ALTERNATE PROCEDURE FOR DEVELOPMENT OF RISK-TARGETED SEISMIC HAZARD

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Abstract

Starting with the 2010 edition of ASCE/SEI 7 Minimum Design Loads for Buildings and Other Structures, the design seismic ground motions changed from being based on ground motion probabilities to being risk targeted. The specified risk target is for the design of buildings is to have a 1 percent probability of collapse in 50 years. As described in the 2009 NEHRP Recommended Seismic Provisions upon which the seismic provisions of ASCE/SEI 7-10 are based, the uniform hazard ground motions are adjusted to produce the risk-targeted ground motion parameters: peak ground acceleration and spectral accelerations at 0.2 second and at 1-second. The procedure used by the U.S. Geological Survey for developing the risk coefficients is described by published literature as a combination of the site-specific hazard curves with a building fragility curve. A targeted risk coefficient is defined in ASCE/SEI 7 as the ratio of the risk-targeted probabilistic ground motions to the uniform hazard ground motions based on a 2 percent probability of exceedance in 50 years.

The U.S. Geological Survey has developed maps of risk coefficients for the United States and U.S. Territories; however, there is not sufficient data for use of the ASCE/SEI 7-10 seismic design requirements for areas outside of the United States for which the risk-targeted ground motions have not been developed. An approximate procedure for developing the targeted risk coefficients is proposed that considers the shape of the hazard curve for the site relative to the hazard curve for a representative site in the U.S. The results of this procedure are compared with the values for several locations in the United States and are able to closely match the risk-targeted values provided by the U.S. Geological Survey data.

Keywords: Risk-Targeted, Ground Motion, Hazard Curve, Probabilistic Seismic Hazard Analysis

1. Introduction

Ground motion and seismicity criteria have evolved over the past 60 years from simple seismic zonation to detailed response spectra parameters. From the 1970s through 1997, building codes used as its basis, a ground motion hazard based on an earthquake with a 10 percent probability of being exceeded in 50 years, otherwise referred to as the 475-year earthquake. The basis for the ground motion hazard in later building codes in the United States is taken as the ground motion with a 2 percent probability of being exceeded in 50 years (2475-year earthquake) [1]. A value of two-thirds of this hazard is used for design. ASCE/SEI 7-10 introduced a new concept for determining the ground motion hazard: risk-targeted ground motions [2]. The basis for the risk-targeted ground motions is produce a hazard with a 1 percent risk of collapse in 50 years [3]. The development of ground motion hazards using this new design ground motion is currently limited to the United States. Risk-target ground motions are not generally available for locations outside of the United States and therefore the use of building codes that rely on such values is difficult for these areas.

2. Seismic Hazards

A Probabilistic Seismic Hazard Analysis (PSHA) can be performed to determine the seismic hazard for a site. The PSHA accounts for potential seismic sources that may affect the site to define the seismic source model. Ground motion prediction equations are used to determine the level of ground motion at the site from each of the seismic sources. The PSHA accounts for uncertainty in the recurrence intervals and distance for the seismic source events. The results of the PSHA is a hazard curve that defines the variation in ground motion and spectral acceleration values with recurrence intervals (time).

The ground motion hazards are defined as accelerations for a range of structural periods of vibration. Currently in the United States, the ground motion hazard is defined by the hazard at three periods of vibration: the peak ground acceleration, where the period of vibration is essentially 0; the spectral acceleration at 0.2 seconds, and the spectral acceleration at 1 second. The acceleration values at these periods are used to define the response spectrum for the site. The spectral acceleration at 0.2 second is used to define the constant acceleration or short period portion of the response spectrum curve and the spectral acceleration at 1 second is used to define the constant velocity portion of the response spectrum curve, as shown in Fig. 1.

The United States Geological Survey (USGS) has developed hazard curves for locations throughout the United States; however, building codes and seismic evaluation standards, such as ASCE/SEI 41-17 [4], consider specific seismic hazard recurrence intervals, e.g. 250-, 475-, 975-, and 2,475-year return period earthquakes. Comparison of these hazard curves shows a wide variation in seismic hazard throughout the United States. Fig. 2 shows the hazard curves for six locations in the United States, with the peak ground acceleration (g) plotted against return period (years). Also indicated are the 250-, 475-, and 2,475- year return periods.

