Table 1), but those goals are *assumed* to be met if the building response is analyzed according to Chapter 16 requirements and is found to fulfill the acceptance criteria. Where possible, acceptance criteria were calibrated to be consistent with the fundamental collapse goals of Table 1. Where this was not possible given limited research, acceptance criteria were set conservatively based on expert judgment; such criteria may be modified as a result of future research. Regardless, the authors believe the criteria represent a substantial improvement over prior approaches. A non-exhaustive study to evaluate and confirm this approach is provided in a companion paper (Jarrett et al. 2016).

LITERATURE REVIEW AND STEPS IN RESPONSE HISTORY ANALYSIS

HISTORIC PROCEDURES

The 1991 Uniform Building Code (UBC) was the first to include procedures for use of nonlinear RHA in design. In that code, RHA was required for base-isolated buildings and buildings incorporating passive energy dissipation systems. Analyses using a minimum of three pairs of ground motions were required. Ground motions could be amplitude-scaled or spectrally matched for compatibility with design spectra. The interpretation of the range of RHA results depended on the number motions – a mean response was used when seven or more pairs of ground motions were applied, whereas the maximum response was used if fewer than seven motions were applied. Uncertainties were accounted for, in part, by requiring use of upper and lower bounds on isolator or energy dissipation device properties. The design process is subject to review, as are all other design procedures summarized in this section.

The FEMA-273/274 (1997) rehabilitation guidelines adapted the UBC requirements for more general application to building structures. The guidelines required scaling (or spectral matching) of the motions to a target spectrum over a period range of $0.2T$ to $1.5T$, where T is the structure’s fundamental period. The intent was to capture both higher mode effects and period elongation resulting from nonlinear response. In the same manner as done in the UBC, the interpretation of analysis results depended on the number of motions utilized. Uncertain structural properties were not directly accounted for; however, it was recognized that nonlinear analysis results were likely more accurate predictions of building response than linear analysis results. Accordingly, nonlinear analysis results were interpreted using less conservative acceptance criteria. The procedures included methods for developing acceptance criteria based on laboratory testing of prototype specimens, but also included a substantial library of recommended element hysteretic characteristics and acceptance values.

CONTEMPORARY PROCEDURES

Haselton et al. (2017). "Response-History Analysis for the Design of New Buildings in the NEHRP Provisions and ASCE/SEI 7 Standard: Part I - Overview and Specification of Ground Motions." Earthquake Spectra, 33(2), 373–395. https://doi.org/10.1193/032114EQS039M

Table 2 summarizes specifications governing application of RHA from contemporary standards and resource documents. The final column of Table 2 also provides the approach taken in the updated Chapter 16 RHA procedure.

Chapter 16 of ASCE 7-05 and ASCE 7-10 (ASCE 2005 and 2010) are similar and include both linear and nonlinear RHA procedures. The linear procedure provides force and drift demands for use with the basic load combinations specified by the Standard. The nonlinear procedure was adapted directly from the procedures contained in FEMA-273/274. Nonlinear analysis is performed at the Design Earthquake (DE) level, though acceptance criteria are taken as two-thirds of the expected useful capacity of the element, to account indirectly for response at the MCE level. Acceptance criteria are enforced for both story drifts and member deformations. The nonlinear procedure has no limitation on building strength.

The City of San Francisco Administrative Bulletin 083, enforced in the 2010 San Francisco Building Code (AB-083 2008), governs the use of nonlinear RHA in performance-based design for tall buildings. The Administrative Bulletin assumes that the design will meet the code's prescriptive requirements with limited exceptions, most typically, exceedance of system height limits and use of a redundancy coefficient value of 1.0. RHA is used to demonstrate that designs incorporating these and other code exceptions are capable of performance equivalent to that of fully conforming designs. The Bulletin's requirements include:

- Buildings must comply with all code requirements except as specifically identified. Other than these exceptions, the design must comply with the code requirements.
- Perform a code-level evaluation. This entails an elastic response spectrum analysis (RSA) performed at the DE level. The purpose of this step is to enforce minimum levels of strength and stiffness consistent with that required by the code for conforming buildings and to assure basic design compliance with the code requirements.
- Perform a service-level evaluation. This elastic analysis uses ground motions with a 50% probability of exceedance in 30 years (43-year mean return period). The purpose of this step is to demonstrate that buildings will be serviceable and have only minor damage from moderate earthquakes.
- Perform an MCE-level evaluation. This nonlinear RHA uses the MCE ground motion level from ASCE 7-05. The intent of this step is to (a) demonstrate that the building has predictable response under severe ground motions, (b) demonstrate an acceptable mechanism of nonlinear deformation, and (c) determine maximum forces for design of force-controlled (brittle) components.

The PEER Tall Building Initiative (PEER 2010) guidelines are based on experience from research and design reviews. The procedures consider reliability concepts, which were incorporated into the acceptance evaluation for critical force-controlled behaviors. Major points in this document include:

- Buildings must comply with all code requirements (e.g., detailing, height limits, etc.) except as specifically identified. Explanation of the design precautions taken to justify the exceptions is required.

