Cross-validated probabilistic seismic hazard

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Abstract

We propose a cross-validated seismic hazard (CVSH) method contrasting time-independent and dependent models via the Poisson and Weibull probability cumulative distributions. Based on the upper-limit spectral accelerations retrieved from the time-dependent models, we infer that in the memoryless Poisson approach, the selected lifetime of buildings is location-dependent rather than a fixed classical value of 50 years for all sites. All models compute the seismic hazard for magnitudes M 5-7.83 by the influence of the interface subduction zone in El Salvador at three locations, the Capital City San Salvador, the Port of Acajutla on the coastline, and Arcatao Town in the North of the country returning average spectral accelerations with less than 10% differences in all cases.

Keywords

Lifetime, cross-validation, conditional probability, response spectra
1. Introduction

The time-independent probabilistic seismic hazard assessment is the core of any building design guidelines. After the seminal work of Esteva (1967, 1968) and Cornell (1968), and later being Fortran coded by McGuire (1975), this method has been applied extensively around the globe and replicated over and over through several computer codes. On the other hand, Woo's exceptional work (1996) gave us light as an alternative approach to compute free-zone design accelerations and compare with the rigid-zone former method. However, there is a lack of a validation procedure in the results of a memoryless seismic hazard assessment; although, in some cases, this method overestimates peak ground accelerations compared with historical data in California and other parts of the world (Salditch et al., 2020; Stein et al., 2017).

Salazar (2021) studied earthquake interoccurrence times using Weibull and Poisson magnitude probabilities distributions connected with hazard models for the volcanic chain in El Salvador and neighboring Central American countries. Within this article, we augment the work of Salazar (2021) for the interface subduction zone in the region and propose a methodology to cross-validate the classical time-independent seismic hazard schemes via a comparison of time-dependent calculations in a rigid and free-zone fashion.

2. Earthquake Catalog

The Middle America Trench runs parallel to the coast where the Oceanic Cocos Plate submerges underneath the Continental Caribbean Plate at a rate of 7-8 cm/yr. Shallow
Earthquakes occur in the inclined seismic zone with focal depth less than 60 km, yielding a thrust focal mechanism. We updated the homogenized moment magnitude catalog compiled by Salazar et al. (2013), covering the years 1609-2019 employing global earthquake solutions (ISC, 2020; PDE, 2020; CMT Ekström et al., 2012) and special studies that have recalculated origin parameters of large earthquakes (Ambraseys & Adams, 1995; Ambraseys, 1995; Guzmán-Speziale, 2005; Leeds, 1974; Molnar & Sykes, 1969; White et al., 2004). The final list contains 1320 events with M 5.0 – 7.83 (Figure 1). The maximum magnitude of 7.83 corresponds to September 7th, 1915, at a depth of 60 km, causing severe damage in the western part of El Salvador. We propose a seismogenic geometrical delimitation comprising the subduction trench to the south (Lemenkova, 2019), the coastal area to the North, and the depth contours of the subducted slab proposed by Slab’s USGS project (Hayes et al., 2012; Salazar et al., 2013). However, epicenters of historical earthquakes (1609-1915) lay outside our delimitation since their locations correspond to the centers inland of the isoseismal curves rather than being offshore. We consider such location uncertainty in the seismic hazard calculation in Section 3.3. The reverse-slip focal mechanism obeys Hauksson (1990), yielding rake angles of 45° to 135° and within ±20° of the strike of the trench. The northern limit of the interface subduction zone matches the southern limit of the volcanic chain seismogenic source in Central America (Salazar, 2021).

The completeness analysis of the catalog for several magnitude bins relies on Tinti & Mulargia (1985) method; see Table 1 and Figure 2. The catalog and its completeness found the study of the earthquake interoccurrence times in the following section.
3. Earthquakes Interoccurrence times

This section aims to corroborate the time between consecutive earthquakes – the interoccurrence times - that belong to a particular magnitude bin follow a Poisson or Weibull probability distribution. Once we assure that such distributions are adequate to the interface subduction zone seismic activity, we evaluate the seismic hazard employing magnitude likelihood distributions on time-independent and dependent models.

The Poisson probability cumulative distribution $F(t)$ is given by:

$$F(t) = 1 - e^{-\lambda t} \quad t > 0, \lambda > 0$$

Eq. 1

where $\lambda$ is the number of earthquakes per unit time, and $t$ is the interoccurrence time (Anagnos & Kiremidjian, 1988).

