Operational Earthquake Forecasting and Decision-Making

Gordon Woo[1], **Warner Marzocchi**[2]

1- Risk Management Solutions, London, UK

2- Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

Abstract

Traditionally, seismic risk reduction is achieved only through a sound earthquake building code. Nonetheless, some recent seismic disasters have highlighted the need for enlarging the range of risk mitigation actions beyond that. In particular, the occurrence of a seismic sequence may increase the weekly probability of a large shock by orders of magnitude, although the absolute probability usually remains below 1/100. Here, we summarize the state of the art in short-term earthquake forecasting and discuss how these forecasts may be used to mitigate seismic risk in this time horizon. Because of the low probabilities and high false alarm rates of possible advisories, mandatory mitigation actions would not be an effective practical strategy to reduce risk. Alternatively, we propose some low cost strategies, such as increasing vigilance and preparedness, for using probabilistic forecasting to mitigate seismic risk. These are based on the 'nudging' principle of devolving decision-making down from civic authorities to the individual level.

1 Introduction

In an ideal world, all buildings would be properly constructed according to a modern regional earthquake building code, drafted to protect occupants from fatal injury, except for extreme levels of ground motion. Given that earthquake deaths are primarily caused by building damage, high quality earthquake engineering is the best defence against earthquake shaking.

The target of building improved earthquake-resistant structures is, and remains, imperative. Nonetheless, in the real world we face challenges that call for additional seismic risk reduction measures. In particular, many existing buildings have been constructed before the most recent building code update, or without adequate code compliance, and therefore would benefit from retrofitting to the seismic resistance level of new buildings. Yet, retrofitting requires a certain amount of time and it cannot be considered a reliable mitigation measure in a short-time window.

Furthermore, the marginal cost of retrofitting, which may be as much as 30% to 50% of the building value, is substantially greater than for new-build anti-seismic construction.

Moreover, building codes are generally based on probabilistic hazard maps, corresponding to a prescribed ground motion exceedance tolerance. As tragically illustrated in Christchurch, New Zealand, in February 2011, seismic strong ground motion levels may exceed the design basis of buildings and cause their collapse.

Rather than place the onus for seismic safety just on a reliable building code, scientists and decision makers have a humanitarian incentive and are under professional pressure to develop innovative seismic risk reduction strategies that use the best and most authoritative scientific information available. This is the principal goal of Operational Earthquake Forecasting [9].

2 Operational Earthquake Forecasting

The term *Operational Earthquake Forecasting* (OEF hereafter) was proposed by the *International Commission on Earthquake Forecasting* for Italian Civil Protection [9] nominated by the Italian government after the L'Aquila earthquake, 2009. This commission had two main tasks: (1) report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes, and (2) indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions, including the use of probabilistic seismic hazard analysis in the wake of a large earthquake.

The commission recommended the development of OEF, and of quantitative and transparent decision making protocols that encompass mitigation actions of different impact levels that might be implemented if certain probability thresholds are exceeded.

In essence, OEF comprises procedures for gathering and disseminating authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes [9]. This process involves two key activities: the continual updating of authoritative information about the future occurrence of potentially damaging earthquakes; and the officially sanctioned dissemination of this information to enhance earthquake preparedness in threatened communities.

The term *time dependence* signifies that the seismic hazard is not constant through time. This point deserves to be examined in detail. Traditionally, seismic risk is mitigated in the long-term through the definition of suitable building codes, i.e., the definition of appropriate rules for constructing buildings and infrastructure able to resist earthquake shaking, with limited damage. The primary scientific input in this field is a seismic hazard map that specifies ground shaking at some probability of exceedance level during a time interval of typically 50 years.

Almost always, the earthquake occurrence process that underlies a hazard map is presumed to be time-independent [4], and the mean seismic hazard rate is expected to remain constant through time. This modeling is still common, and some authors have proposed extending the use of these hazard maps also to shorter time intervals [17]. Nonetheless, we know that the earthquake occurrence process has significant time variability in the seismic rate; such variations are much larger then would be anticipated with a pure time-independent process. The clearest of these variations is the time and space clustering of seismicity; an earthquake suddenly alters the dynamic conditions within fault systems that may lead to future nearby earthquakes.

