IMPLEMENTING TIME-DEPENDENT SEISMIC HAZARD IN SEISMIC DESIGN AND BUILDING CODES: IT'S TIME!

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Abstract

Current seismic design practice as reflected in building codes is based on time-independent probabilistic seismic hazard analyses. Time-independent hazard does not account for the elapsed times on faults i.e., the time since the last large earthquake. We argue that elapsed times should be accounted for in time-dependent hazard analyses and hence, building codes particularly if the elapsed time exceeds the mean recurrence interval on a fault suggesting that a large earthquake may be eminent. The key to an accurate time-dependent seismic hazard assessment for a fault is information on its mean recurrence interval, elapsed time since the most recent earthquake, and their uncertainties. However, such information is generally unavailable for most regions around the world. Although the data exists for several major faults in the U.S., time-independent probabilistic seismic hazard analysis is still the methodology used by the U.S. Geological Survey to develop the National Seismic Hazard Maps which are the basis for the International Building Code used in the U.S. In this paper, we illustrate the time-dependent impacts on ground motions using the Wasatch Front, Utah as a case study. The seismic hazard in this region is generally dominated by the five central segments of the 350-km- long Wasatch fault zone, which has ruptured repeatedly in moment magnitude (**M**) 6.8 and larger earthquakes. We illustrate the differences in time-independent and time-dependent hazard for three cities along the Wasatch Front where the mean recurrence intervals equal, exceed, or are a fraction of the elapsed time since the last large earthquake and discuss the implications to seismic design.

Keywords: time-dependent hazard, time-independent hazard, seismic design, building codes

INTRODUCTION

Current seismic design practice as reflected in building codes is based on time-independent probabilistic seismic hazard analysis (PSHA). In other words, seismic design ground motions are developed for exposure periods that are time-independent (e.g., any random 50-year period) rather than a specified time period such as the ***next*** 50 years. Time-independent hazard does not account for the elapsed times on faults i.e., the time since the last large earthquake. For example, in the San Francisco Bay region in northern California, the last major event was the 1906 Great San Francisco moment magnitude (**M**) 7.9 earthquake. In time-independent hazard calculations, the elapsed time of 114 years is not accounted for. The event could have occurred yesterday or a million years ago and it would not impact the calculated time-independent hazard i.e., the probability of a future earthquake is independent of time. In a time-dependent hazard calculation, that 114 years is included and so if hypothetically the mean interval between 1906-type earthquakes (called recurrence interval) is 100 years, the fact that the event is "overdue", would be reflected in the time-dependent hazard i.e., it would be higher than the time-independent hazard. Time-dependent hazard is predicated on the elastic rebound theory where a fault has a seismic cycle: elastic strain builds up along a fault and releases that strain periodically in a large characteristic earthquake. Hence the probability of a large earthquake is small soon after a large event occurs and increases with time.

The key to an accurate time-dependent seismic hazard assessment of a fault is having the information on its mean recurrence interval and elapsed time since the most recent earthquake, and addressing their uncertainties. However, such information is generally unavailable for the vast majority of regions around the world. Although the data exists for several major faults in the U.S., time-independent PSHA is still the methodology used to develop the U.S. Geological Survey National Seismic Hazard Maps [1] (Fig. 1) which are the basis for the International Building Code used in the U.S. There is hesitation on the part of the U.S. engineering community to adopt time-dependent seismic hazard assessments in seismic design for reasons that are unclear. One of the reasons could be that the concept of time-independent and time-dependent hazard is unfamiliar to them. This is due in part to the fact that few seismic hazard practitioners perform time-dependent PSHA. In this paper, we argue that elapsed times ***should*** be accounted for in time-dependent hazard and seismic design particularly if the elapsed time exceeds the mean recurrence interval on a fault suggesting that a large earthquake may be eminent.

PSHA METHODOLOGY

The PSHA methodology is based on the model developed principally by Cornell [2]. In his model, the occurrence of earthquakes on a fault is assumed to be a Poisson process which is a reasonable assumption in regions where data are sufficient to provide only an estimate of average recurrence rate [2]. The occurrence of ground motions at a site in excess of a specified level is also a Poisson process, if (1) the occurrence of earthquakes is a Poisson process, and (2) the probability that any one event will result in ground motions at the site in excess of a specified level is independent of the occurrence of other events.

A probability model describes how events are distributed in time. The simplest model is the time-independent Poisson (memoryless) model that has been assumed appropriate in PSHA for decades [3]. The Poisson model assumes that each earthquake is completely independent of the timing of all other events.

In contrast to the Poisson model, a time-dependent renewal process model embodies the expectation that after one characteristic earthquake on a fault or fault segment, another characteristic earthquake on that fault or fault segment is unlikely until sufficient time has elapsed for stress to re-accumulate. Such models generally require two parameters and typically include knowledge of the time of the most recent rupture. One required parameter is the mean recurrence interval and the other describes the variability of recurrence intervals or the aperiodicity parameter coefficient of variation (COV). Time-dependent models include the traditional lognormal model and Weibull distribution. The Brownian Passage Time (BPT) model [4] has been used recently in earthquake forecasts i.e. Working Group on Utah Earthquake Probabilities [5].

