New Site-Specific Ground Motion Requirements of ASCE 7-16

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Abstract

This paper describes the seismic design criteria of ASCE 7-16 and specifically the new requirements for site-specific ground motions. Initially developed by the Provisions Update Committee of the Building Seismic Safety Council for the 2015 NEHRP Recommended Seismic Provisions, FEMA P-1050 (FEMA 2015), the new site-specific ground motion requirements address an identified short-coming with ELF (and MRSA) seismic design procedures related to the use of only two response periods, $T = 0.2$ s and $T = 1.0$ s, to define seismic design forces in the domains of constant acceleration and constant velocity, respectively.

Although approximate, the domains of constant acceleration and velocity provide a reasonably accurate and conservative representation of the frequency content of design ground motions when peak response spectral acceleration occurs at or near $T = 0.2$ s and peak response spectral velocity (i.e., peak response spectral acceleration divided by response period) occurs at or near $T = 1.0$ s. Such is the case for response at stiffer sites governed by smaller magnitude earthquakes, but generally inaccurate and un-conservative at softer sites (e.g., Site Classes D and E).

To ensure a conservative basis for ELF (and MRSA) design, the new site-specific ground motions requirements of ASCE 7-16 now require design ground motions to be based on a site-specific hazard analysis for most Site Class D and E sites. In lieu of performing a site-specific analysis, the new site-specific design requirements include exceptions that permit ELF (and MRSA) design using conservative values of seismic design parameters. Based on these exceptions and new site coefficients, the value of the seismic response coefficient ($C_s$) of ASCE 7-16 can be as much as 70 percent greater than that of ASCE 7-10 for mid-period buildings at Site Class D sites.

Overview of ASCE 7-16 Seismic Design Methods and Parameters

The American Society of Civil Engineers (ASCE), Standard, Minimum Design Loads for Buildings and Other Structures, ASCE 7-16, includes Chapter 11 which describes seismic design criteria, Chapter 12 which prescribes seismic design requirements for buildings, Chapter 21 which describes site-specific earthquake ground motion procedures and Chapter 22 which provides maps of risk-adjusted maximum considered earthquake (MCE$_R$) earthquake ground motion parameters ($S_s$ and $S_T$) and the long-period transition period parameter ($T_L$). Section 12.6 defines the applicability of permitted analytical procedures which include the equivalent lateral force (ELF) procedure of Section 12.8, the modal response spectrum analysis (MRSA) methods of Section 12.9 and the seismic response history procedures of Chapter 16.

Section 11.4.4 provides equations for determining values of the MCE$_R$ spectral response acceleration parameters at short periods ($S_{MS}$) and at 1.0 s ($S_{M1}$) adjusted for site class effects. Section 11.4.5 defines the design earthquake spectral acceleration parameter at short periods ($S_{DS}$) and at a period of 1.0 s ($S_{D1}$) as 2/3 of the parameters $S_{MS}$ and $S_{D1}$, respectively. Section 11.4.6 defines the frequency content of design ground motions using Figure 11.4-1 with domains of constant acceleration ($S_{DS}$), constant velocity ($S_{D1}/T$) and constant displacement ($S_{D1}T_L/T^2$), as shown in Figure 1. The parameters $S_{DS}$ and $S_{D1}$ are used in Section 12.8 to determine seismic base shear of the ELF design procedure and the design response spectrum of Figure 11.4-1 is used in Section 12.9 for MRSA.
The ELF procedure is permitted for design of all SDC B and C structures and for design of SDC D, E, F structures of regular configuration that are less than 160 feet in height, or which have a design period $T < 3.5 T_s$, or which are less than 160 feet and do not have severe irregularity (Table 12.6-1), where the transition period, $T_s$, is defined by the ratio of the design spectral acceleration parameters, $T_s = S_{D1}/S_{DS}$. MRSA is permitted for all structures, regardless of configuration or design period, using the design response spectrum shape of Figure 11.4-1, unless site-specific ground motion procedures are required to define response spectral accelerations (Section 11.4.8). The vast majority of all buildings are designed for seismic loads using either the ELF procedure or MRSA methods and the design spectrum of Figure 11.4-1.

New Ground Motion Maps of ASCE 7-16

Chapter 22 of ASCE 7-16 includes new MCE$_R$ ground motion maps developed by the Provisions Update Committee of the Building Seismic Safety Council for the 2015 NEHRP Recommended Seismic Provisions. (Luco et al., 2014). The new ground motion maps incorporate the 2014 update of the United States Geological Survey National Seismic Hazard Model (USGS NSHM) for the conterminous United States (Peterson et al., 2014). While the “science” has been updated, the hazard analysis methods used to develop the new MCE$_R$ ground motion maps of ASCE 7-16 are essentially the same as those used to develop the MCE$_R$ ground motion maps of ASCE 7-10 and follow the site-specific ground motion procedures of Section 21.2 of ASCE 7-16. The 2014 update of the USGS NSHM utilizes recent revisions to the models of earthquake sources and ground motion propagation; examples of which include Version 3 of the Uniform California Earthquake Rupture Forecast (UCERF3), Central and Eastern U.S. source characterization for nuclear facilities and the Next Generation Attenuation relations for the Western U.S. (NGA West2, Bozorgnia et al., 2014).

