Seismic Design

Historically, the seismic design of mechanical equipment was primarily focused on the equipment supports, and the attachments. The intent of the seismic design provisions in building codes was to reduce the hazard to life by sliding, tipping, or falling equipment during an earthquake.

Today, mechanical systems often serve vital functions in critical building facilities such as hospitals, communication centers, and emergency response centers, etc. The mechanical systems serving these types of facilities must be operational after an event, as non-functioning equipment could constitute a hazard to life. Therefore, the seismic design for this higher level of earthquake safety must assure functionality as well as position retention.

As a result, the 2015 International Building Code® (IBC) incorporates both functionality and position retention within the structural design requirements which also remains in the 2021 International Building Code.

Factory assembled cooling towers are considered nonstructural components that are permanently attached to building structures for their support and attachment. Therefore, the cooling tower structural design falls within the scope of building codes. This section will discuss the basis of seismic design requirements, define the seismic variables, discuss the seismic qualification methods, and provide an example with a suggested specification.

Basis of Seismic Design Requirements

The International Building Code® (IBC) is a model code developed by the International Code Council® (ICC) and available for adoption by jurisdictions internationally. The IBC was first issued in 2000 and is updated triennially. The latest edition is 2021.

Up to eight editions of the IBC have been adopted and are effective at the local or state level in all 50 states and the District of Columbia. Once adopted, the IBC provisions become enforceable regulations governing the design of buildings and structures.

The IBC defines design requirements for buildings, structures, and parts thereof. Contained within the structural design provisions of the IBC are requirements for cooling towers that may be subjected to various types of environmental factors, such as wind loads and seismic loads. The 2021 IBC refers extensively to and incorporates many provisions of ASCE/SEI 7-16, the consensus standard published by the American Society of Civil Engineers (ASCE).

Seismic Design Requirements for Factory-Assembled Cooling Towers

As noted above, factory assembled cooling towers typically are permanently attached to buildings. This means cooling towers are subject to the seismic design requirements for “nonstructural components,” which are defined as elements of mechanical, electrical, or architectural systems within buildings.

Several key variables must be looked at to determine the seismic design requirements for cooling towers. These variables are unique for a given project and independent of the cooling tower type. Per the IBC, the variables should be provided in the project structural documents and filtered into the cooling tower specification by the engineer of record.

Determining if a Seismic Resistant Cooling Tower is Required

The following 7 step procedure can be used to determine seismic design requirements for a building (therefore the cooling tower), select the appropriate cooling tower, and provide a suggested specification.

As the paper outlines the procedure, the sidebar follows the procedure for a specific application and provides a sample specification for the cooling tower.

Example:
The example throughout this document illustrates the process to determine whether a seismic resistant cooling tower is required for an application and how to select the tower.

A 400 ton cooling tower is required for a 5-story hospital with emergency treatment facilities located in Glenrock, Wyoming (zip code 82637). The cooling tower will be installed on the roof of the 5-story hospital. Determine the seismic requirements that must be included in the cooling tower specification for this project.

Step 1: Determine the Risk Category of the Facility
From **Table 1604.5** on the following page: Risk Category of Buildings and Other Structures, a hospital with emergency treatment services is Risk Category IV.

NOTES:

1. Steps 1 through 4 are shown to illustrate the use of seismic design provisions contained in the IBC. In application, the seismic design criteria including the Risk Category, Importance Factor, SDS, SD1, and Seismic Design Category should be provided by the Engineer of Record.
2. The figures, tables and sections referred in the analysis can be found in the 2021 IBC.

Step 1: Determine the Risk Category of the Building

Risk Category is a classification ranging from I to IV for buildings and other structures based on the level of risk and the nature of use. Category I buildings represent a low hazard to life in the event of failure while Category IV buildings are considered essential facilities.

Important Note: Risk category classifications are not consistent in the five editions of the IBC, and thus may vary from jurisdiction to jurisdiction depending on the edition adopted. It is important that design professionals include the edition of the IBC in project specifications.

The 2021 edition of the IBC defines the Risk Category in **Table 1604.5** which has been reproduced on the following page.