These time variations are more evident in the short-term (days to weeks), in particular after a large shock. The use of time-dependent models based on earthquake clustering to track the evolution of aftershock sequences is becoming more and more popular [21, 7, 12]. The short-term forecasting models so far proposed are of three types: the ETAS models [e.g. 18, 19, 30] that have been used to forecast aftershocks after L'Aquila earthquake [12] and are the most popular; the Short Term Earthquake Probability, STEP, model [7]; and the Agnew and Jones model (AJ; [1]). Another popular model is the one proposed by Reasenberg and Jones [21] that may be considered as a simplified ETAS model. All of these models depend solely on the use of the seismic catalog. The AJ model uses also some constraint on the magnitude of the impending earthquakes taken from geology and paleoseismology.

The stochastic Epidemic-Type Aftershock Sequence (ETAS) model has been primarily used to forecast the evolution of an aftershock sequence. ETAS is based on simple physical components such as a tectonic seismic background that varies with space and a stationary Poisson distribution in time, with radially-symmetric triggering. The ETAS model is generically described by an equation of this form [18, 19, 30]:

$$\lambda(\vec{x},t,m) = \left[\gamma\mu(\vec{x}) + \sum_{t_i < t_0} f_1(M_i - M_{\min}) f_2(\vec{x} - \vec{X}_i) f_3(t - T_i)\right] g(m - M_{\min}) \qquad (1)$$

where λ is the rate of events expected in the location $\vec{x}$, at the time t and of magnitude m. The first term represents the background varying with space (and not in time), and the summation takes into account the triggering effects of all previous earthquakes as a function of the distance, elapsed time and magnitude of the triggering event. The function $g(m - M_{\min})$ is the frequency-magnitude law that is independent of space. In the most commonly used version, $f_1(M_i - M_{\min})$ is the Utsu exponential scaling, $f_3(t - T_i)$ is the Omori-modified power-law scaling, $g(m - M_{\min})$ is the exponential Gutenberg-Richter law, and $f_2(\vec{x} - \vec{X}_i)$ is a power-law spatial decay that may mimic the co-seismic stress transfer. Originally, all these functions were established empirically looking at how aftershocks depend on the mainshock magnitude and decay in time and space; more recently, they have been physically justified.

Once $\lambda(\vec{x},t,m)$ has been estimated, the probability of earthquakes in a specific time-space-magnitude window Ω is

$$P = 1 - \exp\left\{-\iiint_{\Omega} \lambda(t,\vec{x},m)\,dt\,d\vec{x}\,dm\right\} \tag{2}$$

Sometimes, the seismological output needs to be formulated in terms of ground shaking. In this case, the short-term models have to be implemented in conjunction with a ground motion prediction equation (GMPE). The choice of the most appropriate GMPE is far from trivial, and may depend on the model application. Here, we do not explore this important issue, but we remark that the choice of the GMPE may be difficult from a technical point of view, although it does not introduce any conceptual problems.

Jordan et al [9] emphasized the possibility of extending the use of clustering models also to track the evolution of a seismic sequence that may anticipate a large shock.

The occurrence of a seismic sequence with shocks felt by people raises concerns about the possibility to have large shocks in the short term. Although, most destructive earthquakes occur without being anticipated by such sequences [20, 14], some of them are anticipated by more or less prolonged seismic sequences. Seismologists are not yet able to distinguish the features that characterize foreshock sequences with respect to seismic sequences that do not end with large earthquakes; nonetheless, it is clear that the occurrence of a seismic sequence increases the probability to have a large shock in the short-term.

To date, this kind of information has almost never been used to take practical mitigation actions like in L'Aquila earthquake 2009 [12] and the more recent Tohoku earthquake 2011 that was anticipated by a strong foreshock sequence that lasted few days (see below). There are several reasons for this. First, it is not helpful to talk about an increase of probability if we are not able to quantify it in a reliable way; there are many trivial probability increases where small earthquakes occur. But, as we will show later, this information can be of practical use within the framework of a quantitative assessment.

Secondly, the models so far proposed for short-term earthquake forecasting show that the occurrence of a seismic sequence may increase the probability with respect to the background as much as a thousand times, but the absolute probability still remains very low (usually below 1%). These probabilities represent a formidable challenge for taking mitigation actions because it is obvious that in this low probability environment any warning would very likely be a false alarm.