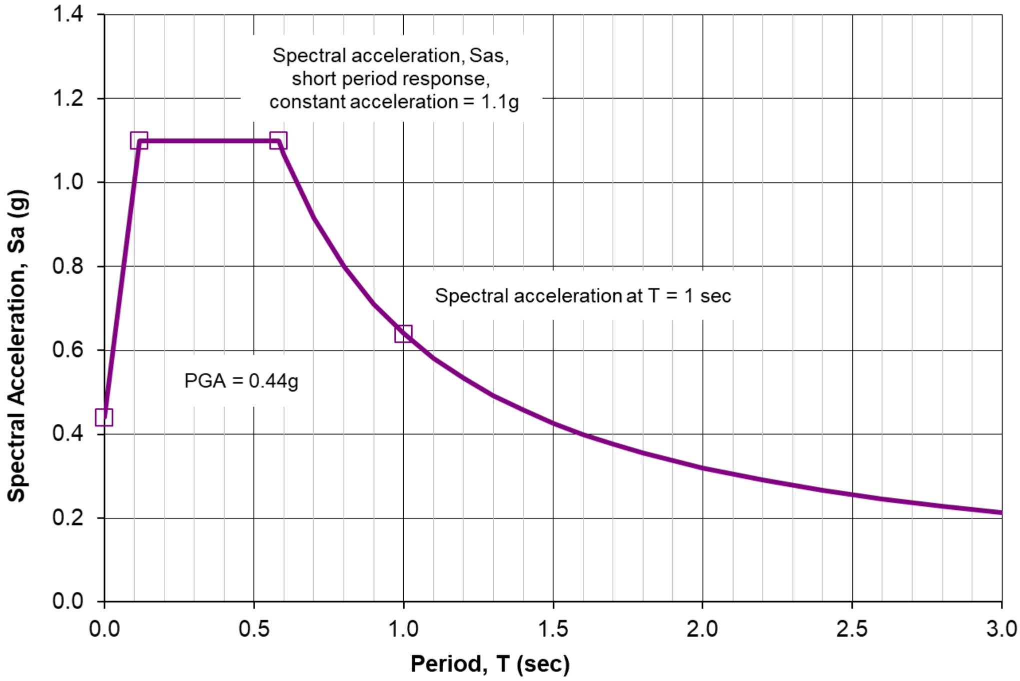

Fig. 1 - Sample Standard Response Spectrum

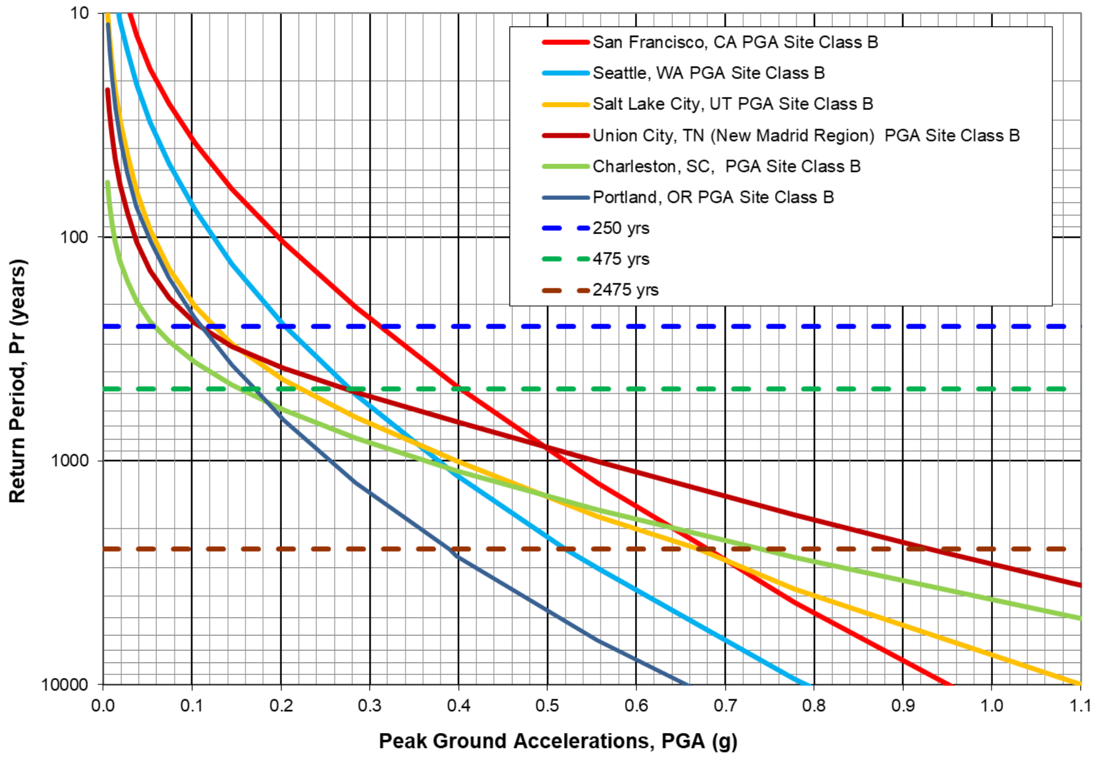

Fig. 2 - Seismic Hazard Curves for Six Locations in the United States

2.1 Uniform Seismic Hazard

For United States building codes starting with the 2003 IBC and continuing through the 2015 IBC, the seismic hazard was based on the hazard with a 2 percent chance of being exceeded in 50 years. This is also described as the hazard associated with an average return period of 2475 years. The IBC defines this value as the Maximum Considered Earthquake (MCE)[1]. A uniform hazard is meant to produce a probabilistic hazard would be uniformly defined for all areas of the country across the range of structural vibration periods [3]. The design of buildings using this definition of hazard was intended to produce buildings with a margin of about 1.5 against collapse when subjected to the design ground motion, which is defined in the IBC as two-thirds of the MCE.

2.2 Risk-Targeted Seismic Hazard

Using a uniform hazard ground motion definition for the design of buildings does not provide an equal margin against collapse for all buildings. It was recognized that due to the variations in seismic hazards, that a uniform hazard definition of the seismic hazard would result in buildings designed to these uniform hazard values to produce buildings with varying risks of collapse [5]. This is due in large part to the variations in the shapes of the hazard curves, as well as the difference in design accelerations. The uniform hazard also does not account for the uncertainty in the collapse capacity of a building.

In areas with more frequent moderate to strong seismic activity, such as the west coast of the United States, the hazard curve tends to be relatively steep compared to areas in the central and eastern United States, as shown in Fig. 1. As a result, buildings in these areas higher seismic activity