Are mitigation actions warranted? The case of the 2009 L'Aquila earthquake

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ABSTRACT

The disastrous earthquake in L'Aquila Italy (Mw 6.3, 6 April 2009) again highlights the issue of potentially reducing seismic risk by releasing warnings or initiating mitigation actions. Because earthquakes cluster strongly in space and time, periods of increased seismic hazard are known. During such seismic crises, seismologists typically convey their knowledge of earthquake clustering based on past experience, basic statistics and 'gut feeling'. However, this information is often not quantitative nor reproducible and difficult for decision-makers to digest. We define a novel interdisciplinary approach that combines probabilistic seismic hazard and risk assessment with cost-benefit analysis to allow objective risk-based decision-making. Our analysis demonstrates that the current approach to mitigation actions should be re-thought, because it will almost never be cost-effective. Instead, future mitigation actions must be based on the weakest buildings and the ones on the poorest soil, just as flooding evacuations are targeted to flood-prone areas only.

INTRODUCTION

Increased seismic activity in the days to months before a significant earthquake can be a sign for an upcoming catastrophic event. Strong foreshocks to subsequent devastating

mainshocks as well as precursory swarms have saved many human lives throughout history; it is in fact the only known precursory activity that has saved lives. For example, it was a widely accepted practice in Italy in the 17th century to remain outside of buildings for two days after a moderate to strong earthquake, in order to avoid casualties due to subsequent events [Boscarelli, 1992]. However, the observation that the vast majority of earthquakes and swarms are not followed by damaging events leads to the fact that measures are taken very rarely in modern days. A recent example is the devastating M_w6.3 L'Aquila earthquake of 6 April 2009, which killed 299 people. There was a volley of reproaches that the Italian Civil Protection had ignored foreshock activity. Because swarm-like activity was detected in the region for some weeks (Figure 1), a meeting of seismologists and civil protection had been conducted on the evening of 31 March 2009. This meeting recommended no further mitigation actions and no evacuation, a decision criticized heavily in hindsight by the mass media and public. Currently, it is believed that a 'foreshock' is physically indistinguishable from any other earthquake, until a subsequent 'mainshock' retroactively marks it as special [Christophersen and Smith, 2008; Felzer, et al., 2004; Reasenberg, 1999]. Therefore, seismologists are constrained to using probabilistic models to translate knowledge on earthquake clustering for the benefit of the society.

A typical statement that seismologists make to the public, media and decision-makers after the occurrence of a moderate earthquake is: 'It is possible but unlikely that this event will be followed by a subsequent larger event in the next few days'. In regions, such as California, Italy and Japan, quantitative 'aftershock' probabilities are calculated [Gerstenberger, et al., 2005; Marzocchi and Lombardi, 2009]. In rare instances, based on these calculations, authorities issue a statement of increased probability, such as

recently done by the California Earthquake Prediction Evaluation Council on 24 March 2009, when swarm-like activity near Bombay Beach was punctuated by a M_w4.8 earthquake. The panel reported: 'The probability for a large earthquake (magnitude 7.0 or greater) on the San Andreas Fault over the next few days is 1% to 5%'. No event occurred in this case. Following [Reasenberg and Jones, 1994] the probability for a M_w4.8 earthquake to be followed by a magnitude 7 or greater earthquake within 7 days is 0.06%. A more refined approach to time-dependent seismic hazard assessment is the 'Short-Term Earthquake Probabilities' [Gerstenberger, et al., 2005] model that converts earthquake probabilities into ground motion hazard in real-time (http://earthquake.usgs.gov/eqcenter/step).