For the sake of example, we report the case of the Tohoku earthquake. The map of the annual probability for 2011 of a M≥8.5 in Japan is reported in Figure 1. This map has been extrapolated using the model submitted to CSEP (International

Collaboratory for the Study of Earthquake Predictability) Japan and published by Lombardi and Marzocchi [10]. The annual probability for the area of the fault that slipped during the Tohoku earthquake was 0.64% (about 0.21% for M≥9.0).

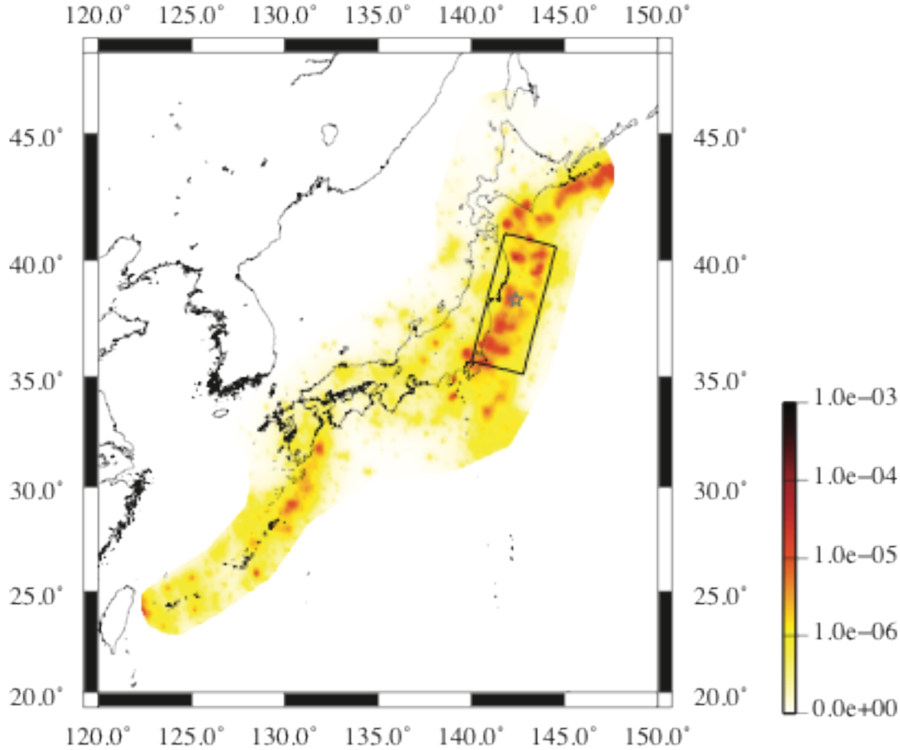

Figure 1. Probability map for the period Jan.1-Dec.31 2011. The legend reports the annual probability map for a M≥ 8.5 earthquake in each cell of 0.1x0.1 degrees. The box is the fault of the Tohoku earthquake and the star is the epicenter.

A few days before the giant shock, a strong seismic sequence started with the strongest foreshock of M 7.2 that occurred on March 9. The weekly probability after the M 7.2 event increased, relative to the background probability, by a factor of 100 in a circular area around the epicenter with a radius of 100 km (see figure 2). In particular, the weekly probability calculated before the foreshock was 0.0012%, whereas immediately afterwards it was raised to 0.12%. If we consider a smaller circle around the epicenter of the M 7.2 event, the probability gain is much higher than 100, but the absolute weekly probability of a M≥8.5 is less than 0.12%.