may experience more frequent strong ground motions that can cause structural damage or collapse compared to buildings in areas with less frequent strong ground shaking. In areas with less frequent strong shaking, such as Charleston, South Carolina, the hazard curve is shallower. For comparison, Fig. 2 shows that the average return period for an earthquake with a PGA of 0.3 g is about 250 years for San Francisco, whereas the return period for that same PGA for Charleston is about 800 years. Note that the hazard curves for San Francisco and Charleston have nearly the same PGA value for a 2000-year return period. This variability in the shape of the hazard curves leads to a variability in the probability of collapse of collapse for buildings that are designed using the same value of MCE.

2.2.1 Building Fragility

To assess a building's risk of collapse, the ground motion hazard should consider the probabilities of collapse over the range of hazards and consider the uncertainties in the probability of collapse of a building given each level of shaking. The uncertainty in collapse of a building is represented by a fragility curve that relates the conditional probability of collapse to the spectral acceleration. The USGS has assumed that a building fragility curve can be represented using a lognormal distribution with an assumed value for the uncertainty of collapse and the 10th-percentile capacity [5]. The probability distribution of the collapse capacity is also assumed to vary depending on the spectral acceleration values for the site. An example of a fragility curve computed for determining risk-targeted ground motions is shown in Fig. 3 [6]. The spectral acceleration in Fig. 3 is the short period (0.2 second) spectral acceleration value.

[1] The probabilistic MCE is applicable to most areas of the United States. In some areas, such as those close to major faults, the MCE value is capped deterministically.