Table 2. Summary of Contemporary RHA Requirements and Recommendations

Components of the Response History Analysis	Design/Assessment Method							Updated Chapter 16 RHA Procedure
	ASCE 7-05	ASCE 7-10	ASCE 41-06	ASCE 41-13	LATBSDC (2008)	SF DBI AB-083 (2008)	PEER TBI (2010)	
Explicit Goals:	Small (but undefined) probability of collapse given MCE shaking	See Table 1 above	Target performance level for each selected level of seismic hazard (e.g., “Collapse Prevention in BSE-2.”)		Well-defined behavior, functional for service motion, low probability of collapse given MCE shaking	Performance equivalent to code-prescriptive design	P[C] < 10% for MCE shaking, low residual drift, low cladding failure risk	See Table 1 above
Ground Motion Intensity Measure:	Geometric mean Sa	Max direction Sa	Geometric mean Sa	Max direction Sa	Geometric mean Sa, per ASCE7-05	Geometric mean Sa, per ASCE7-05	Geometric mean or max direction Sa, per ASCE7-05/10	Max direction Sa
Ground Motion Level for Assessment:	2/3 MCE	2/3 MCE$_R$	MCE and 2/3 MCE (or 10% in 50-yr)	MCE$_R$, 2/3 MCE$_R$, 5% in 50-yr, or 20% 50-yr.	MCE, service-level	MCE, DBE, service-level	MCE, service-level	MCE$_R$
Target Spectrum:	UHS	UHS with risk adjustment	UHS	UHS with or without risk adjustment	UHS, per ASCE7-05	UHS, per ASCE7-05	UHS or multiple CMS	UHS or multiple scenarios (CMS), with risk adjustment
Minimum Base Shear Requirements (for forces and/or drifts):								
Enforced for modal analysis	Forces only	Forces and drifts^1	None		0.03W for forces	Forces only	None	Force and drifts^1 in trial design^2
Enforced for nonlinear response history analysis?	No		No		No	No	No	No
Ground Motion Selection:								
Number of motions	≥7 (or 3) pairs		≥7 (or 3) pairs	Varies	≥7 pairs	≥7 pairs	≥7 pairs	≥11 pairs
Other	None		None	Directivity motions if needed	"Appropriate number" of directivity motions	Goal is to be consistent with practice	Directivity motions if needed	Appropriate number of directivity motions
Scaling/Modification of Motions to Match Target Spectrum:								
General approach	Scaling (spectral matching not mentioned)		Scaling (spectral matching not mentioned)	Scaling or spectral matching	Scaling or spectral matching	Scaling or spectral matching	Scaling or spectral matching	Scaling or spectral matching
Specific instructions for far-field sites	SRSS is above 1.17x target spectrum		SRSS is above target spectrum		SRSS is above 1.17x target, per ASCE7-05	None	"Match records to target..."	Match records to target, enforce 90% floor
Specific instructions for near-fault sites	None		Average of FN is above target		None, per ASCE 7-05	Only general discussion	None	Same as far-field component
Period range for matching	0.2T - 1.5T		0.2T - 1.5T		0.2T - 1.5T, per ASCE7-05	0.2T - 1.5T, per ASCE7-05	Not specified	T_{MIN} - 2.0T, where T_{MIN} captures 90% mass participation

cont. Table 2. Summary of Contemporary RHA Requirements and Recommendations

Components of the Response History Analysis	**Design/Assessment Method**							**Updated Chapter 16 RHA Procedure**
	ASCE 7-05	**ASCE 7-10**	**ASCE 41-06**	**ASCE 41-13**	**LATBSDC (2008)**	**SF DBI AB-083 (2008)**	**PEER TBI (2010)**	
Application of Ground Motions to Structural Model:								
Far-field sites	Apply motions together; no rules for orientation		Apply motions together; no rules for orientation		Orient motions randomly; no need for multiple orientations	Orient motions randomly; no need for multiple orientations	"Apply along principle directions" (but no rotation mentioned)	Arbitrarily orient motions; no need for multiple orientations of GMs
Near-fault sites	No rules for orientation.	Apply FN/FP if site < 5km from fault	No rules for orientation	Apply FN/FP if site < 5km from fault	Apply in FN and FP directions	Apply in FN and FP directions	Apply in FN & FP directions if directivity dominates	Apply in FN and FP directions; no need for multiple orientations
Treatment of Vertical Ground Motion	Not considered		Include for specific cases		Not considered, per ASCE7-05	Not considered	Included in rare cases	Included in rare cases
Response Metrics and Acceptance Criteria (at MCE or 2/3 MCE):								
Peak story drifts	$\mu < 1.25$*limit		No limit	No limit	$\mu < 0.03$	$\mu < 0.03$	$\mu < 0.03$, max < 0.045	$\mu <$ twice typical limit; no max. check beside collapse
Residual story drifts	No limit		No limit	No limit	No limit	No limit	$\mu < 0.01$, max < 0.015	No limit
Deformation-controlled actions	$\mu <$ limit		$\mu <$ limit	$\mu <$ limit	$\mu <$ limit	$\mu <$ limit	No limit (except within reliable anal. range).	$\mu <$ ASCE 41 CP limit divided by Ie, or $\mu < 0.3\Delta_{LVCC}$ / Ie for critical and $0.5\Delta_{LVCC}$ / Ie for ordinary [where Δ_{LVCC} is deformation at loss of vertical load carrying capacity
Force-controlled actions (critical, well-defined mech.)	Basic design approach, which could include use of overstrength factor		$\mu < F_{n,lower\text{-}bound}$		$\mu <$ limit	$\mu + 1.0\sigma \leq \varphi F_n$	$\max(\mu + 1.3\sigma, 1.2\mu) \leq \varphi F_{n,e}$	$(2.0Ie)^*\mu \leq F_e$
Force-controlled actions (critical, no well-defined mech.)							$1.5\mu \leq \varphi F_{n,e}$	$(1.5Ie)^*\mu \leq F_e$
Force-controlled actions (non-critical)							$\mu \leq Fn,e$	$(1.0Ie)^*\mu \leq F_e$
Loss in story strength	No limit		No limit	No limit	No limit	No limit	≤ 20% loss	No limit
Treatment of collapse or unacceptable response 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.		Not discussed. Average drift limits suggest collapses are not allowed.	Not discussed	Collapses are not allowed	No more than 1 motion may produce unacceptable response
Other	None		None	None	None	None	Response in reliable range	Response in reliable analysis range

1. Only Equation 12.8-6 is enforced for drifts (and this only applies in high-seismic regions were $S_1 \geq 0.6g$)
2. The minimum base shear requirement is enforced for forces and drifts by requiring that a trial design be completed using either the RSAP or the ELFP.