METHOD

To make a real difference to societies and to assist civil protection in rapidly making very difficult decisions, we introduce Short-Term Earthquake Risk (STEER) analysis (Supplementary Figure S1), combining time-dependent probabilistic seismic risk assessment with Cost-benefit Analysis (CBA). As an example, we consider the 2009 L'Aquila earthquake sequence (Figure 1). A region's seismic risk is defined as the joint product of the regional seismic hazard, the local site conditions, the building vulnerability, and the distribution of people in buildings. To perform time-dependent probabilistic seismic hazard assessment, we use a time-dependent occurrence model [Reasenberg and Jones, 1989; 1994] with region-specific parameters [Lolli and Gasperini, 2003] to compute hazard between 1 November 2008 and 1 May 2009 for 24 hours time windows, updated every 3 hours. The forecasted rates combined with a predictive ground motion model, using the ShakeMap implementation for Italy

[Michelini, et al., 2008], define time-dependent probabilistic hazard. The site amplification is assumed to be +1.25 intensity units. This site amplification is chosen based on the verification of the loss model. For L'Aquila, it estimates fatalities of 160 (low), 240 (mean), 355 (high), which matches with the observed number of fatalities. We determine the rates of exceeding a given intensity by stacking up the rates at each settlement. Combining time-dependent probabilistic hazard with loss estimations [Trendafiloski, et al., 2009] yields the time-dependent probabilistic risk. The loss estimation follows established procedures, which are used either for scenario based risk ([Fäh, et al., 2000; Wyss, 2007]), real-time loss ([Earle, et al., 2003; Wyss, 2004]), or probabilistic loss [Crowley and Bommer, 2006] assessments. The probabilistic loss curve per se allows risk-based decision-making, albeit with no clear systematic empirical or quantitative basis for decision-making criteria [Marzocchi and Woo, 2009]. We therefore employ CBA to derive a Boolean indicator – take or not take an action - which can be used by decision-makers around the globe. CBA is commonly used in other disciplines, such as climate forecasts [Katz and Murphy, 1997], earthquake retrofitting of buildings [Smyth, et al., 2004], avalanche risk mitigation [Fuchs, et al., 2007], or volcanic risk mitigation [Marzocchi and Woo, 2007; , 2009] and allows a transparent and quantitative scheme for the decision-making process. This is important because it can justify any mitigation action (even a posteriori in the case of false alarm). To evaluate if a probability supports a mitigation action or not, it is necessary to define an optimal probability threshold that represents the 'acceptable risk': Given the cost, C, of a mitigation action and the potential loss, L, the action is favourable whenever the probabilistic risk exceeds C/L.

RISKS AND CBA FOR EVACUATION IN L'AQUILA

Figure 2 shows the probabilistic loss curve for the city of L'Aquila (72,000 inhabitants; distributed in EMS-98 vulnerability classes A(30%), B(30%), C(30%), and D(10%)) on 6 April 2009 at 2 pm, 1.5h before the M_w6.3 L'Aquila earthquake. The chance of 100 fatalities or more in the subsequent 24 hours period is about $5*10^{-4}$. This time-dependent risk of having 100 fatalities exceeds the long-term probability [Meletti, et al., 2008] by a factor of about 30 ($1.4*10^{-6}$). By integrating the probabilistic loss curve and normalizing it by the population, we can estimate, for an individual person living in a house of EMS-98 building class A (the most vulnerable), the probability of dying in a destructive earthquake in the next 24 hours. Immediately preceding the L'Aquila earthquake, this probability reaches 10^{-5}. To put these numbers into perspective, the typical estimated probability of dying in an earthquake for an individual person in the next 24 hour is 10^{-9}, whereas the average probability of dying in a car accident in Italy in any 24 hours period is $2.7*10^{-9}$ [Istat, 2009]. Thus, the average risk of dying in an earthquake in L'Aquila is about the same as dying in a car accident; however, during the 2009 seismic crisis, the risk of dying in an earthquake increased by three to four orders of magnitude.

Given such a high probability gain, one might assume that mitigation actions, even a widespread evacuation, must certainly be warranted. However, one has to keep in mind that the absolute probabilities are still small and that with more than 99.99% probability, fewer than 100 people will die. Indeed, with more than 99% probability nobody will die at all. To decide if, in light of these numbers, mitigation actions are warranted and which mitigation actions may be most appropriate, a CBA can be performed.