The cumulative $F(t)$ Weibull distribution with parameters $\alpha$ and $\beta$ yields (Walpole et al., 2007):

$$F(t) = 1 - e^{-\alpha t^\beta} \quad t>0, \alpha, \beta >0$$

Eq. 2

We first test the two probability functions depicted in Figure 3 and constants listed in Table 2 for several magnitude bins employing the whole earthquake catalog without removing foreshocks and aftershocks. To get the Weibull $\alpha$ and $\beta$ parameters, we use the algorithm developed by Bean et al. (1981); the Poisson $\lambda$ constant is a simple count of the number of earthquakes in a magnitude bin. The Root Mean Square RMS is used to represent the error between observed and predicted values. Note that the interoccurrence times are effective after the year of completeness for a specific magnitude bin; otherwise, small and intermediate events might give false information due to the unreported earthquakes before
the completeness year. We also use magnitude bins since our objective is to perform seismic hazard calculations.

Figure 3 on the left depicts the predicted and observed Weibull probability cumulative distribution vs. interoccurrence times. We also present the linearized Weibull plots on the right to visualize better the goodness to the fit (Abaimov et al., 2008). Weibull probability distribution yields lower RMS (0.012-0.06) than the Poisson distribution (0.049-0.081) for all magnitudes bins; the linearized plots also reveal the goodness to the Weibull fit; the Poisson distribution does not fit to the seismicity times patterns of the subduction interface zone for small magnitudes less than 6, as a logical consequence of incorporating dependent events in the analysis. However, for magnitudes greater than 6, the analysis suggests that the Poisson model can represent the level of seismic activity. We confirm such statement since the $\alpha$ Weibull parameters yields near zero yielding $e^\alpha \approx 1$, so Equating the right side of Eq. 1 and 2 would yield similar predicted values.

Since we assure that Weibull distribution is suitable when all events play in the analysis, we proceed to calculate the conditional probability $f(M)_{t,\Delta t}$ that gives the probability that an earthquake within a magnitude bin might happen after an elapsed time $\Delta t$ once an earthquake has happened at the time $t$:

$$f(M)_{t,\Delta t} = \frac{R(t) - R(t+\Delta t)}{R(t)}$$

Eq. 3
where $R(t) = 1 - F(t) = e^{-\alpha t^\beta}$. Figure 4 shows the conditional probability for several magnitude bins; in general, the greater the magnitude, the lesser the conditional probability, and the longer the interoccurrence time greater the probability of occurrence. We keep this information to use in the time-dependent seismic hazard assessment of the next section (e.g., Table 2 lists the conditional probabilities for the year 2070).

We secondly test the Poisson probability function depicted in Figure 5 for several magnitude bins removing from the catalog the foreshocks and aftershocks employing the Gardner & Knopoff (1974) time-distance dynamic window scheme. The RMS yields lower (0.030-0.062) compared with the Weibull previous analysis for all magnitude bins, and Figure 5 shows a good Poisson fit in all cases. It means that removing the dependent events in the catalog effectively converts the seismicity to a Poissonian distribution. Once we have assured that the declustered catalog fits a Poissonian distribution, we proceed to perform the seismic hazard assessment in the next section.

4. Cross-validated probabilistic seismic hazard (CVSH)

This section proposes a cross-validated probabilistic seismic hazard (CVSH) employing the results of the seismicity patterns and probability distributions for the interface subduction
zone obtained in the previous section. The CVSH method consists of contrasting the computed spectral ordinates from time-independent and dependent probabilistic schemes in rigid and free-zone fashions to find a suitable building lifetime consistent with the upper-limits of the dependent models. We demonstrate applying the CVSH methodology for three sites in El Salvador that such lifetime is location-dependent rather than a fixed arbitrary value, e.g., 50 years at all sites.

4.1 Time-independent

We present a basic theory of two time-independent models, the classical rigid-zone Cornell-McGuire approach and the free-zone Woo (1993). An in-depth discussion of these methods is elsewhere (e.g., Salazar, 2018).