- A code-level (i.e., Design-Basis Earthquake (DBE) level) evaluation is not required.
- Perform a service-level evaluation. This evaluation is to establish minimum building strength and demonstrate minimal damage in frequent, moderate earthquakes.
- Perform an MCE-level evaluation. The basis and purpose is similar to AB-083. No limits are specified for deformation-controlled (ductile behaviors) other than element response being limited to the valid range of modeling. Acceptance criteria for brittle, force-controlled behaviors are set based on the importance of the individual element to overall structural response. Demands for critical force-controlled behaviors are taken at one standard deviation above the mean. Limits are placed on peak transient story drift, residual story drift and story strength loss. Extensive guidance on appropriate modeling assumptions, including hysteretic behaviors and damping is provided.

The Los Angeles Tall Buildings Structural Design Council published alternative design procedures for buildings in the Los Angeles region. The 2005 edition was largely prescriptive and similar in concept to AB-083. The 2008 edition (LATBSDC 2008) moved from prescriptive requirements toward a performance-based methodology. The 2011 edition (LATBSDC 2011) was developed in parallel with PEER (2010) and includes many of the same concepts, with the exception that acceptance criteria for force-controlled behaviors were somewhat relaxed.

OVERVIEW OF THE UPDATED PROCEDURE

PRIMARY COMPONENTS

The Chapter 16 RHA procedure uses the following framework:

1. Ensure that the design conforms to all applicable requirements of the ASCE 7 Standard. Exceptions to these requirements, other than those explicitly incorporated in the procedures, as indicated below, must be handled under the criteria of ASCE 7 Section 1.3 for performance-based designs.
2. Perform a code-level (i.e., DBE-level) evaluation using either the equivalent lateral force procedure of Section 12.8 or response spectrum method of Section 12.9, including the minimum base shear requirement. The purpose of this step is to enforce the same minimum levels of strength required for all buildings and to provide a basic evaluation of torsional behavior. Bearing in mind that further requirements will be imposed in the MCE_R-level evaluation, the following modifications are incorporated to the procedures of Section 12.8 and 12.9:
    - For Risk Category I, II, and III structures, the drift limits of Section 12.12.1 do not apply.
    - For Risk Category IV structures, the drift limits are 125 percent of those specified in Section 12.12.1.

        - The overstrength factor, Ω_0, is permitted to equal 1.0 for the seismic load effects of Section 12.4.3.
        - The redundancy factor, ρ, is permitted to equal 1.0.

3. A service-level evaluation is not required.
4. Perform an MCE_R-level evaluation. The step is intended to (a) demonstrate that the building has predictable and stable response at MCE_R ground shaking levels and (b) determine the deformation demands on ductile elements for the design of force-controlled (brittle) components. Fulfillment of the acceptance criteria implicitly demonstrates that the building has equivalent or better seismic resistance as compared with designs using the basic Chapter 12 requirements.
5. Complete an independent design review of work performed for the above steps.

The code-level evaluation (Step 2) was retained for two reasons. First, it provided a clear basis for establishing minimum strength and stiffness. Second, the code-level evaluation step takes care of many of the detailed design safeguards that then did not need to be specifically incorporated into the MCE_R-level evaluation. For example, the code-level evaluation includes provisions for accidental torsion, enforcement of multiple gravity load combinations, and wind loads, in addition to many other requirements. Accordingly, these design safeguards are not expressly required in the MCE_R-level RHA evaluation.

The Chapter 16 RHA procedure focuses on nonlinear RHA methods. The procedure requires the use of a three-dimensional structural model. It is applicable to buildings of any Risk Category.

MINIMUM BASE SHEAR REQUIREMENTS

Elastic design procedures in ASCE 7 specify required structure strength through base shear equations. The base shear equations are generally tied to spectral acceleration demands computed using ASCE 7-10 Section 11.4.5, but two additional limits, known as minimum base shear requirements, are given as:

$$C_S = 0.044 S_{DS} I_e \geq 0.01 \tag{1}$$

$$C_S = 0.5 S_1/(R/I_e), \text{ enforced when } S_1 \geq 0.6g \tag{2}$$

where C_s is the minimum base shear, S_{DS} is the short-period design acceleration (at 0.2 seconds), S_1 is the design acceleration at 1.0 seconds, R is the response modification factor, and I_e is the importance factor for seismic loading.

Eq. (1) is based on the Riley Act, adopted in California following the 1933 Long Beach earthquake. Thought to be arbitrary, this limit was removed in the 2005 edition of the Standard. However, the FEMA P-695 study determined it was needed to provide acceptable performance for frame-type structures (FEMA 2009, Haselton et al. 2011) and it was returned to the Standard in Supplement #2 of ASCE 7-05; it is accordingly retained here. Eq. (2) applies only at sites located near a major active fault.

We also enforce a minimum base shear in Step 2 (only for force demands) because no minimum base shear is included in the MCE_R-level nonlinear RHA evaluation. Application of some minimum base shear is needed to ensure that the buildings designed using Chapter 16 are not weaker than those designed using Chapter 12.