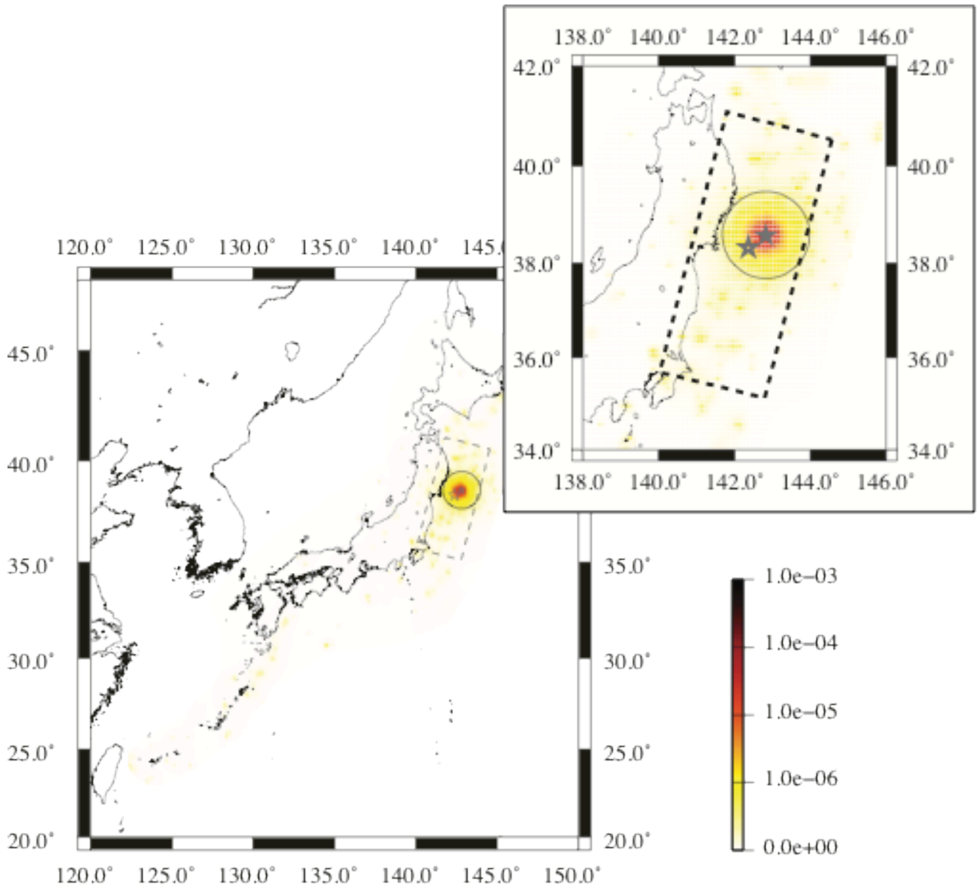

Figure 2. Probability map for the period March 9 - March 16, 2011. The legend reports the weekly probability map for a M≥ 8.5 earthquake in each cell of 0.1x0.1 degrees. The box is the fault of the Tohoku earthquake; the circle is around the epicenter of the M7.2 earthquake occurred on March 9; the star is the epicenter of the Tohoku earthquake.

Another term in the OEF definition is worth noting: the scientific information has to be *authoritative*. This means that we should use forecasting models that are widely accepted and statistically tested. The statistical test of earthquake occurrence models is the primary objective of an international initiative named *Collaboratory for the Study of Earthquake Predictability*, CSEP (http://www.cseptesting.org; [8]). Specifically, the main purpose of the CSEP is to carry out scientific experiments to evaluate the reliability and skill of any forecasting/prediction model in different time windows (from 1 day to years). Reliability is the capability to produce forecasts/predictions compatible with the future seismicity; once a set of reliable models is identified, the skill measures the relative precision of one specific model compared to the others. The best model is the reliable model with the highest skill.

Each experiment consists of comparing statistically the forecasts produced by the models and the real seismicity observed in a truly prospective way. CSEP can be considered the successor of the *Regional Earthquake Likelihood Model* (RELM) experiment [22]. While RELM was focusing on California, CSEP extends this focus to many other regions (New Zealand, Italy, Japan, part of China, and the whole world) as well as global testing centers (New Zealand, Europe, Japan, China). All testing regions are selected according to a high-level standard of seismic monitoring and to their capability to provide homogeneous and authoritative datasets required for the input of the models and for the testing phase. The coordinated international experiment has two main advantages: the evaluation process is supervised by an independent scientific international committee, not only by the modelers themselves, and the cross-evaluation of a model in different regions of the world can facilitate its evaluation in a much shorter period of time [29].

The results of prospective tests are of fundamental importance to give an objective credibility to earthquake occurrence models, and, eventually, to merge all models in an average model [e.g. 16]. The achievement of a consensus model is the main target of many important scientific initiatives like IPCC [23], and long-term seismic hazard [3]. This approach is probably the best solution to get an authoritative forecast whilst minimizing the unavoidable different opinions among scientists. Last, but not least, an authoritative and timely information is the best approach to challenge possible mavericks who may lay claim to predicting earthquakes.