U.S. BUILDING CODE

The building code that governs the design of new buildings and structures in the U.S. is the International Building Code [6]. The current edition was published in 2018. The seismic provisions in the code are adopted from the *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures* (FEMA P-750) [7]. FEMA P-750 in turn adopts ASCE/SEI-7-16 *Minimum Design Loads and Associated Criteria for Buildings and Other Structure* [8]. The seismic design maps in Chapter 22 of ASCE7-16 show the risk-adjusted maximum considered earthquake (MCE_R) ground motion parameters S_S and S_1. These maps are prepared by the USGS in collaboration with the Building Seismic Safety Council (BSSC) and ASCE. These design maps are derived from the USGS National Seismic Hazard maps which display the probabilistic ground motions at 2% probability of exceedance in 50 years or a return period of 2,475 years [1] (Fig. 1).

In some areas, the 2,475 year ground motions have a deterministic cap. Again these maps are based estimates of time-independent hazard.

Other codes that depend on the National Seismic Hazard Maps include ASCE41-17 *Seismic Evaluation and Retrofit of Existing Buildings* [9] and the American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications for LRFD Seismic Bridge Design* [10].

CASE STUDY: WASATCH FRONT

Regional time-dependent seismic hazard analyses go back at least 30 years in the U.S. Such hazard estimates have been made for the San Francisco Bay region [11], California [12], Alaska [13], Cascadia subduction zone [14], Wasatch Front region, Utah [15], and New Madrid and Charleston, South Carolina [16]. Time-dependent hazard assessments have been made in these regions because the recurrence and timing information are available and yet this research has not been implemented in the IBC seismic design maps. Some site-specific projects have also included time-dependent hazard in peer-reviewed seismic design (e.g., [17]).

We illustrate the time-dependent impacts on seismic hazard using the Wasatch Front as a case history. The WGUEP [5] forecasted a 43% probability that one or more **M** 6.75 earthquakes would strike the Wasatch Front region during the period 2014 to 2063 (Fig. 2). Much of Utah's population, 2.4 million, and economy is concentrated in the hanging wall of the 350-km-long Wasatch fault zone and a large earthquake would be devastating (Fig. 3). The cities of Brigham City and Nephi define the northern and southern ends of the urban Wasatch Front region, respectively, and Salt Lake City, the largest city in Utah is near its center. The seismic hazard in this region is generally dominated by the five central segments of the Wasatch fault zone, the Brigham City, Weber, Salt Lake City, Provo, and Nephi, which have ruptured repeatedly in **M** 7 and larger earthquakes (Fig. 3). Fig. 4 shows the timing of large surface-faulting earthquakes on the five central segments based on the paleoseismic record [5]. The interpretation shown on Fig. 4 assumes that the earthquakes are the result of single segment ruptures (characteristic earthquakes). The WGUEP [5] favored this model (weighted 0.70) but four multi-segment rupture models were considered in the forecast because the uncertainties in the timing of the earthquakes allowed for the possibility that multi-segment ruptures were possible. Based on this chronology, the Salt Lake City segment beneath Salt Lake City has a mean recurrence interval of 1,300 years and it has been 1,400 years since the last large earthquake. The Brigham City segment has a mean recurrence interval of about 1,500 years with an elapsed time of about 2,500 years, well in excess of the mean recurrence interval. Finally, the Nephi segment ruptured only about 300 years ago and the mean recurrence interval is about 1,100 years (Table 1).

Hence based on the elapsed time since the last large earthquake and the mean recurrence intervals, we have three very different scenarios (Table 1). For the Brigham City segment, the elapsed time exceeds the mean recurrence interval by almost a factor of two. For the Salt Lake City segment, the elapsed time exceeds the mean recurrence interval by about 100 years. Finally for the Nephi segment, the 300-year elapsed time is not even a third of the mean recurrence interval and so a future earthquake would seem to be unlikely in the next 100 years (Table 1).

To illustrate the differences in hazard from these three scenarios along the Wasatch Front, we have performed both a time-independent and time-dependent PSHA for the three cities: Brigham City adjacent to the Brigham City segment, Salt Lake City next to the Salt Lake City segment, and finally Nephi next to the Nephi segment (Fig. 3). The WGUEP [5] seismic source model including the characterization of the Wasatch fault zone was used in the PSHA. The NGA-West2 ground motion models assuming a Vs30 (time-averaged shear-wave velocity in the top 30 m) were used. The WGUEP [5] used the BPT renewal model to model the time-dependent behavior of the single-segment model of the five central segments. Because there were insufficient data to constrain recurrence intervals, the BPT model was only used for the single-segment ruptures in the multi-segment rupture models. Hence what we refer to as the time-dependent model for the five central segments is not totally time-dependent. The effective weights for the time-dependent model for the five central segments ranged from 0.70 to 0.83. Even for the single-segment rupture model, the WGUEP [5] gave 0.2 weight to a Poisson model and 0.8 to the BPT. In the PSHA, we did increase the weight to 1.0 for the BPT model in the single-segment rupture model. From the BPT rupture probabilities, equivalent Poisson rupture rates can be back-calculated for a specified time interval and used in the PSHA to calculate the time-dependent hazard. The weighted time-independent Poisson and time-dependent equivalent Poisson recurrence intervals are listed in Table 1.