EXCEPTIONS TO CODE PROVISIONS

We considered including in the revisions to Chapter 16 a specific allowance for exceptions to code provisions. We ultimately decided to not structure the chapter in that manner, to avoid the potential for unintentionally omitting exceptions which could be valid. Such omissions could be interpreted by building officials as explicit prohibitions. Instead, the "alternate means and methods" approach embodied in ASCE 7 Section 1.3 can still be used to invoke exceptions to the Standard's requirements. It is important to note that Chapter 16 can still be used as the "alternate means and methods" guideline/document under Section 1.3. Chapter 16 can therefore be reached by two paths - one for buildings that do not take exceptions to the code and the other for those that do invoke one or more exceptions and use Section 1.3 (e.g. a building with a non-prescribed lateral force resisting system).

GROUND MOTION TARGET SPECTRUM

GROUND MOTION INTENSITY MEASURE

Until recently, design ground motions in building codes were specified in terms of geometric mean spectral accelerations, computed as the square root of the product of spectral accelerations in two orthogonal directions. ASCE 7-10 instead defines spectral acceleration values in terms of the maximum direction response. The structural assessment should not depend on what type of spectral acceleration definition is being used to quantify the ground motion, provided that each step of the RHA process is completed in a manner that is consistent with the chosen spectral acceleration definition (i.e., selection, scaling, application to the structural model, and interpretation of response predictions). The Chapter 16 RHA procedure was developed to account for this new maximum direction spectral acceleration definition and avoid undue conservatism that could otherwise result from its application (Stewart et al. 2011).

LEVEL OF GROUND MOTION

To more directly evaluate the collapse safety goals of ASCE 7, as summarized in Table 1, the updated Chapter 16 RHA procedure is directly based on MCE_R-level ground motions rather than design-level ground motions (which are two-thirds of of MCE_R). This MCE_R-level approach is consistent with recent performance-based design procedures (Table 2). Note that the MCE_R spectrum itself is defined in Chapters 11, 21 and 22, and is simply utilized in the Chapter 16 procedures.

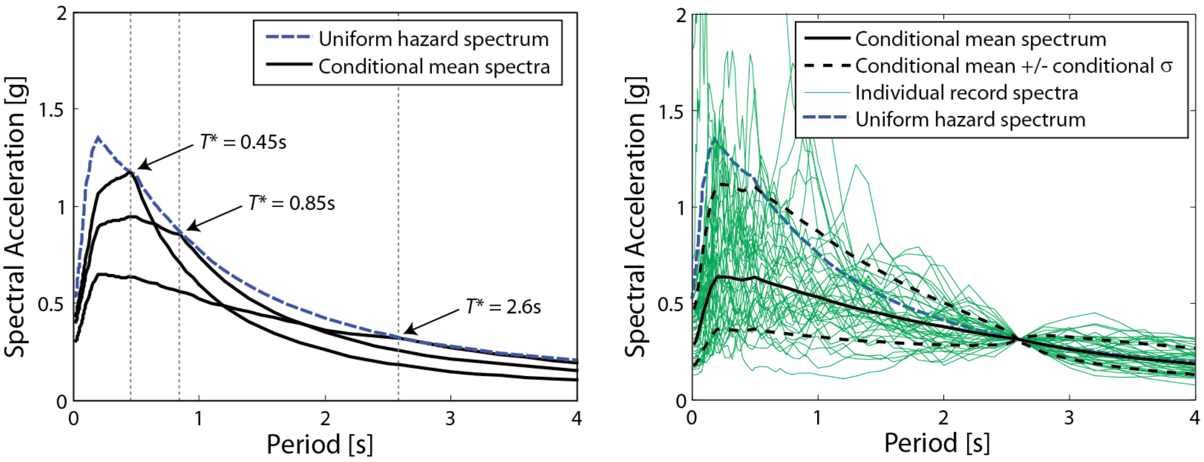
AVAILABLE DEFINITIONS OF TARGET RESPONSE SPECTRUM

Uniform Hazard Spectrum (UHS)

For the past two decades, design practice has used UHS to define design ground motions. The UHS is created by enveloping the spectral acceleration values with a given probability of exceedance, which are obtained from independent seismic hazard analyses for each period. The UHS values at any period are not associated with a given earthquake, however, but rather are a composite consisting of contributions from many magnitude-distance and ground motion realization combinations. The UHS will generally be a conservative target spectrum if used for ground motion selection and scaling, especially for large and rare ground motions, unless the structure exhibits only elastic first mode response. This conservatism derives from the fact that the spectral values in a UHS are unlikely to all occur in a single ground motion realization (e.g., Bommer et al. 2000).

Conditional Mean Spectra (CMS)

The CMS is an alternative target spectrum to the UHS spectrum (e.g., NIST 2011). The CMS conditions the spectrum calculation on the spectral acceleration at a single period, and then computes the mean spectral acceleration values for other periods, producing a spectrum that is more representative of real ground motions. The CMS calculation is no more difficult than the UHS calculation and is arguably more appropriate for use as a ground motion selection target in risk-assessment applications. The CMS is based on the ground motion intensity level, disaggregation information, and a selected period on which to condition the CMS (commonly the first-mode period of the building). Figure 1a provides example CMS for a site in Palo Alto, California, conditioned on three different candidate periods.



(a) (b)

Figure 1. (a) Example Uniform Hazard Spectrum and Conditional Mean Spectra for an example site in Palo Alto, for a 2% in 50-year exceedance probability and with conditioning periods of T^* = 0.45s, 0.85s, 2.6s. (b) Conditional Spectra for the same example with a conditioning period of T^* = 2.6s. (Figures adapted from NIST 2011)

Conditional Spectra (CS)

The CMS is a mean spectrum and as such does not capture spectral variability. A comparable target spectrum that considers variability is the Conditional Spectrum (CS). Figure 1b provides an example of a ground motion set selected and scaled using a CS anchored at T^* = 2.6 sec. Use of the CMS and CS are permitted in ASCE-7 Chapter 16.