3 Decision-making in a low-probability environment

The rigorous scientific method of gathering evidence and seeking truth is resolutely upheld by the scientific community: scientists are generally reluctant to make premature statements about events over which there remains significant uncertainty. Decision-making is a different world: urgent decisions may have to be made irrespective of the state of uncertainty. One way of bridging the gap between seismologists and non-expert decision-makers is to use quantitative and formal techniques developed in operational research. Here we use the specific example of cost-benefit analysis.

3.1 Cost-Benefit Analysis

In the way that human beings deal with environmental threats, cost-benefit analysis is a key element. It has been said that evolution is Nature's way of doing cost-benefit analysis [5]. An evolutionary perspective redefines the assumptions many psychologists hold about what counts as rational. Our human ancestors needed to avoid getting killed, protect their families, and not succumb to diseases. The evolutionary pressure for survival has given modern Man a natural instinct to avoid environmental hazards. This survival instinct conforms well with a primitive cost-benefit analysis. People steer clear of dangerous animals just in case they are aggressive, and of sick humans, just in case of infectious disease contagion. Accidental deaths caused by animals are extremely low, because people heed warnings to avoid sharks, lions etc..

Since the ability to avoid hazards (predators, poisonous creatures, cliffs, etc.) would have been of significant evolutionary advantage to our ancestors, we should expect to find within the brain a cognitive system specialised for reasoning about hazards and precautions. This is the central idea in evolutionary psychology of hazard management theory [2]. Fiddick et al [6] characterize precaution rules as being of the form: if a valued entity is subjected to a hazard, then taking an appropriate precaution lowers the risk of harm to an individual and his family.

Expressed in general quantitative terms in the context of operational earthquake forecasting (OEF), a particular personal risk mitigation action may be warranted if the cost C is less than the expected loss $p\ L$, where p is the probability of a dangerous earthquake, and L is a financial measure of the physical harm caused by the earthquake if evasive action is not taken [11, 13].

Even allowing for progress in OEF, the probability value in the short-term (days to week) p is almost always very low, and hence most mitigation actions will actually turn out to be unnecessary. In the second half of the twentieth century, the type of mitigating action in the forefront of the minds of seismologists was large scale urban evacuation. Even a rudimentary cost-benefit analysis would rule out such a drastic response to any foreseeable type of operational earthquake forecast, because the p value is nowhere near high enough [25].

The high number of expected false alarms suggests that mandatory mitigation actions imposed on society would not be the best solution since they can increase distrust of public officials and decision makers. A possible solution adopted in many fields is to provide different warnings to the public without imposing any specific mitigation action, instead nudging people to adopt their own mitigation strategy (see below). In the past, when facing low p values and high expected false alarm rates, consideration of less drastic responses than mass evacuation was generally dismissed on the grounds that public panic would ensue, which might lead to crush injuries, heart attacks and traffic accidents arising from the commotion and disorder.

The twenty-first century offers a very different environment for OEF. First, the world changed on 9/11. In common with earthquakes, terrorism is now also a low level global threat to life. In every airport in the world, passengers have to go through security before boarding a flight. Routinely, terrorism risk advisories are given to warn of potential attacks. But intelligence officers are no better at forecasting terrorist attacks than seismologists are at forecasting earthquakes [28]. The false alarm rate for such advisories is very high, nevertheless these advisories are considered worthwhile in encouraging public vigilance, and they do not cause mass panic.

A second development of this century significant for OEF is the widespread ownership of personal cell phones. Almost everyone in the industrialized world nowadays either owns a cell phone or has a close family member who owns one. In the future, advisory messages can be targeted at individuals, according to their geographical location, the construction of their home or place of work or worship, etc.. Already text messages are sent to warn US residents of tornado and wildfire threats. Communication technology in the twentieth century did not permit such fine population segmentation of hazard warnings. Segmentation is important because mandatory actions for all would be unsuitable for many, who would understandably become distrustful of scientists.

3.2 Nudging individual decision-making

The spectrum of possible hazard warnings is very broad, as is the diverse range of crisis situations. However well civic leaders choose the warnings they issue, people have to learn to make good decisions for themselves and their families in a crisis. In many awkward situations, an individual ultimately may have to be his or own decision-maker.