The results of the PSHA calculations are shown in terms of hazard curves in Fig. 5 for the three cities for peak horizontal ground acceleration (PGA) and 1.0 sec horizontal spectral acceleration (SA). Values for a return period of 2,475 years are listed in Table 2. The time-dependent PGA in Brigham City is 42% higher than the time-independent value. The 1.0 sec SA is higher by 53% for the time-dependent hazard. These differences are significant. Similarly the differences for Nephi are significant but in an opposite sense. The differences in hazard are due solely to the modeling of the time-dependent and time-independent behavior of the five central segments. All other faults have been modeled as Poissonian.

Time-independent and time-dependent Uniform Hazard Spectra (UHS) for a 2,475 year return period are shown in Fig. 6. These spectra are the starting point for the MCE_R as defined by ASCE7-16. As expected, the time-dependent hazard is higher than the time-independent hazard for Brigham City and Salt Lake City at all spectral periods less than 2 sec (Fig. 6). The pattern is reversed for Nephi.

DISCUSSION AND CONCLUSIONS

The differences in hazard between the time-dependent and time-independent for the three cities adjacent to the Wasatch fault are significant. Yet these differences as stated earlier are not reflected in the USGS National Seismic Hazard Maps which date back to 1976. So for buildings constructed to the IBC after 1976 in Brigham City and to a lesser extent, Salt Lake City may have been designed to levels that could be too low if the time-dependent hazard is considered. Note that there are other factors that come into play in determining Design Earthquake ground motions e.g., 2/3 factor applied to the MCE_R but the impact of modeling major seismic sources in a time-dependent manner can still be significant as illustrated by the Brigham City example (Table 2). There are other areas in the U.S. where the elapsed times of the dominant seismic sources are close to or exceed the mean recurrences interval. The highly populated eastern San Francisco Bay area is one example where it has been 152 years since the last major earthquake (1868) ruptured the Hayward fault which traverses through the East Bay. Paleoseismic data for the last 12 earthquakes indicate a mean recurrence interval of 150 years [18]. The Cascadia subduction zone last ruptured in a **M** 9 earthquake in 1700 and paleoseismic data using marine turbidites indicate a mean recurrence interval of 559 years. However, the mean recurrence intervals for characteristic earthquakes range from 260 to 1,012 yrs depending on whether the megathrust is within a cluster or between clusters [19]. These models and their observations need to be included in time-dependent PSHAs.

The vast majority of the engineering community and building owners in the U.S. are unaware that the National Seismic Hazard Maps do not consider the elapsed time since the last large earthquakes on seismic sources and that the IBC can be unconservative in areas where these elapsed times have been exceeded. Obviously this does not occur everywhere and certainly the paleoseismic record is insufficient to model the vast majority of Quaternary faults in the National Seismic Hazard Map model [1]. However, for those areas where the data are adequate to include time-dependent modeling of significant Quaternary faults and where there is a significant threat in populated areas (e.g., Salt Lake City and Eastern San Francisco Bay), we believe it is time for the USGS and governing agencies to include time-dependent fault behavior in the National Seismic Hazard Maps.

We appreciate that the engineering community does not like significant changes in the IBC design ground motions from one edition to another. One approach would be to weigh both time-dependent and time-independent approaches in the USGS National Seismic Hazard Map model with weights being re-evaluated in every cycle of the maps. For those areas where the data indicate that a large earthquake is unlikely because of the recency of occurrence such as the area adjacent to the Nephi segment, then simply staying with the Poisson hazard is a reasonably conservative approach.

Table 1 – Recurrence for Wasatch Fault Central Segments

Segment	**Weighted Mean Time-Independent Recurrence Interval (Poisson) (yrs)**	**Elapsed Time (in 2016) (yrs)**	**Weighted Mean Time-Dependent Recurrence Interval (Equivalent Poisson) (yrs)**
Brigham City	1500	2500	500
Weber	1400	600	2400
Salt Lake City	1300	1400	700
Provo	1200	600	1500
Nephi	1100	300	6100

Table 2 – 2,475-Year Return Period PGA and 1.0 Sec SA

City	**PGA**		**% Change**	**1.0 Sec SA**		**% Change**
	TI	**TD**		**TI**	**TD**	
Brigham City	0.52	0.74	+42%	0.36	0.55	+53%
Salt Lake City	0.64	0.75	+17%	0.46	0.56	+22%
Nephi	0.57	0.33	-42%	0.42	0.21	-50%

