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Get it Right or Go to Jail: A Review of Probabilistic Seismic Hazard Analysis

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Get it Right or Go To Jail: A Review of Probabilistic Seismic Hazard Analysis

Abstract:

Probabilistic Seismic Hazard Analysis (PSHA) is a technique for making long-term estimations of the maximum intensity of seismic ground motion expected at any location. While PSHA cannot be used to make short-term predictions about the timing of future earthquakes, it remains a valuable tool for civil engineering and disaster planning. PSHA methodology requires the development of three distinct models: (1) a physical earthquake source model, (2) a probabilistic earthquake recurrence model, (3) a geologic model used to quantify seismic wave propagation. The three models are then applied to compute the likelihood of strong ground motion. These models present a simplified perspective of the complex process of earthquake occurrence, introducing both bias and uncertainty into PSHA estimates. This review article outlines the basic techniques used in modern PSHA and discusses both its appropriate applications and fundamental limitations. By identifying the primary weaknesses in current methodology, this review provides direction for future research that will ultimately increase the value of PSHA to society.

Introduction:

The earthquake that the scientists should have predicted struck the city of L’Aquila, Italy on April 6th, 2009. During the months preceding the magnitude 6.2 main shock, sequences of small earthquakes, or “seismic swarms,” repeatedly shook the region. Anxiety over these microseismic events compelled community leaders in L’Aquila to ask a team of prominent seismologists to determine whether or not a large earthquake was about to occur. The seismologists utilized a technique known as Probabilistic Seismic Hazard Analysis (PSHA) to
evaluate the situation in L’Aquila. Using these probabilistic models, team-leader Enzo Boschi reported on March 31st: “it is unlikely that an earthquake like the one in 1703 [that destroyed L’Aquila] could occur in the short term, but the possibility cannot totally be excluded” (Hall, 2011). Politicians used this statement to assuage the alarmed local population. Six days later, however, everyone’s worst fears were realized. An earthquake leveled L’Aquila, killing more than 300 people and injuring thousands more.

Enzo Boschi and five of the other Italian scientists were tried and convicted of manslaughter for “failing to accurately communicate the risk of the 2009 quake” (Mullen, 2012). While it is true that the seismologists did not predict the devastating L’Aquila earthquake, they could not realistically have done so with the available scientific data. Boschi’s team made a probabilistic assessment of the seismic hazard for the region. The seismologists did their job to the best of their abilities. They now face a six-year prison sentence because the people of L’Aquila misinterpreted their probabilistic analysis as a deterministic prediction, one with a clear-cut, right-or-wrong answer.

The unfortunate circumstances in L’Aquila illustrate the key distinction between seismic hazard analysis and earthquake prediction. In its essence, Probabilistic Seismic Hazard Analysis (PSHA) is an estimate of the probability that ground motion will exceed a certain level of shaking at a given location (Convertito et al., 2006; Hanks et al., 2012). Advances in geophysics have helped seismologists identify the areas around the world that are most at risk for devastation by earthquakes. Over long time scales, earthquakes exhibit consistent statistical properties that allow seismologists to assess seismic hazard probabilistically. However, seismologists cannot predict the precise timing of these events (Hanks et al. 2012; Stein et al, 2011). While PSHA cannot forecast the occurrence of an individual earthquake, it is used
extensively in the development of building codes and in the selection of construction sites for high-risk facilities like nuclear reactors (Douglas and Aochi, 2008; Gonzales et al., 2006).

This paper reviews PSHA, and in particular the strengths and weaknesses of current methodology. In practice, PSHA applies three distinct models - of the earthquake source region, of earthquake recurrence rates, and of the source-to-surface seismic-wave propagation - to compute the resulting ground motion (Klugel, 2009; Hanks et al, 2012). In each of these three models, seismologists make simplifying assumptions about the physical processes underlying earthquake occurrence. Though these assumptions introduce uncertainty into hazard estimates, PSHA is a valuable tool in disaster mitigation and construction engineering. My review addresses the implications of model uncertainty in each phase of PSHA method, distinguishing the contexts in which PSHA can be applied appropriately from the situations in which it will likely fail to produce realistic assessments. Finally, this review will present directions for future research that have the potential to drastically improve the efficacy of seismic hazard analysis.
Seismic Hazard Maps