To answer the key public policy question how people can be helped to make good decisions for themselves, without a curtailment of freedom, a leading behavioural economist, Richard Thaler, teamed up with a law professor, Cass Sunstein, to write the highly influential book, *Nudge* [24]. Nobody likes being pushed or shoved to do what is right for them - but being nudged is quite acceptable. Advocating a policy of libertarian paternalism, Thaler and Sunstein have suggested ways in which people can be 'nudged', rather than coerced or obligated, to make decisions that serve their own long-term interests. There are informed and unintrusive ways of achieving this goal. But it takes enterprise to find creative and viable solutions to the challenge of helping people to make good decisions for themselves. The primary tool for nudging people to make better decisions for themselves is education. Without needing to ban the sale of cigarettes or junk food, a government can encourage healthier lifestyles by educating the public about the risks of such consumption.

In the context of seismic safety, governments can do much to educate people about earthquake risks. Just as people should know if there is a cancer risk associated with any consumer product that is purchased (e.g. tobacco or some cheap processed food), or from aerosol emissions from industrial installations, people should know if their home, office, factory, school or church is in an active seismic zone, and whether it is collapse-prone, in the event of strong ground shaking. In the first instance, a simple indicator is just the style and date of earthquake construction – e.g. reinforced concrete structure, built to the 1970's Uniform Building Code. Already, the assignment of earthquake vulnerability to individual buildings is routine for earthquake insurance risk management. Modern technology is making this easier. The street level mapping capability of Google Earth facilitates this type of building-specific vulnerability classification.

It is crucial for the occupants of a building to have an awareness of its degree of earthquake vulnerability, in order to make an informed choice on action in the event of a hazard advisory. If it is not collapse-prone, then, as with windstorms, occupants may well be safer inside than outside, where they may be struck by debris. However, for occupants of on old unreinforced masonry construction, planning for an alternative place of shelter may be desirable.

Suppose that a building occupant is well informed about the seismic vulnerability of the building. An individual's response to an earthquake advisory, which may ultimately be tailored to building vulnerability, will then depend on personal circumstances, which is why an individual should optimally be his or her own decision-maker. Civil protection authorities may aspire to know the earthquake vulnerability of each address, but could never know the urgency of the need for the occupant to be there at any given time. With privacy of personal information comes the responsibility of making personal safety decisions.

Furthermore, people differ in their level of risk aversion and their reluctance to take a gamble with their safety. This is tantamount to placing an especially high value on L. Accordingly, some people, e.g. parents with young children, may be willing to bear a higher cost to avoid the risk than others, e.g. single unattached men. Conversely, there are some risk-seeking individuals who would act as if they placed a comparatively low value on L. This may apply in particular to some reckless young students, and professionals, such as media journalists and photographers, who have become insensitive over time to high risk situations.

3.3 Low cost individual actions

Mandatory actions imposed on society have to be based on sound quantitative cost benefit analysis, which is transparent to the public. In this way, any action can be justified at each step of the decision-making process. When each single person becomes responsible for taking actions, it is not anymore necessary to have written rules for any decision that we have to take in our private life. Nonetheless, it is clear that even in this case, weighing the pros and cons is expected to be advantageous.

As has been stated before, the probability value p for an OEF will always be low; usually very low. The essential cost-benefit inequality $C < pL$ would only be a call for action if C is low. The threshold cost for any individual would be dependent on personal risk aversion. There are numerous low cost actions that might be taken which would help to reduce the risk of harm coming to an individual in the event of an earthquake occurring. Just because most people may not be saved by an earthquake advisory does not diminish the value of saving even one life. This principle underlies the issuance of terrorism advisories. A selection of low cost options is listed.

[a] Vigilance

An individual who is vigilant and alert to danger will be able to react faster to an event, if one occurs. Terrorism advisories urge citizens to remain vigilant, and earthquake advisories should do the same. As with the terrorist threat, situation awareness is crucial for rapid reaction to ground shaking. Advisories can help to reduce cognitive bias of people who are slow at believing what is happening.

As a simple example of a low cost act of vigilance, suppose that a magnitude 4 earthquake occurs at night, and is felt quite strongly within a radius of 50km. Those woken by the shaking would be advised to get dressed, and be alert just in case of further strong ground motion during the night. Even if the hazard probability gain associated with the magnitude 4 event occurrence may be small, the cost of extra vigilance is commensurately low.