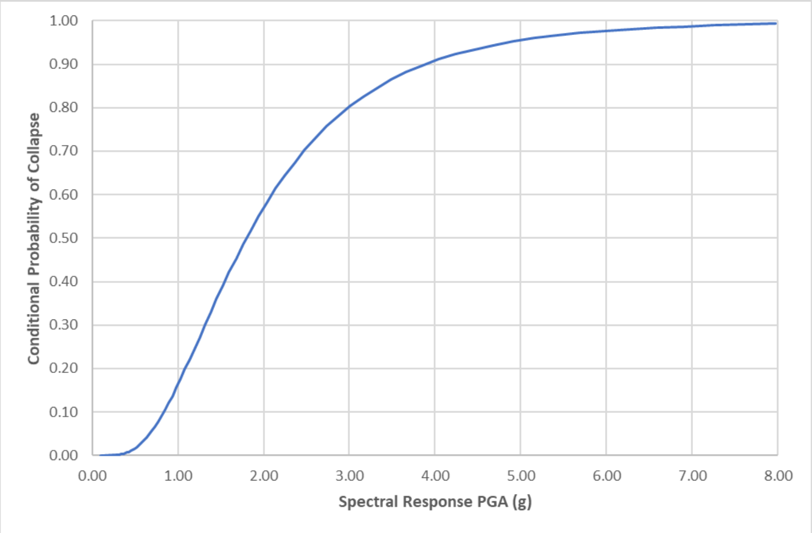

Fig. 3 - Example Fragility Curve from USGS

The collapse probability is calculated as the integral of the probabilities of collapse that represents a probability that the ground motion will exceed the collapse capacity times the probability of occurrence of the collapse capacity.

2.2.2 Targeted Risk Coefficient

The USGS developed risk-targeted ground motions for the entire United States. Using an iterative approach, the ground motion is varied, starting with an initial value equal to the uniform hazard value for the 2475-year return period value and integrated with a fragility curve as described above. The fragility curve also varies based on the ground motion. The iteration continues until the cumulative integral of the hazard curve times the derivative of the fragility curve results in a cumulative 50-year collapse probability of 1 percent. The ground motion that produces this collapse probability is termed the risk-targeted ground motion. A more detailed description of the procedure is provided in the paper by Luco, et al [5].

The risk-targeted ground motion obtained using this procedure is then divided by the uniform hazard ground motion associated with the 2 percent in 50-year probability of exceedance. This ratio is termed the targeted risk coefficient. The values of this risk coefficient vary across the United States, but the typical values range from 0.89 to 0.95 [7]. Table 1 shows the targeted risk coefficients for several representative cities in the United States. Targeted risk coefficients less than 1.0 represent locations where buildings can be designed to ground motion hazards less than the 2475-year earthquake to achieve a 1 percent probability of collapse in 50 years, whereas areas with a targeted risk coefficient greater than 1.0 indicates that the design ground motion needs to be greater than the 2475-year earthquake to achieve a 1 percent probability of collapse in 50 years.

Table 1 – Targeted Risk Coefficients for Representative United States Cities

City	**PGA at 2475 years**	**Targeted Risk Coefficient**	**Risk Targeted PGA**
San Francisco	0.678	0.95	0.645
Los Angeles	0.853	0.90	0.767

Seattle	0.523	0.91	0.476
San Diego	0.726	0.86	0.624
Portland	0.387	0.88	0.340
St. Louis	0.268	0.92	0.247
Charleston	0.739	0.85	0.628
Boise	0.136	0.91	0.124
Sacramento	0.241	0.94	0.238

3. Proposed Methodology

Review of the USGS methodology for developing the risk-targeted ground motion values indicates that the shape of the hazard curve has a significant influence on the value of the risk-targeted ground motion relative to the uniform hazard ground motion. This is due to the influence of strong frequent earthquakes on the cumulative probability of collapse. A simplified method of evaluating the relative shape of various hazard curves would be to compare the ratio of two points on the hazard curve. For comparison, the PGA at 2475 years and the PGA at 475 years are used to bound the range of typical design values. Table 2 provides the PGA values for 475 years and 2475 years for each of the example cities along with the ratios.

Table 2 – Ratio of PGA at 2475 years to 475 years for Representative United States Cities

City	PGA at 2475 years	PGA at 475 years	Ratio of PGA at 2475 years to 475 years
San Francisco	0.678	0401	1.69
Los Angeles	0.853	0.430	1.98
Seattle	0.523	0.277	1.89
San Diego	0.726	0.270	2.68
Portland	0.387	0.170	2.28
St. Louis	0.268	0.100	2.69
Charleston	0.739	0.154	4.79
Boise	0.137	0.056	2.45
Sacramento	0.241	0.130	1.85

Although there is a general trend that the ratios of 2475-year to 475-year PGA are generally inversely proportional to the TRC, this trend does not provide a reliable basis for determining a value for the TRC. One factor that is not accounted for is that the ratio does not consider the actual values of the PGA.