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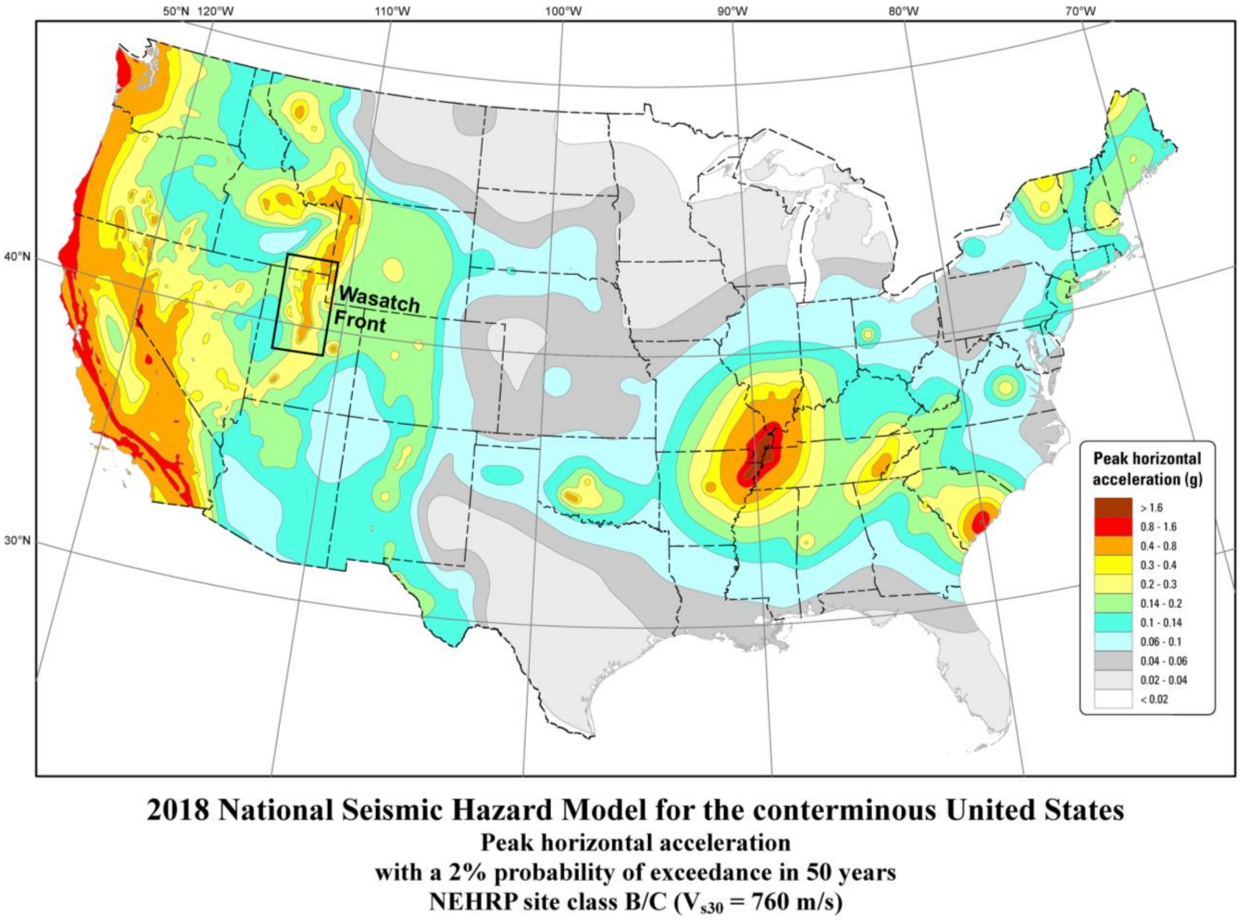


Figure 1. USGS National Seismic Hazard Maps for PGA and a return period of 2,475 years (2% probability of exceedance in 50 years) for a V_S30 of 760 m/sec (from Petersen *et al*. [1]). The maps show time-independent hazard.