[b] Preparedness

Every household and office should have an emergency kit in case disaster of any kind strikes. This kit should include food and water supplies, batteries, torch, breathing masks, first aid equipment, shovels, etc. Any hazard advisory should nudge citizens to ensure that they comply with this minimum level of preparedness.

Earthquake drills are known to save lives. If there has not been an earthquake drill in a region for more than a year, an earthquake hazard advisory would be a good opportunity to hold a public earthquake drill [27].

On a practical level, engineering risk mitigation and retrofit are expensive (in contrast with new-build), and more importantly, time-consuming to undertake, but many low cost acts of preparedness are worthwhile to minimize injury, such as restraining objects from toppling off indoor shelves, or falling from outdoor parapets.

[c] Visitor options

Any visitor to an area for which a hazard advisory has been issued may choose to review his or her travel plans. If a trip is discretionary, and can be altered in date or destination, then the cost of plan substitution may be minimal. However, if there is some specific urgent personal or business reason for being in the hazard zone at the time of issuance of the hazard advisory, then this would need to be weighed carefully against the risk. In October 2010, the US State Department issued a terrorism advisory for US travellers to Europe. Some corporate travel plans were affected by this advisory, but most were not. It is right that every corporation should be free to decide for itself, in accordance with its own risk aversion.

[d] Resident options

In response to an OEF, a local resident living in a seismically vulnerable building may have available a range of alternatives which involve low additional cost, e.g. staying for a short while in a safer place with a neighbour, friend or family member, taking an early vacation away from home, or even staying outside in a tent or a car or caravan. For a short improvised stay of this kind, the cost should conform with the cost-benefit criterion, and be justifiable. However, whether it would be worth paying for a hotel on a nightly basis depends on the hazard level, and the resident's risk aversion.

Suppose that the weekly risk of a destructive earthquake is of the order of 0.1%. (This is the approximate absolute risk arrived at above for the Tohoku foreshock analysis.) Assume that an occupant of a seismically highly vulnerable building has an even chance of being killed or seriously injured in the destructive earthquake through building collapse. Then the daily risk of being killed or seriously injured in an earthquake is of the order of (1/1000) *(1/7)*(1/2) = 1/14000 (1/7 reduces the probability from week to day, and 1/2 is the supposed even chance to be killed or seriously injured by the earthquake). This is a very significant degree of excess daily accidental risk: by comparison, the chance of a sky-diver being killed in a jump is 1/100,000.

Suppose that, rather than taking advantage of the free hospitality of neighbours, friends or family, the occupant of a seismically vulnerable building decides to stay at an inexpensive budget hotel for €60 per night. Then $L=C/p$ is €840,000. This figure is similar to that obtained for the willingness to pay to move someone away from Vesuvius red zone [13]. If the occupant were rather risk averse, she would be advised to think about checking into a hotel.

Just because a seismic crisis may last for months does not negate the value of local residents reducing their hazard exposure for even a brief time window. If every family living in a vulnerable building within a hazard region were to manage to get away for a total of A weeks over a crisis period of W weeks, the overall population exposure would be reduced by about A/W. It can be left to individuals to self-organize their own periods away from the hazard zone. Achieving 100% reduction of exposure when a major earthquake occurs is nigh impossible. Assuming that a family might be able to spend a cumulative amount of two weeks away from a vulnerable home, spread over a number of time intervals within a crisis period of 6 months (i.e. 26 weeks), a reduction of 1/13 ~ 7% is well possible, and is significantly better than zero.

This same argument applies to the occupancy of vulnerable public buildings. In Italy, the heritage of beautiful old churches leaves also a legacy of danger to congregations, in the event of severe earthquake shaking. During a seismic crisis, effort may be made to find alternative safer buildings for church services. Alternatively, if weather permits, there may be open-air services, or some curtailment of the weekly frequency of services. Hazard adjustment to church practices is nothing new: during the 2009 influenza pandemic, traditional communion practices changed to limit the oral transmission of infection. If, over a seismic crisis period of W weeks, services for A weeks are relocated or cancelled, the exposure reduction would be A/W, which is a saving achievable at comparatively low cost and inconvenience.