Probabilistic Seismic Hazard Analysis offers a long-term perspective on the potential for strong ground motion caused by future earthquakes. The end result of most PSHA studies is a “hazard map” (e.g. Figure 1). PSHA estimates the probability of different intensities of ground motion acceleration at each point in a region of interest. To construct a hazard map, seismologists choose a hazard probability threshold and compute the ground motion acceleration expected at this probability level for each point on the map (Hanks et al., 2012). For example, the hazard map in Figure 1 shows areas with a 10% chance of exceeding the listed acceleration in a 50-year time period. The earthquakes causing such shaking would be classified as “500-year disasters”, meaning that they have an average recurrence interval of 500 years. At this probability threshold, the hazard map tells us that high levels of ground motion are expected in, for example, the densely populated San Fernando Valley (labeled SFV in Figure 1). The most important conclusion that can be drawn from PSHA is that seismic hazard is not spatially uniform. Hazard maps are used to pinpoint the areas that are most at risk for strong shaking in an earthquake.
Modern PSHA follows the basic methodology outlined in Figure 2. The first three steps of PSHA are the development of: (1) a physical model of the earthquake source, (2) a probabilistic model of earthquake occurrence, and (3) a physical model of the subsurface to characterize seismic wave propagation. The fourth and final step in PSHA is to integrate the three models to assess seismic hazard. As we shall see in the following sections, each step in the PSHA method requires simplifying assumptions about seismological processes that ultimately influence hazard assessments.

**Step 1: Earthquake Source Characterization**

Earthquake source models define the essential characteristics of the region of the fault from which the earthquake originates. These characteristics, or “earthquake source parameters”, include properties that describe the earthquake as a whole, such as hypocenter location, seismic
moment (a measure of the size of an earthquake), and fault geometry (Hutchings, 1991).

Earthquake source parameters also include properties that vary across the earthquake source region, as in the spatial and temporal distribution of slip along the fault (Mai and Beroza, 2002).

Physical models of the earthquake source region have become increasingly complex over the years, mirroring seismologists’ improved understanding of the earthquake rupture process. Early conceptualizations treated earthquakes as point sources of seismic radiation. These “moment-tensor” models can provide useful approximations for the earthquake source when assessing seismic hazard in the “far-field”, at locations well away from earthquake (Madariaga, 2007). Furthermore, moment-tensor models can be used as the building blocks of more complex source models, since seismic waves obey the mathematical principle of superposition (Kostrov and Das, 1988). Modern PSHA, however, is based on “finite” source models: models in which the earthquake source occupies a finite, non-zero volume (Kluegel, 2009).

The two most common finite source models are “kinematic” and “dynamic” models. Seismologists must carefully weigh the advantages and disadvantages of each approach before

**Figure 3:** Kinematic model for the Loma Prieta Earthquake (1989). The model describes the final slip distribution along the vertical fault interface. This slip distribution was determined from an inversion of the waveforms from seismograms during the earthquake. Figure adapted from *Beroza* (1991).
choosing one to use in PSHA. In the kinematic perspective, the earthquake is characterized solely by the relative motion of rock on either side of the fault: the “slip distribution” (Madariaga, 2007). In principle, the slip distribution in a kinematic model can be completely arbitrary. In practice, however, the models used in PSHA are constrained to be consistent with the fundamental properties of the slip distributions observed in real earthquakes (Hutchings, 1994; Olsen et al., 2009). Figure 3 provides a visual example of a kinematic model of the 1989 Loma Prieta “World Series” earthquake. Consistent with observations of real earthquakes, the slip distribution is quite heterogeneous along the fault interface. Because these heterogeneities strongly influence the pattern of seismic radiation from the earthquake source, kinematic models used in PSHA must capture this natural variability (Andrews, 1980; Mai and Beroza, 2002; Somerville, 1999).

Dynamic models differ from kinematic models in that they are explicit simulations of the earthquake rupture process. In the dynamic perspective, earthquakes are approximated as propagating shear cracks that continuously radiate seismic energy (Guatteri et al., 2003).

