Simplified Probabilistic Aftershock Hazard Analysis

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Abstract

Current hazard estimation within seismic design codes do not address anticipated intensity or duration of aftershocks. Following major earthquake events, the intensity and duration of aftershocks have significant impact on the recovery efforts and the public psyche. A simplified methodology was developed to calculate the probability of a future damaging aftershock over a specified time interval. The methodology considers each scenario earthquake using the magnitude-distance deaggregation results of the PSHA combined with an aftershock temporal and spatial window function to estimate the probability that the design motions will be exceed by an aftershock within a certain time interval. The relative difference in aftershock probability results from different magnitude-distance deaggregation of the design basis ground motions at different hazard levels. Bettering understanding of the potential for aftershocks is essential to resilient seismic design and the ability of a community to recover quicker.

Keywords: probabilistic aftershock hazard analysis, probabilistic seismic hazard analysis, resilient seismic design, magnitude-distance deaggregation

1 INTRODUCTION

Following major earthquake events, the intensity and duration of aftershocks have significant impact on the recovery efforts in both terms of life safety and the public psyche. The Christchurch 2011 earthquake is a particular example where a significant aftershock sequence, had a lasting impact on recovery efforts through recurrent damage, the need to keep areas closed for safety. Post event there was considerable awareness of the aftershock hazard and impact to the community (Dorahy and Kannis-Dymand, 2012).

The spatial heterogeneity of seismicity in aftershock zones show that the activity, size and distribution of events and decay rate all vary significantly with location. The common practice of simply assigning an overall a, b and aftershock decay is an oversimplification of the complex and spatially heterogeneous internal structure of aftershock sequences (Wiemer 2000).

Current methods to estimate ground motions from aftershocks, is predicated on knowing the mainshock and using observed time-dependant aftershock rates as input to model. Wiemer (2000) introduced a model for probabilistic aftershock hazard mapping, applying the same concepts to model epistemic uncertainty within a PSHA to an aftershock sequence following a mainshock. After the Christchurch 2011 earthquake, GNS developed time-dependent seismicity models to reflect the greatly enhanced seismicity in the region and its gradual decrease of the seismicity over the next few decades (Gerstenberger et al., 2014). These seismicity models, along with modified ground-motion prediction equations and revised hazard calculation procedures have been used to derive new seismic hazard estimates for timeframes from months to 50 years. The hazard estimates have been used for a variety of applications crucial to planning and implementing the recovery of Christchurch.

Current building codes do not focus on earthquake resilience – the ability of an organization or community to quickly recover after a future large earthquake. Instead they are designed to protect the lives of building occupants. Significant damage to the building structure, architectural components and facades, mechanical/electrical/plumbing (MEP) equipment and building contents is allowable, as long as lives are kept safe. As such, when a major earthquake strikes an urban region, the financial costs of demolition, repair and restoration of utilities are immense. Indirect losses due to downtime, business interruption, the loss of culture, sense of community, and quality of life can impact communities and hinder recovery for years and even decades after the earthquake. As current seismic is evolving to consider more resilient concepts such as the Resilience-based Earthquake Design Initiative (REDi™) Rating System for the Next Generation of Buildings (Almufti and Wilford, 2014) and other similar resilience initiatives. A key consideration for resilience design is a holistic understanding of the hazard, in this case the intensity and duration of aftershocks. Resilience concepts accept that damage will occur, but also need to include the ability to recover quickly when the event occurs. This drives the need to better understand the potential for aftershocks during resilient design.

This can be exemplified in the design for the re-opening of the Sumner Road in the Port Hills of Christchurch against subsequent rockfall. The design brief stated that the road needed to safely reopen within a certain amount of time following the mainshock, so the design needed to not only consider the future design basis earthquake, but the impact of potential aftershocks following the next mainshock. As the intensity and temporal nature of aftershocks are not considered by current seismic design codes or estimated in their accompanying seismic hazard products, how does one estimate the impact from aftershocks from a future earthquake? For Sumner Road, it is hard to not presume that any future aftershock sequence would be similar to what occurred in 2011 or any design basis ground motion. But, one must recognise that the future earthquake could be any of a number of probabilistic scenario events and the next event could be far away from the Port Hills and along the Alpine Fault, ~70km away. If this occurred would the aftershock sequence have had as much impact?