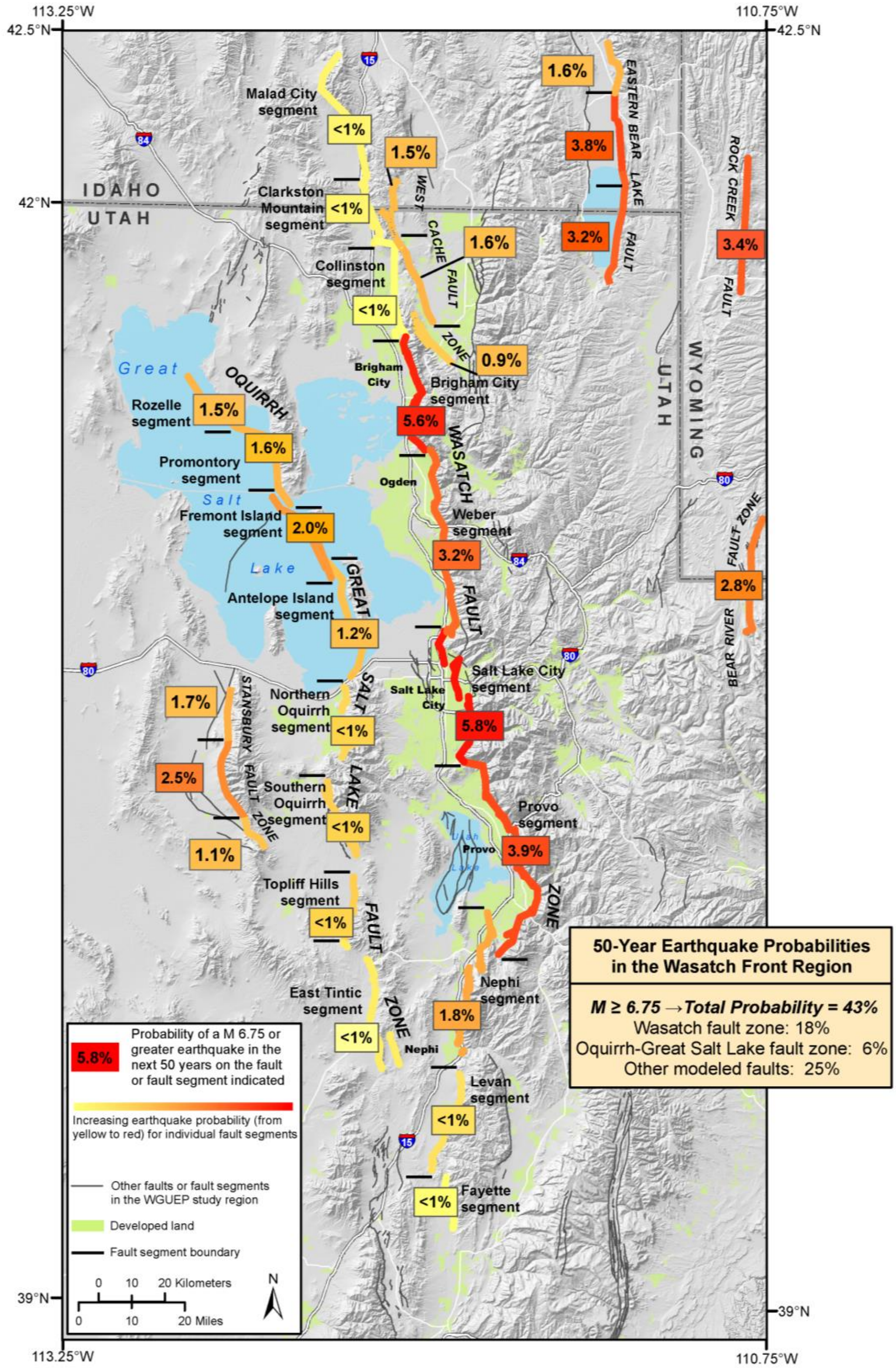


Figure 2. Probabilities of one or more earthquakes of **M** 6.75 or greater during the period 2014 to 2063 for selected faults and fault segments in the Wasatch Front region, Utah (from WGUEP [5])