Step 2: Determine the Importance Factor of the Building

All cooling towers are assigned a component importance factor, I_p, equal to 1.0 or 1.5. Towers that are needed for continued operation of an essential facility (a building with a Risk Category IV) or are required to function after an earthquake are assigned an importance factor of 1.5. All other towers receive a factor of 1.0.

Towers with an importance factor of 1.5 are further classified as “designated seismic system” components and may require certification that the unit will fully function following a seismic event.

Table 1604.5 Risk Category of Buildings and Other Structures

Risk Category	Nature of Occupancy
I	Buildings and other structures that represent a low hazard to human life in the event of failure, including but not limited to: • Agricultural facilities • Certain temporary facilities • Minor Storage facilities
II	Buildings and other structures except those listed in Risk Categories I, III or IV
III	Buildings and other structures that represent a substantial hazard to human life in the event of failure, including but not limited to: • Building and other structures whose primary occupancy is public assembly with an occupant load greater than 300. • Buildings and other structures containing one or more public assembly spaces, each having occupant load greater than 300 and a cumulative occupant load of these public assembly spaces of greater than 2500. • Buildings and other structures containing Group E or Group I-4 occupancies or combination thereof, with an occupant load greater than 250. • Building and other structures containing educational occupancies for students above the 12th grade with an occupant load greater than 500. • Group I-2. Condition 1 occupancies with 50 or more care recipients. • Group I-2. Condition 2 occupancies not having emergency surgery or emergency treatment facilities. • Group I-3 occupancies. • Any other occupancy with an occupant load greater than 5000[a]. • Power-generating stations, water treatment facilities for potable water, waste water treatment facilities and other public utility facilities not included in Risk Category IV. • Buildings and other structures not included in Risk Category IV containing quantities of toxic or explosive materials that: • Exceed maximum allowable quantities per control area as given in Table 307.1 (1) or 307.1(2) or per outdoor control area in accordance with the International Fire Code, and are sufficient to pose a threat to the public if released[b].
IV	Buildings and other structures designated as essential facilities, including but not limited to: • Group I-2, Condition 2 occupancies having emergency surgery or emergency treatment facilities. • Ambulatory care facilities having emergency surgery or emergency treatment facilities. • Fire, rescue, ambulance and police stations and emergency vehicle garages. • Designated earthquake, hurricane or other emergency shelters. • Designated emergency preparedness, communications and operations centers and other facilities required for emergency response. • Power-generating stations and other public utility facilities required as emergency backup facilities for Risk Category IV structures. • Buildings and other structures containing quantities of highly toxic materials that: • Exceed maximum allowable quantities per control area as given in Table 307.1(2) or per outdoor control area in accordance with the International Fire Code, and are sufficient to pose a threat to the public if released[b]. • Aviation control towers, air traffic control centers and emergency aircraft hangers. • Buildings and other structures having critical national defense functions. • Water storage facilities and pump structures required to maintain water pressure for fire suppression.

NOTE:

a. For purposes of occupant load calculation, occupancies required by Table 1004.5 to use gross floor area calculations shall be permitted to use net floor areas to determine the total occupant load.

b. Where approved by the building official, the classification of buildings and other structures as Rick Category III or IV based on their quantities of toxic, highly toxic or explosive materials is permitted to be reduced to Category II, provided it can be demonstrated by a hazard assessment in accordance with Section 1.5.3 of ASCE 7 that a release of the toxic, highly toxic or explosive materials is not sufficient to pose a threat to the public.

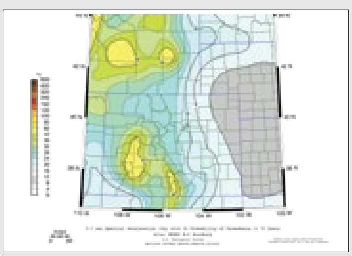
Step 3: Determine the Seismic Design Category

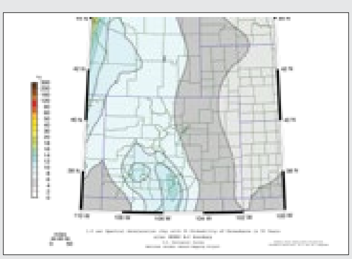
The Seismic Design Category (S_{DC}) is a structure classification ranging from A to F that is based on the following factors:

- Risk Category
- Design Spectral Accelerations (S_{DS} & S_{D1}) – Defined below. The most severe of the S_{DS} and the S_{D1} is used to determine the S_{DC}.