**Figure 4:** Snapshot in time of a dynamic rupture simulation on a 2D, nonplanar fault. The colors correspond to the y-component of the particle velocity of the rock around the fault. The rupture front is visible as a concentration of high velocity rock. Seismic waves (e.g. the hypocentral S wave, hypo S) can be seen radiating concentrically from the current and previous positions of the rupture front. Figure adapted from Dunham et al. (2011).
Dynamic models work by specifying an initial stress distribution and a governing frictional law for the fault of interest. These source parameters dictate the nucleation and evolution of the simulated earthquake, which in turn controls the fault’s slip distribution and seismic wave radiation. Figure 4 shows a snapshot in time of a typical 2D dynamic earthquake simulation. Nearly-circular seismic wavefields emanate from the rupture front, which in this case propagates from left to right along the fault.

Dynamic models have several important advantages over kinematic models. Notably, dynamic models tend to provide more realistic characterizations of the earthquake source than do kinematic models, since the relevant source parameters like the slip distributions are computed rather than assumed (Olsen et al., 2010). Because the physics of the earthquake source has such a strong influence on the eventual ground motion, PSHA would ideally incorporate dynamic, rather than kinematic models. However, the explicit, dynamic modeling of the time-evolution of the rupture is an inherently nonlinear computational problem (Kostrov and Das, 1988) Dynamic earthquake models are therefore much more computationally intensive than kinematic models, which exploit linear relationships between the source parameters and the resulting ground motion. Because PSHA typically requires hundreds of simulations (to characterize natural variability) for each of thousands of earthquake scenarios, dynamic models are often too computationally inefficient to be used in PSHA applications. Seismologists are usually forced to implement kinematic source models in PSHA, a simplifying assumption that contributes additional uncertainty to hazard estimates.
Step 2: Choosing an Earthquake Recurrence Model

The next step in the PSHA method is to develop a model for earthquake recurrence. The ultimate goal of such models is to estimate the probability of future earthquake occurrence for specific magnitudes and hypocentral locations. Earthquake recurrence models are based upon observations of the occurrence patterns of real earthquakes. Using historical seismic data in this manner assumes that we have perfect records of the occurrence patterns of recent earthquakes (Hanks et al, 2012, Stein et al 2011). This assumption may prove invalid, particularly for large, rare earthquakes or for regions of the earth with long interseismic periods (Main et al., 2011).

Small earthquakes occur more frequently than large earthquakes. This relationship between earthquake frequency and magnitude can be described by a power-law distribution, with the logarithm of the frequency of earthquake occurrence proportional to the earthquake magnitude (Stein and Wysession, 2002). In general, the constant of proportionality is close to negative one, meaning that magnitude 5 earthquakes occur about ten times more frequently than magnitude 6 earthquakes, which occur about ten more frequently than magnitude 7 earthquakes, and so on. Though applications of PSHA assume a frequency-magnitude relationship of this general form, several plausible models exist that differ substantially in the estimate of recurrence rates for the largest earthquakes. One of the most commonly used recurrence models is the Gutenberg-Richter distribution. In the Gutenberg-Richter model, smaller earthquakes follow the usual power-law distribution: the frequency of occurrence decreases logarithmically with magnitude.
For large earthquakes, this relationship may be more complicated because there is a theoretical upper bound on the maximum magnitude earthquake that a given fault can produce. Gutenberg-Richter recurrence models (Figure 5a) deal with this issue by simply truncating the power-law distribution at an upper bound, $M_{\text{max}}$ (Gonzalez et al., 2006). In the Gutenberg-Richter perspective, $M_{\text{max}}$ is the largest possible earthquake in a certain seismic zone: the probability of earthquakes with $M > M_{\text{max}}$ is identically zero.

Another widely used recurrence model is based on the notion of “characteristic earthquakes”. Small earthquakes in this model follow a similar power-law distribution to the Gutenberg-Richter model. However, in the Characteristic Earthquake model (Figure 5b), the strict logarithmic relationship is truncated at a lower level, $M_a$, and there is a subsequent spike in the frequency of earthquake occurrence at a magnitude $M_{\text{max}}$ (Wesnousky, 1994). Earthquakes of magnitude of order $M_{\text{max}}$ are large, periodic events that characterize the tectonic properties of the

![Figure 5](image)

**Figure 5:** Recurrence Models used in PSHA. Frequency of earthquake occurrence (log scale) is plotted against earthquake magnitude.