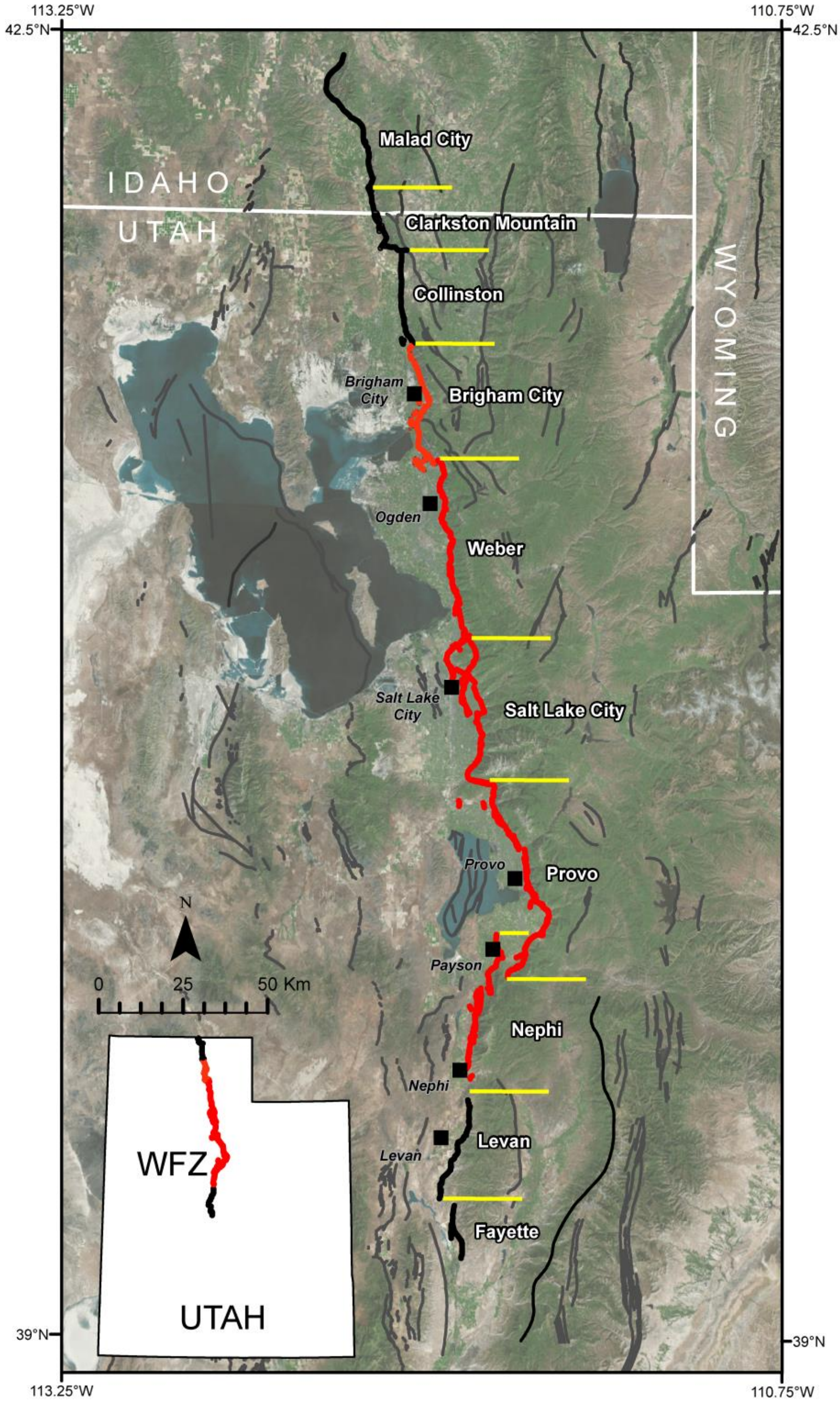


Figure 3. The Wasatch fault zone in northernmost Utah and southernmost Idaho. The five central segments are shown in red. Cities of Brigham City, Salt Lake City, and Nephi also shown (from WGUEP [5])