Step 2: Determine the Component Importance Factor Required
Since the building is an essential facility (Risk Category IV) and the cooling towers are required to function after an earthquake, the importance factor is equal to 1.5.

Step 3a: Calculate the S_{DS} and S_{D1}
To determine the Design Spectral Accelerations, the Spectral Acceleration for short period and 1-second period (S_S and S_1), Site coefficient for short period and 1-second period (F_a and F_v) are required. Below are examples of the short period and 1 second period hazard maps provided by the USGS.





These values can also be found using the web tool at the following website:
https://asce7hazardtool.online

Step 3a: Calculate the S_{DS} and S_{D1}

The design spectral accelerations (at short periods, S_{DS}, and at 1-second period, S_{D1}) are dependent on site class (defined below) and maximum ground shaking intensity (defined below) at a given location.

Site Class is based on the site soil properties, which can range from Hard Rock (Site Class A) to Peat and Clays (Site Class F). To determine site class, refer to Chapter 20 of the ASCE/SEI 7-16. The 2021 IBC states: “Where the soil properties are not known in sufficient detail to determine the site class, Site Class D (subject to the requirements of section 1613.2.3) shall be used unless the building official or geotechnical data determines that Site Class E or F soil is likely to be present at the site.”

Ground Shaking Intensity can be obtained from probabilistic seismic hazard maps provided in the IBC. However, due to the fine gradation of acceleration values in some regions, such as the West Coast of the United States, it is more expedient and accurate to use the ASCE 7 Hazard Tool at **https://asce7hazardtool.online**.

Input values for the ASCE Hazard Tool are map coordinates for the project site.

To calculate the Design Spectral Accelerations, the following equations are used:

Design Spectral Acceleration - At short periods (0.2 second)

The design spectral acceleration, S_{DS}, is determined using the following equations:

$$S_{DS} = 2/3 * S_{MS}$$

Where SMS is the maximum considered earthquake spectral response acceleration for short period as determined in the following equation:

$$S_{MS} = F_a * S_S$$

Combining both equations results in:

$$S_{DS} = 2/3*F_a*S_S$$

Where:

S_S is the mapped spectral accelerations for short periods as determined in Section 1613.2.1 of the Code or using the ASCE 7 Hazard Tool.

F_a is the site coefficient defined in Table 1613.2.3(1) of the 2021 IBC which is reproduced below. Reference Table 1613.2.3(1) from the 2021 IBC is reproduced on the next page.

Table 1613.2.3(1). Values of Site Coefficient F_a [a]

Site Class	Mapped Spectral Response Acceleration at Short Period					
	$S_S \geq 0.25$	$S_S = 0.50$	$S_S = 0.75$	$S_S = 1.00$	$S_S = 1.25$	$S_S >= 1.5$
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.9	0.9	0.9	0.9	0.9	0.9
C	1.3	1.3	1.2	1.2	1.2	1.2
D	1.6	1.4	1.2	1.1	1.0	1.0
E	2.4	1.7	1.3	Note b	Note b	Note b
F	Note b	Note b	Note b	Note b	Note b	Note b

NOTES:

a. Use straight-line interpolation for intermediate values of mapped spectral response acceleration for short period, S_S.

b. Values shall be determined in accordance with Section 11.4.7 of ASCE 7.

Go to https://asce7hazardtool.online to use the web tool:

- Under Design Code Reference Document, select 2012 IBC.
- Select the site's soil classification.
- Select the Risk Category. For this example, IV was selected.
- Enter the site's Longitude and Latitude or enter an address.
- The web tool returns the S_S, S_1, and calculates the S_{MS}, S_{M1}, S_{DS}, and S_{D1}. For this example:

$S_S = 0.481$ g	$S_1 = 0.163$ g
$S_{MS} = 0.577$ g	$S_{M1} = 0.267$ g
$S_{DS} = 0.385$ g	$S_{D1} = 0.178$ g

Step 3a: Calculate the S_{DS} and S_{D1} (con't)

The design spectral acceleration (at 1second period), S_{D1}, is determined using the following equations:

$$S_{D1} = 2/3 * S_{M1}$$

Where SM1 is the maximum considered earthquake spectral response acceleration for 1-second period as determined in the following equation:

$$S_{M1} = F_V * S_1$$

Combining both equations results in:

$$S_{D1} = 2/3 * F_V * S_1$$

Where:

S_1 is the mapped spectral accelerations for 1-second period as determined in Section 1613.2.1 of the Code or using the ASCE 7 Hazard Tool.