New Site Coefficients of ASCE 7-16

During the last Seismic Code development cycle, revised values of site coefficients ($F_a$ and $F_v$) were developed for the 2015 NEHRP Recommended Seismic Provisions and subsequently adopted with some reformatting by ASCE 7-16. In brief, the revised site factors, based on a research study of the NGA West2 Project (Seyhan and Stewart, 2014), relate site amplification at the period of interest to site shear wave velocity and hence site class. This new approach is possible, since the NGA West2 ground motions now include shear wave velocity terms; whereas, older versions of ground-motion relations did not.

Tables 1 and 2 show values of the site coefficients of ASCE 7-10 and changes to these values adopted by ASCE 7-16 and provide additional notes identifying site conditions requiring site-specific analysis as per Section 11.4.8 of ASCE7-16.

Table 1. Site coefficient, $F_a$ (Table 11.4-1, ASCE 7-10 showing ASCE 7-16 changes) and notes on the new site-specific analysis requirements

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$S_a &lt; 0.25$</th>
<th>$S_a &gt; 0.25$</th>
<th>$S_a = 0.25$</th>
<th>$S_a = 0.5$</th>
<th>$S_a = 1.0$</th>
<th>$S_a = 1.25$</th>
<th>$S_a = 1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
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<td>D</td>
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<td>1.4</td>
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<tr>
<td>E</td>
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<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Note - Use straight-line interpolation for intermediate values of $S_a$. At the Site Class BC boundary, $F_a = 1.0$ for all $S_a$ levels. If Site Class B or C is established without the use of on-site geological measurements of shear wave velocity, use $F_a = 1.0$.

Note - Site Class B is no longer the “reference” site class of MCE$_R$ ground motion parameters $S_a$ and $S_v$ (i.e., new coefficients reflect Site Class BC boundary of 2.500 ft/s) and Site Class D is no longer the “default” site class (when Site Class C amplification is greater, i.e., $S_v > 1.0$).

Table 2. Site coefficient, $F_v$ (Table 11.4-2, ASCE 7-10 showing ASCE 7-16 changes) and notes on the new site-specific analysis requirements

<table>
<thead>
<tr>
<th>Site Class</th>
<th>$S_v &lt; 0.1$</th>
<th>$S_v = 0.1$</th>
<th>$S_v = 0.2$</th>
<th>$S_v = 0.3$</th>
<th>$S_v = 0.4$</th>
<th>$S_v = 0.5$</th>
<th>$S_v = 0.6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
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<td>0.5</td>
</tr>
<tr>
<td>B</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>C</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>D</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>E</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

Note - Use straight-line interpolation for intermediate values of $S_v$. At the Site Class DE boundary, $F_v = 1.0$ for all $S_v$ levels. If Site Class B or C is established without the use of on-site geological measurements of shear wave velocity, use $F_v = 1.0$.

The Problem with ELF (and MRSA) Seismic Design Methods and Parameters

The value of parameter $S_{MS}$ is based on response at a period of 0.2 s and the value of the parameter $S_{M1}$ is based on response at a period of 1.0 s. The domain of constant acceleration defined by the parameter ($S_{MS}$) and the domain of constant velocity ($S_{M1}/T$) are crude approximations to the actual shape of response spectral accelerations of MCE$_R$ ground motions, such as those calculated using the site-specific ground motion procedures of Section 21.2 of ASCE 7-16 for a number of different periods of response (so-called multi-period MCE$_R$ response spectra).

Although approximate, the two domains of constant acceleration and velocity provide reasonably accurate and conservative representation of the frequency content of design ground motions when peak response spectral acceleration occurs at or near $T = 0.2$ s, the period used to define $S_{MS}$, and peak response spectral velocity (i.e., peak response spectral
acceleration divided by response period) occurs at or near $T = 1.0$ s, the period used to define $S_M$. Such is the case for response at stiffer sites governed by smaller magnitude earthquakes, but generally inaccurate and potentially unconservative at softer sites (e.g., Site Classes D and E), in particular, softer sites for which seismic hazard is dominated by large magnitude earthquakes. In the latter case, values of $S_M$ and $S_M^T$ would be more accurately calculated if based on response at periods that better represent peak response spectral acceleration and peak response spectral velocity and hence the frequency content, of MCE$_R$ ground motions.

The potential short-coming in seismic design criteria is illustrated in Figures 2, 3, 4 and 5 each of which show an example plot of a multi-period MCE$_R$ response spectrum for reference (Site Class BC) site conditions, the corresponding multi-period MCE$_R$ response spectrum and design response spectrum (i.e., two-thirds of the MCE$_R$ spectrum) for the site class of interest, and a two-domain “ELF” design spectrum.

