Short Note

Biases in the estimation of earthquake recurrence and seismic hazard from geologic data

Steven G. Wesnousky
Center for Neotectonic Studies
University of Nevada, Reno
Reno, NV 89557
Email: wesnousky@unr.edu
Tel: 775 784 6067
Abstract

Aseismic deformation, an integral part of the earthquake process, may be leading to systematic biases in the estimation of earthquake size, recurrence, and attendant strong ground motions in seismic hazard analyses founded on the geologic description of the locations, lengths and slip rates of active faults.

Introduction

Regional seismic hazard analysis is now constructed on ‘fault models’ that describe the slip rate, length and width of earthquake producing faults across a region. The premise for the approach was developed, outlined and demonstrated some 25 years ago (Wesnousky, 1986; Wesnousky et al., 1984), and has not really changed since that time. The return times T of earthquakes on faults are estimated by dividing either the expected coseismic slip \( U_{\text{exp}} \) on a fault by the geologists’ or geodecists’ estimate of fault slip rate \( U_{\text{geo}} \) or, equivalently, the expected seismic moment \( M_{\text{o}}^{\text{exp}} \) by the seismic moment rate \( M_{\text{o}} \). The coseismic slip \( U_{\text{exp}} \) and seismic moment \( M_{\text{o}}^{\text{exp}} \) of the expected earthquake are generally estimated from empirical regressions relating fault rupture length or area to the respective parameters from historical observations (e.g. Figure 1). The seismic moment rate \( M_{\text{o}} \) is equal to \( \mu LW U_{\text{geo}} \), where L and W are the dimensions of the fault and \( \mu \) is crustal rigidity. While aseismic deformation is now recognized to be a fundamental part of the earthquake process, not all its facets are considered systematically in seismic hazard analyses. Here I put forth some observations to suggest that aseismic deformation may be leading to systematic biases in current estimates of seismic hazard and, analogously, its consideration may go toward resolving some issues that currently exist in seismic hazard analysis.

The Problems

The prediction of the size and frequency of earthquakes from geology is generally calibrated or checked by comparing the rate of seismicity predicted from a regional fault model to what has been observed historically (Figure 2; Field et al., 2008; Wesnousky et al., 1983). While the approach has served well, there are two problems that arise in its application to the development of seismic hazard maps that I consider here. The first of these is that predictions of seismicity from geologic data tend to overestimate the number of moderate sized events in a region as compared to what is observed. This has been true for more than 20 years and apparently remains a problem today (Field, 2009; Field et al., 2008; Wesnousky, 1986; Wesnousky et al., 1984). The
mismatch is now commonly referred to as ‘the bulge’ (Field et al., 2008 and **Figure 2**). The second of these is that existing fault models require that the amount of average slip per unit area on a fault plane systematically increases with rupture length, a prediction unsupported by instrumental seismological analyses. Thus, to avoid that increase and a concomitant increase in predicted long-period strong ground motions, physics based numerical models of earthquake rupture are generally required to allow a relatively greater down-dip extent of rupture than used for the respective fault in the fault model (Graves et al., 2009; Somerville, 2006). There thus exists an internal inconsistency between the depth dimensions used in fault models to predict earthquake recurrence and those required for prediction of strong-ground motions from physics-based numerical models.

**Aseismic Deformation and the Estimation of the Rate of Seismic Moment Release along Mapped Faults**

Fault displacement occurs by both seismic and aseismic processes. At one end of the spectrum the entirety of cumulative slip along a fault is accommodated by the repeated occurrence of large earthquakes with interevent times being marked only by the continual accrual of elastic strain, akin to the concept of elastic rebound (Reid, 1910). At the other end resides the fault where the entirety of slip is accommodated by the steady continual movement of a fault in the absence of large earthquakes, generally referred to as aseismic creep (e.g., Burford and Harsh, 1980). The latter phenomenon though well exhibited along the central San Andreas is rare in continental environments. Within that spectrum is the manifestation of aseismic deformation temporally associated with the occurrence of earthquakes. Afterslip was perhaps first recognized with the mapping of the moderate sized 1968 Borrego Mtn earthquake (USGS, 1972). Surface offsets at the time of the earthquake were observed to continue aseismically and double in the weeks after the earthquake. In this case, the cumulative geologic offset being registered along the particular fault was accommodated by a mix of seismic and aseismic deformation. The phenomenon is now well recognized to be an integral part of the earthquake process, having been observed geologically and geodetically for numerous moderate to large earthquake since (e.g., Bilham and Behr, 1992; Burgmann et al., 2002; Donnellan et al., 2002; Owen et al., 2002; Segall et al., 2000; Segall and Davis, 1997). Aseismic deformation also may occur contemporaneously with seismic slip along a fault. The process is most easily observable in the examination of dip-slip earthquakes where coseismic displacement is divided between slip on a fault plane and
production of fold deformation. The 1980 El Asnam, Algeria, 1983 Coalinga, and 1994 Northridge, California earthquakes are examples of the phenomenon (Davis and Namson, 1994; King and Yielding, 1984; Stein and King, 1984). There fault slip was confined to depth and fault displacement is recorded toward the surface not by fault slip but rather by folding. So, similar to the process of afterslip, cumulative slip registered at the surface is a result of both seismic and aseismic deformation.