This paper presents a simplified methodology to assess the probability of a future aftershock generating ground motions equivalent to the design basis ground motions as derived from the possible mainshock.

2 METHODOLOGY

The methodology is based on the tenant that a probabilistic seismic hazard analysis defines the design basis ground motions by considering the likelihood of all possible “scenario” earthquakes able to generate ground motions that exceed the design level of interest.

At a conceptual level, the methodology considers each scenario earthquake and the potential for that earthquake to generate a significant aftershock. The magnitude-distance deaggregation results of the PSHA allows isolation of each scenario earthquake by its magnitude-distance and its contribution to the hazard to assess the probability of an aftershock that could exceed the design level of interest.

Practically, the magnitude-distance earthquake deaggregation is combined with an aftershock temporal and spatial window function to estimate the probability that the design motions will be generated by an aftershock within a certain time interval. The aftershock time and distance window following Gardner and Knopoff 1974 is used (Table 1).

Table 1 Aftershock time and distance window following Gardner and Knopoff (1974).

Magnitude	Distance (km)	Time (days)
2.5	19.5	6
3.0	22.5	11.5
3.5	26	22
4.0	30	42
4.5	35	83
5.0	40	155
5.5	47	290
6.0	54	510
6.5	61	790
7.0	70	915
7.5	81	960
8.0	94	985

The simplified method follows these assumptions:

1. The aftershock ground motion of concern exceeds the design basis ground motion.
2. A single aftershock approaching the magnitude of the mainshock is considered.
3. The aftershock can occur anywhere within a distance from the epicentre of the mainshock as defined by the aftershock window.
4. For simplicity spatial distribution of aftershocks along fault sources are not considered.
5. Design ground motions can only be exceeded when the aftershock epicentre-to-site distance is less than mainshock epicentre-to-site distance.

The methodology calculates the probability that an aftershock will exceed the design basis ground motions (P_{af}) by summing the product of the probability of the mainshock (P_{ms}), the probability that it will occur in the time interval of concern (P_t) and the probability that it will occur within a distance to exceed the design basis ground motions (P_d) over all mainshock magnitude-distance scenarios ($M_{ms\ (m-d)}$) from the PSHA.

$$P_{af} = \sum^{Mms(m-d)} P_{ms} * P_t * P_d \qquad [1]$$

Probability of the Mainshock (P_{ms})

The probability of the mainshock is directly from the magnitude-distance deaggregation results within the PSHA corresponding to each scenario mainshock magnitude distance pair ($M_{ms(m-d)}$) for the design basis ground motion and period of interest.

Temporal Probability (P_t)

The temporal probability (P_t) is the probability the aftershock will occur within the time interval of concern. It is calculated as the ratio of the allowable aftershock time window to the time interval of concern considering the magnitude of the aftershock (M_{af}).

For example following the mainshock of $M_{ms}5.0$, an aftershock of $M_{af}5.0$ has a 150 day window that it could occur. If considering aftershocks within a 365 day time interval, the temporal probability for $M_{af}5.0$ would be 42% (155 days /365 days) of occurrence. If considering aftershocks within a 100 day window, the temporal probability would exceed 100% (155/100) and be considered unity.

Distance Probability (P_d)

The probability that the aftershock will occur within a distance close enough to the site to exceed the design basis is termed the distance probability (P_d). It is calculated as the ratio of the area where an aftershock could occur closer to the site than the mainshock to the area of all potential aftershocks considering the magnitude distance window. The area where an aftershock could occur closer than the mainshock can be expressed as the intersection of two circles with radii of mainshock epicentre-to-site distance (L_{ms}) and aftershock epicentre-to-site distance (L_{as}). Figure 1 schematically illustrates the calculation of the P_d through two scenario events ($M_{af}5.0$ and $M_{af}7.0$).

