Beating Fear with Hope: On Sustaining Earthquake Preparedness

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ABSTRACT

The closure of the "L'Aquila Trial" has prompted the scientific community to revisit the question of what lessons have been learned. An issue of concern is the rise of short-term forecasting in the aftermath of the earthquake that triggered the trial, such as using patterns of small earthquakes to provide probabilistic warnings of occurrence of damaging events in the ensuing day or week. Because most damaging earthquakes are not preceded by diagnostic precursory patterns and the vast majority of observed anomalies such as swarms of small earthquakes are not followed by a damaging event, forecasting of this type is not likely to be useful for mitigating seismic risk. Instead, long-term earthquake preparedness should be the goal, and the most effective way of doing so is strengthening the built environment against earthquake shaking. Great progress has been made in this regard over the past few decades, and numerous lives were saved in a number of recent earthquakes owing to the implementation of earthquake-resistant design and construction practices. Long-term mitigation strategies face scientific, financial, regulatory, and cultural challenges. The scientific community should lead the way in dealing with these challenges.

INTRODUCTION

On 9 April 2009, a moment magnitude (M_w) 6.3 earthquake struck L'Aquila, Italy. The resultant building collapse killed over 300 people. Several scientists were initially convicted of manslaughter for misinforming the public but were later exonerated by higher courts (Stucchi *et al.*, 2016). The closure of the L'Aquila Trial has prompted the scientific community to think about what lessons have been learned.

The hardest lesson is that there is much work to do to make our built environment more resilient to seismic shaking. Questions arise regarding whether some of the collapsed newer buildings met current Building Code standards and how the code standard can be further improved. A more difficult question is how to protect residents who live in pre- and low-code buildings (such as historical buildings) from strong shaking. One might expect that the extensive building collapse in the L'Aquila earthquake would inspire a new phase of improving building safety.

However, what actually transpired went in a different direction. Survivors, lawyers, and judges questioned whether scientific and civil authorities should have done better just before the earthquake to let people stay away from vulnerable buildings (Stucchi *et al.*, 2016). The Italian government nominated an International Commission on Earthquake Forecasting (ICEF) to assess the state of knowledge of short-term earthquake prediction and forecasting and to make relevant recommendations in this regard. The ICEF concluded that the L'Aquila tragedy and subsequent legal actions demonstrated a need for "authoritative, scientific, consistent, and timely" information on short-term seismic risk and that operational earthquake forecasting (OEF) was the best method to provide such information (Jordan *et al.*, 2011). Shortly thereafter, an official OEF system was established in Italy (Marzocchi *et al.*, 2014). The most prominent aspect of the sequence of post-L'Aquila events is an intense focus on short-term forecasting.

The vast majority of the scientific community considers long-term strategies such as strengthening the built environment on the basis of hazard assessment to be the most effective in mitigating seismic risk. Short-term prediction or short-term probabilistic forecasting are meant to play a complementary role, but in reality they can be in competition with long-term measures for resources and for the attention of the public, governments, and the media, as was vividly played out after the L'Aquila earthquake. In this article, we discuss from a historical perspective the operational feasibility of the two options and explore why society is often faced with the challenge of having to decide on the best balance between the two. We emphasize that the short-term measures are driven mainly by a fear for building collapse, but the long-term measures are driven by a hope for continuing improvement in building safety.

THE FEAR

For generations, humans accepted building collapse in earthquakes as a fact of life. The fear of building collapse led to

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a desire for short-term forecasting or prediction because timely escape from buildings seemed to be a logical way of survival. This attitude is true regardless of differences in culture, economy, and political system. Because China used to be thought of as the world's champion in short-term prediction and learned extremely hard lessons as a result (Chen and Wang, 2010), it is illuminating to recall some of the Chinese experience in comparison with the L'Aquila experience.

The situation of L'Aquila before the 2009 earthquake is reminiscent of the situation in the Haicheng area in China before the 1975 M_s 7.3 Haicheng earthquake (Wang *et al.*, 2006). Prior to the Haicheng earthquake, there were also amateur prediction efforts, although these efforts were encouraged by the government. Residents in the Haicheng area were also in a state of confusion. They were exposed to small earthquakes, prediction rumors, and a number of false alarms. Similar to the L'Aquila earthquake, the Haicheng earthquake was preceded by foreshocks. However, what is rather unique in Haicheng is that a cluster of over 500 events occurred in a very small area within 24 hrs prior to the mainshock. That small area later hosted the epicenter of the mainshock.