In Figure 2, 3, 4 and 5 multi-period MCE$_R$ response spectra are calculated in accordance with the deterministic MCE$_R$ procedures of Section 21.2 of ASCE 7-16 for an assumed earthquake magnitude, fault distance and other source parameters. Median geomean multi-period response spectra are initially calculated using a NGA West2 ground motions spreadsheet (Seyhan, 2014) and then converted to 84$^{th}$ percentile maximum direction MCE$_R$ response spectra using the same methods and factors as those used by the USGS to develop deterministic MCE$_R$ ground motions of ASCE 7-16.

The ELF design spectrum is defined by the value of the ELF seismic response coefficient, $C_s$, factored by $R/I_s$. The ELF design spectrum is calculated using the methods of Section 11.4.4 for values of $S_1$ and $S_1$ extracted from the multi-period MCE$_R$ response spectrum (Site Class BC) at periods of 0.2 seconds and 1 second, respectively, and values of site coefficients of the site class of interest (i.e., Tables 1 and 2). For example, the domain of constant acceleration of the ELF design spectrum shown in Figure 3 (Site Class D conditions) is defined by the value of the parameter $S_{DS} = 2/3 \times 1.0 \times 1.5$ g = 1.0 g and the domain of constant velocity is defined by the value of the parameter $S_{DV} = 2/3 \times 1.7 \times 0.72$ g = 0.82 g.

In Figures 2, 3, 4 and 5, the ELF design spectra intentionally ignore the exceptions of the new site-specific requirements of Section 11.4.8 (e.g., the ELF design spectra do not include spectrum shape adjustment). In this sense, the ELF design spectra effectively show what the response spectral accelerations would have been if the new site-specific requirements had not been adopted. In each of these figures (red) shading is used to indicate the amount by which the multi-period design spectrum exceeds the ELF design spectrum quantifying the potential lack of conservatism of ELF design methods.

In Figures 2, 3 and 4, multi-period response spectra represent ground motions of a magnitude M8.0, earthquake at $R_s = 9.9$ km which has values of the parameters $S_2 = 1.5$ g and $S_1 = 0.72$ g for Site Class BC conditions ($V_{s,30} = 2,500$ fps). Comparison of peak acceleration response of MCE$_R$ response spectra in Figures 2, 3 and 4 shows the frequency content of the ground motions shifting to longer periods for softer site conditions.
In Figure 2 (Site Class C), peak acceleration response is at or near 0.2 seconds and peak velocity response is at or near 1 second and the ELF design spectrum conservatively envelops the multi-period design response spectrum.

In Figure 3 (Site Class D), peak acceleration response is at about 0.4 seconds and peak velocity response is at about 2 – 3 seconds and the shaded area indicates that the ELF design spectrum is generally un-conservative with respect to the multi-period design response spectrum (by about a factor of 1.5 at longer periods). The same trends are seen in Figure 4 for Site Class E site conditions, only more pronounced at longer periods (ELF design spectrum is un-conservative by about a factor of 2.0 at longer periods).

In Figure 5, multi-period spectra represent ground motions of a magnitude M7.0, earthquake at \( R_e = 6.8 \) km which has values of the parameters \( S_2 = 1.5 \) g and \( S_1 = 0.6 \) g for Site Class BC conditions \( (v_{s,30} = 2,500 \text{ fps}) \). Comparison of shaded areas in Figures 4 and 5 illustrates the influence of earthquake magnitude on the potential underestimation of ground motions (i.e., potential underestimation is less severe for M7.0 ground motions than M8.0 ground motions, all else equal).

**Interim Solution (of ASCE 7-16)**

Site-specific ground motions are now required for design of structures at softer soil sites and stronger ground motion intensities for which the two domains of constant acceleration and constant velocity (e.g., of the design response spectrum) do not adequately characterize site response and MCE\(_R\) response spectral acceleration cannot be reliably calculated using procedures and formulas of Section 11.4. Softer soil sites requiring site-specific ground motions were identified by a study that investigated and developed possible solutions to the short-comings in ELF (and MRSA) design procedures (Kircher, 2015). The impetus for the ELF Study came from an interest by the Provisions Update Committee of the Building Seismic Safety late in the 2015 Seismic Code development cycle to define seismic design forces at additional response periods beyond 1.0s; a first step toward ultimately basing seismic design forces on multi-period MCE\(_R\) response spectra.

Multi-period MCE\(_R\) response spectra would eliminate potential short-comings associated with the use of seismic forces based on only two response periods by directly providing reliable values of seismic demand at all design periods of interest. Unfortunately, multi-period hazard characterization and associated design methods were not mature enough for incorporation during the last Seismic Code development cycle. The new site-specific requirements of Section 11.4.8 provide an interim solution to a problem that will ultimately be resolved by adoption of design methods based on multi-period response spectra. In fact, based on the recommendations of Project 17 (Hamburger, 2017) the Provisions Update Committee of the Building Seismic Safety Council is working with the United States Geological Survey to incorporate multi-period design spectra in the 2020 NEHRP *Recommended Seismic Provisions* and presumably multi-period design spectra will also be adopted by ASCE 7-22.