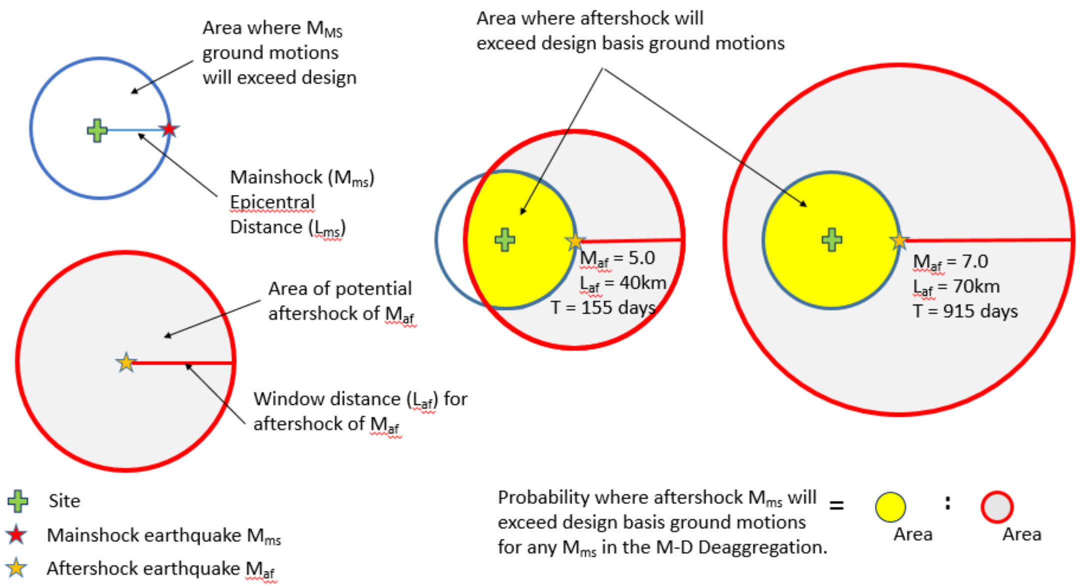

Figure 1. Schematic illustration of the distance probability through two scenario events (M_{af}5.0 and M_{af}7.0).

3 EXAMPLE APPLICATION

To demonstrate, consider two possible scenario earthquakes that could generate the 500-year PGA design basis ground motions for Christchurch; M_{ms}7.0 at ~49km and M_{ms}5.5 at ~17km. In this example the percentage of contribution to this ground motion is arbitrarily assigned 25% and 75%, respectively. The hypothetical magnitude-distance deaggregation showing the two events is presented in Figure 2.

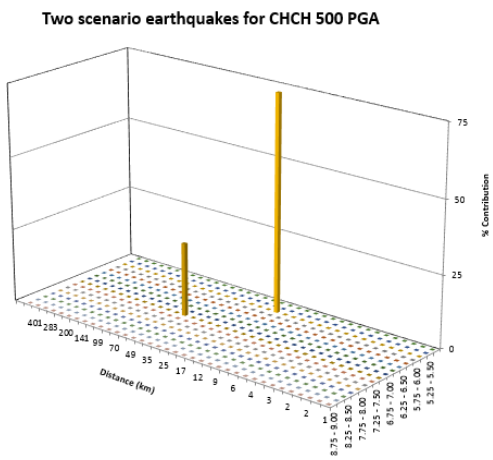

Figure 2. Magnitude-distance deaggregation plot for two scenario events for Christchurch PGA at a 500-year return period.

Applying the methodology at various time intervals of concern, both magnitude-distance events are assessed relative to the time distance aftershock window, assuming it will generate an aftershock M_{af} approaching the magnitude of the mainshock M_{ms}. The temporal probability that it could occur within the time interval of concern and the distance probability that it could be located closer to the site than the mainshock were calculated. These probabilities were multiplied by the probability of the mainshock occurring from the magnitude-distance deaggregation results (e.g. 25% and 75%). The probabilities were summed for both magnitude-distance events to provide a probability for aftershock to generate the design basis earthquake (Table 2).

