The role of stress transfer in earthquake occurrence

Ross S. Stein

US Geological Survey, MS 977, Menlo Park, California 94025, USA

An earthquake alters the shear and normal stress on surrounding faults. New evidence strengthens the hypothesis that such small, sudden stress changes cause large changes in seismicity rate. Rates climb where the stress increases (aftershocks) and fall where the stress drops. Both increases and decreases in seismicity rate are followed by a time-dependent recovery. When stress change is translated into probability change, seismic hazard is seen to be strongly influenced by earthquake interaction.

During the 75 years before the great 1906 earthquake on the San Andreas fault, the San Francisco Bay area suffered at least 14 shocks of moment magnitude (M_w) equal to or exceeding 6; these occurred on all major faults, and included two events of $M_w \geqslant 6.8$. In the succeeding 75 years, there was but one $M_w \geqslant 6$ shock[1] (Fig. 1). Elsewhere, $M_w \geqslant 6$ earthquakes in the extensional regime seaward of subduction zones occur, with few exceptions, only in the years following great subduction events[2]. Evidently, the rate of seismicity is therefore not constant, and the rate—or probability—of earthquakes on one fault is not independent of the rate on another. Yet there is nothing in probabilistic seismic hazard assessment (the principal tool of the engineering, insurance, financial, and emergency-response communities) that reflects or can reproduce such observations. Earthquake interaction is a fundamental feature of seismicity, leading to earthquake sequences, clustering, and aftershocks. One interaction criterion that promises a deeper understanding of earthquake occurrence, and a better description of probabilistic hazard, is Coulomb stress transfer.

Coulomb failure stress

An earthquake reduces the average value of the shear stress on the fault that slipped, but as Chinnery first showed in 1963, shear stress rises in more areas than just the fault tips[3]. The importance of this discovery was realized about 20 years later, when lobes of off-fault aftershocks were seen to correspond to small calculated increases in shear[4] or Coulomb stress[5,6]. In its simplest form, the Coulomb failure stress change, $\Delta\sigma_f$ (also written ΔCFS or ΔCFF) is

$$\Delta\sigma_f = \Delta\tau + \mu(\Delta\sigma_n + \Delta P) \quad (1)$$

where $\Delta\tau$ is the shear stress change on a fault (reckoned positive in the direction of fault slip) and $\Delta\sigma_n$ is the normal stress change (positive if the fault is unclamped). ΔP is the pore pressure change in the fault zone (positive in compression), and μ is the friction coefficient (with range 0–1). Failure is encouraged if $\Delta\sigma_f$ is positive and discouraged if negative; both increased shear and unclamping of faults promote failure. The tendency of ΔP to counteract $\Delta\sigma_n$ is often incorporated into equation (1) by a reduced 'effective' friction coefficient, μ' (ref. 7).

The calculated off-fault stress increases are rarely more than a few bars (1 bar = 0.1 MPa, which is approximately atmospheric pressure at sea level), or just a few per cent of the mean earthquake stress drop. In addition, the proximity to failure at any site is presumably variable but in any event unknown. So why would aftershocks concentrate at the site of such small stress increases? New studies

Figure 1 Comparison of earthquakes before and after the $M_w = 7.8$ San Francisco earthquake on the San Andreas fault. Solid red lines, interpreted rupture positions[42]; dashed red lines, the 1906 earthquake. Urban areas are shown grey. S.F. Bay, San Francisco Bay. Although this is the longest historical earthquake record in the western United States, it is probably complete for $M_w \geqslant 6$ only since the 'gold rush' of 1849, and so underestimates the rate of shocks during the pre-1906 period. The southern end of the 1906 rupture lies near the bottom of the image; the northern end lies 200 km northwest of the image. Processing by R. E. Crippen.