The new site-specific requirements of Section 11.4.8 were adopted by the 2015 *NEHRP Recommended Seismic Provisions* and subsequently by ASCE 7-16 (with some modifications) in lieu of a more comprehensive approach to
add new “spectrum shape adjustment” factors, \( C_a \) and \( C_v \), to the equations of Section 11.4 that would have defined values of \( S_{MS} \) and \( S_{MI} \), as follows:

\[
S_{MS} = C_a F_a S_s \\
S_{MI} = C_v F_v S_I
\]

While addition of spectrum shape adjustment factors to Section 11.4 was not deemed to be the best interim solution, values of \( C_a \) and \( C_v \) developed by the ELF Study (Kircher, 2015) provided the technical basis for determining when site-specific procedures would be required, in lieu of the incorporation of spectrum shape adjustment factors in Eqs. (1) and (2), and for establishing conservative values of seismic design parameters that could be used for ELF (or MRSA) design in lieu of performing a site-specific analysis.

Values of the \( C_a \) and \( C_v \) factors were developed by the ELF Study for a variety of different site conditions and ground motion intensities. Values the \( C_a \) and \( C_v \) factors were based on the new requirements of Section 21.4 of ASCE 7-16 for determining values of \( S_{DS} \) and \( S_{DI} \) from a site-specific multi-period design response spectrum, as illustrated in Figure 6 for ground motions of a large magnitude (M7.5) earthquake at a soft soil site (Site Class DE boundary, \( \nu_{s,30} = 600 \) fps).

In general, the new requirements of Section 21.4 define \( S_{DS} \) (domain of constant acceleration) as 90 percent of the maximum spectral acceleration, \( S_a \), obtained from the site-specific spectrum over the period range 0.2 to 5 s, and define \( S_{DI} \) (domain of constant velocity) as 100 percent of the maximum value of product of \( T S_a \) over the period range 1 to 2 s (\( \nu_{s,30} > 1,200 \) fps) or over the period range 1 to 5 s (\( \nu_{s,30} \leq 1,200 \) fps). The new requirements of Section 21.4 of ASCE 7-16 obtain a better fit of the design spectrum (Figure 11.4-1), defined by \( S_{DS} \) and \( S_{DI} \), to the corresponding multi-period site-specific design response spectrum, than those of ASCE 7-10.

Values of the spectrum shape factor \( C_a \) significantly greater than 0.9 and values of the spectrum shape factor \( C_v \) significantly greater than 1.0 were used to identify those site classes and ground motion intensities for which ground motions are not well represented by the two domains of constant acceleration and velocity and site-specific analysis should be used for design. For example, values of \( C_a = 2.2 \) and \( C_v = 1.8 \), shown in Figure 6, indicate that site-specific analysis should be used to properly quantify ground motions for design of all (short-period and long-period) buildings located at a soft-soil site (\( \nu_{s,30} = 600 \) fps) for which site seismic hazard is governed by a large magnitude (M7.5) earthquake.

**New Site-Specific Requirements of ASCE 7-16**

The new requirements of Section 11.4.8 require site-specific hazard analysis of Chapter 21 to be used for design of:

1. Structures on Site Class E with values of \( S_{DS} \) greater than or equal to 1.0 g, and

2. Structures on Site Class D or Site Class E for values of \( S_{DI} \) greater than or equal to 0.2 g.

The new site-specific requirements could significantly impact the use of practical ELF (and MRSA) design methods, of particular importance for design of buildings at Site Class D sites which are quite common. To minimize the impact of proposed changes on design practice, the new requirements include three exceptions permitting the use of conservative values of seismic design parameters in lieu of performing a site-specific ground motion analysis. The three exceptions permitting ELF (or MRSA) design without performing a site-specific ground motion analysis are given below for:

1. Structures on Site Class E sites with \( S_{DS} \) greater than or equal to 1.0, provided the site coefficient \( F_a \) is taken as equal to that of Site Class C.

2. Structures on Site Class D sites with \( S_{DI} \) greater than or equal to 0.2, provided the value of the seismic response coefficient \( C_v \) is determined by Eq. (12.8-2) for values of \( T \leq 1.5T_i \), and taken as equal to 1.5 times the value computed in accordance with either Eq. (12.8-3) for \( T_i > 1.5T_i \) or Eq. (12.8-4) for \( T_i > T \). 

3. Structures on Site Class E sites with \( S_{DI} \) greater than or equal to 0.2, provided that \( T \) is less than or equal to \( T_i \) and the equivalent static force procedure is used for design.
The first exception permits use of the value of the site coefficient $F_u$ of Site Class C ($F_u = 1.2$) for Site Class E sites (for values of $S_2$ greater than or equal to 1.0 g) in lieu of site-specific hazard analysis. The ELF study found that while values of the site coefficient $F_u$ tend to decrease with intensity for softer sites, values of spectrum shape adjustment factor $C_s$ tend to increase such that the net effect is approximately the same amplitude of MCE 12.8-2 for $S_2 \geq 0.2$ g, provided that the value of the seismic response coefficient $C_s$ tends to decrease with intensity. This exception recognizes that short-period structures are conservatively designed using the ELF procedure for values of seismic response coefficient $C_s$ based on the domain of constant acceleration ($S_{20}$) which is, in all cases, greater than or equal to response spectral accelerations of the domain of constant velocity. In general, the shape of the design response spectrum (Figure 11.4-1) is not representative of the frequency content of Site Class E ground motions and MRSA is not permitted for design unless the design spectrum is calculated using the site-specific procedures if Section 12.9.4.