F_V is the site coefficient defined in **Table 1613.2.3(2)** (on **page J32**) of the 2021 IBC.

Table 1613.2.3(2). Values of Site Coefficient F_V [a]

Site Class	Mapped Spectral Response Acceleration at 1-Second Period(s)					
	$S_1 \le 0.1$	S_1 =0.20	S_{S1}=0.30	S_1=0.40	S_1=0.50	S_1 >=0.6
A	0.8	0.8	0.8	0.8	0.8	0.8
B	0.8	0.8	0.8	0.8	0.8	0.8
C	1.5	1.5	1.5	1.5	1.5	1.4
D	2.4	2.2	2.0	1.9	1.8	1.7
E	4.2	3.3	2.8	2.4	2.2	2.0
F	Note b	Note b	Note b	Note b	Note b	Note b

Step 3b: Determine the Seismic Design Category.

From, **Table 1613.3.5(1)**: Seismic Design Category Based on Short-Period Response Accelerations, the Seismic Design Category is D.

From, **Table 1613.3.5(2)**: Seismic Design Category Based on 1-Second Response Accelerations, the Seismic Design Category is D.

According to Section 1613.3.5, the Seismic Design Category is based on the most severe category. In this example, the seismic design category is D.

Step 3b: Determine the assigned Seismic Design Category (S_{DC})

Risk Category I, II or III structures located where the mapped spectral response acceleration parameter at 1-second period, S_1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category E.
Risk Category IV structures located where the mapped spectral response acceleration parameter at 1-second period, S_1, is greater than or equal to 0.75 shall be assigned to Seismic Design Category F.
For all other structures, knowing the S_{DS} , S_{D1} , and Risk Category, the S_{DC} can be determined using the following tables (The tables are identical in the 2021, 2018, 2015, 2012, 2009, 2006, and 2003 versions of the code; it varies slightly in the 2000 version). According to Section 1613.2.5, the Seismic Design Category is based on the most severe as defined from the short-period and 1-second response tables. The 2021 version of the tables is reproduced below.

Table 1613.2.5(1). Seismic Design Category Based on Short Period Response Accelerations

Value of S_{DS}	Risk Category		
	I or II	III	IV
S_{DS}<0.167g	A	A	A
0.167g <= S_{DS} <0.33g	B	B	C
0.33g <=S_{DS} <0.50g	C	C	D
0.50g <=S_{DS}	D	D	D

Table 1613.2.5(2). Seismic Design Category Based on 1-Second Period Response Accelerations

Value of S_{D1}	Risk Category		
	I or II	III	IV
S_{D1}<0.067g	A	A	A
0.067g <= S_{D1} <0.133g	B	B	C
0.133g <=S_{D1} <0.20g	C	C	D
0.20g <=S_{D1}	D	D	D

Step 4: Determine if the Cooling Tower is Exempt from IBC Seismic Requirements

Cooling towers that meet the following conditions are exempt from seismic design requirements of the IBC.

1. All towers in Seismic Design Categories A and B.
2. Towers in Seismic Design Category C provided Ip is equal to 1.0, and the component is positively attached to the structure.

All other cooling towers require seismic certification per IBC.

Step 5: Determine the Location of the Cooling Tower

The elevation of the cooling tower structure within a building has an impact on the design seismic acceleration. As the installed elevation of the cooling tower increases relative to the building height, the ground seismic accelerations are amplified. This amplification is determined utilizing a ratio of the installation elevation to total building height (z/h).

It is an accepted industry practice for equipment manufacturers to state seismic qualification using the terms, "restricted" and "unrestricted". For cooling tower installations, a restricted seismic qualification means the cooling tower is qualified for installation on grade (z/h=0). On the other hand, an unrestricted seismic qualification means the tower is qualified as if the unit is installed on top of a building (z/h=1). In other words, for projects with restricted seismic qualification, the cooling tower must be installed on the ground. With an unrestricted seismic qualification, the cooling tower can be installed in any building location, from the roof to the ground level. These will normally be expressed as an S_{DS} for a restricted (z/h=0) or unrestricted (z/h=1) application.