By analyzing declassified official documents and interviewing key witnesses, Wang *et al.* (2006) reconstructed the history of what is known as the Haicheng prediction. On the day of the Haicheng earthquake, the provincial and local governments (then called Revolutionary Committees) issued messages that were in effect official earthquake warnings. Evacuation of houses took place in an organized fashion in most of Yingkou County (today's Dashiqiao City) and sporadically in some other parts of the earthquake area. When the earthquake occurred in the evening, many people were outside of their houses. Haicheng thus made history as the only documented success story of earthquake prediction. Detailed analyses of the Haicheng prediction show that the foreshock sequence was the only precursor that triggered the imminent prediction (Wang *et al.*, 2006). Other reported anomalies such as aberrant animal behavior and ground water fluctuations made no direct contribution, although some of these observations may have some scientific value.

The fortuitous Haicheng success was not to be repeated in China or elsewhere. In the following year, an M_s 7.8 earthquake struck the city of Tangshan without foreshocks (Chen *et al.*, 1988). Much of Tangshan was razed to the ground, and about 240,000 people died in collapsed buildings. In 2008, an M_s 8.0 (M_w 7.9) earthquake occurred in the Wenchuan area of China, again without an identifiable foreshock sequence (Chen and Wang, 2010), causing over 80,000 deaths. The demonstrated ineffectiveness of short-term strategy resulted in major changes in how the mitigation of seismic risk is done in China (Chen and Wang, 2010). The importance of improving and enforcing seismic resistant design codes is being increasingly recognized, although earthquake prediction is still stipulated in Chinese laws (Articles 26–30, Law of the People's Republic of China on Protecting Against and Mitigating Earthquake Disasters, amended at the 6th Meeting of the Standing Committee of the 11th National People's Congress on 27 December 2008).

Even those who participated in the Haicheng prediction would not make the prediction if the earthquake were to happen today. In 1975, seismologists did not know that the majority of damaging earthquakes are not preceded by identifiable foreshocks and that the vast majority of earthquake swarms are not foreshocks of damaging earthquakes. Today, these facts are common knowledge (Reasenberg, 1999; Marzocchi and Zhuang, 2011; Woo and Marzocchi, 2013). If equipped with today's knowledge, the Haicheng seismologists would probably have made the same judgment about the surge of small earthquakes as did the Italian seismologists just before the L'Aquila earthquake (Stucchi *et al.*, 2016). That is, it is very unlikely that a large earthquake will follow, although the possibility cannot be completely ruled out. Moreover, the social environment in China is very different now. In 1975, in the political environment of the Cultural Revolution of China, primary members of Revolutionary Committees showed extraordinary willingness to issue earthquake warnings, with little concern about economic and social consequences of false alarms (Wang *et al.*, 2006).

Although emphasis on the short term begins to subside in China, it has gained momentum elsewhere since the L'Aquila earthquake, but in a new form as represented by the OEF. In a way similar to the Haicheng prediction, current OEF uses patterns of precursory seismicity. Instead of giving specific predictions of the time, location, and size of damaging earthquakes, OEF provides updates of probabilities of earthquake occurrence for the near future, such as the next day or week. Although a newer interpretation of OEF includes long-term forecasting such as decades (Field *et al.*, 2016), here we only consider the original purpose and form of OEF as defined by ICEF (Jordan *et al.*, 2011; Marzocchi *et al.*, 2014). OEF is based on rigorous science that shows that the probability of a large earthquake following a cluster of small earthquakes is typically of the order of 1% (Woo and Marzocchi, 2013). However, OEF emphasizes the "probability gain" from background values like 0.001% (practically impossible) to 1% (extremely unlikely), in the hope that government officials and the public can make sensible mitigation decisions by comparing the orders of magnitude difference between these numbers. The promotion of OEF emphasizes that mitigation decisions based on these numbers must be left to users such as civil authorities and individuals (Jordan *et al.*, 2011, 2014; Marzocchi *et al.*, 2014). In normal situations, scientists can proactively advise the users on how to make decisions based on OEF probabilities (Woo and Marzocchi, 2013) or retroactively endorse decisions made in response to OEF-type warnings (Jordan and Jones, 2010). However, the OEF process recommends that scientists should stay clear of decision making during a real seismic crisis (e.g., 1% or higher OEF probability).