The second exception permits both ELF (and MRSA) design of structures at Site Class D sites for values of $S_2$ greater than or equal to 0.2 g, provided that the value of the seismic response coefficient $C_s$ is conservatively calculated using Eq. 12.8-2 for $T \leq 1.5T_s$ and using 1.5 times the value computed in accordance with either Eq. 12.8-3 for $T_L > T > 1.5T_s$ or Eq. 12.8-4 for $T > T_L$. This exception recognizes that structures are conservatively designed for the response spectral acceleration defined by the domain of constant acceleration ($S_{02}$) or by a 50 percent increase in the value of seismic response coefficient $C_s$ for structures with longer periods ($T > 1.5T_s$). The underlying presumption of this exception for MRSA design of structures is that the shape of the design response spectrum (Figure 11.4-1) is sufficiently representative of the frequency content of Site Class D ground motions to permit use of MRSA methods and that the potential underestimate of fundamental-mode response using the design response spectrum shape of Figure 11.4-1 is accounted for by scaling MRSA design values (Section 12.9.4) with a conservative value of the seismic response coefficient $C_s$.

The third exception permits ELF design of short-period structures ($T \geq T_s$) at Site Class E sites for values of $S_2$ greater than or equal to 0.2 g. This exception recognizes that short-period structures are conservatively designed using the ELF procedure for values of seismic response coefficient $C_s$ based on the domain of constant acceleration ($S_{20}$) which is, in all cases, greater than or equal to response spectral accelerations of the domain of constant velocity. In general, the shape of the design response spectrum (Figure 11.4-1) is not representative of the frequency content of Site Class E ground motions and MRSA is not permitted for design unless the design spectrum is calculated using the site-specific procedures if Section 21.2.

The three exceptions effectively limit mandatory site-specific analysis to taller buildings (i.e., buildings with a design period, $T \geq T_s$ located at Site Class E sites). Table 3 provides example heights of eight common seismic force resisting systems for which site-specific analysis is mandatory. In Table 3, values of $\bar{h}_{max}$, are based on the height limits of Table 12.2-1 for Seismic Design Category (SDC) D structures. In all cases, buildings located at Site Class E sites with $S_i \geq 0.2$ or $S_i \geq 1.0$ (i.e., buildings requiring site-specific analysis) should be assigned to SDC D (or SDC E, if $S_i \geq 0.75$). Although Tables 11.4-1 and 11.4-2 of ASCE 7-16 do not provide all values of Site Class E site coefficients required to determine design parameters $S_{20}$ and $S_{D3}$, SDC D may be inferred from Table 11.6-1 since the value of $S_{20}$ will, in all cases, be greater than or equal to 1.0. Similarly, SDC D may be inferred from Table 11.6-2 since the value of $S_{D3}$ will be greater than 0.2 for $S_i \geq 0.2$ because Site Class E amplification is at least 1.5 (see Table 11.4-2 of the 2015 NEHRP Provisions).

Table 3. Example building heights of eight common seismic force resisting systems for which site-specific analysis is mandatory (Site Class E sites)

<table>
<thead>
<tr>
<th>Seismic Force Resisting System (Table 12.2-1, ASCE 7-16)</th>
<th>Site-Specific Analysis Mandatory for Building Height, $h$ (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFRS Material System Detailing</td>
<td>$h_{max}$ (ft)</td>
</tr>
<tr>
<td>A.15 Wood SW Light Frame</td>
<td>$h &gt; 107$</td>
</tr>
<tr>
<td>B.2 Steel CBF Special</td>
<td>$h &gt; 160$</td>
</tr>
<tr>
<td>B.3 Steel CBF Ordinary</td>
<td>$h &gt; 107$</td>
</tr>
<tr>
<td>B.4 Concrete SW Special</td>
<td>$h &gt; 160$</td>
</tr>
<tr>
<td>B.25 Concrete BF BRBF</td>
<td>$h &gt; 160$</td>
</tr>
<tr>
<td>C.1 Steel MF Special</td>
<td>$h &gt; 107$</td>
</tr>
<tr>
<td>C.3 Steel MF Intermediate</td>
<td>$h &gt; 107$</td>
</tr>
<tr>
<td>C.5 Concrete MF Special</td>
<td>$h &gt; 107$</td>
</tr>
</tbody>
</table>