Step 6: Select an Independently Certified Cooling Tower— Seismic Qualification Methods & Independent Certification

As mentioned earlier, the IBC refers extensively to ASCE/SEI 7, the consensus standard published by the American Society of Civil Engineers. The seismic design requirements for nonstructural components including mechanical equipment are contained in Chapter 13 of ASCE 7 Code.

Step 4: Determine if the Cooling Tower is Exempt from IBC Seismic Requirement

Since the Seismic Design Category is D and the Importance Factor is 1.5, the cooling tower is not exempt from the structural requirements of the IBC.

Step 5: Determine the Location of the Cooling Tower.

Since the cooling tower will be installed on the roof of the hospital, the S_{DS} determined in Step 3a would be compared to the unrestricted (z/h=1) S_{DS} for the desired product.

Specifically Section 13.2.1 requires mechanical equipment to be qualified using one of the following methods:

a. Analysis b. Testing c. Experience data

A summary of each method follows:

1. **Analysis** – A cooling tower is mathematically evaluated to determine if it can resist the code-prescribed, seismic design forces. Typically, an analysis of this type focuses on the anchorage only or on the anchorage and main structural components, depending on the component importance factor. Analysis cannot effectively address the non structural portions of a tower that affect functionality, such as the drive system, water distribution system, and heat transfer system. The analysis method is also more difficult for code bodies to review and accept/reject. It takes a great deal of time to examine the analysis and understand all the assumptions made and their validity.

2. **Testing** – A full-scale cooling tower is subjected to a simulated seismic event in a test laboratory. Typically, the test method is a shake-table test conducted in accordance with a code-recognized test procedure, such as the "Acceptance Criteria for Seismic Qualification by Shake Table Testing of Non-Structural Components and Systems" (AC156), published by ICC Evaluation Service (ICC ES), Inc. The standard is applicable to all types of equipment including mechanical and electrical equipment. This requires a test plan be developed for all the pre and post-seismic test verification activities. Test results are unequivocal and much easier for a code body to review and accept/reject.

3. **Experience Data** – A cooling tower is qualified using actual earthquake performance data collected in accordance with a nationally recognized procedure. Though this method is used to some extent in the nuclear power industry, it is not used in commercial mechanical equipment applications due to the following limitations:
   a. Lack of a recognized data collection procedure and a national database with widespread access.
   b. Infrequency of strong motion earthquakes.
   c. Low probability of data being applicable to the current generation of products.
   d. Low probability that the actual seismic accelerations experienced by a unit in the field can be translated to current levels of seismic demand.

Based on the preceding limitations, experience data is excluded as a viable qualification method. The remaining methods are not equally suitable for verification of all aspects of cooling tower seismic performance. For example, mathematical analysis is well suited for verification of anchorage resistance, analysis can be used verify maintaining containment but not reliable for verification of cooling tower functionality after a seismic event. The applicability of Analysis, Testing, and Experience Data for equipment is shown in the following table:

Applicable Methods of Seismic Qualification for Cooling Towers

Seismic Design Category	$I_p = 1.0$	$I_p = 1.5$ Remain operable following the design seismic event	$I_p = 1.5$ Maintain containment following the design seismic event
A and B	Exempt	Exempt	Exempt
C	Exempt	Testing Experience Data	Testing Experience Data or Analysis
D, E, and F	Testing Experience Data or Analysis	Testing Experience Data	Testing Experience Data or Analysis

Step 7: Recommended Specification

In light of the IBC code requirements discussed previously, BAC suggests using the following specification.