For the rigid zone approach, the mean annual rate $E(z)$ for ground motion $z$ is:

$$E(z) = \nu \int_{R=0}^{\alpha} \int_{M_{min}}^{M_{max}} f(M)f(R)P(Z > z|M,R)\,dR\,dM$$

Eq. 4

where $\nu$ is the number of earthquakes per year between the minimum magnitude maximum magnitude $M_{max}$; $f(M)$ is the probability of a magnitude $M$ and depends on the classical Gutenberg-Richter (G-R) relationship $\log N = A - BM$ based on the declustered catalog. $f(R)$ is the probability of various earthquake locations at a distance $R$ from the site. $P(Z > z|M, R)$ is the probability that a given earthquake of magnitude $M$ and epicentral distance $R$ exceeds the motion level $z$. The probability of exceedance $q$ of a given ground or spectral motion $z$ for a fixed lifetime of the building $L$ is given by:
\[ q = 1 - e^{-LE(z)} \]  

Eq. 5

An acceleration design level is retrieved usually at 2% and 10% of exceedance.

The free-zone approach \( f(M) \) yields the probability of exceeding \( M-\Delta M \) less the probability of exceedance \( M+\Delta M \) according to a Gaussian distribution that depends on the magnitude error based on the clustered catalog. The equivalent of the number of earthquakes per year \( v \) and the probability \( f(R) \) in Eq. 1 is substituted by the Kernel \( K \) probability function \( f(M, R) \) that depends on the bandwidth of average distance between earthquake epicenters on several magnitudes.

For the case of the rigid-zone method, the G-R relationship and magnitude probability \( f(M) \) is presented in Figure 6a and b, yielding a \( B \) value of nearly one – typically of tectonic earthquakes worldwide - after the completeness analysis and the declustering process (Gardner & Knopoff, 1974). Figure 7 shows the bandwidth of epicentral distance-magnitude for the subduction interface zone used in the free-zone method.

4.2 Time-dependent

Previous works on time-dependent seismic hazard provided consensus estimates of the magnitude, location, and likelihood of potentially damaging earthquake ruptures in the greater California (Field et al., 2015). They employed physics-based earthquake simulators related to elastic-rebound predictability employing Monte Carlo simulations. We propose a
more oriented engineering simplified time-dependent models for rigid and free zones

relying on the substitution of the term \( f(M) \) on Equation 4 by the conditional probabilities \( f(M)t, \Delta t \) yielded from the Weibull distribution analysis and correspondent elapsed times (see Figure 4).

In the rigid model, the mean rate of occurrence \( \nu \) must be calculated based on the clustered catalog. A key consideration when using time-dependent models for calculating the probability of exceedance in Eq. 5 is to set a lifetime \( L \) of one year to consider that a level of motion might be exceeded in the next year after the selected elapse time for a specific earthquake size (Salazar, 2021).

4.3 Computation of cross-validated probabilistic seismic hazard (CVSH)

We computed the seismic hazard at three sites: Capital city San Salvador (89.25°W, 13.7°N), Acajutla Port in the coastal area (89.8314°W, 13.5761°N) and the Town of Arcatao at the North of the country (88.7489°W, 14.0936°N). We used the rigid-zone and free-zone methods in a time-independent and dependent fashion. We homogenized the hazard computations establishing the following parameters:

a) A flat topography surface integration grid of 0.1° x 0.1° in longitude and latitude;

b) A minimum and maximum magnitude of 5.0 and 7.83 respectively with a magnitude increment \( \Delta M=0.1 \); we adopted the maximum magnitude listed in the catalog to avoid bias in the hazard determination due to an increments of such value. Correa-Mora et al. (2009) suggested GPS-derived coupling estimates for the
Middle America trench, resolving a weak coupling between the Cocos and the Caribbean plates, so a maximum magnitude of 7.83 seems reasonable in this case.

c) The Youngs et al. (1997) ground motion prediction equation (GMPE) developed subduction earthquakes worldwide applicable in the magnitude range M 5-8+
setting the interface mechanism and the motion prediction at rock sites class
NEHRP A/B; the distance definition is the closest distance to the rupture area;

d) A seismogenic fix depth of 30 km;

e) A truncation value of 3 standard deviations $\sigma$ in the GMPE;

f) For the free-zone methods: Table 3 shows the magnitude and epicentral uncertainties adopted. Note that the epicentral location uncertainties are larger for historical earthquakes (see Section 2).