The example building heights shown in Table 3 (based on $T = T_s$) are derived from the fundamental period formula, Eq. (12.8-7), for two values of the transition period, $T_s = 0.67$ s and $T_s = 0.86$ s. The value of the transition period, $T_s = 0.67$ s, is calculated, $T_s = F_s S_3 / F_s S_2 = 2.0(0.6)/1.2(1.5) = 0.67$ s and the value of the transition period, $T_s = 0.86$ s, is calculated, $T_s = F_s S_3 / F_s S_2 = 2.8(0.3)/1.3(0.75) = 0.86$ s. In these calculations, the value of the site coefficient, $F_u = 1.2 (S_i \geq 0.6)$, missing from Table 11.4-1 of ASCE 7-16 for Site Class E is conservatively based on the Site Class C value of that table in accordance with the first exception of Section 11.4.8; and values of the site coefficient, $F_i = 2.0 (S_i \geq 0.6)$ and $F_i = 2.8 (S_1 = 0.3)$, missing from Table 11.4-2 of ASCE 7-16, are taken from Table 11.4-2 of the 2015 NEHRP Recommended Seismic Provisions.

The example building heights shown in Table 3 are based on conservative assumptions of the values of $T_s$. A more liberal interpretation of the third exception permitting ELF design in lieu of site-specific analysis for Site Class E sites could be to design the structure for short-period design seismic forces, i.e., $C_s$ defined by Eq. (12.8-2), implicitly assuming that $T < T_s$. In this case, site-specific analysis would not be mandatory, unless the building height exceeded that permitted for ELF design by Table 12.6-1 (e.g., 160 feet).
Example Values of the Seismic Response Coefficient (C_s)

Figures 7 through 14 provide plots of example values of the seismic response coefficient, C_s, as a function of the design period, T_s, for a Risk Category II building with a steel special moment frame system (i.e., RIl = 8). In each figure, values of the C_s coefficient are shown for ASCE 7-10, ASCE 7-16 and ELF Study criteria, as described below.

ASCE 7-10 – Values of the C_s coefficient are based on the ELF design procedures of ASCE 7-10.

ASCE 7-16 – Values of the C_s coefficient are based on the ELF design procedures of ASCE 7-16 including the new site coefficients of ASCE 7-16 and, the exceptions of the new site-specific requirements of Section 11.4.8 that permit design using conservative values of C_s, in lieu of performing a site-specific analysis.

ELF Study – Values of the C_s coefficient are based on the site amplification and spectrum shape adjustment factors developed by the ELF Study (Kircher, 2015) that represent the “best fit” of C_s coefficients to the underlying multi-period response spectra (i.e., deterministic MCE_a response spectra based on the NGA West2 ground motions, Seyhan 2014).

The plots of the seismic response coefficient, C_s, are characterized by three distinct period domains: (1) short-period domain of constant acceleration, defined by SMD/8, (2) mid-period domain of constant velocity, defined by SDV/8 and a domain of constant acceleration at longer periods defined by the minimum C_s criteria of Eq. (12.8-5) and Eq. (12.8-6) of ASCE 7-16. In each figure, values of the C_s coefficient are identified for a 4-story (45-foot tall) and a 15-story (160-foot tall) special steel moment frame buildings with approximate periods of 0.59 s and 1.62 s, respectively. The 4-story building with a period of 0.59 s represents the near tallest steel moment frame building permitted for ELF design at a Site Class E site without mandatory site-specific analysis (based on the conservative values of building height given in Table 3). The 160-foot building represents the tallest building permitted for ELF design.

In each figure, (red) shading highlights the difference between values of the C_s coefficient of the ELF Study and those of ASCE 7-10, illustrating the degree of “conservatism,” or lack thereof, in the seismic design criteria of ASCE 7-10 and multi-period response spectra based on NGA West2 ground motions. In concept, values of the C_s coefficient of ASCE 7-16 should be the same, or similar, to those shown for the ELF Study. In some cases, however, significant differences may be seen in the figures due to (1) inherent differences in the values of site coefficients of ASCE 7-16 and corresponding site amplification of the NGA West2 ground motions, and (2) the simplifying assumptions made during the development of the exceptions of Section 11.4.8.

Each figure shows the plots of the C_s coefficient for a given site class (i.e., Site Class B, C, D or E) and one of two MCE_a ground motion amplitudes (i.e., S_s = 1.5 and S_s = 0.6 or S_s = 0.5 and S_s = 0.2). The two MCE_a ground motion amplitudes bound the range of ground motions for which site-specific analysis is required for Site Class D and E sites. Plots of C_s shown for Site Class B and C sites reflects differences in the seismic response coefficient due to site effects only; whereas plots of C_s shown for Site Class D and E sites also include the effects of the spectrum shape adjustment, in accordance with the exceptions of Section 11.4.8.