TARGET RESPONSE SPECTRUM: SELECTED PROCEDURE

In the Chapter 16 RHA procedure, we retain the $\mathrm{MCE_R}$ target spectrum as a simple and conservative target spectrum, but include an alternative that can more realistically represent the spectral shape of expected ground motions. These target spectra reflect the general level of design ground motion as introduced in BSSC (2009) and discussed further in Luco et al. (2015), and this design ground motion level was not subject to revision in this Chapter 16 effort. As shown in Table 2, this dual-method strategy is consistent with the approach recommended in the PEER-TBI Guidelines (PEER 2010). To generalize the language, the CMS or CS approaches are collectively referred to as “scenario spectra,” which allows future use of alternate scenario spectra definitions.

Method I: $\mathrm{MCE_R}$ Target Spectrum

Method I retains the traditional MCE_R target spectrum; either the generalized approach of ASCE 7-10 Section 11.4.6 or the site-specific approach of Section 11.4.7 may be used. Examples of developing the MCE_R target spectrum are provided in Zimmerman et al. (2016); those examples include detailed step-by-step illustrations for creating the MCE_R spectrum considering a maximum direction correction factor, application of the risk coefficient, and the enforcement of ceiling values to reduce the MCE_R target spectra for near-fault sites.

Method II: Multiple Scenario Target Spectra

Method II has the following steps:

1. Select two or more periods that correspond to periods of vibration that significantly contribute to the building’s dynamic response. This will include a period near the building’s fundamental mode periods (e.g., an average of the two horizontal direction periods, if they are similar), or an extended period to account for inelastic period lengthening. The second period may be near the translational second-mode periods of the building.
2. For each selected period, create a scenario spectrum (using the CMS or a similar method) that matches or exceeds the MCE_R value at that period and has appropriate amplitudes at other periods. When developing the scenario spectrum (a) perform site-specific disaggregation to identify earthquake events likely to result in MCE_R ground shaking, and (b) develop the scenario spectrum to capture one or more spectral shapes for dominant magnitude and distance combinations revealed by the disaggregation.
3. Enforce that the envelope of the scenario spectra not be less than 75 percent of the MCE_R spectrum (from Method I) for any period within the period range of interest (as defined below).

This use of scenario spectra to test a building relative to acceptance criteria is consistent with the analyses undertaken in FEMA (2009), the results of which helped confirm the appropriateness of the 10% probability of collapse goal in Table 1. Zimmerman et al. (2016) illustrates the development of scenario spectra by providing step-by-step illustrations of selecting anchor periods, deciding on the required number of scenario spectra, computing scenario spectra, and enforcing the 75% floor.

The purpose of the 75% floor is to (a) provide a basis for determining the required number of scenario spectra and to (b) enforce reasonable lower bound on ground motion used for design (to assure that the structure can tolerate demands from scenarios other than those selected). The role of the floor in controlling the number of spectra can be understood by noting the fall-off of scenario spectra relative to the UHS in Figure 1a. The wider the period range under consideration, the more likely is a scenario spectrum to fall below the floor, thus requiring the use of additional scenario spectra or adjustments to the scenario spectra (details in Zimmerman et al. 2016). For most structures, with first and second translational modes dominating response, two scenarios will be sufficient; the need for three scenarios is less common but may be required for more complex cases (as confirmed in the examples of Zimmerman et al. 2016).

GROUND MOTION SELECTION

MINIMUM NUMBER OF GROUND MOTIONS

The number of ground motions needed for analysis depends on whether prediction of mean and variability of responses, or just mean responses, is desired; the required accuracy of the estimated values of mean and variance; the expected degree of inelastic response; and the possible prediction of collapse responses. Focusing primarily on prediction of mean response, ASCE 7-10 requires seven ground motions, which is consistent with many other contemporary methods (as shown in Table 2) but also permits analysis using as few as three ground motions.

Prior studies (FEMA 2012) evaluated the potential error in predicted structural responses depending on the number of ground motions used for analysis (with the ground motions being randomly selected). The findings showed that when 11 motions are used, mean response parameters (primarily story drift) are predicted within 30% at a 70% confidence level. Results for fewer ground motions demonstrated significantly more variability. We recommend the use of a minimum of 11 motions based on the FEMA (2012) findings and the judgment of the team. The decision to require 11 motions is intended to balance the competing objectives of more reliable estimates of mean structural responses (through use of more motions) against computational effort (reduced by using fewer motions). It is expected that the minimum level of effort in the Chapter 16 RHA procedure will actually be lower than in the current ASCE 7-10 RHA procedure, because the increased number of motions is offset by not requiring accidental torsion in the RHA and not requiring multiple orientations of ground motion, as have sometimes been used in application of the present ASCE 7-10 procedure. There may be an increase in this effort level should the analyst adopt the Conditional Mean Spectrum approach (as one suite of ground motions is needed for each spectrum), but this approach is optional and can be avoided for those wishing to minimize analysis time.

COMPONENTS OF GROUND MOTION

In the Chapter 16 RHA procedure, a ground motion set typically consists of two horizontal components, but the framework also includes the possibility of a vertical component for the less typical case where vertical dynamic responses are important (as discussed in the Part II companion paper).

DIFFERENTIATION OF NEAR-FAULT FROM NOT NEAR-FAULT SITES

Near-fault sites are defined as those having a reasonable probability of experiencing ground motions strongly influenced by rupture directivity effects. These effects can include changes in the response spectrum relative to a spectrum obtained with standard ground motion models (Spudich et al. 2014), large velocity pulses (e.g., NIST 2011), and polarization of ground motions where the maximum direction of response tends to be in the direction perpendicular to the fault. The issue of pulse-type ground motions affects the manner by which individual ground motions are selected for the site, as described below. The issue of ground motion polarization affects the way that horizontal ground motions are applied to the structure, as described in a later section. The effect of near-fault rupture directivity on the seismic hazard analysis (and resulting MCE_R design spectrum) is covered in Chapter 21 of ASCE7 and is beyond the scope of this Chapter 16 effort.