To discuss the effectiveness and usefulness of short-term forecasting, it is necessary to consider two end-member categories of short-term measures of risk mitigation: (1) high-impact measures such as evacuation of vulnerable buildings and (2) low-impact measures such as reminding people to check their emergency kits and asking firefighters to stay vigilant. Note that forecasting the likelihood of aftershocks is not discussed here. The occurrence of aftershocks following large earthquakes is better understood in seismology by orders of magnitude than the occurrence of earthquakes that are not aftershocks.

The ineffectiveness of specific short-term predictions has been demonstrated by history, but it is still a fair question as to whether probabilistic short-term forecasting can be effective in enabling high-impact life-saving measures. Let us consider what would have happened had OEF always been available. In Haicheng 1975 and in L'Aquila 2009, it is likely that a probability gain from about 0.001% to 1% (or perhaps a bit more) for a damaging earthquake would have been broadcast. It may not take behavioral science or social psychology to envision that the governments and residents would not have found such warning very useful. In Tangshan 1976 and in Wenchuan 2008, because of the absence of identifiable foreshocks, a probability of about 0.001% would have been broadcast for a damaging earthquake to occur anytime soon, information that would not have prevented loss of lives in these earthquakes. Because the majority of damaging earthquakes are not preceded by identifiable foreshock sequences, there are numerous similar examples, one of them being Haiti 2010 with a death toll exceeding that of Tangshan 1976.

Thus, the main criticism of the OEF type of warnings by Wang and Rogers (2014, p. 569), is that they "send and reinforce a wrong message, that is, if scientifically estimated probability is very low, such as 0.001%, the public can afford to be less prepared for damaging earthquakes." Although the promotion of OEF makes it abundantly clear that scientists do not make decisions for residents living in vulnerable buildings, the residents are implicitly assured that they only need to worry about their buildings' safety when they see "authoritative, scientific, consistent, and timely" information of higher earthquake probability. Specific advice such as taking an early vacation or staying in hotels or neighbors' houses for a short time during an OEF-defined "seismic crisis" (Woo and Marzocchi, 2013) reinforces such assurance.

Is short-term forecasting effective in enabling low-impact mitigation measures? Here, we do not discuss whether actions triggered by false alarms are useful but only ask whether short-term warning is really needed for low-impact actions. None of the low-impact measures discussed by Woo and Marzocchi (2013), such as having an emergency kit, securing lose items, advising visitors about earthquake risk, and so on, has any logical dependence on short-term warning because these measures should be taken at any time. The same can be said about the readiness of emergency-response workers and facilities. Most damaging earthquakes occur without foreshocks or other types of scientific warning. Emergency-response workers are trained to respond at any time. No one should be influenced to become less prepared by a probability decrease from 1% to 0.001% announced by scientific authority.

One might think that short-term forecasting could be useful at least for earthquake education. For example, it is proposed that OEF-defined high-alert episodes will make people more educated about building vulnerability and thus more motivated to demand long-term remedial actions (Jordan *et al.*, 2014). There are, however, many more proactive, more effective, and simpler ways of doing earthquake education. Do we really need false alarms as an additional education tool? One may ask, after hearing the boy cry wolf a number of times, would most villagers become more motivated to find a long-term solution for wolf attack, or would they simply lose confidence in the boy? Anomalous events such as a surge of small earthquakes indeed offer important moments for earthquake education. Both authors of this article live in a seismically active area, and we frequently face these moments. The following is typical of what we would say to the media and public during these moments: "The ongoing event again reminds us that we live in an earthquake country. A large earthquake can strike at any time with or without precursory events, and we should always be prepared. Strengthening our built environment is our best protection." An important message of earthquake education is that society should not base mitigation decisions on precursory warning signals before damaging earthquakes.

If short-term forecasting is mainly to facilitate decision making to deal with authoritatively defined "practically impossible" or "extremely unlikely" events, one might hope that people would soon learn to ignore it so that its negative impact on long-term risk mitigation is negligible. This may be true for countries where earthquake-hazard assessment (i.e., long-term forecasting) and building code improvement and implementation are holding firm ground, but it is not true for many other countries where the inertia of fear-driven desire of finding the short-term easy way out is still very strong. In these places, the promotion or execution of long-term measures is often in a fragile state and can be derailed or delayed to various degrees by short-term excuses.