We consider an evacuation of all people in vulnerable buildings (EMS-98 class A), costing $500/person/day on average and the willingness to pay for a life saved by the government is $1M; latter is based on a study of volcanic risk around Vesuvius [Marzocchi and Woo, 2007; , 2009]. The resulting CBA threshold (Figure2) is always more than two orders of magnitude greater than the probabilistic loss curve. Therefore, evacuation even of only the weakest buildings as a mitigation action is not cost effective. The CBA thus confirms the decision of 'no evacuation' taken by the Italian civil protection in the hours and days preceding the M_w6.3 mainshock. Even if the observed seismicity before the mainshock would have been one magnitude larger, the CBA threshold is exceeded only when costs are taken to be less than $20/person/day. During an ongoing seismic crisis, the probability of losses will change continuously, increasing as each new event occurs and gradually decreasing until the next event occurs. We therefore suggest that instead of analyzing the probabilistic loss curve and CBA threshold at a given time, it is sensible to view a time series of the probability of exceeding a specific loss. To illustrate this procedure, we show in Figure 3 the time-varying probability of having 100 fatalities in L'Aquila due to an earthquake between 1 November 2008 and 1 May 2009 for 24 hours time windows, updated every three hours. The sudden jumps in these curves correspond to the occurrence of potential foreshocks. Due to the increased regional seismicity, the probability is already $3*10^{-5}$ in early February compared to the background seismicity of November until January. The most considerable steps then occur on 30 March, after two events of about M_w4 and on 5 April, in the evening before the destructive mainshock, when a M_w4 and a M_w4.3 foreshock occur. It is noteworthy that while the largest foreshocks dominate the probability, the probabilities of numerous small events also lead to noticeable increase

in probability. In this case, the probabilistic loss curve never exceeds the threshold of the CBA threshold before the mainshock. Even assuming unrealistically low costs for the evacuation, it evacuation never favourable. The CBA threshold is clearly exceeded after the M_w6.3 mainshock, and evacuation of at least the weakest buildings is sensible. Note that in this case, our calculations likely represent at most a lower bound because buildings were damaged by the mainshock, and therefore the risk factor based on building fragility has increased but we haven't accounted for it.

Determining the optimal duration of a mitigation action is another critical and complex task. Earthquake hazard and risk for an individual triggering event decays very rapidly: after one hour, it has decreased already by 40%, after 3hours by 75% and after 9 hours by 90%. Here, we calculate the time-dependent risk and CBA after an initiating earthquake for an individual (Figure 4a). Assuming an initial earthquake of magnitude 5.5 and evacuation costs of $50/person/day, we can derive that the 'optimal' evacuation duration is only a few minutes, even for a poor building (Figure 4b). After an event such as the L'Aquila earthquake, buildings of class A should be abandoned for about six hours, and class B for less than one hour. Consequently, mitigation actions need to be rapid, possibly automatically triggered. If it takes authorities several hours to convene a meeting after a moderate earthquake, the majority of the risk has already passed.

DISCUSSION AND CONCLUSION

Certainly, making a decision regarding any loss mitigation action is difficult and involves many dynamic factors such as weather conditions, time of day, size of the city, availability of emergency communication systems and shelters, and preparedness of the population. Nevertheless, the approach presented here can provide valuable input to

decision-makers, and we believe that our application of the method to the L'Aquila sequence is the first fully quantitative earthquake risk assessment applied during seismic crises.

Sensitivity analyses indicate that mitigation actions, to be cost-effective, should emphasize the weakest buildings and the ones on least stable soil. This hypothesis is also confirmed by the damage pattern of the L'Aquila earthquake. Calibrating the analysis in such a way lowers the CBA threshold because total mitigating costs are lower. This is similar to risk analysis regarding hazards such as floods and avalanches, were the risk (and therefore the mitigation actions) varies at a local scale. Thus, smart mitigation strategies of the future target the inhabitants of individual buildings. For example, evacuating an entire city for a few hours only is not realistic, but evacuating individual, vulnerable buildings or closing certain building types such as schools, universities, churches, stadiums, or other critical facilities may be feasible in such a case. Such an approach for earthquakes would require a substantial change in how civil protection is organized, communication is distributed and people are trained to respond. Not many people know how vulnerable the building is that they inhabit, but maybe they should just like we should always know were a fire extinguisher can be found in our home.

A broad range of mitigation actions can be explored for seismic mitigation during a seismic crisis. Depending on the focus of the study, costs and losses have to be quantified in each individual case.