"Seismic Specification: The cooling tower unit shall be designed, tested, and certified in accordance with the 2021 IBC and ASCE/SEI 7-16. The unit shall be suitable for application with Design Spectral Acceleration at Short Period (S_{DS}) for z/h=1.0 up to g with a Component Importance Factor (I_p) of 1.0 and 1.5. The unit shall be certified by the manufacturer as functional following an earthquake for Ip = 1.0 application. For Ip = 1.5 application, the special. The certification shall be based on full-scale, shake table testing conducted in accordance with ICC-ES Acceptance Criteria AC156, and shall be reviewed and approved by a licensed professional engineer independent of the manufacturer. Experience data or analysis is not acceptable to verify post-earthquake functionality for I_p = 1.5. "

NOTE: The specification covers an importance factor of 1.5 and defaults to an unrestricted (z/h=1.0) installation. This eliminates the concern of having to determine risk category, if compliance is required, or the installation location.

Conclusion

The IBC sets forth criteria to identify facilities that are critical for the protection of human life during and immediately following a seismic event and prescribe structural design requirements to ensure the safe and continued operation of such facilities.

Mechanical systems often serve vital functions in critical facilities such as emergency response centers, communication centers, and hospitals. Following an earthquake, the continued operation of these facilities could be dependent on the ability of the mechanical systems to remain operable. Failure of equipment to function in these applications could constitute a hazard to life.

The most reliable method to assure post-event functionality of the equipment is shake table testing in accordance with AC 156. The Series 3000, Series 1500, PT2, FXV, VCA, CXVB, PFi, and PCC have been tested in accordance with AC 156. All are certified in accordance with ASCE 7 to withstand the seismic forces prescribed for the continued operation of essential facilities.

If seismic certification is required, the engineer should be able to provide the information listed below. To learn more about BAC's comprehensive seismic design and qualification approach, please contact your local BAC representative.

Attachment 1: Site Specific Seismic Requirements

Per the IBC, these variables should be provided in the project structural documents and filtered into the cooling tower specification by the engineer of record.

Requirement	
Site Location (Latitude and Longitude or Address)	Installation elevation ratio to structure height (z/h)
Equipment Importance Factor (I_p)	Rigid or Flexible Support (i.e. on vibration isolators)
Seismic Design Category (A-F)	IBC Edition
Acceleration at Short Period (S_{DS})	