g) We estimate the peak ground acceleration and 5% damped spectral ordinates for 12 structural periods between 0 - 3 s at 2 and 10% probability of exceedance; in the case of the time-independent models, we use a lifetime $L$ of 25, 50, 75, and 100 years, and for the dependent models we calculated the accelerations that can stand for the year 2025, 2045, 2070, 2095 and 2120 according to the conditional probabilities depicted in Figure 4 for each magnitude bin.

h) In the case of the time-dependent models, we assume that we started to build infrastructure in 2020, a year after the last one reported in our earthquake catalog.

i) We used and modified the KERFRACT Fortran program by Woo (1996) for the time-independent and dependent free model and developed our HAZARD Fortran code for the rigid zone methods.
We firstly examine the results for the capital city San Salvador (see location in Figure 1), located about 25 km distant from the coastline. Figure 8a shows that time-independent methods for both rigid and free zone yields practically the same ground and spectral acceleration level for all lifetimes. The longer the lifetime, the more significant the spectral acceleration (see also Table 4). It also confirms that the rigid seismogenic source delimitation and its correspondent level of seismic activity agree with the contributions of gridded sources developed in the free-zone method; it also asserts the quality of the compiled earthquake catalog and its completeness periods. Figure 8b shows the results retrieved from the time-dependent methods; again, the rigid and free-zone yield nearly acceleration levels for all structural periods under consideration; shorter the elapsed times lower the hazard; nevertheless, they are not dependent on the elapsed time themselves after the 2045 year. It is a logical result seeing Figure 4, in which conditional probabilities are above 0.85 for all cases after this year. Although, the analysis reveals an essential feature of the time-dependent methods: the level of spectral acceleration has an upper limit when considering all conditional probabilities in all magnitude bins near or equal to unity (e.g., at the year 2095 or 2120, see Figure 4). On the other hand, classical independent-time models might have no acceleration limitations establishing lifetime and its correspondent probability of exceedance.

Let us take as a reference the spectral accelerations giving the chance of all earthquakes to occur to give the conditional probabilities near or equal to 1.0 (e.g., year 2120 in Figure 5 and Figure 8b). We can go back to Figure 8a and select a spectrum from the time-independent analysis with a lifetime that better matches the average of time-dependent methods. We suggest in Figure 8c-d that a lifetime of 100 years fits the upper limits of
time-dependent methods for both the 2 and 10% probability of exceedance with average spectral differences of 6 and 3% respectively; presumably, such lifetime is the same as the difference between 2120 and 2020 (the start year of construction) in the time-dependent scheme. Note that a classical lifetime of 50 years underestimates by 20% the time-dependent estimations.

Analyzing the Port of Acajutla at the coastal area (see location in Figure 1), the results imply that time-independent methods - rigid and free-zone- give similar spectral acceleration levels (Figure 9a). Still, time-independent methods are sensitive to the structure's lifetime selection. In this case, the time-dependent accelerations calculated for the year 2095 with conditional probabilities nearly one to all magnitudes (see Fig. 5 and Fig. 9b) pair the spectral motions for 75 years of lifetime with average differences of 7 and 3%, respectively, for 2 and 10% exceedance (Fig. 9c-d). Such a lifetime is a different one of San Salvador city - 100 years- and presumably the same 75 years between 2095 and 2020. We attribute that such differences of a selected lifetime with San Salvador due to the nearest location of the Acajutla Port to the interface subduction seismogenic source. We build a hypothesis: in the time-independent scheme, a building constructed near an active seismic source might have a shorter period of life, and it must be equal to the time between the start year of construction –in our case 2020 - and the last year to calculate the elapsed times in the time-dependent models. On the other hand, selecting a lifetime at Acajutla Port of 100 years would give spectral accelerations that might have never occurred and increase the building construction cost at the coastal area.