After an earthquake, seismologists are often asked if and for how long people should abandon their houses. Finding the optimal duration for mitigation actions depends primarily on the mitigation itself, thus lead-time and minimal duration of the chosen

mitigation action should be taken into account. STEER provides a framework to answer these important questions.

Although the results presented here are calibrated for the L'Aquila region, a final conclusion of our analysis is that the current understanding of time-dependent earthquake processes is poor; too poor to warrant mitigations actions in most cases. The lack of more predictive statistical or physics-based models that accurately describe earthquake interaction are the primary obstacle for initiating mitigation actions.

FIGURE CAPTION

Figure 1: Map of the region affected by the 6 April 2009 L'Aquila M_w6.3 earthquake (red star), including the ground motion predicted by the ShakeMap approach, the foreshocks between 1 November and 6 April (yellow), aftershocks between 6 April and 1 May (gray), and the settlements (black squares). Inset shows the national seismic hazard map ([Meletti, et al., 2008]) with the white box indicating the region in the main panel.

Figure 2: Probabilistic loss curve and cost-benefit curves for EMS-98 building class type A, using site amplification of 1.25, in L'Aquila at 6 April 2009 at 2a.m. local time, for a duration of 24 hours using earthquake data from November through May. The probabilistic loss curve is shown for two cases: 1. previous seismicity (black); 2. hypothetical seismicity with increase in magnitude by 1 (dash-dotted-black). Three CBA thresholds are indicated for the mitigation action based on different assumptions, i.e. the cost of the evacuation of $500 (red), $50 (dashed-red), and $20/person/day (p.p.p.d.) (dash-dotted-red).

Figure 3: Probability of exceeding 100 fatalities in the next 24 hours, updated every 3 hours (black), and the CBA for evacuation of people in EMS-98 class A buildings and site amplification of 1.25 for L'Aquila. The CBA thresholds are equivalent to Figure 2. This figure shows the mainshock (red-star), the probability of exceeding 100 fatalities with the next 24 hours based on the background [Meletti, et al., 2008] (blue-dashed), and the uncertainties by the loss estimation that correspond to the high and low plausible estimates (dashed-black). Inset a) shows details of the curve immediately preceding and following the occurrence of the mainshock. Right axis: earthquake magnitudes as a function of time. Note: the probability is based on the seismicity within a box 25 by 25 km around L'Aquila.

Figure 4: a) Probability of dying in an 'aftershock' for one person living in an EMS-98 class A (red), B (green), or C (blue) building in L'Aquila. An individual earthquake source ('foreshock') is assumed to be in an epicentral distance and depth of 5 km. 'Aftershock' and ‘foreshock’ have the same location. ‘Foreshock’ magnitudes are calculated between 4 and 7 (0.1 steps for A, 0.5 steps for B and C). The probability of dying is calculated hourly after the 'foreshock' for the following hour. CBA-thresholds are shown in grey. b) Optimal evacuation duration (intersections between probabilistic loss curves and CBA-thresholds) for different building classes and CBA assumptions.