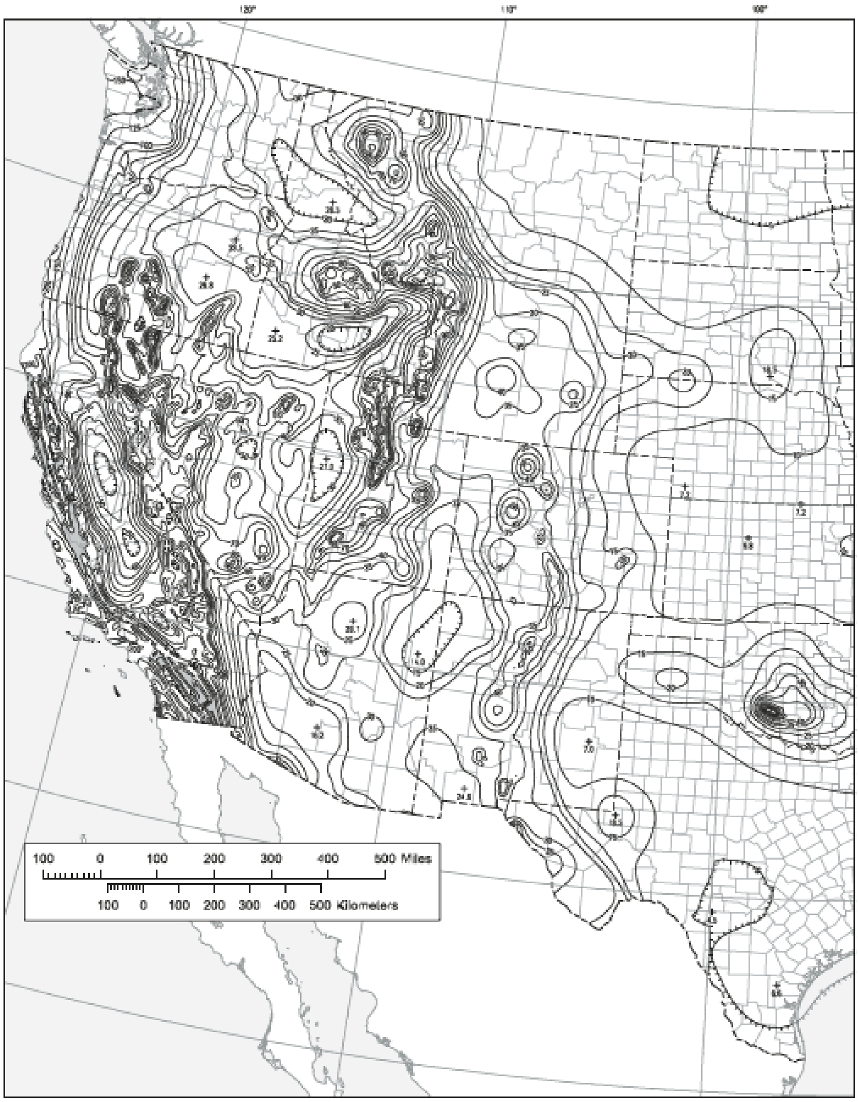


Figure 22-1 S_S Risk-Targeted Maximum Considered Earthquake (MCE_R) Ground Motion Parameter for the Conterminous United States for 0.2-s Spectral Response Acceleration (5% of Critical Damping)

NOTE:

Maps prepared by the United States Geological Survey (USGS) in collaboration with the Federal Emergency Management Agency (FEMA)-funded Building Seismic Safety Council (BSSC) and the American Society of Civil Engineers (ASCE).
The basis is explained in commentaries prepared by BSSC and ASCE and in the references.

Ground motion values contoured on these maps incorporate:

- a target risk of structural collapse equal to 1% in 50 years based upon a generic structural fragility
- a factor of 1.1 to adjust from a geometric mean to the maximum response regardless of direction
- deterministic upper limits imposed near large, active faults, which are taken as a 1.8 times the estimated median response to the characteristic earthquake for the governing fault (1.8 is used to represent the 84th percentile response), but not less than 150% g.

It is recommended that the web tool **https://asce7hazardtool.online** be used to determine the mapped value for a specified location.