THE HOPE

"Short-term earthquake forecasting and prediction thrive on people's lack of confidence in the safety of their buildings" (Wang and Rogers, 2014, p. 570). As discussed above, the fear of building collapse is well founded, because too many lives have perished under collapsed buildings over human history. But the world is different now. Today, with modern knowledge of tectonics, seismology, and construction engineering, seismic risk mitigation is driven by a goal—buildings should not collapse in earthquakes. It is an ambitious goal that will encounter many setbacks. However, with hard work and perseverance, there is great hope that fewer and fewer people will have to live in vulnerable buildings in fear. Again, it is illuminating to recall lessons learned in China over the past few decades. Further details of the following narrative can be found in Chen and Wang (2010).

In the 1960s, there was hardly any seismic safety design for residential buildings in China. The government thus decided to pursue earthquake prediction as an inexpensive measure of risk mitigation. In the 1970s, no seismic designs were required for areas such as Haicheng and Tangshan, and the two earthquakes in 1975 and 1976 caused massive building collapse. Although the fortuitous prediction of the 1975 Haicheng earthquake greatly reduced fatalities, the 1976 Tangshan earthquake was one of the deadliest natural disasters in human history. The Tangshan catastrophe resulted in a gradual increase in attention paid to long-term seismic risk mitigation in the whole country. Since 1979, progressively improved versions of a seismic design code were introduced. Seismic design provisions in the 1989 and 2001 versions are comparable with practices elsewhere in the world. There was rapid economic growth and expansion of construction since the 1980s. In the Wenchuan area, numerous buildings were built after the 1989 or 2001 versions of the seismic design code came into effect. In 2008, many of these buildings did not collapse during the Wenchuan earthquake, even though the actual shaking exceeded the design level for parts of that region.

Because there was no seismic design requirement, the 1976 M_s 7.8 Tangshan earthquake resulted in $\sim$240,000 deaths. Because there was seismic design requirement, the death toll in the 2008 M_s 8.0 Wenchuan earthquake was much smaller, about 80,000. The first author of this article worked in the Wenchuan region following the earthquake and witnessed many standing buildings in the hardest-hit areas, many of them located right next to collapsed buildings (Chen and Wang, 2010). If such an earthquake had occurred in 1976, most of these buildings would certainly have collapsed. There is little doubt that the death toll in this earthquake would have far exceeded Tangshan's had there not been the seismic design code. Even though the code standard was later recognized as having been too low for some of the affected areas, it did save hundreds of thousands of lives. In contrast, short-term forecasting, whether in the form of specific predictions or probabilities, would have done nothing to save these lives. The comparison of Wenchuan with Tangshan brings hope that lives can be saved by improving and enforcing seismic design codes.

Needless to say, up until 2008, the dominant belief in the Chinese populace about dealing with earthquake hazard was prediction. According to Chen and Wang (2010, p. 2855) "The promotion of prediction success stories led to a false sense of security, which might have been partially responsible for the elasticity seen in the enforcement of mitigation regulations." It is tragic that too many buildings (particularly schools) that were built after 1989 and 2001 did not meet code standards, and many buildings were built on very poorly chosen sites with foreseeable hazards such as landslides and active faulting. Many of these buildings collapsed during the earthquake. Stricter enforcement of the code and wiser selection of building sites would have prevented many more deaths. The lessons are tragic, but they also bring hope that a better effort on long-term mitigation can reduce life loss in future earthquakes.

The situations of the large subduction earthquakes off Chile in 2010 and Japan in 2011 bring even greater hope. Because of the proper design and implementation of contemporary building codes, few modern buildings collapsed in the M_w 8.8 and 9.0 earthquakes in Chile and Japan, respectively. It is well known that most of the deaths in these events were caused by tsunamis generated by the earthquakes. Much more work is needed in dealing with tsunami hazard, but the performance of building codes in Chile and Japan in protecting buildings against collapse from strong shaking sets up great examples for the world to follow. It is not just a utopian dream that things will continue to improve with scientific and engineering research.

Those who choose to advocate short-term forecasting and prediction emphasize that it may be unaffordable to retrofit old buildings (e.g., Jordan *et al.*, 2014). It is known that for a new building, the incremental cost to include seismic resistance is an extremely small fraction of the total construction cost. In contrast, the cost of retrofitting an old building to code standard is often much higher and can be as high as on the order of half of the value of the building itself, although it is almost always less costly than replacing the building with a new one. Assessments of vulnerabilities and solutions need to be done on an individual building or class of building basis. The challenge of dealing with old buildings is indeed a very difficult one, but it is also motivation for creativity and hard work, not reason for pessimism and cynicism.