Table 2. Probability of aftershock exceeding the design ground motions considering 2 scenarios for Christchurch at 500-year PGA.

Design Event (probability)	**30 days**	**100 days**	**365 days**	**730 days**	**1095 days**
M_{ms}7.0 @ 49km (25%)	*29%*	*29%*	*29%*	*29%*	*25%*
M_{ms}5.5 @ 17km (75%)	*16%*	*16%*	*12%*	*6%*	*4%*
Probability of aftershock exceeding design basis:	19%	19%	16%	12%	9%

The methodology is applied to two sites in NZ, Christchurch and Hokitika. The respective, magnitude-distance deaggregation plots for PGA at a 500-year return period derived from a site specific PSHA are shown in Figure 3. The distribution of the magnitude-distance scenarios earthquakes shows a different percentage magnitude-distance pair contribution to the ground motion hazard at this level controlled by the relative location of active faults to each site.

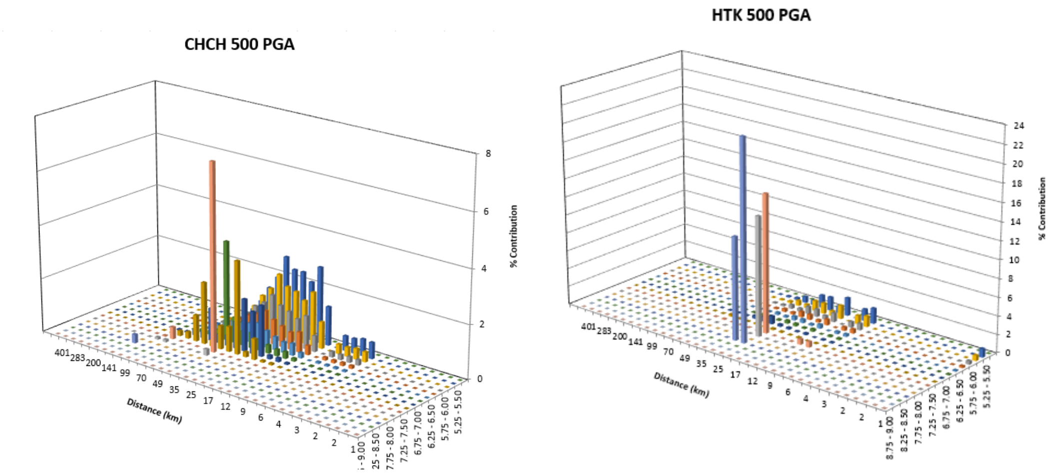

Figure 3. Magnitude-distance deaggregation plots for PGA at a 500-year return period derived from a site specific PSHA

The results from Christchurch and Hokitika are presented in Table 3.

Table 3. Probability of aftershock exceeding the design ground motions for Christchurch and Hokitika at 500-year PGA.

Design Event	**30 days**	**100 days**	**365 days**	**730 days**	**1095 days**
ChCH 500 PGA	22%	22%	20%	14%	11%
HTK 500 PGA	9%	9%	9%	8%	6%

The results show that Christchurch has a higher probability of an aftershock occurring that could exceed the design basis ground motion over a three year period when compared to Hokitika. Examination of the respective magnitude-distance deaggregation plots (Figure 3), show that the hazard in Christchurch has a greater contribution of events from sources at greater distances, whereas Hokitika is dominated by events 25-35km away. The difference in aftershock probability can be explained, by a larger contribution from the events at greater distance in Christchurch resulting in a greater ratio of area where an aftershock can exceed the design ground motions to the area where an aftershock can occur (P_d).

4 APPLICATION TO FOUR SITES

To understand the influence of varying tectonic setting and seismicity to the probability of significant aftershock occurring the methodology was applied to four sites (Sydney, Perth, Christchurch, and Manila) at two different design return periods (500- and 2500-years) for two spectral acceleration (PGA and SA 1-sec) considering five time intervals (30 days, 100 days, 1 year, 2 years, and 3 years).

The results are presented with corresponding magnitude-distance deaggregation plots expressing the relative difference in tectonic setting and seismicity.