A proposed method of comparing hazard curves that would not be affected by the differences in the short period spectral would be to normalize the hazard curves to a common value. The short period spectral acceleration is used as a better representation of hazard associated with building damage than PGA. For example, Fig. 4 shows the short period spectral acceleration hazard curves for twelve representative cities from with the curves normalized to a value of 1.5g at a return period of 2475 years. The cities were chosen from the thirty-four city locations listed in the description of the commentary to the 2009 Edition of the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* [3], with three cities from Northern California, Three from Southern California, and two from each the Pacific Northwest, other western United States locations, and the central and eastern United States. The hazard curves are based on the ground motion for the site class B/C boundary.

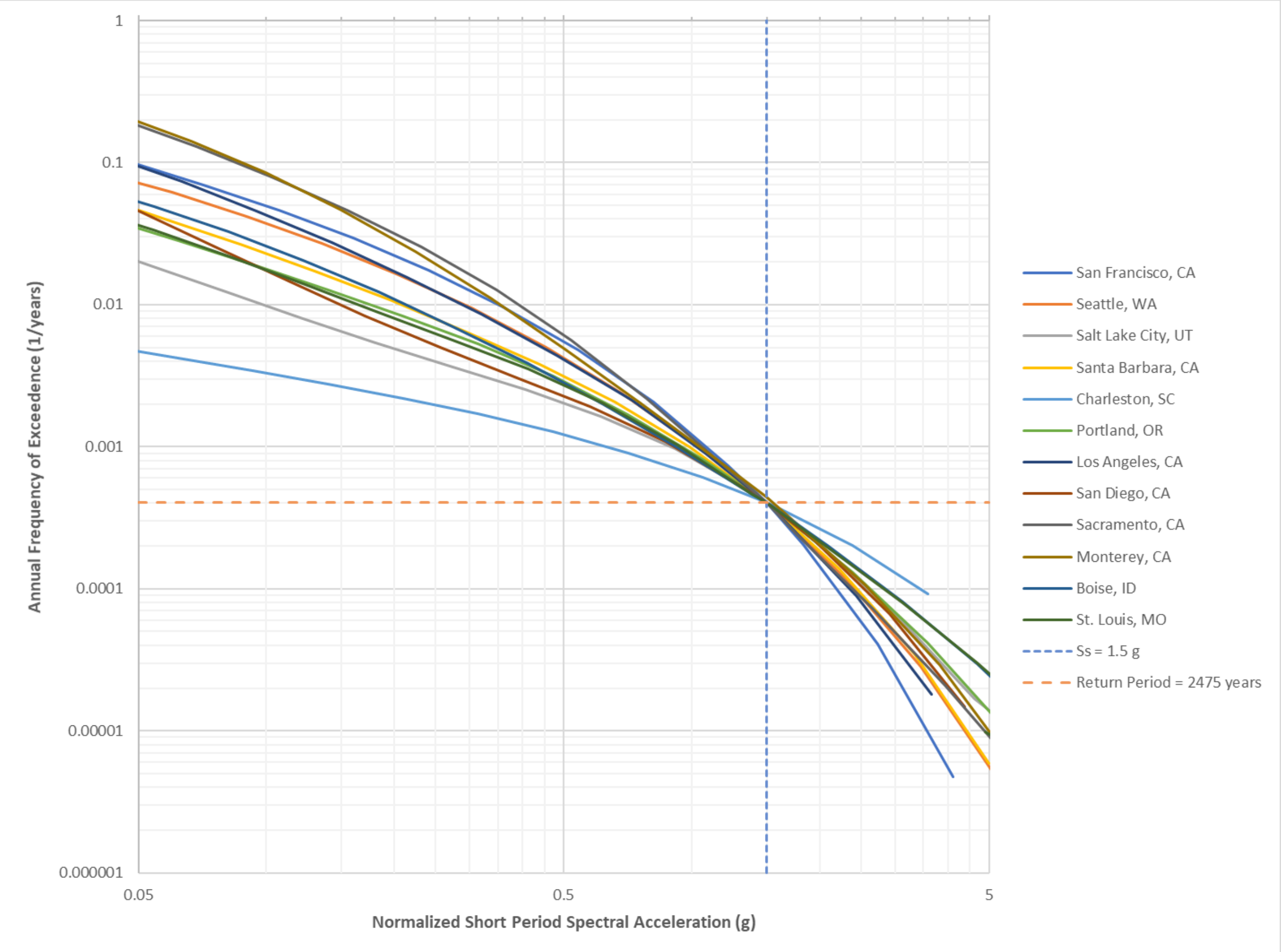

Fig. 4 - Hazard Curves Normalized to Short Period Spectral Acceleration = 1.5 g at 2475 years