![Figure 7. Example values of the seismic response coefficient, C_s, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class B, S_s = 0.5, S_s = 0.2](image1)

![Figure 8. Example values of the seismic response coefficient, C_s, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class B, S_s = 1.5, S_s = 0.6](image2)
Figure 9. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class C, $S_s = 0.5$, $S_i = 0.2$

Figure 10. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class C, $S_s = 1.5$, $S_i = 0.6$

Figure 11. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class D, $S_s = 0.5$, $S_i = 0.2$

Figure 12. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class D, $S_s = 1.5$, $S_i = 0.6$

Figure 13. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class E, $S_s = 0.5$, $S_i = 0.2$

Figure 14. Example values of the seismic response coefficient, $C_s$, of ASCE 7-10, ASCE 7-16 and the ELF Study for 4-story and 16-story steel special moment frame buildings - Site Class E, $S_s = 1.5$, $S_i = 0.6$
Plots of the seismic response coefficient, $C_r$, are shown in Figures 7 and 8 for Site Class B ($v_{s,30} = 3,500$ fps) site conditions. Values of the $C_r$ coefficient of ASCE 7-16 are less than those of ASCE 7-10 due to changes in the site coefficients of this site class (see Tables 1 and 2). The site coefficients of ASCE 7-10 are in all cases 1.0, based on the assumption of Site Class B as the reference site class. The new coefficients of ASCE 7-16 are now less than 1.0 (i.e., $F_a = 0.9$ and $F_s = 0.8$) as a results of the redefining of the reference site class as the Site Class BC boundary.

Plots of the seismic response coefficient, $C_r$, are shown in Figures 9 and 10 for Site Class C ($v_{s,30} = 1,750$ fps) site conditions. Values of the $C_r$ coefficient of ASCE 7-16 are greater than those of ASCE 7-10 due to changes in the site coefficients of this site class (see Tables 1 and 2). For example, at $S_3 = 1.25$, the value of $F_a = 1.0$ of ASCE 7-10 is now the value of $F_a = 1.2$ of ASCE 7-16 and at $S_3 = 0.5$, the value of $F_s = 1.3$ of ASCE 7-10 is now the value of $F_s = 1.5$ of ASCE 7-16. Ironically, the ELF Study suggests that the site coefficients of ASCE 7-10 better represent site amplification for Site Class C sites than the new values of ASCE 7-16.

Plots of the seismic response coefficient, $C_r$, are shown in Figures 11 and 12 for Site Class D ($v_{s,30} = 850$ fps) site conditions. Values of the $C_r$ coefficient of ASCE 7-16 are the same as those of ASCE 7-10 at short periods (e.g., $T < 0.6$ s) and at longer periods governed by the minimum $C_S$ criteria (e.g., $T > 2.5$ s), but substantially greater than, by as much as 70 percent, those of ASCE 7-10 at mid-periods. For example, in Figure 12, at the design period, $T_o = 1.62$ s, the ASCE 7-10 value of seismic response coefficient is calculated, $C_r = 2/3 F_s S_3/(8 T_o) = 2/3(1.5)(0.6)/(8 x 1.62) = 0.046$ and the ASCE 7-16 value of the seismic response coefficient is calculated, $C_r = 1.5 x 2/3 F_s S_3/(8 T_o) = 1.5 x 2/3(1.7)(0.6)/(8 x 1.62) = 0.079$. The 70 percent increase in the seismic response coefficient of ASCE 7-16 for this Site Class D site is due to an increase in the site coefficient from $F_s = 1.5$ (ASCE 7-10) to $F_s = 1.7$ (ASCE 7-16) plus the additional 1.5 increase in the seismic response coefficient required by Exception 2 of Section 11.4.8 of ASCE 7-16. As shown in Figure 11, the ELF study supports the 50 percent increase in the seismic response coefficient for Site Class D sites with moderate MCEg ground motions (i.e., $S_i = 0.2$), but, as shown in Figure 12, the ELF Study suggests that an even larger increase could be used to better represent ground motions at Site Class D sites with strong MCEg ground motions ($S_i = 0.60$).

Plots of the seismic response coefficient, $C_r$, are shown in Figures 13 and 14 for Site Class E ($v_{s,30} = 500$ fps) site conditions. Values of the $C_r$ coefficient of ASCE 7-16 are only shown for the short-period domain of constant acceleration since site-specific analysis is required for design of buildings with longer periods. As shown in Figure 13, seismic response coefficient values of ASCE 7-16 are approximately the same as those of ASCE 7-10 for Site Class E sites with moderate MCEg ground motions (i.e., $S_i = 0.2$), but, as shown in Figure 14, substantially greater than those of ASCE 7-10 for Site Class E sites with strong MCEg ground motions ($S_i = 0.60$). In the latter case, substitution of values of Site Class C site coefficients for undefined values of Site Class E site coefficients, in accordance with Exception 3 of Section 11.4.8, affects a conservative value of the seismic response coefficient. As the ELF Study suggests, however, the actual degree of conservatism is modest and design using the ELF procedure with a conservative value of $C_r$ based on Exception 3 of Section 11.4.8 will likely be preferred to performing a sitespecific analysis for most short-period buildings.