Being nudged to take a mitigating action gets harder as the period of disruption increases: a few days of inconvenience is acceptable; a week is tolerable; but two weeks may be hardship. Beyond two weeks, some civic compensation plan may have to be introduced, which will become more costly for the authorities as more people at risk are assisted.

Figure 3 charts the increasing marginal economic cost in reducing population exposure in seismically vulnerable buildings in zones for which an earthquake advisory is issued. Classical earthquake prediction was preoccupied with the tail of the curve: the grossly unaffordable economic cost of evacuating many thousands from a hazard zone. Through self-organization of the population, acting as their own decision-makers in response to an OEF with no official management or logistical assistance, quite a significant proportion of the population exposure might be reduced at a reasonable and affordable cost.

Further reductions would require more than nudging. Depending on the relative proportion of seismically vulnerable buildings, civic provision could be made to subsidize the cost of people staying away from their vulnerable homes, or to accommodate a modest proportion in designated earthquake-resistant shelters or hostels, or specially converted modern safe civic buildings. But this would be progressively more expensive and unaffordable, as indicated in Figure 3.

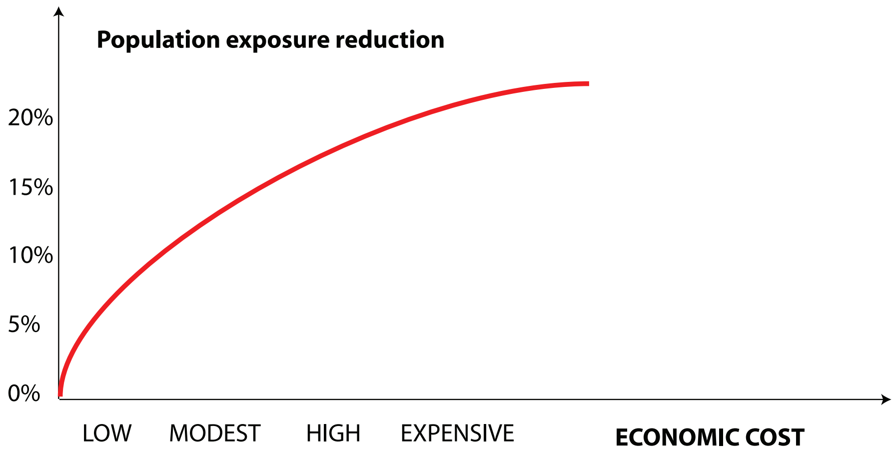

Figure 3. Schematic graph indicating the marginally increasing economic cost associated with achieving a % reduction of population exposure in vulnerable buildings.

4 Final Remarks

The verifiable record of lives saved through earthquake forecasting is almost non-existent. Realistically, evidence of an imminent earthquake will never be unambiguous enough to warrant the evacuation of even a small town. But for scientists and decision-makers, thinking should not stop there. First, it is only those in seismically vulnerable buildings who would be in serious danger from strong shaking. In future, it should become feasible for occupants to check online the vulnerability status of any building.

Secondly, some significant saving of human life is feasible through official nudging of low cost measures that individuals can choose themselves to adopt, according to their own circumstances and sense of risk aversion. For example, exposure can be reduced through the simple process of advising occupants of vulnerable buildings to take whatever opportunities arise for getting away to visit neighbours, friends, family etc. The smaller the proportion of vulnerable buildings, the easier it would be for the occupants of these buildings to be temporarily accommodated elsewhere.

Hardly anyone might be prepared to be away from home for the entire duration of a seismic crisis, so there is a degree of randomness in who might be saved by an earthquake advisory. The benefit is achieved at a community level. Already, with the present state-of-the-art level of OEF, earthquake advisories might be issued capable of reducing the community death toll of an earthquake disaster by a few per cent. This is a worthwhile start for scientists to save lives through operational earthquake forecasting. Progressively, this death toll percentage reduction factor could be increased to double figures. But as low cost options for hazard avoidance gradually become exhausted, the nudge limit will be reached – after a few weeks, a family may outstay its welcome away from home, and be impatient to return. The mortality reduction factor is then expected to saturate due to rising costs for civic authorities in subsidizing families for the expense of being away from home, or providing alternative safe accommodation.

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