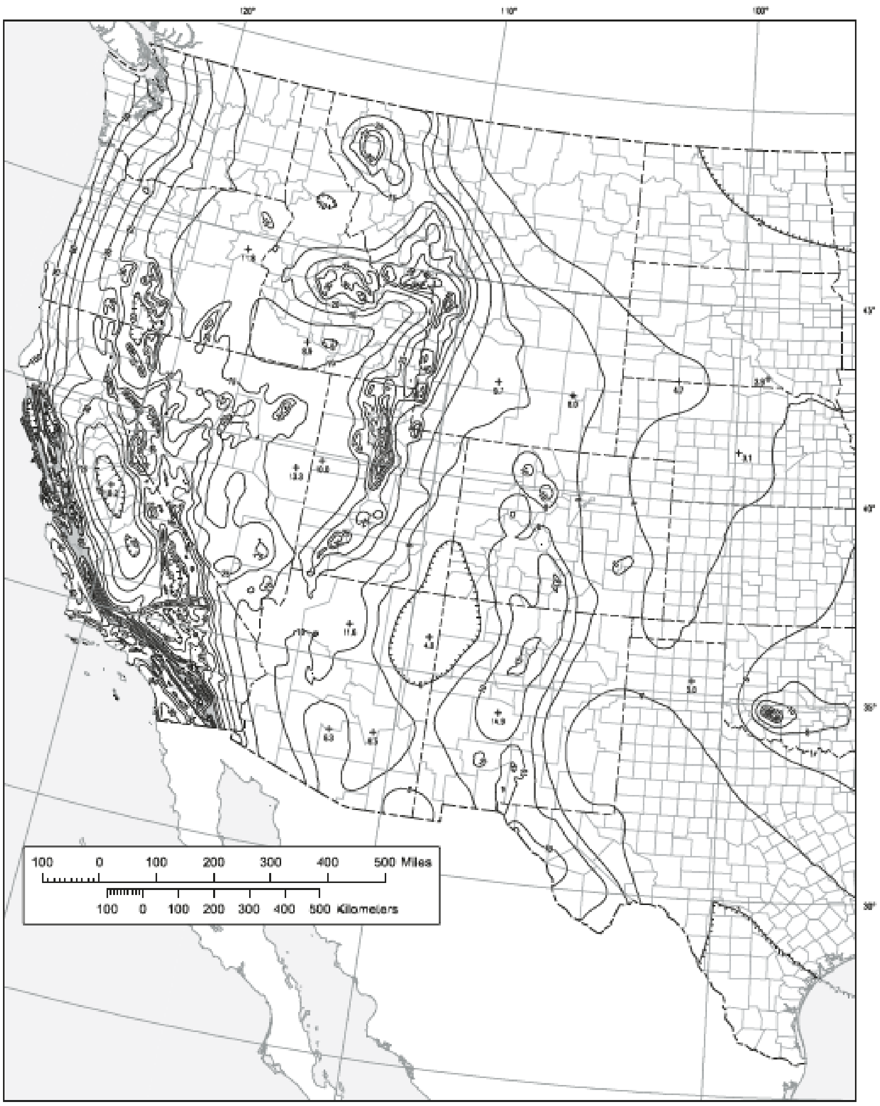


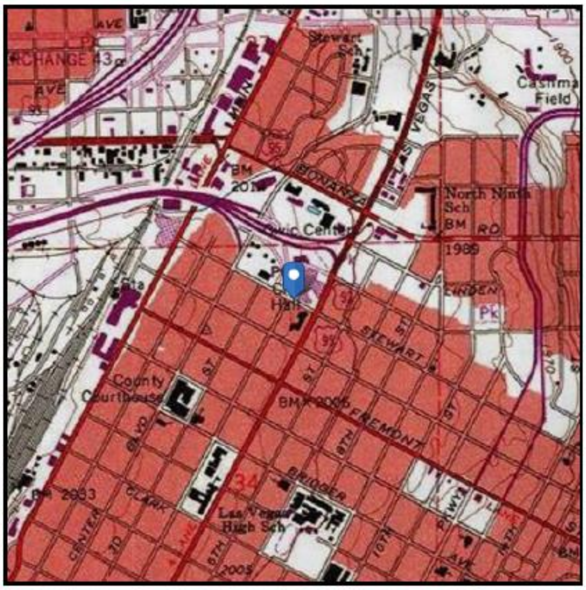
Figure 22-2 S_1. Risk-Targeted Maximum Considered Earthquake (MCE_R) Ground Motion Parameter for the Conterminous United States for 1.0-s Spectral Response Acceleration (5% of Critical Damping)

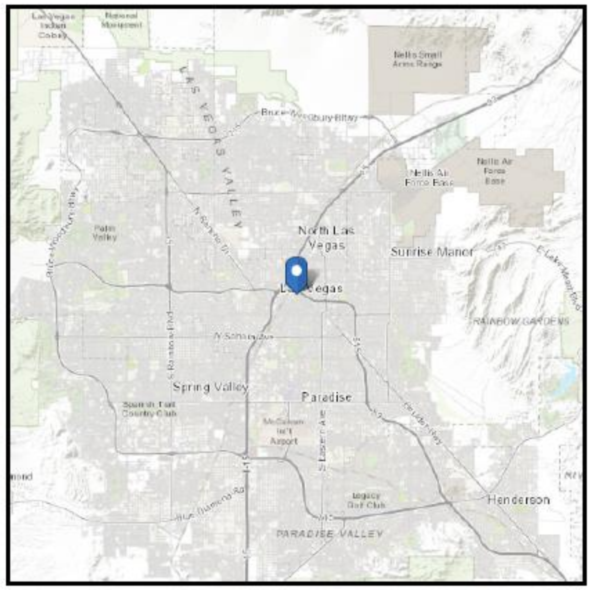
ASCE 7 Hazards Report

Address:
Las Vegas
Nevada,

Standard: ASCE/SEI 7-16
Risk Category: IV
Soil Class: D - Default (see Section 11.4.3)

Elevation: 2011.44 ft (NAVD 88)
Latitude: 36.17193
Longitude: -115.14001





Site Soil Class: D - Default (see Section 11.4.3)

Results:

S_S :	0.59	S_{D1} :	0.284
S_1 :	0.193	T_L :	6
F_a :	1.328	PGA :	0.26
F_v :	2.215	PGA_M :	0.348
S_{MS} :	0.783	F_{PGA} :	1.34
S_{M1} :	0.427	I_e :	1.5
S_{DS} :	0.522	C_v :	1.093

Seismic Design Category D