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Figure 1

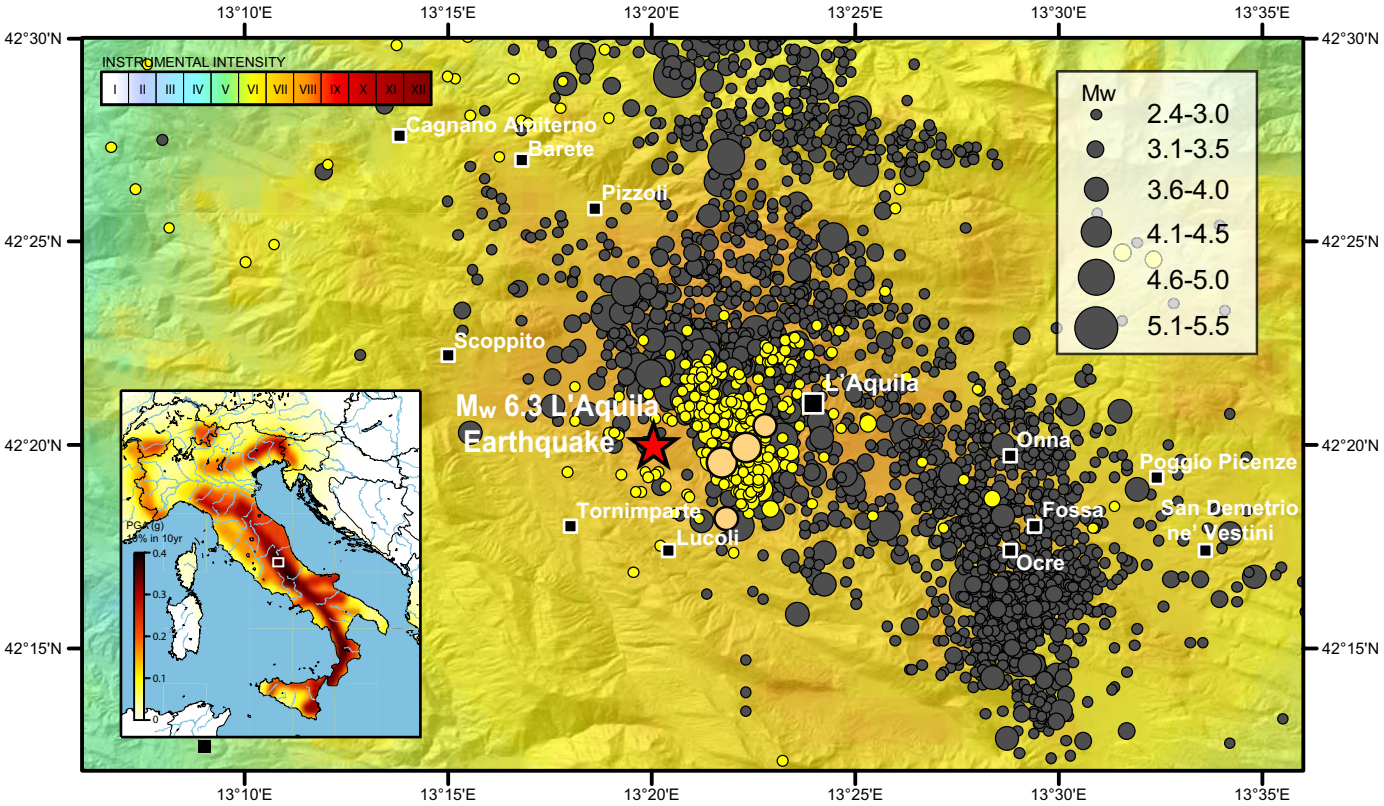

13°10'E
13°15'E
13°20'E
13°25'E
13°30'E
13°35'E
42°30'N
42°25'N
42°20'N
42°15'N
INSTRUMENTAL INTENSITY
I
II
III
IV
V
VI
VII
VIII
IX
X
XI
XII
Mw
2.4-3.0
3.1-3.5
3.6-4.0
4.1-4.5
4.6-5.0
5.1-5.5
Cagnano Amiterno
Barete
Pizzoli
Scoppito
L'Aquila
Mw 6.3 L'Aquila
Earthquake
Onna
Poggio Picenze
Fossa
San Demetrio
ne' Vestini
Ocre
Tornimparte
Lucoli
PGA (g)
10% in 10yr
0.4
0.3
0.2
0.1
0