A) Gutenberg-Richter model. Earthquake frequency decreases logarithmically with magnitude to the maximum value expected on the fault.

B) Characteristic Earthquake model. Earthquake frequency decreases logarithmically, but the presence of large, characteristic earthquakes causes a spike in frequency at large magnitudes.
fault system (Convertito et al., 2006). The magnitude $M_a$ corresponds to the largest possible aftershock or foreshock for a large, characteristic earthquake, and the more frequent events of lesser magnitude consist of smaller aftershocks and foreshocks, as well as low-level, background seismicity.

Seismologists actively debate whether the Gutenberg-Richter or Characteristic Earthquake models better approximate true earthquake recurrence patterns. The reason there is no consensus is that there is a much smaller data set for large earthquakes than there is for small earthquakes (Gonzales et al., 2006; Hanks et al., 2012). The true recurrence rates of these large, rare, earthquakes are therefore quite uncertain. Wesnousky (1994) examined instrumental and paleoseismic data from different fault systems within California and concluded that the Characteristic Earthquake model best described the recurrence properties of these faults. Because of these and other observations of similar fault systems, the Characteristic Earthquake model has been applied extensively in PSHA (Convertito et al., 2006; Gonzales et al., 2006).

However, recent studies have called into question the plausibility of the Characteristic Earthquake model. The Parkfield region of the San Andreas Fault, which had neatly followed the recurrence pattern of the Characteristic Earthquake model, has recently demonstrated strong deviations from this behavior (Stein et al., 2011). Because of the extreme uncertainty in recurrence frequency for the largest earthquakes, it is impossible to know which model better fits the observed seismic record. One could therefore apply Occam’s razor to argue that a Gutenberg-Richter model should therefore be preferred, as it is the simpler model, and both models fit the data equally well.
Step 3: Modeling the Subsurface

The next step in PSHA is to choose an appropriate geologic model of the earth’s subsurface. While the source and recurrence models describe the properties of the earthquake itself, the geologic model is used to characterize the propagation of seismic waves from the source to the surface. The details of the earthquake rupture process determine the amplitude and the radiation pattern of seismic waves as they leave the source region (Kostrov and Das, 1988). The seismic waves then spread radially outward from the earthquake source and travel through the subsurface.

Strong ground motion is produced by the arrival of high-amplitude seismic waves at the surface during an earthquake. Seismic-wave amplitude is proportional to the square-root of the energy density contained within the wavefront (Stein and Wysession, 2002). The size of the earthquake therefore controls the initial amplitude, but this amplitude tends to decrease as the waves propagate further and further away from the earthquake source. As the seismic wavefront moves away from the earthquake source, it spreads out over a greater effective area, reducing the energy density (and therefore, amplitude) in a phenomenon called “geometric spreading” (Madariaga, 2007). In geometrical spreading, the total energy within the wavefront is conserved; the energy is just distributed over a larger effective volume. Thus, the greater the distance from the earthquake, the lower the expected level of shaking at the surface.

Seismic-wave amplitudes are further reduced during propagation through “attenuation” (Stein and Wysession, 2002). As in geometrical spreading, this reduction in amplitude is caused by a decrease in the energy density of the seismic wavefront. In contrast to geometrical spreading, wave attenuation results in a net loss of the energy in the wavefront in a process analogous to frictional heating.
Another important distinction between geometrical spreading and wave attenuation is that the decrease in wave amplitude due to geometrical spreading is largely independent of the structure of the subsurface, whereas seismic attenuation depends strongly on the medium through which the seismic waves propagate. The choice of a realistic geological model of the subsurface is therefore essential to PSHA, and hazard estimates can vary widely depending on the form of the attenuation relationships and site effects derived from such models (Main et al., 2011). 1D geologic models, i.e. models that vary only with depth, used to be the standard for PSHA, but recent studies have begun to incorporate 3D models that capture the lateral variation in structure within the earth (Figure 6). For example, in the 2009 ShakeOut PSHA assessment of Southern California, the USGS used a detailed 3D geologic model generated from seismic tomography experiments of the region (Olsen et al., 2009). The ShakeOut study of the Los Angeles region exemplifies the importance of the geologic model to PSHA, as wave-focusing effects due to the presence of a sedimentary basin amplified the expected ground motion (in this study) in the San Fernando Valley.
Step 4: Putting It All Together: The Hazard Integral