Near-fault sites are located close to the causative fault for an earthquake (a circumstance that describes regions where most of California’s population lives). To identify whether a site qualifies as near-fault, one must develop a site-specific MCE_R spectrum, followed by site-specific disaggregation at the periods of interest. If the controlling earthquakes identified through disaggregation are in close proximity to the site, the site should be considered as near-fault. ASCE 7-16 indicates that near-fault effects are present when the fault distance is less than 15km for magnitude 7 or larger earthquakes, or a fault distance of less than 10km for magnitude 6.0 earthquakes. The engineering characterization of near-fault ground motions in rapidly evolving, but research to date suggests that pulses in high-amplitude ground motions are reasonably probable up to 10-20 km from the site and that ground motion polarization in the fault-normal direction occurs for distances up to approximately 3-5 km (NIST 2011).

SELECTION OF GROUND MOTIONS FOR FAR-FIELD SITES

The traditional approach has been to select or simulate ground motions having magnitudes, fault distances, source mechanisms, and site soil conditions that are roughly similar to those likely to cause the ground motion intensity level of interest, and not to explicitly consider spectral shape in ground motion selection. In many cases, however, response spectrum shape is the ground motion property most correlated with structural response (PEER 2010), so the Chapter 16 RHA method includes spectral shape as an important consideration when selecting ground motions. When spectral shape is considered in the ground motion selection, the allowable range of magnitudes, distances, and site conditions can be relaxed so a sufficient number of ground motions with appropriate spectral shapes are available.

The selection of recorded motions occurs in two steps. Step 1 involves pre-selecting the ground motion records in the database (e.g., Ancheta et al., 2014) having reasonable magnitude, fault distance, source mechanisms, site soil conditions, and range of useable frequencies. In completing this pre-selection, it is permissible to use relatively liberal ranges because Step 2 involves selecting motions that provide good matches to a target spectrum (which implicitly accounts for many of the above issues). If a database of suitable recorded ground motions cannot be developed, a database of appropriate simulated ground motions can be used instead or as a supplement.

Step 1 criteria for initial screening of ground motions are as follows:

- **Tectonic Regime:** Select recordings from the same tectonic regime as present at the site (typical choices are active crustal regions, stable continental regions, and subduction zones; details in Garcia et al. 2012).
- **Magnitude and Distance:** These parameters are obtained from disaggregation of the hazard at a period of interest. Selecting ground motions having reasonably similar magnitude and distance is intended to provide generally compatible durations and spectral contents. Since spectral shape criteria are separately enforced in Step 2, the duration compatibility is the principal consideration.
- **Site Soil Conditions:** Site soil conditions (Site Class) exert a large influence on ground motions, but are already reflected in the spectral shape used in Step 2. For Step 1, reasonable limits on site soil conditions should be imposed but should not be too restrictive as to unnecessarily limit the number of candidate motions.
- **Useable Frequency of the Ground Motion:** Only processed ground motion records should be considered for RHA. Processed motions have a usable frequency range and the most critical parameter is the lowest usable frequency. It is important to verify that the useable frequencies of the record (after filtering) accommodate the range of frequencies important to the building response; this frequency (or period) range is discussed in the next section on scaling.

Step 2 criteria for final selection of ground motions are as follows (NIST 2011):

- **Spectral Shape:** The shape of the response spectrum should be the primary consideration when selecting ground motions.
- **Scale Factor:** A scale factor limit of approximately 0.25 to 4.0 is not uncommon.
- **Maximum Motions from a Single Event:** Although less important than spectral shape and scale factor, it is common to limit the number of motions from a single seismic event to three or four motions when possible.

SELECTION OF GROUND MOTIONS FOR NEAR-FAULT SITES

For near-fault sites, a certain fraction of selected ground motions should exhibit pulse-like characteristics, while the remainder can be non-pulse records selected according to the standard process described above. The probability of experiencing pulse-like characteristics is dependent principally on (1) distance of site from fault; (2) fault type (e.g., strike slip or reverse); and (3) location of hypocenter relative to site, such that rupture occurs towards or away from the site.

Criteria (1) and (2) above are available from conventional disaggregation of probabilistic seismic hazard analysis. Criterion (3) can be computed as well in principle, but is not generally provided in a conventional hazard analysis. However, for the long ground motion return periods associated with MCE_R spectra, it is conservative and reasonable to assume that the fault rupture will be towards the site for the purposes of evaluating pulse probabilities.

Once the pulse probability is identified, the proper percentage of pulse-like records should be included in the ground motion selection. For example, if the pulse probability is 30% and 11 records are to be used, then 3 or 4 records in the set should exhibit pulse-like characteristics in at least one of the two horizontal components. The predominant period of the pulse is also an important selection criterion for pulse-like records. Further guidance on selection of ground motions with appropriate near-fault effects and pulse periods can be found in, e.g. Almufti et al. (2015) and Hayden et al. (2014).

We note that these requirements relate only to the selection of time series with appropriate features for a given site. Near-fault sites’ target spectra may also be influenced by these effects, and if so this should be addressed in the seismic hazard analysis.

GROUND MOTION SCALING

PERIOD RANGE

Ground motions must be scaled to match the target spectrum over a period range corresponding to the vibration periods that significantly contribute to the building's dynamic response. Recent versions of ASCE 7 have specified this period range as $0.2T$ to $1.5T$, with T being the building's fundamental translational period. The lower-bound is intended to assure that important higher response modes are properly excited. The upper-bound is specified to assure that, as the structure yields and the period lengthens, the ground motions still contain sufficient energy to properly excite the structure.