With the hazard curves normalized, a comparison of the curves can be made to estimate the effect of the shape of the curve on the probability of collapse by calculating the area under the hazard curve. An upper bound for the hazard curve over which to calculate the area is taken as 2475 years, since that is the value of the MCE. A lower bound limit for determining the area under the hazard curve is arbitrarily taken as a 50-year return period. Seismic hazards at lower return periods have a negligible effect on the area under the curve and thus the probability of collapse. An example of this methodology is shown in Fig. 5. The areas under the short period spectral acceleration hazard curve (Ss = 0.2 seconds) using this proposed methodology was computed for the twelve representative cities in the United States.

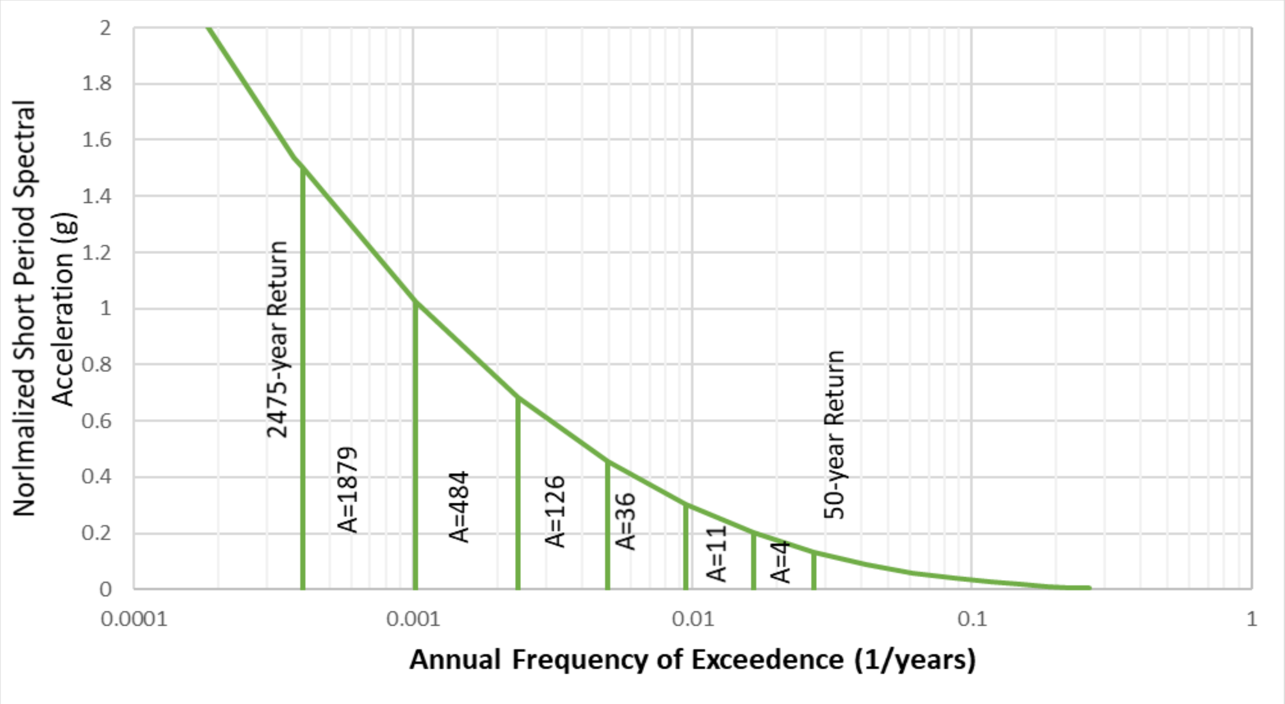

Fig. 5 - Example Hazard Curve Area Calculation where A is the area under the segment of the curve

The computed area under the normalized curves is compared to the area under the hazard curve for a representative location. Table 3 compares the targeted risk coefficients calculated with the proposed approximate methodology to those provided by the U.S. Geological Survey using the seismic maps web interface developed by the Structural Engineer's Association of California and the California Office of Statewide Health Planning and Development [8].