The seismic moment of historical surface rupture earthquakes determined from geologic measures of surface slip is plotted as a function of the instrumentally determined seismic moment of the respective earthquakes in Fig 3. Geologic moment is computed by multiplication of geologists measures of coseismic offset $U^{exp}$ and surface rupture length $L$ on the ground surface by seismologists estimates of fault width $W$ from seismicity and crustal rigidity $\mu$. The observations show that the geologic moment and seismic moment agree most closely for the largest earthquakes. But as earthquakes become smaller the geologic moments invariably underestimate the seismic moments derived from instrumental measures. One may infer from the observation that the lesser-sized events do not completely rupture to the surface and hence do not produce seismic slip across the entire fault plane. If earthquakes such as these represent repeating earthquakes along a particular fault or fault segment, it seems that a portion of the fault slip rate for these moderate sized faults or fault segments must ultimately be accommodated by aseismic deformation. When viewing Fig 3, and recognizing that the plot does not include the many moderate-sized earthquakes characterized by an absence of significant surface rupture (e.g. the 1983 M6.4 Coalinga, 1994 M6.7 Northridge, and 1989 M6.9 Loma Prieta earthquakes), it may be inferred there is a tendency for the percentage of slip accommodated by aseismic deformation to increase inversely to the length of the fault or fault segment producing an earthquake. The observations, if indeed correct, will lead to a systematic error in estimating the seismic moment rate from geologic slip rates. That is to say, the seismic moment rate calculated from fault slip rate assuming rupture across the entire seismogenic zone will, as an inverse function of fault length, increasingly overestimate the actual seismic moment release rate to be expected on a particular fault segment.
The Base of the Seismogenic Layer and the Estimation of Earthquake Size and Strong Ground Motions from Fault Data

The long-recognized but oft-ignored observation that coseismic slip in large strike-slip earthquakes increases with rupture length (Fig 1) was recently revisited by King and Wesnousky (2007). The particular observation results in a conundrum whereby calculations of static stress drop of large earthquakes increase with rupture length, a prediction that has not been borne out by seismological observation. The conundrum arises because elasticity models show stress drop is proportional to the average displacement on a fault divided by the shortest dimension of the fault, and, as generally assumed, that the shortest dimension of a fault is equal to the depth to which seismicity is observed, about 15 km in continental environments. We showed that the conundrum can be resolved by assuming (1) a simple displacement-depth function of tapered and ‘self-similar’ form that better reflects observation and is consistent with frictional models of fault behavior and (2) it is allowed that larger earthquakes progressively rupture a greater though modest amount below the seismogenic layer into a region of stable-sliding, where rupture may propagate but not initiate. The static model then leads to prediction of constant stress drop and self-similarity for earthquakes across the entire spectrum of earthquake sizes. Since that time, physics based models have yielded the same result (Hillers and Wesnousky, 2008; Shaw, 2009; Shaw and Wesnousky, 2008).

It is current practice to use empirical regressions of fault area determined from aftershocks versus seismic moment to estimate the expected size of future earthquakes on mapped faults (e.g., Field et al., 2008; Hanks and Bakun, 2002, 2008). Fault area is generally determined from background seismicity and earthquake aftershocks. If coseismic rupture extends below the seismogenic layer and the depth extent increases with rupture length, the seismic moment per unit area expected on mapped faults may be systematically overestimated for increasingly longer earthquakes, and the overestimation will systematically increase as a function of rupture length. The idea is illustrated in Fig 04. The process would also go toward remedying the existing need of physics based numerical models (used to estimate strong ground motions) to require rupture to extend to greater down-dip widths than are used in existing fault models where fault widths are based on background seismicity or aftershocks. That the seismic moments approach equality for the largest earthquakes in Fig 03 would in this context imply that coseismic displacement below the seismogenic layer as depicted in Fig 04 is coupled with relatively little seismic slip per unit area.
Consequence of observations on prediction of seismicity and strong ground motion from active fault data sets

The observations presented in the preceding two sections suggest that 1) estimates of the seismic moment of earthquakes on mapped faults based on fault area may be overestimated and that the overestimation is a function of fault length and 2) that estimation of the seismic moment rate on mapped faults determined from fault slip rates may be systematically biased such that they are overestimated and the degree of overestimation is an inverse function of fault length. In this context we can write the expression for the return time of earthquakes on an active fault as $T = \alpha M_o^{\exp} / \beta M_o$, where $\alpha$ and $\beta$ are negative and positive functions of fault length, respectively, and limited to between 0 and 1. The net effect of the two systematic biases when considered over a region will lead to a change in the predicted seismicity as expressed in a magnitude-frequency distribution plot. The manner of change is schematically illustrated in Fig 5. Inclusion of the biases represented by $\alpha$ will lead to estimates of smaller return times $T$ for the largest earthquakes. In a constrasting manner, if the seismic component of fault slip rates is now systematically biased to be high for lesser fault lengths, correction of the bias with $\beta$ will lead to relatively longer return time $T$ estimates for smaller earthquakes. The net effect will be a shift of the slope of magnitude-frequency distribution. The resulting shift may work to diminish or remove ‘the bulge’. The crossing point of the dashed and black lines will depend on the functional dependence of $\alpha$ and $\beta$ on fault length $L$.