In the updated Chapter 16 RHA procedure, we increased the upper-bound period to $2.0T$, where T is redefined as the *maximum* fundamental period of the building (i.e., maximum of the fundamental periods in both translational directions and in torsion). The increase to the upper-bound period is associated with application of the higher MCE_R ground motion level, which produces greater inelastic response than use of the design spectrum. Smaller upper-bound periods could be justified if demonstrated by analyses using MCE_R motions.

For the lower-bound period, the $0.2T$ limit is retained but is supplemented with a requirement that the lower-bound period be small enough to capture the periods needed for 90% mass participation in both directions of the building. This change provides consistency with the 90% mass participation requirement in the Modal Response Spectrum Analysis procedure of ASCE 7-10 (Section 12.9).

In many cases, below-grade portions of the structure are included in the structural model, which substantially affects the system's mass participation characteristics. Unless the foundation system is designed using the results of the response history analyses, the 90% mass participation requirement pertains only to the superstructure mass (i.e., the period range does not need to include the very short periods associated with response of the subgrade structure).

HORIZONTAL COMPONENTS OF GROUND MOTION

The basic scaling approach of ASCE 7-10 (Section 16.1.3.2) requires that, after scaling, the square root of the sum of the squares (SRSS) spectrum for a given ground motion pair exceed the target spectrum over the period range of interest. In the Chapter 16 RHA scaling procedure, we drop the use of the SRSS spectra and operate instead on the maximum direction spectrum for consistency with the ASCE 7-10 MCE_R ground motion (which is based on the maximum component). Each ground motion is scaled (with an identical scale factor applied to its two or three components) such that the average of the maximum-direction spectra from all ground motions matches the target $\mathrm{MCE_R}$ spectrum. Moreover, we require that the average spectrum does not fall below 90% of the target spectrum, for any period within the period range of interest. These revisions remove the conservatism associated with requiring the average spectrum to exceed the target spectrum within the period range of interest.

This procedure requires computation of a maximum direction response spectrum for each ground motion. For some ground motion databases, this response spectrum definition is pre-computed and publically available (e.g., Ancheta et al. 2014). There are also a number of software tools that can compute this spectrum for a given pair of horizontal records.

SPECTRAL MATCHING

Spectral matching of ground motions is the process of modifying a real recorded earthquake ground motion in some manner such that its response spectrum matches a desired target spectrum across a period range of interest (e.g., Al Atik and Abrahamson 2010). Spectrally matched ground motions are permitted in lieu of motions scaled to the target spectrum. There are several spectral matching procedures in use, as described in NIST (2011). Because of the close match to the target spectrum, variability in the resulting structural responses is suppressed. This is a concern to some engineers, who feel it is important for designers to understand the record-to-record variability associated with response prediction in order to avoid a false sense of precision. Another concern with the approach is that researchers report mixed conclusions as to whether spectrally matched ground motions produce smaller average structural demands than comparable un-matched ground motions (e.g., Luco and Bazzurro 2007, NIST 2011, Grant and Diaferia 2012, Reyes et al. 2014). A final concern is that some of the acceptance criteria in Chapter 16 are easier to satisfy if spectrally matched motions are used (because of the suppressed response variability).

For these reasons, when spectral matching is used, the average of the spectra from all ground motion components in a given horizontal direction, are not allowed to be less than the target response spectrum. This is intentionally more stringent than the requirements for scaled (but unmatched) motions, to compensate for the potential un-conservatism in responses obtained from spectrally matched motions. Spectral matching is not allowed for near-fault sites, unless the pulse characteristics of the ground motions are retained after the matching process has been completed. The initial language on this topic in the NEHRP provisions (BSSC 2015) is currently being updated in the ASCE 7 requirements.

APPLICATION OF GROUND MOTIONS TO THE STRUCTURAL MODEL

ORIENTATION OF GROUND MOTIONS IN PLAN

The manner in which the two horizontal ground motion components are oriented can significantly affect the predicted results. In existing guidelines, there is little guidance on how this should be done and what guidance exists is inconsistent (see Table 2).

From the perspective of the structural engineer, this lack of guidance has left the orientation issue open to interpretation. Some engineers and authorities having jurisdiction have insisted on the importance of applying the suite of motions at multiple orientations so as to capture the "worst possible" responses; others have argued that the orientations in future earthquakes are unpredictable, so random orientation of motions is best suited for the purpose predicting mean responses.

Concerns about the applications of maximum direction spectra (Stewart et al. 2011) apply principally to structures analyzed using simplified procedures (i.e., Chapter 12 of ASCE/SEI 7) or with two-dimensional RHA methods. This section provides clearer guidance, describing how ground motions are applied in the Chapter 16 RHA procedure, for both far-field and near-fault sites.

Far-Field Sites

Because ASCE 7 uses the maximum direction spectral acceleration to describe the ground motion intensity (since ASCE 7-10), some care is required to ensure that motions are applied to the structure in a way that does not overestimate demands for a particular direction in the structure. The direction in which the maximum spectral acceleration occurs is random at distances beyond approximately 5km from the fault, is unlikely to align with a principal building response axis, and is variable from period to period. For the RHA procedure to result in an unbiased prediction of mean structural response, the orientation of the maximum component should be random, which can be approximately achieved by applying the as-recorded components with an arbitrary orientation angle for each ground motion. This approach is used in the updated Chapter 16 RHA procedure, following a prior consensus study of this issue (NIST 2011).