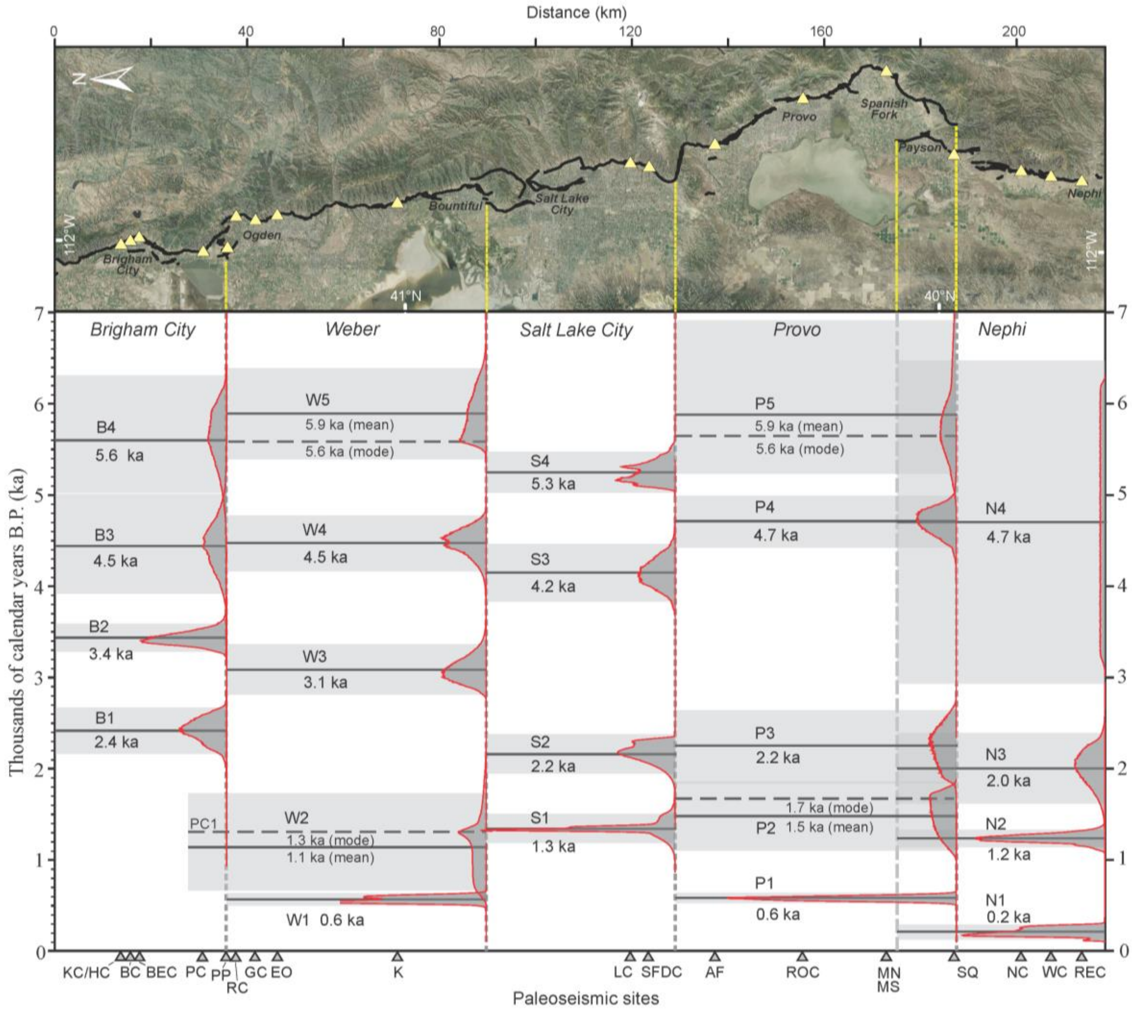
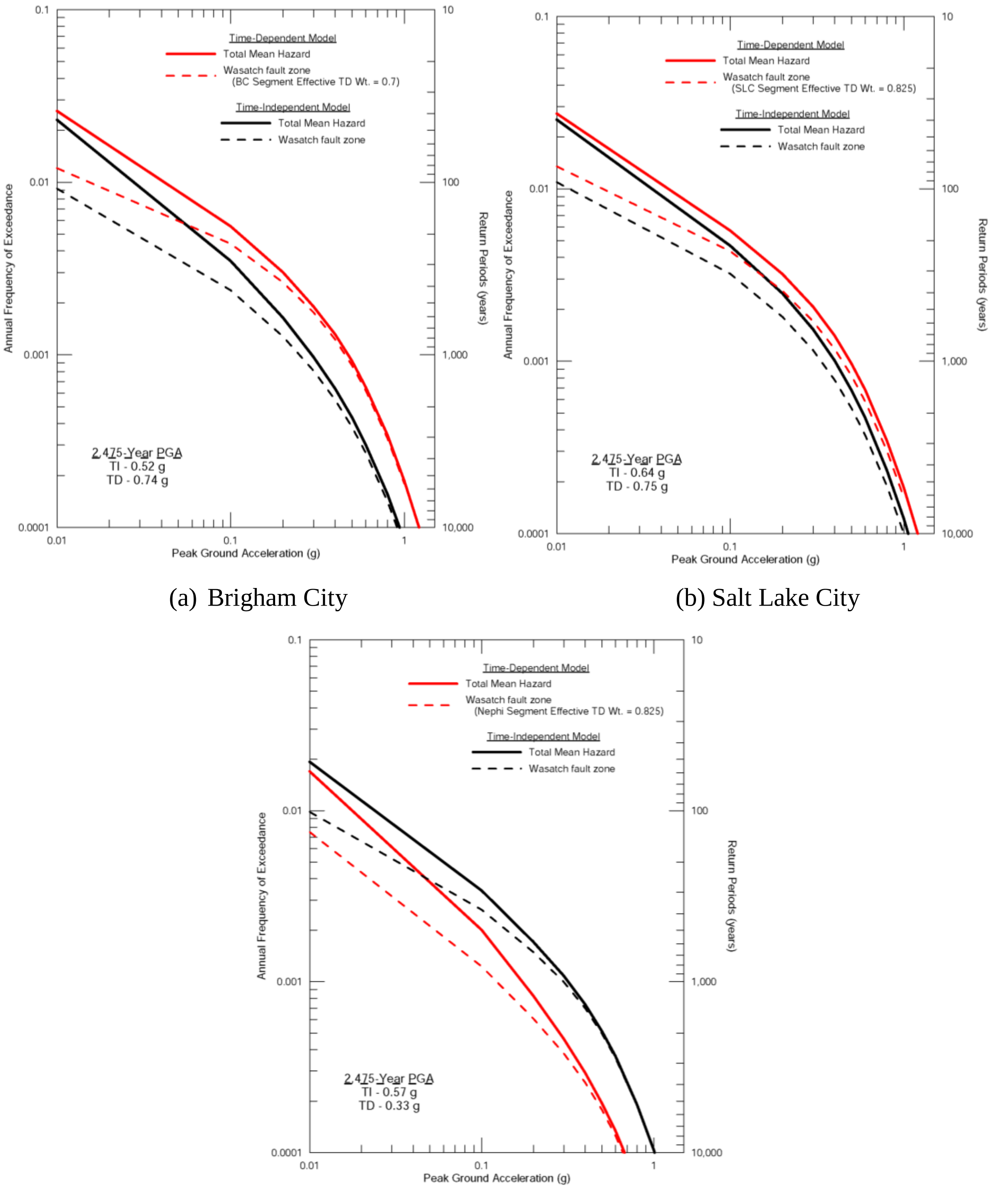