There have been various attempts to deal with seismic retrofitting in different jurisdictions. For example, the implementation of the Field Act in California 1933 and the current school seismic retrofit program in Canada's British Columbia province are legislated solutions that target one type of building, public schools, with multibillion dollar multidecadal programs to ensure, over time, appropriate seismic resistance in public schools. California is considering tax rebates on retrofitting of vulnerable structures.

To eliminate the scourge of collapse from susceptible buildings, it is important to have a long-term plan that is effective and affordable for the jurisdiction considered, because governments have many financial pressures. The plan needs to remain a continuing budget item at an affordable level. Scientific and engineering communities can exert positive influence on governments to set higher priorities for retrofitting old buildings. In some countries, the positive influence begins by explaining the ineffectiveness of short-term earthquake forecasting.

Seismic upgrading of existing structures often needs a different approach from that used in new construction. If the focus is just on collapse prevention, the main source of risk can be significantly reduced sometimes without meeting all the aspects of present codes (e.g., Allen, 1995; Applied Technology Council, 1997a,b). Less expensive remedies should be explored that can either improve the buildings' resilience or improve the safety of their residents. For example, efforts can be made to identify vulnerable structural components that would most likely be responsible for building collapse under shaking (Achilles' heels). Strengthening these components may not fully meet code standards but can reduce the likelihood of total collapse. Relevant engineering, financial, and regulatory issues deserve careful study.

In some cultural environments, work needed by long-term risk mitigation goes much beyond science, engineering, and education. Sociological complications in some places can be so frustrating that a reviewer of this article lamented in the review comments: "There are grounds for arguing that corruption is the most important cause of earthquake disasters." When trying to explain why many buildings in the Wenchuan areas were very poorly built before the 2008 earthquake, Chen and Wang (2010, p. 2854) also reported, "We heard that the shortage of financial resources was particularly acute for schools … and could have been exacerbated by anything from overambitious planning to corruption." In some situations, social issues pose greater challenges than scientific issues. Different walks of society need to work together to face the challenges. Avoiding the challenges by advocating short-term alternatives only causes delays in finding long-term solutions.

RECOMMENDATIONS

Every damaging earthquake triggers a battle between fear and hope. Fear tends to prevail. Reporters in disaster areas naturally, and for good reasons, focus on collapsed buildings. Collapsed buildings and resultant injuries usually leave the strongest memories of these earthquakes. However, in the images of collapsed buildings, there are almost always buildings in the background that are still standing, some being just next to the ruins of the collapsed ones. This is also true for the L'Aquila earthquake. It is these standing buildings that bring hope, real hope, that after the next earthquake, as a result of the hard work of scientists and engineers, more buildings will be standing and fewer buildings will be in ruins. With this hope, we offer (or reiterate) the following recommendations.

To fellow scientists: Research needs to continue to better understand earthquake behavior and to refine seismic-hazard assessment. Explaining and communicating long-term (decades) seismic hazard to appropriate levels of government and the public at large is an ongoing need so that sensible decisions can be made to reduce buildings' earthquake vulnerability. Although forecasting seismic risk and taking action to mitigate the risk are functionally separated, they are not truly separable. Precursory processes of earthquakes are valid targets of scientific research, but for operational purposes, it is the responsibility of the scientific community to help society focus on effective long-term mitigation strategy.

To engineers: It can never be overemphasized that a seismically resistant building stock is a feasible goal from an engineering standpoint. There is sustained need for research into new and innovative ways to seismically retrofit buildings and to develop common practice and guidelines to do retrofitting that suit specific locations. For old buildings, between doing nothing and retrofitting to code standard, there may be potentially life-saving initiatives that require engineering attention. Taking a few critical steps may significantly reduce the likelihood of total collapse in the next earthquake.

To residents: There is immediate need to understand the seismic hazard that your neighborhood is exposed to and to decide your personal tolerance of the risk you face. It is important to understand how vulnerable your building is, find out the cost of retrofitting, and encourage governments to take steps to help mitigate the problem. A large earthquake can strike at any time with or without precursory events, and you should always be prepared. It is impractical and dangerous to expect useful short-term warning signals from nature or scientific authority before a damaging earthquake. Strengthening the built environment on the basis of earthquake and engineering sciences is your best protection.

To government officials: Society needs to address vulnerability to earthquake shaking. Achieving a robust seismically resistant environment takes funding and time. It is important to have a long-term plan to achieve this objective at a level that your jurisdiction can afford, and to stick to the plan.

DATA AND RESOURCES

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