Table 3 - Comparison of Targeted Risk Coefficients from the Proposed Approximate Methodology to the Values from The U.S. Geological Survey.

City	Targeted Risk Coefficient from USGS	Approximate Targeted Risk Coefficient	Ratio of Approximate TRC to USGS value
San Francisco, CA	0.93	0.93	1.00
Seattle, WA	0.90	0.89	0.99
Salt Lake City, UT	0.86	0.80	0.93
Santa Barbara, CA	0.87	0.86	0.99
Charleston, SC	0.87	0.66	0.76
Portland, OR	0.88	0.84	0.95
Los Angeles, CA	0.90	0.89	0.99
San Diego, CA	0.87	0.82	0.94
Sacramento, CA	0.95	0.92	0.97
Monterey, CA	0.92	0.91	0.99

Boise, ID	0.91	0.83	0.91
St. Louis, MO	0.91	0.83	0.91

Comparison of the approximate TRC value to the values provided by USGS shows that the approximate method provides a reasonable approximation of the TRC values for most of the example locations. The locations where the results from the approximate procedure vary by more than 5 percent are Charleston, Boise, and St. Louis. The hazard curves for these locations each have relatively low probabilities of exceedance for spectral acceleration values less than 0.10 g and the ratio of spectral acceleration at a return period of 5000 years to the value at 2475 years is also relatively high. This appears to indicate that the portion of the hazard curve beyond 2475 years may need to be considered for locations with steep hazard curves.

3.1 Example Applications

The approximate procedure was used to estimate the TRC for three undisclosed locations outside of the United States. The locations represent areas of various seismic hazard. For reference one location is characterized as equivalent to Seismic Zone 4 as defined by the Uniform Building Code [9]. A second location is characterized as equivalent to Seismic Zone 3. The third location is characterized as equivalent to Seismic Zone 2A. The hazard curves are shown in Fig. 6.