Figure 2

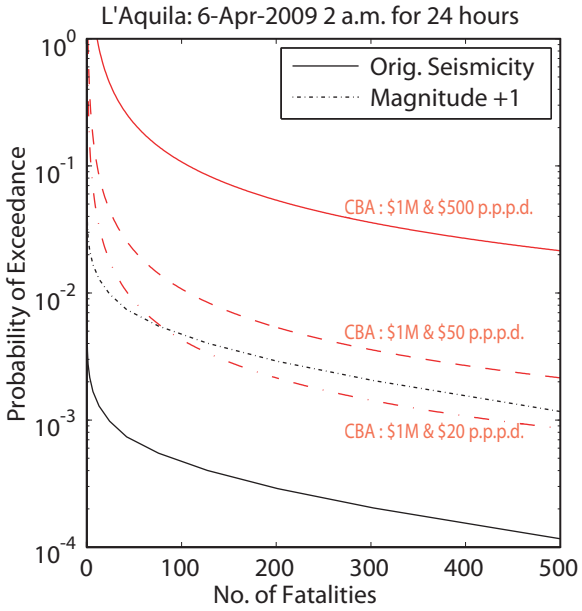

L'Aquila: 6-Apr-2009 2 a.m. for 24 hours
Orig. Seismicity
Magnitude +1
CBA : $1M & $500 p.p.p.d.
CBA : $1M & $50 p.p.p.d.
CBA : $1M & $20 p.p.p.d.
Probability of Exceedance
No. of Fatalities
10^0
10^-1
10^-2
10^-3
10^-4
0
100
200
300
400
500