Near-Fault Sites

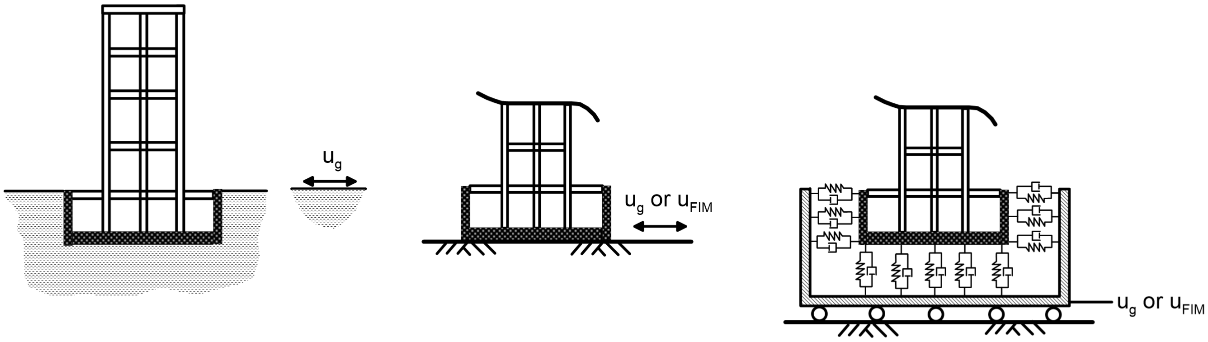
Near-fault sites tend to have larger response spectral ordinates in the fault-normal direction than in the fault-parallel direction, so the updated Chapter 16 RHA procedure requires that those components of the recorded ground motions be applied to the structure such that they correspond to azimuths normal and parallel to the strike of nearby faults that dominate the seismic hazard.

Recall that a site can be near-fault from the standpoint of having expected pulse-like ground motion characteristics (with site-to-source distances less than approximately 10-20km), but not near-fault in terms of polarization of ground motions (with site-to-source distances less than approximately 3-5km). The criteria of this section are only required for sites with the latter polarization characteristics. Even so, for reasons of practicality and simplicity, in the Chapter 16 RHA method, when a site is labeled as near-fault from either standpoint (pulses or polarization), it is allowable to apply the ground motions in the fault-normal and fault-parallel directions.

APPLICATION OF GROUND MOTIONS OVER SUBTERRANEAN LEVELS

The PEER (2010) TBI guidelines and NIST (2012) both recommend inclusion of subterranean levels in the mathematical model of a building. Ground motions can then be applied with two approximate methods having varying degrees of sophistication, depicted below in Figures 2b and 2c. For MCE_R-level assessment, both PEER and NIST describe a "rigid bathtub model" shown in Figure 2c, which includes soil springs and dashpots and identical horizontal ground motions input at each level of the basement. A simpler but less accurate model is to exclude the soil springs and dashpots from the numerical model and apply the horizontal ground motions at the bottom level of the basement (Figure 2b). A more rigorous approach is similar to the rigid bathtub model but involves vertically variable input motions applied to the ends of the foundation springs (details in NIST, 2012).

The Chapter 16 RHA procedures allow either of the approaches shown in Figures 2b and 2c, although the rigid bathtub approach is preferred for accuracy. Although not required, it is also permissible to use a more complete model of the soil-foundation system. The proposed RHA procedure also allows the option of modifying the input ground motions to account for kinematic interaction effects. More detailed guidance on soil-foundation-structure interaction, including both soil-foundation modeling guidelines and treatment of kinematic interaction effects, can be found in NIST (2012).



(a) Complete system

(b) Fixed-base model with subterranean levels

(c) Flexible-base model with far-field ends of soil elements attached to rigid bathtub with depth-invariant horizontal motion

Figure 2. Illustration of the method of inputting ground motions into the base of the structural model. Motion u_g is for free-field conditions; u_{FIM} is modified for kinematic interaction effects.

CONCLUSIONS AND LIMITATIONS

This paper is Part I of a four–part set describing the development of response history analysis procedures for the ASCE/SEI 7 Standard, as given in Chapter 16. Here we provide an overview of the procedures and differentiate them from those in previous guidelines documents and codes. We also describe the ground motion procedures and the rationale behind their development. These procedures have been published in the 2015 NEHRP Provisions (BSSC 2015) and has been adopted into the ASCE/SEI 7-16 Standard with modest modification.

We have taken care in our descriptions of the ground motion procedures to identify which elements of the procedure are supported by prior research and which are based on the committee's collective judgments reached after extensive deliberations. One important issue in the domain of judgment is the required number of ground motions (11), which was not studied in detail in this project. Future research may support changes in this number.

In the Method II scenario spectrum approach, multiple scenario spectra are required, with varying anchor periods, and the acceptance criteria must be passed for each scenario. NIST (2011) has confirmed the intuition that the choice of anchor period is important for assessments of the type considered under Chapter 16. The choice of anchor periods requires some engineering understanding of the specific building being analyzed, and so codified equations or rules for the choice of period in a given situation have not yet been specified. Additional research could better determine which anchor periods are appropriate (depending on building type and characteristics).

Finally, traditionally CMS/CS target spectra have been computed for geometric mean rather than maximum direction spectral accelerations, and have not needed to account for the risk adjustment factors required in Section 21.2.1.1 of ASCE7-10. A companion paper (Zimmerman et al. 2016) explains how these aspects can be accounted for through adjustments to CMS/CS target spectra, and it is proposed that in the future automated tools could be produced to perform these calculations and ease the development of target spectra. An alternative way to provide this consistency in type of spectral acceleration would be to re-define the MCE_R spectrum to be based on arbitrary-component ground motion or the geometric mean, as was done prior to 2010.

The minimum base shear requirements control the design of many tall buildings and, as explained in this paper, are partly based on historic precedent. Future research to further investigate minimum base shear requirements and how they relate to the collapse safety goals would be useful. Such a study would need to address the uncertainty associated with the engineering community's limited knowledge about ground motion acceleration and displacement demands for both long-period structures and large-magnitude earthquakes.

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