The fourth and final step in the PSHA method is to combine the earthquake source model, recurrence model, and wave-propagation model to estimate seismic hazard. Mathematically, this process can be described by equation (1), the “hazard integral” (Convertito et al., 2006; Kluegel, 2009). Descriptions of the individual parameters in equation (1) are listed in Table 1, and are discussed further in the text below.

\[
E(A \geq A_0) = \sum_i \alpha_i \int f_R(r) f_M(m) p_a(A > A_0 | (r, m)) \, dm \, dr
\]

Figure 6: 3D Velocity model of California. Red colors correspond to areas of low seismic velocity, while blue colors correspond to high seismic velocity.

A) Horizontal layer at 1km depth. The San Joaquin Valley (SJV) and San Fernando Valley (SFV), sedimentary basins, stand out as low velocity anomalies.

B) Horizontal layer at 4km depth. Seismic velocity tends to increase with depth.

Figure adapted from Lin (2011).
Table 1: List of parameters used in the hazard integral

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E (A \geq A_0)$</td>
<td>Rate at which ground motion $A$ is expected to exceed a threshold level $A_0$ at a surface site of interest. The recurrence time for events of this magnitude is $1/E$.</td>
</tr>
<tr>
<td>$i$</td>
<td>Fault index. The hazard integral sums over all active faults in the region surrounding the surface site of interest.</td>
</tr>
<tr>
<td>$\alpha_i$</td>
<td>Average earthquake recurrence rate on fault $i$. The average recurrence time for this fault is $1/\alpha_i$.</td>
</tr>
<tr>
<td>$f_R (r)$</td>
<td>Probability distribution for the source-to-site distances of earthquakes on fault $i$. In the event that an earthquake occurs, the probability that the earthquake has a source-to-site distance between $r$ and $r + dr$ is $f_R (r) , dr$.</td>
</tr>
<tr>
<td>$f_M (m)$</td>
<td>Probability distribution for the magnitudes of earthquakes on fault $i$. In the event that earthquake occurs, the probability that the earthquake has a magnitude between $m$ and $m + dm$ is $f_M (m) , dm$.</td>
</tr>
<tr>
<td>$p_a (A \geq A_0</td>
<td>(r,m))$</td>
</tr>
</tbody>
</table>

To use the hazard integral, seismologists first select a site at the earth’s surface for which a hazard estimate is desired. The hazard integral then tells us the rate (in units of events per year, for example) that ground motion is expected to exceed a threshold level, $A_0$ at this site. To calculate this rate, equation (1) computes a weighted sum over all possible earthquake scenarios: different faults, different distances to the earthquake hypocenter, and different magnitudes.

The models chosen in the first three steps of the PSHA method determine the parameters used in the hazard integral. The recurrence model selected in Step 2 specifies the first three parameters: $\alpha_i$, $f_R (r)$, and $f_M (m)$. $\alpha_i$ is the mean earthquake occurrence rate from fault $i$. Because of geometrical spreading and attenuation, only faults near the surface site of interest are considered for use in the hazard integral; those that are further away make negligible
contributions to the hazard estimate (US Dept. of the Interior, 2011). $f_R(r)$ and $f_M(m)$ are probability distributions that describe the recurrence pattern on a given fault. $f_R(r)\, dr$ is the probability that an earthquake will occur at a distance $r$ from the site of interest, while $f_M(m)\, dm$ is the probability that an earthquake of magnitude $m$ will occur. Finally, $p_a$ is the conditional probability that an earthquake at distance $r$ and of magnitude $m$ would produce ground motion that exceeds the threshold $A_0$. This conditional probability is computed by solving the elastic wave equation, which characterizes the propagation of seismic waves from the earthquake source to the surface (Kostrov and Das, 1988; Madariaga, 2007). The source model developed in Step 1 provides important boundary conditions for the wave propagation solution, and the geologic model (Step 3) provides the appropriate attenuation relationships to accurately quantify seismic wave amplitude.