Figure 3

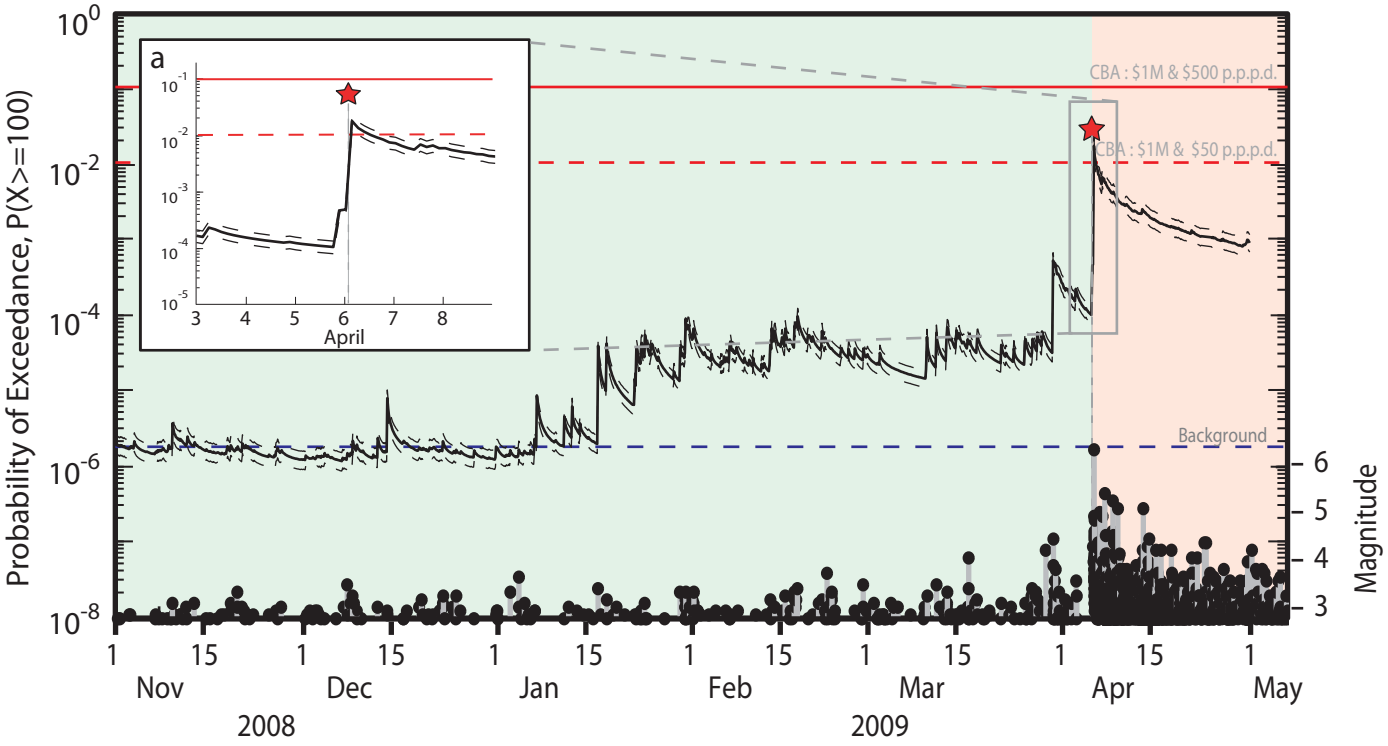
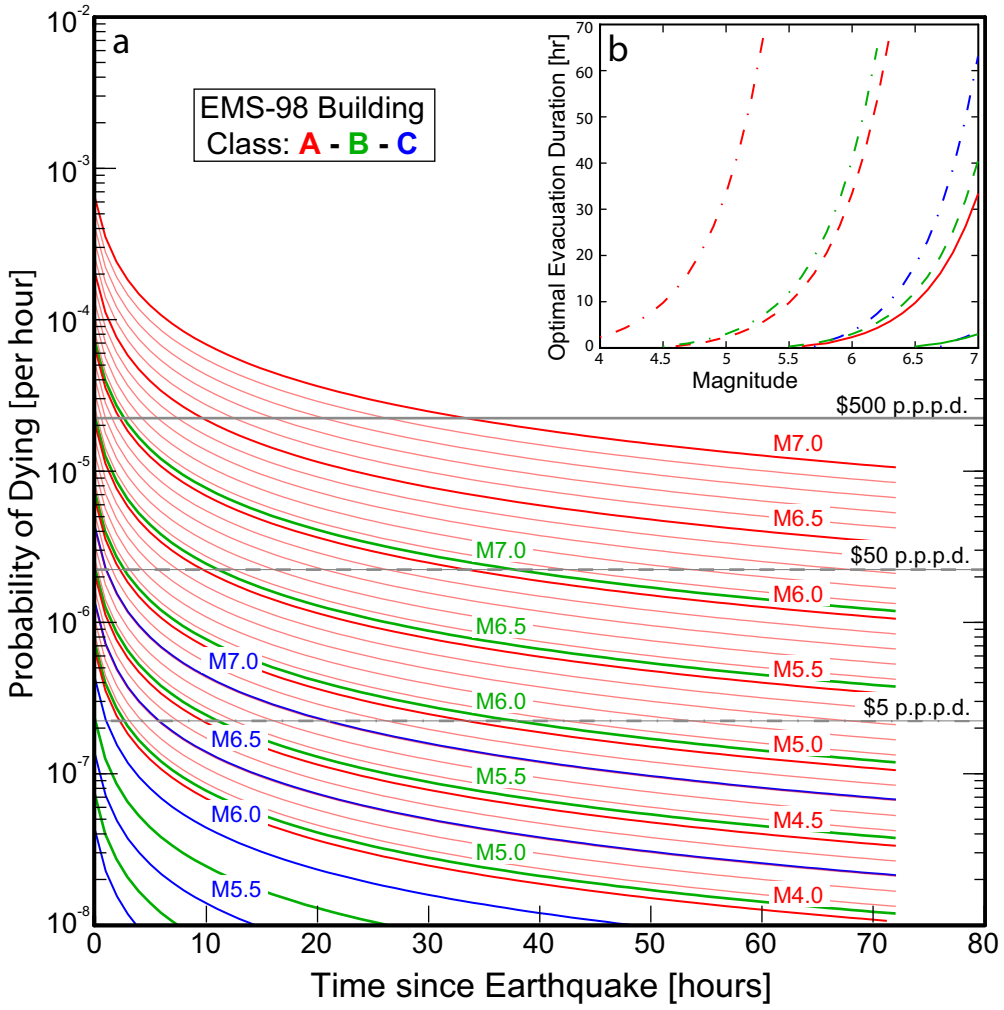

a
April
CBA : $1M & $500 p.p.p.d.
CBA : $1M & $50 p.p.p.d.
Background
Probability of Exceedance, P(X>=100)
Magnitude
Nov
Dec
Jan
Feb
Mar
Apr
May
2008
2009

Figure 4


a
EMS-98 Building
Class: A - B - C
Probability of Dying [per hour]
Time since Earthquake [hours]
$500 p.p.p.d.
$50 p.p.p.d.
$5 p.p.p.d.
M7.0
M6.5
M6.0
M5.5
M5.0
M4.5
M4.0
b
Optimal Evacuation Duration [hr]
Magnitude