**Changes to the Site-Specific Analysis Methods of Chapter 21**

The new site-specific analysis requirements of Section 11.4.8 necessitated changes to the following site-specific analysis methods of three sections of Chapter 21:

1. Section 21.2.2 requirements defining the deterministic lower limit on the MCEg response spectrum,
2. Section 21.3 requirements establishing the 80 percent lower-bound limit on site-specific design spectrum, and
3. Section 21.4 requirements for determining values of $S_{DS}$ and $S_{DI}$ from a site-specific design spectrum.

As previously discussed (and illustrated in Figure 6), changes to Section 21.4 were made to obtain a better fit of the design spectrum (i.e., Figure 11.4-1), defined by $S_{DS}$ and $S_{DI}$, to the corresponding multi-period site-specific design spectrum. Changes to Section 21.4 were initially developed and adopted by the 2015 NEHRP Recommended Seismic Provisions, in parallel with the development and adoption of the new site-specific requirements of Section 11.4.8.

Section 21.2.2 requirements which define the deterministic lower limit on the MCEg response spectrum (Figure 21.2.-1) and Section 21.3 requirements which establish the 80 percent (lower-bound) limit on the site-specific design response spectrum are dependent on values of site coefficient that are neither defined in the site coefficient tables (i.e., Tables 11.4-1 and 11.4-2) nor values of site coefficients given in these tables are not valid (e.g., when site-specific analysis is required by Section 11.4.8). To remedy this short-coming, Sections 21.2.2 and 21.3 now provide values of "pseudo" site coefficients for establishing the deterministic lower limit on the MCEg response spectrum and the 80 percent limit on the site-specific design response spectrum. Changes to Sections 21.2.2 and 21.3 were developed for ASCE 7-16 after finalization of the 2015 NEHRP Recommended Seismic Provisions and hence are not part of the Provisions.
The “pseudo” site coefficients of Sections 21.2.2 and 21.3 are based on the ELF Study and effectively incorporate both site amplification and spectrum shape adjustment when spectrum shape effects are significant (i.e., when site-specific analysis is required). In this sense, “pseudo” site coefficients of Sections 21.2.2 and 21.3 represent the product of the spectrum shape adjustment and pure site amplification, $C_a F_a$ (Eq. 1) or $C_v F_v$ (Eq. 2). For example, Section 21.3 now requires that site-specific design spectrum to be not less than 80 percent of $S_a$ determined in accordance with Section 11.4.6 (Figure 11.4-1) using values of $F_a$ and $F_v$, defined as follows:

(i) Site Class A, B, and C: $F_a$ and $F_v$ are determined using Tables 11.4-1 and 11.4-2, respectively;

(ii) Site Class D: $F_a$ is determined using Table 11.4-1, and $F_v$ is taken as 2.4 for $S_t < 0.2$ or 2.5 for $S_t \geq 0.2$; and

(iii) Site Class E: $F_a$ is determined using Table 11.4-1 for $S_t < 1.0$ or taken as 1.0 for $S_t \geq 1.0$, and $F_v$ is taken as 4.2 for $S_t < 0.1$ or 4.0 for $S_t > 0.1$.

In the requirements of Section 21.3, shown above, the “pseudo” site coefficient value of $F_v = 2.5$ for Site Class D represents approximately the product of 1.5 (spectrum shape adjustment) times 1.7 (site amplification) and the “pseudo” site coefficient value of $F_v = 4.0$ for Site Class E represents approximately the product of 2.0 (spectrum shape adjustment) times 2.0 (site amplification) for sites with strong MCEg ground motions ($S_t = 0.6$). While both site amplification and spectrum shape adjustment are ground motion amplitude dependent, the product of their effects is approximately constant and, for simplicity, Section 21.3 defines a single value for all applicable ground motion amplitudes.

**Summary and Conclusion**

The seismic design criteria of ASCE 7-16 and specifically the new requirements for site-specific ground motions are described in this paper. Initially developed by the Provisions Update Committee of the Building Seismic Safety Council for the 2015 *NEHRP Recommended Seismic Provisions*, the new site-specific ground motion requirements address an identified short-coming with ELF and seismic design procedures related to the use of only two response periods, $T = 0.2$ s and $T = 1.0$ s, to define seismic design forces in the domains of constant acceleration and constant velocity, respectively.

As an interim solution, ASCE 7-16 requires site-specific ground motions for design of structures at softer soil sites and stronger ground motion amplitudes for which the two domains of constant acceleration and constant velocity of the design response spectrum do not adequately characterize site response and MCEg response spectral acceleration cannot be reliably calculated using procedures and formulas of Section 11.4. In lieu of performing a site-specific analysis, the new site-specific design requirements include exceptions that permit ELF (and MRSA) design using conservative values of seismic design parameters. Based on these exceptions and new site coefficients, the value of the seismic response coefficient ($C_t$) of ASCE 7-16 can be as much as 70 percent greater than that of ASCE 7-10 for mid-period buildings at Site Class D sites.

It is envisioned that ASCE 7-22 will incorporate MCEg ground motions defined by multi-period response spectra. Multi-period response spectra would eliminate potential short-comings associated with the use of seismic forces based on only two response periods by directly providing reliable values of seismic demand at all design periods of interest.

**References**