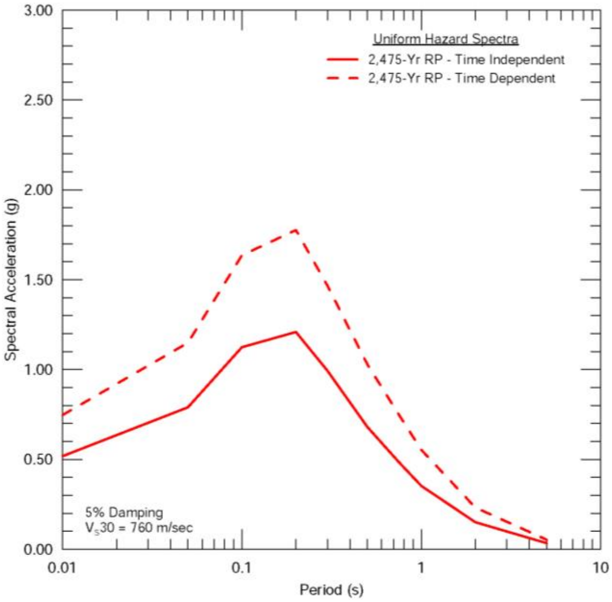
Figure 4. Single-segment rupture model for the five central segments of the Wasatch fault zone. Upper panel shows map of the central segments; yellow triangles show locations of paleoseismic study sites. Lower panel shows times of earthquakes on each segment. Solid horizontal lines indicate mean times and gray boxes show two sigma time ranges (from WGUEP [5])



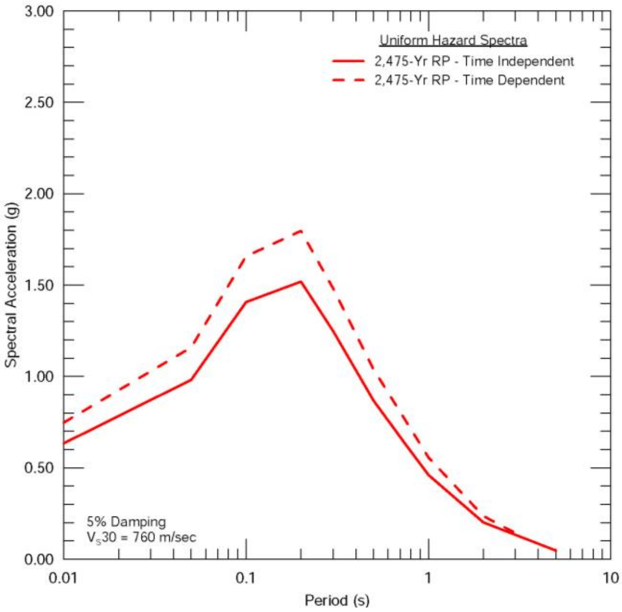
(a) Brigham City (b) Salt Lake City

(c) Nephi

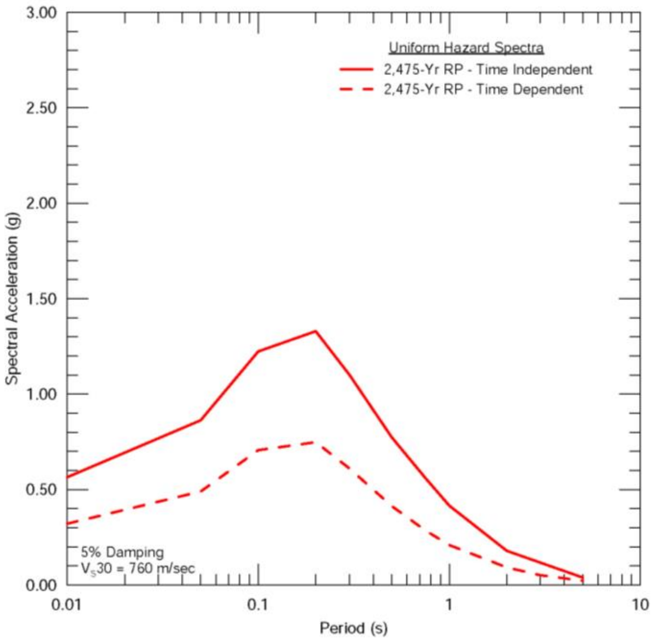
Figure 5. Time-independent and time-dependent mean hazard curves for PGA for (a) Brigham City, (b) Salt Lake City, and (c) Nephi. The contributions of the Wasatch fault are also shown.



(a) Brigham City



(b) Salt Lake City



(c) Nephi

Figure 6. Time-independent (solid line) and time-dependent UHS (dashed line) for a 2,475-year return period for the cities of (a) Brigham City, (b) Salt Lake City, and (c) Nephi.