**Discussion: The Future of PSHA**

Hazard maps like the one shown in Figure 1 are generating by evaluating the hazard integral at each point on a fine spatial grid overlaying the map area. While these maps can be useful to visualize the spatial variability in peak ground motion, they do not typically show the uncertainty associated with the hazard estimates. These uncertainties are a product of the simplifying assumptions about the properties of earthquakes and seismic waves made in the PSHA method. Because of this, analyzing the weaknesses in current PSHA methodology can help pinpoint areas for future research.

One of the most common criticisms of PSHA is that the models selected in the first three phases of the PSHA method – the source model, recurrence model, and geologic model – vastly oversimplify the complex earth processes that ultimately produce seismic ground motion (Hanks
et al, 2012; Petersen et al., 1996). Indeed, consideration of computational efficiency often forces seismologists to use kinematic descriptions of the earthquake source, rather than more realistic dynamic models. The assumption of a kinematic model inevitably leads to an inaccurate projection of seismic ground motion, particularly in the “near-field” region close to the hypocenter, which is strongly influenced by the details of rupture dynamics (Madariaga, 2007).

Seismologists are currently testing different strategies to mitigate the effects of these inaccurate models. Perhaps the most promising such approach is to analyze the results of dynamic earthquake simulations to provide better constraints on kinematic source parameters. These studies have shown, for example, that the slip distributions in dynamic simulations depend strongly on the distance from the nucleation zone and on the geometric properties of the fault itself (Schmedes et al., 2010; Dunham et al.; 2011). This research could be used to construct better kinematic source models, and ultimately provide more realistic estimates of seismic hazard. Very little is currently understood about earthquake nucleation. Most recurrence models are therefore based on the statistical, rather than physical, properties of earthquakes. Reliance solely on historical earthquake data can introduce bias into hazard estimates, especially in locations that experience infrequent seismic events. An example of this bias can be seen in hazard maps of the United States (Figure 7). The map features a prominent “bulls-eye” of high seismic hazard near New Madrid, Missouri. New Madrid experienced a series of devastating earthquakes in the early 1800s, but has shown little dangerous seismic activity since (Stein et al. 2011).
The map features a prominent “bulls-eye” of high seismic hazard near New Madrid, Missouri. These historical events may bias the recurrence models used in PSHA if they are anomalous, rather than typical, for the region.

The statistical recurrence models commonly used in PSHA also assume that earthquake occurrence is a time-independent, “Poisson” process (Petersen et al., 1996, US Dept. of the Interior, 2011). In this “memoryless” perspective, an earthquake on a given fault is just as likely to occur in the year immediately following a major earthquake as it is in any subsequent one-year time interval. The notion of time-independence, while somewhat appropriate for other types of disasters like floods, is an obvious oversimplification in the case of earthquakes. Physical earthquake models are based on the idea of elastic rebound, which is inconsistent with time-independent models (Stein and Wysesssion, 2002). Earthquakes are thought to occur only after a

**Figure 7**: USGS seismic hazard map of the United States (2008). The region surrounding New Madrid, Missouri, is prominently featured as a high-hazard “bulls-eye”. Large, historical earthquakes near New Madrid may bias current PSHA recurrence models if these events were atypical for the region.
critical level of strain energy has built up due to the deformation of tectonic plates. Because this strain energy takes time to accumulate, earthquake occurrence is likely quite time-dependent: the longer strain has been building up, the higher the probability of an earthquake.