4.1 Results for 500-year PGA at Manila, CHCH and Perth

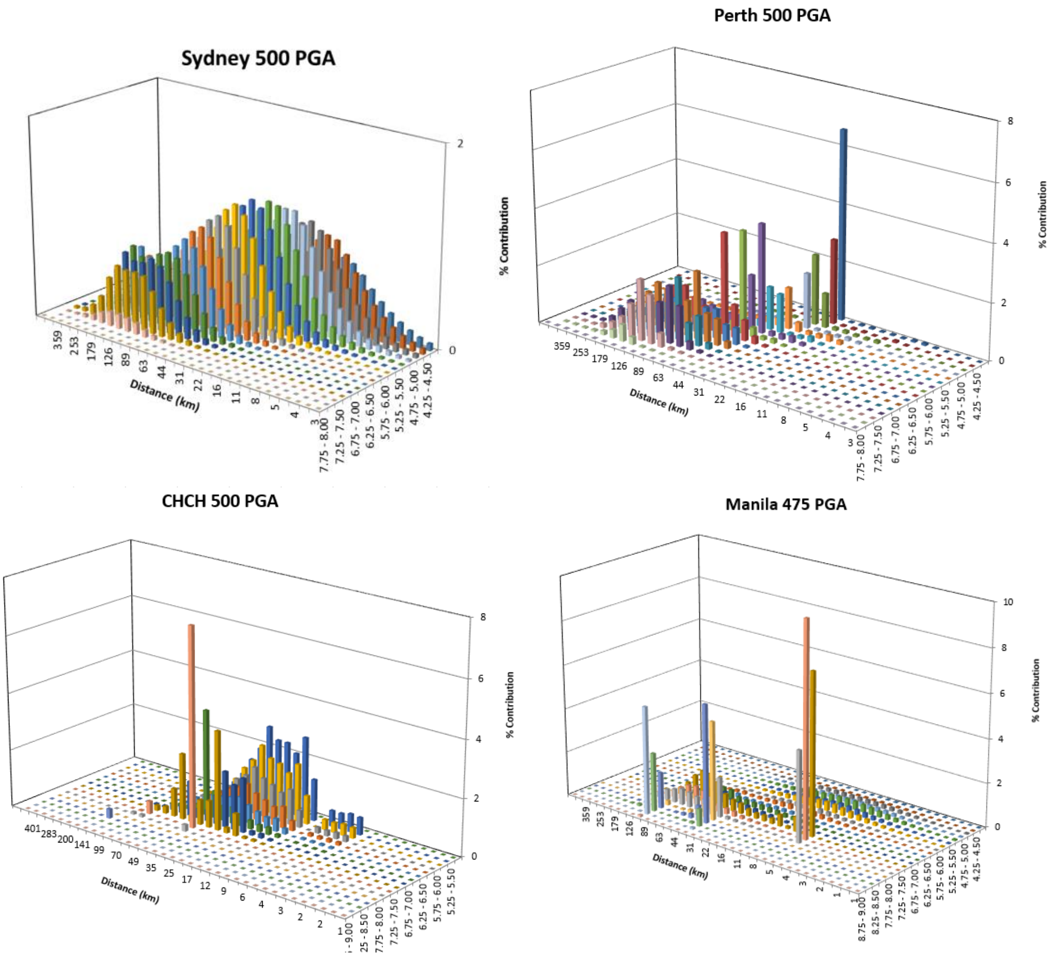

Figure 4. Magnitude-distance deaggregation plots for PGA at a 500-year return period derived from a site specific PSHA for four sites.