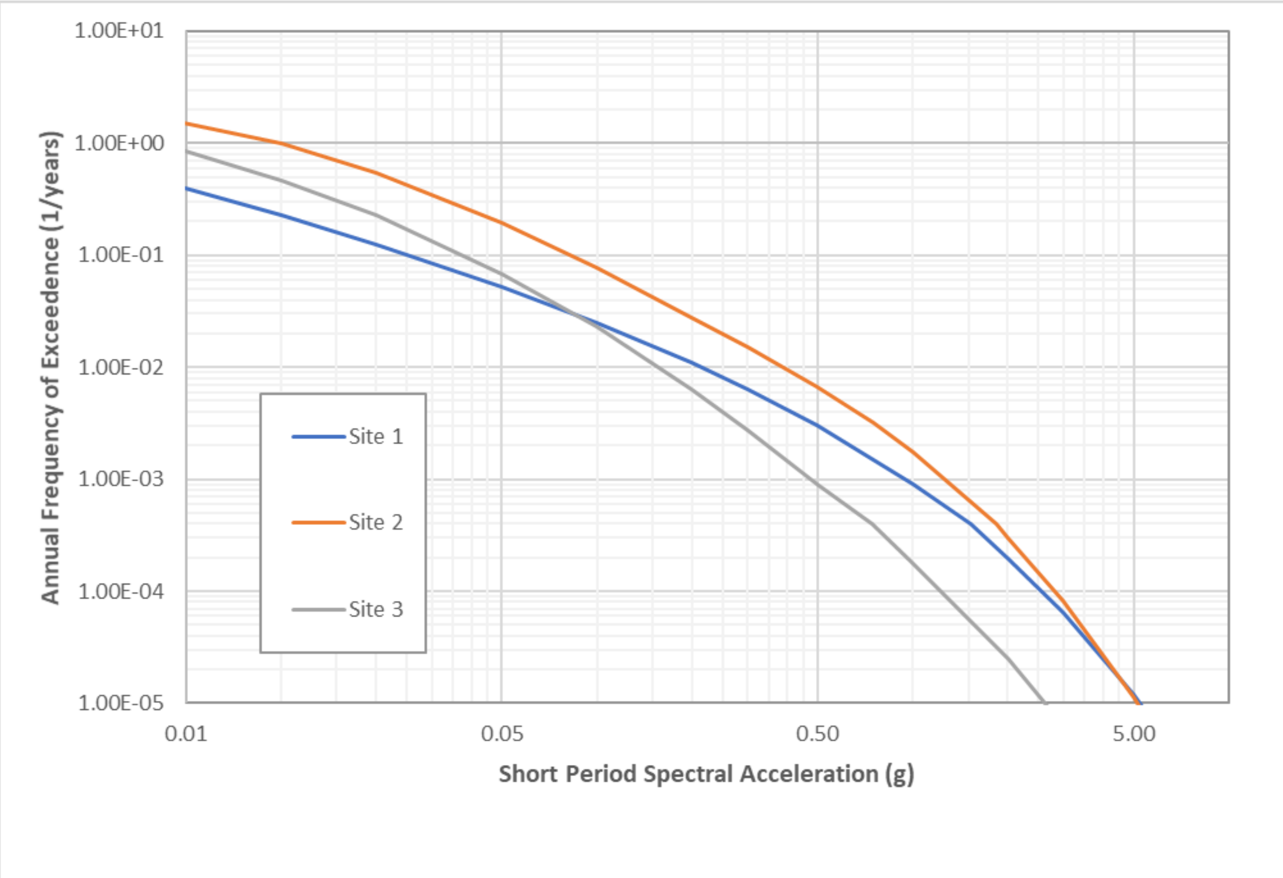

Fig. 6 - Hazard Curves for Example Locations

Table 4 lists the PGA values for the three locations at a 475-year return period, the equivalent seismic zone, and the short period spectral acceleration values at a 2475-year return period.

Table 4 - Estimate TRC values for Three Locations Outside of the United States

Location	Seismic Zone	PGA at 475-Year Return Period (g)	Short Period Spectral Acceleration at 475-years (g)	Short Period Spectral Acceleration at 2475-years (g)
1	3	0.28	0.61	1.52
2	4	0.40	0.92	1.83
3	2A	0.15	0.34	0.75

The results show values for the TRC that are consistent with the range of values provided by the USGS for locations across the United States. The values were also compared to values calculated by the USGS using their Risk-Targeted Ground Motion Calculator web application [10]. Table 5 compares the TRC values using the approximate method to the value obtained from the USGS application. The approximate values are within 5 percent of the values obtained using the USGS tool.

Table 5 - Comparison of TRC values for Three Locations Outside of the United States

Location	Targeted Risk Coefficient using USGS tool	Approximate Targeted Risk Coefficient
1	0.86	0.82
2	0.87	0.87
3	0.88	0.85

4. Conclusions

Changes in the seismic design basis for United States building codes has created a challenge for the implementation of these codes to areas outside of the United States. The risk-targeted ground motions that are currently being used for design are not readily available in other areas. A simplified method of obtaining an approximate TRC was developed that requires development of a site-specific hazard curve.

The methodology was tested using twelve representative locations in the United States and the estimated TRC values were compared to the values available from USGS. In areas of high seismicity, the results from the approximate method produced values that are close to those obtained from USGS. In areas of more moderate seismicity, the approximate method under-estimates the TRC value. The methodology was also used to estimate the TRC for three locations outside of the United States. The approximate values show good agreement with typical values in the United States for sites with similar seismic hazards.

This approximate method relies only on the relative shape of the hazard curve. The building fragility is not directly considered. The method provides a close approximation of the targeted risk coefficient except in areas where the hazard curve is relatively steep, e.g. the ratio of the spectral acceleration at 2475 years to the spectral acceleration at 475 years is greater than 2.5.

5. Acknowledgements

The primary author wishes to acknowledge the immense contribution of his co-author who initially developed the methodology but was unable to continue with the research.

6. References

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