Seismologists are actively working to incorporate a time-dependent component into recurrence models in hopes of making them more physically realistic. One such approach calculates the average recurrence times for characteristic earthquakes within a fault zone. This information is used, along with the elapsed time since the previous earthquake, to construct time-dependent earthquake probabilities (Hanks et al., 2012). However, this modification to the traditional, time-independent model implies that earthquakes can become overdue, a concept that has limited empirical support (Stein et al., 2011). A more creative approach, outlined by Barbot et al. (2012), would be to combine the earthquake source and recurrence models into a single integrated model of the full seismic cycle (Figure 8). Further research is needed before this hybrid model could be incorporated into PSHA, but its ability to replicate the behavior of the San Andreas Fault holds promise for improved insight into earthquake recurrence. Similar steps are being taken to improve the geologic models used in PSHA.

Until recently, geological attenuation relationships were derived from empirical models that were highly dependent on observations of ground motion in past earthquakes (e.g. Petersen et al., 1996). These “ground-motion prediction equations” were unreliable in earthquake scenarios for which historical data was scarce, as is often the case for large, long-recurrence earthquakes (Klugel, 2009). However, modern PSHA studies have begun to use detailed, 3D geologic models of the subsurface that can more realistically simulate the physics of wave propagation (Douglas and Aochi, 2008; Olsen et al., 2009).
The use of ever-improving physical subsurface models instead of the antiquated “black-box” attenuation relationships should help to limit uncertainty in future hazard estimates.

**Conclusion: The Value of PSHA**

Probabilistic Seismic Hazard Analysis is a long-term forecast for the intensity of ground motion. Because large earthquakes have such long recurrence times, it is difficult to objectively test whether PSHA accurately quantifies the potential for strong ground motion (Hanks, 2012). Political leaders in L’Aquila demonstrated the danger of using these hazard estimates to make short-term earthquake predictions. While the city of L’Aquila was located in an area of high seismic hazard, there have been other notable instances of earthquakes causing significant damage in regions that were previously thought to be of low hazard (Stein et al., 2011). One

![Figure 8](image)

**Figure 8:** Simulation of the full seismic cycle. Colors correspond to the particle velocity of rock along the San Andreas Fault, near Parkfield, CA. Prior to nucleation, part of the fault is locked, while the rest experiences slow, aseismic slip. The locked zone experiences large slip velocity during rupture. After the earthquake occurs, the fault returns to the interseismic phase, with strain energy building up in the locked zone. Figure adapted from Barbot et al. (2011).
recent example was the 2008 magnitude 7.9 Wenchuan earthquake, which killed 68,000 people in the Sichuan province of China. Unexpected events like this call into question the value of PSHA to society.

Critics of PSHA contend that because we understand so little about the mechanisms controlling earthquake occurrence, current hazard estimates are hardly better than random guesses (Stein et. al, 2011). PSHA, they argue, should be discontinued until it has been conclusively proven to be of value. Basing disaster mitigation plans on inaccurate assessments of seismic hazard would at best result in wasted resources, or worse, cause widespread panic. Most seismologists, however, are decidedly more optimistic about the ability of PSHA to provide useful information about the global distribution of seismic hazard. These proponents note that the presence of earthquakes in low-hazard regions does not necessarily invalidate the projections of PSHA. Indeed, because low-hazard regions comprise such a large fraction of the earth’s total area, we should expect on the order of one large, “unexpected” earthquake per year (Hanks, 2012). Anomalous events notwithstanding, PSHA assessments are essential for the long-term planning of infrastructure projects, the development of adequate building codes and the implementation of effective emergency management practices.

The two prominent earthquakes that occurred in the winter of 2010 underscore the value that PSHA can provide to governments that choose to trust and act upon its assessments. In January of that year, a magnitude 7.0 earthquake devastated the island nation of Haiti, killing more than 200,000 people. Over a month later, a much larger, magnitude 8.8 earthquake occurred off the coast of Chile, causing only 500 casualties - a comparatively small number. Chile suffered so few casualties because their cities devised and implemented strict seismic building codes (Padgett, 2010). Both Haiti and coastal Chile were thought to be regions of
considerable seismic hazard, though only the government of Chile took the initiative to prepare for a major earthquake. We as society are powerless to control the occurrence of future earthquakes. But if the findings of Probabilistic Seismic Hazard Analysis are taken more seriously, we may be able to prevent the next humanitarian disaster, the next Haiti, from occurring.
References:


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