Table 4. Probability of aftershock exceeding the design ground motions for four sites at 500-year PGA

Design Event	30 days	100 days	365 days	730 days	1095 days
Sydney 500 PGA	33%	31%	23%	17%	12%
Perth 500 PGA	41%	39%	34%	27%	20%
CHCH 500 PGA	22%	22%	20%	14%	11%
Manila 500 PGA	21%	21%	19%	18%	15%

4.2 Results for 2500-year PGA at Sydney, Perth, CHCH and Manila

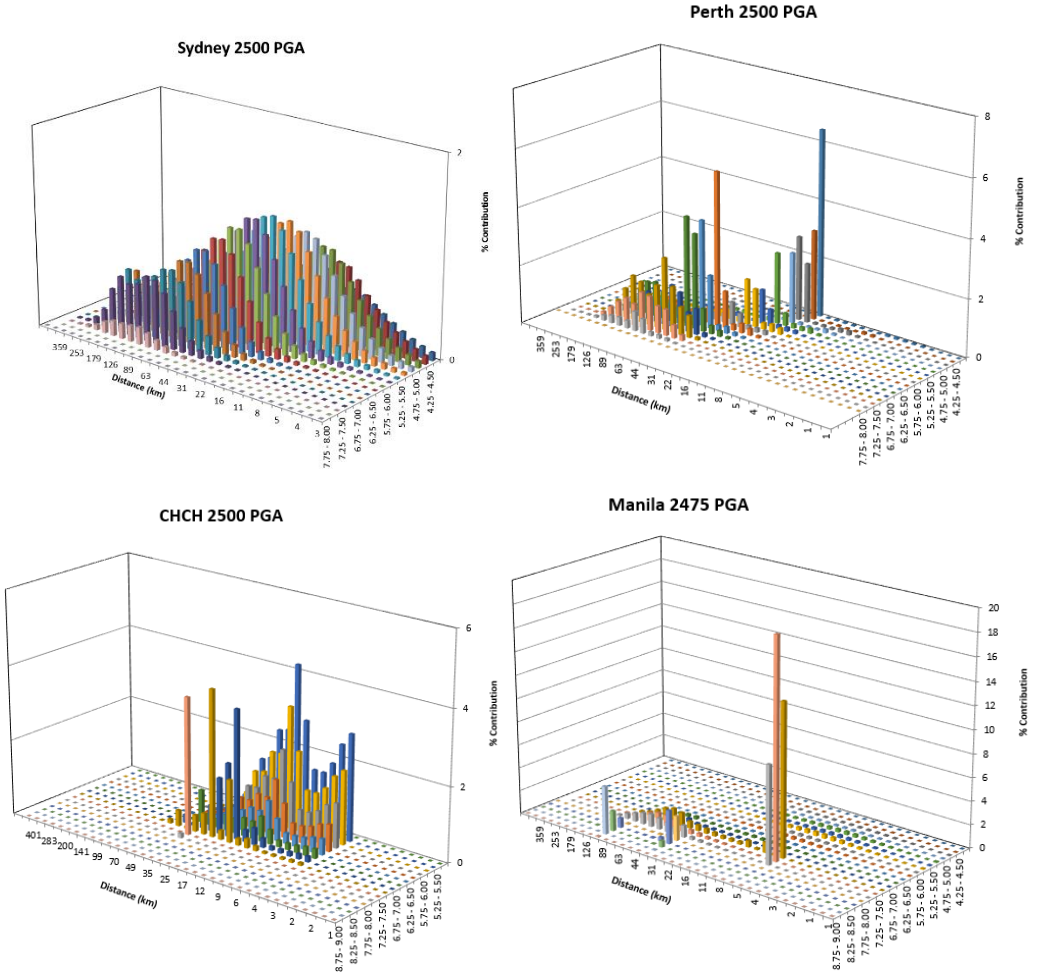

Figure 5. Magnitude-distance deaggregation plots for PGA at a 2500-year return period derived from a site specific PSHA for four sites.

Table 5. Probability of aftershock exceeding the design ground motions for four sites 2500-year PGA

Design Event	**30 days**	**100 days**	**365 days**	**730 days**	**1095 days**
Sydney 2500 PGA	29%	28%	21%	16%	11%
Perth 2500 PGA	35%	34%	30%	25%	20%
CHCH 2500 PGA	14%	14%	12%	9%	6%
Manila 2500 PGA	16%	16%	15%	14%	12%