To validate our hypothesis above, we also performed a seismic hazard at the Town of
Arcatao in the North of El Salvador (see location in Figure 1) 90 km away from the interface subduction zone's northern limit. In general, free-zones methods generate spectral ordinates 10-15% higher than rigid zones methods at longer lifetimes; we attribute such difference due to smooth seismicity patterns created by the Kernel $K$ functions in the null subduction epicenter region from a distant site of the subduction zone with the combination of the epicentral error of 30 km employed in historical shocks analysis (Figure 10a-b, Table 3). However, average spectral ordinates from both methods yield similar when comparing the upper limits of time-dependent models and 200 years of lifetime for both 2 and 10% probability of exceedance with average spectral differences of 9 and 7%, respectively (Fig. 10a-d). In this case, the accelerations in 2220 on the dependent scheme would also return upper-limit accelerations employing $f(M)t$, $\Delta t = 1$ as an extension of Fig. 5 to that year. The period of life from a distant site of a seismogenic source must be more extended than a building located inside a seismogenic source. Nevertheless, taking a shorter lifetime (e.g., the classical 50 years) might underestimate the seismic actions yielding structural damage even far away from the interface subduction seismogenic source if time-independent methods are lonely applied.

In practice, structural designers seek seismic coefficients for all possible earthquakes to design a building; then, the time-dependent schemes give maximum spectral accelerations engaging all conditional probabilities near or equal to unity. When using the time-independent methods, one must investigate the lifetime that accords to such time-dependent upper limits; the procedure cross-validates the seismic hazard once the lifetime pairs the time from the starting year of construction and the last year employed to calculate the elapsed times. In general, it seems that the classical lifetime of 50 years obeys more due to
a financial interest rather than scientific ones, e.g., such years set as the intermediate-term for which a person can buy and own property, so the risk transfers to the individuals that acquire old buildings (Salazar, 2018).

4. Conclusions

The author has manifested that Weibull probability distributions fit the earthquake interoccurrence times for the interface subduction offshore El Salvador when considering all the catalog events and that the Poisson distribution fits the time between earthquakes when removing dependent events. Consequently, both probabilities distributions successfully give elastic response spectra at three sites in El Salvador, employing time-independent and dependent hazard models in a rigid and free-zone fashion; however, the time-independent calculation produces spectral accelerations that are arbitrary due to the building lifetime speculation. The cross-validated method suggests that the lifetime of structures must be location-dependent rather than an arbitrary value, and if more accuracy is needed, it might be structural period-dependent as well (see Figures 8-10).

The building lifetime in the time-independent schemes must be selected equal to the time between the start year of construction and the last year to calculate the elapse times agreeing to magnitude conditional probabilities equal or near to unity. It is indeed when the spectral acceleration levels yield the upper-limits in the time-dependent methods. The nearest the building's location to a seismogenic source, the shorter the structure's period of life might be. It is a natural survival process; an individual immersed in a hazardous
environment has less life expectancy than another settled in a low threat region. The selection of a long lifetime might also induce seismic actions that would never happen, and the selection of a short one would underestimate seismic actions even if a building settles away from the seismogenic source. The CVSH methodology might be implemented to risk models if building fragility curves are time-dependent calculated; indeed, the structure's vulnerability is not independent of time as we usually consider using an arbitrarily selected lifetime to calculate the correspondent spectral ordinates in the hazard calculations.

The cross-validated seismic hazard (CVSH) naturally implies that the selected lifetime is seismogenic source dependent as well. Then combining several sources simultaneously in a Poisson model setting a fixed lifetime would mislead the resulting spectral accelerations for design. Although the hazard assessment gives spectral motions for the subduction interface zone, we corroborated the lifetime location-dependency due to the volcanic chain zone's influence at three sites under analysis based on Salazar (2021). We confirm that for the nearby sites to the volcanoes centers - San Salvador city and Port of Acajutla - a lifetime of 50 and 60 years matches time-independent and dependent models; a lifetime of 75 years is suitable for the Town of Arcatao 55 km away from the volcanic zone axis (Fig. 11a-c).

The new seismic code regulations in El Salvador must include a seismic zonation and correspondent lifetimes for each seismogenic source rather than one general zonation that combines all influences of earthquake sources. For example, based on the first instance on the PGA at the three sites evaluated, the coastal area yields 1.3 and 2.5 times more shaking than the central and north parts of the country, respectively. Consequently, the building code may charter three zones and their correspondent spectra due to the interface subduction earthquake's influence with distinctive lifetimes. Our dependent hazard scheme
limits the analysis to the maximum magnitude reported in the catalog since conditional probabilities are calculated only for the listed events within magnitude bins. In this case, time-independent methods can incorporate a maximum magnitude (e.g., 0.2 to 0.5 units more than the maximum one listed in the catalogue) after applying the cross-validated procedure explained in this article.

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