Summary

Systematic biases in the estimation of earthquake size and return time from geologic data sets describing the length and slip rate of active faults may arise from aseismic processes. Estimates of the expected size of earthquakes on mapped faults are currently being overestimated if large earthquakes extend below the seismogenic layer and the extent is a function of rupture length. In turn, the estimates of the seismic moment rate on mapped faults may be systematically overestimated for smaller faults when processes of aseismic deformation at and close in time to earthquakes are ignored. The observations suggest that the expression for return time $T$ on active faults may be described by the expression $\alpha M_o^{\exp} / \beta M_o$, where $\alpha$ and $\beta$ are negative and positive functions of fault length, respectively. While current observations are insufficient to prove aseismic deformation is sufficiently systematic to define unique parameters of $\alpha$ and $\beta$ to
regional data sets, the observations at hand appear sufficient to suggest that an increased understanding of these parameters and the physical processes they represent may ultimately lead to more accurate and internally self-consistent estimates of seismic hazard.

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References


Figure 1. Example of empirical correlation of earthquake size to fault dimension. In this case average surface displacement is plotted as a function of surface rupture length for continental strike-slip earthquakes (adapted from Wesnousky, 2008).
Figure 2. Schematic illustration of the manner in which predictions of seismicity from geologic fault models are calibrated to historical observations in magnitude-frequency plots. The seismicity emanating from a regional set of faults is typically estimated from each mapped fault with the assumption that the return time $T$ of earthquakes on each mapped fault is equal to the seismic moment of the earthquake expected $M_o^{\text{exp}}$ on the fault divided by the estimated seismic moment rate $\dot{M}_o$ for each fault. The size of the expected earthquake $M_o^{\text{exp}}$ is taken from modern empirical regressions relating fault dimension to seismic moment and the seismic moment rate $\dot{M}_o$ is proportional to the geologically determined fault slip rate $U^{\text{geo}}$. It is common that more moderate sized events are predicted from geologic fault models than observed. The mismatch of observed to predicted number of earthquakes per year at moderate magnitudes has been referred to as 'the bulge'.

\[ T = \frac{M_o^{\text{exp}}}{\dot{M}_o} \]
Figure 3. Geologic Moment versus Seismic Moment for large surface rupture earthquakes. Geologic moment is computed by multiplication of geologists’ measures of surface offset and surface rupture length by seismologists estimates of fault width from seismicity and crustal rigidity. Perfect agreement of the two measures would plot on a line of slope 1. Shaded region encompasses all points on and below the line of slope 1. For the largest earthquakes the geologic and instrumental measures of Moment agree best and the scatter of data below the line of slope 1 increases inversely with magnitude. Data are replotted from Wesnousky (2008). Strike-slip (SS), normal (N), and Reverse (R) earthquakes plotted with different symbols. Vertical error bars span a factor of 3 in seismic moment. Horizontal error bars represent the range of multiple estimates of seismic moment from various investigators.
Figure 4. Contemporary regressions of fault area versus seismic moment may be overestimating the size of future earthquakes on mapped faults. The lower portion of the figure shows schematically the rupture area of 4 large earthquakes of increasingly greater rupture length. The black indicates the portion of rupture within the seismogenic layer and marked by seismicity or aftershocks. The dashed gray lines depict rupture propagating below the seismogenic layer into a region of velocity-strengthening material. The region of velocity strengthening would be devoid of aftershocks. The idea is consistent with state-variable frictional laws of fault behavior (King and Wesnousky, 2007; Ruina, 1983; Tse and Rice, 1986). The upper left schematically shows a hypothetical regression between instrumentally derived seismic moment \( M_0 \) and fault area for the 4 earthquakes were it determined from aftershocks (black line and solid dots) or from accounting for propagation to some extent below the seismogenic layer (gray dashed line and open dots). The black line would be analogous to what is used today.
Figure 5. Schematic illustration of the sense of change that would be expected in seismicity predicted from geologic data if the return time of earthquakes on each fault is written \( T = \alpha M_o^{\alpha} / \beta \dot{M}_o \), and \( \alpha \) and \( \beta \) are taken to represent negative and positive functions of fault length, respectively, and limited between 0 and 1. The black line schematically depicts a magnitude-frequency distribution calculated from a regional distribution of faults assuming that the return time on each fault \( T = M_o^{\alpha} / \dot{M}_o \), whereas the dashed line includes the effect of \( \alpha \) and \( \beta \). Inclusion of the biases represented by \( \alpha \) and \( \beta \) will lead to estimates of smaller return times \( T \) (more frequent occurrence) of the largest earthquakes and relatively longer return time \( T \) estimates (less frequent occurrence) for smaller earthquakes, respectively. The net effect will be a shift of the slope of magnitude-frequency distribution to the dashed line.