4.3 Results for Sydney and Manila at 2500-years, SA 1 second

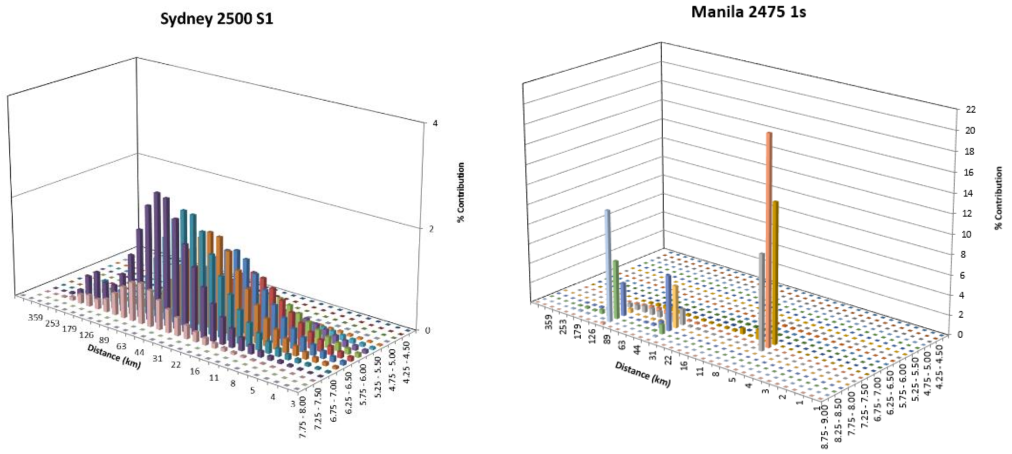

Figure 6. Magnitude-distance deaggregation plots for SA 1-sec at 2500-year return period derived from site specific PSHA for Sydney and Manila.

Table 6. Probability of aftershock exceeding the design ground motions for SA 1-sec at 2500-years in Sydney and Manila.

Design Event	30 days	100 days	365 days	730 days	1095 days
Sydney 2500 1s	19%	19%	19%	17%	13%
Manila 2500 1s	18%	18%	18%	18%	15%

4.4 Discussion

It is acknowledged that this method has limitations in that it simplifies the problem by only considering a single aftershock, ignoring fault structures, assuming an equal spatial distribution within the aftershock window, and not considering the amount that an aftershock exceeds the design basis. The “aftershock probability” quantum reported has large uncertainty when added onto the inherent epistemic and aleatory uncertainty in the PSHA.

Nevertheless, the relative difference in aftershock probability resulting from different magnitude-distance deaggregation at different hazard levels allow us to start to understand the influence that different seismotectonic setting have on potential aftershocks. The results show that the magnitude-distance deaggregation has some control over the probability that an aftershock will exceed the design basis ground motion over a given time frame. The greater contribution of larger earthquakes at distance that contribute to the hazard will increase the probability of a significant aftershock. Ground motions at longer structural periods are controlled by larger magnitude events and therefore less sensitive to time. The results of this methodology show that when considering longer periods the probability of an aftershock will exceed the design basis ground motion over time decrease less than when compared to short period motions.

5. CONCLUSIONS

A simplified methodology was developed to calculate the probability of a future damaging aftershock over a specified time interval considering the design basis ground motions. The methodology considers each scenario earthquake using the magnitude-distance deaggregation results of the PSHA combined with an aftershock temporal and spatial window function to estimate the probability that the design motions will be exceed by an aftershock within a certain time interval.

The method is a work in progress and needs to develop to consider multiple aftershocks, exceedance of design ground motions from smaller aftershocks, and spatial distribution aftershock (e.g. fault structures). A thorough treatments of the potential for a damage aftershock would entail taking each scenario mainshock event and applying a probabilistic aftershock hazard approach (e.g. Wiemer, 2000) to sum all of the probabilities.

The quantum of aftershock probability reported here needs to be explored further, nevertheless the relative difference of the results support the influence of the seismotectonic setting on aftershock probability as expressed by the magnitude-distance deaggregation from a PSHA.

Better understanding of the probability of aftershock ground motion, before the mainshock, can help plan for faster recovery and reduce indirect losses due to downtime, business interruption, the loss of culture, sense of community, and quality of life.

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