



Effect of seismic moment–area scaling on apparent stress–seismic moment relationship

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ABSTRACT

Two alternative formulations of the apparent stress, representing homogeneous crack and triangle pulse rupture models, are tested. They are termed seismic state equations and express the apparent stress, τ_a , as a function of, respectively, two or three other earthquake parameters: seismic moment, M_0 , rupture area, A , and, in the latter case, mean slip acceleration, g . The number of parameters is the key difference between the two models. A variety of possible τ_a – M_0 scalings is obtained by substitution of different moment–area relations, M_0 – A , into the seismic state equations, $\tau_a(M_0, A, g)$. Both seismic state equations enable us to explain the observed τ_a – M_0 global trend. However, the triangle pulse solution fits the empirical trend with much higher correlation coefficient. Also the trends obtained for regional data sets are more consistent with the pulse model than with the crack one.

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1. Introduction

Two relations between earthquake parameters: the seismic moment versus rupture area scaling, M_0 – A (e.g., Hanks and Bakun, 2002, 2008; Mai and Beroza, 2000; Romanowicz, 1992; Romanowicz and Ruff, 2002; Scholz, 1982; Shaw and Scholz, 2001; Wells and Coppersmith, 1994) and the apparent stress versus seismic moment scaling, τ_a – M_0 (e.g., Abercrombie, 1995; Choy and Boatwright, 1995; Ide and Beroza, 2001; Izutani and Kanamori, 2001; Pérez-Campos and Beroza, 2001), have been disputed for over two decades as separate problems. The former relation is important in the seismic hazard context, whereas the second one can be treated as a test of seismic source self-similarity (Prieto et al., 2004). Kanamori and Rivera (2004) pointed out that the M_0 – A scaling provides constraints on the τ_a – M_0 relation. They demonstrated that the constant static stress drop condition implies that the apparent stress does not scale with M_0 either. This result assumes a homogeneous crack earthquake source model or any model, in which the apparent stress is proportional to the static stress drop. However, the apparent stress, τ_a , and the static stress drop, $\Delta\sigma$, are two different physical characteristics of the earthquake rupture process. Their ratio depends, in general, on the radiation efficiency or the radiated energy to the fracture energy ratio (e.g., Kanamori and Brodsky, 2004). It is expected, therefore, that different earthquake source models lead to a variety of τ_a – M_0 relationships.

A three step scheme is proposed in this paper. First, apparent stress is expressed in terms of seismic moment and other parameters that specify a given earthquake source model. This relationship is termed a seismic state equation, in analogy to statistical physics. Second, a complementary relation among the seismic moment and rupture area is defined. Third, this complementary relation is substituted into the seismic state equation to obtain the τ_a – M_0 scaling.

The reasoning presented by Kanamori and Rivera (2004) can be considered within this scheme with $\tau_a \propto M_0/A^{3/2}$ as the seismic state equation and $\Delta\sigma \propto M_0/A^{3/2} = \text{const}$ as the complementary relation. Both of these factors are model dependent. The triangle pulse rupture model proposed by Senatorski (2007, 2008) is used in the present paper as an alternative for the homogeneous crack solution. The triangle pulse model involves average slip acceleration, g , as the third extra parameter to define the slip velocity pulses. This is the key feature of the model that determines its scaling characteristics. Consequently, the seismic state equation involves three parameters in this case, $\tau_a = \tau_a(g, M_0, A)$. It is shown that, unlike the homogeneous crack model, the triangle pulse model does not imply the $\tau_a \propto \Delta\sigma$ relation and, therefore, it leads to different τ_a – M_0 scalings. These theoretical results are compared with real trends observed for earthquake populations extending from the smallest mining induced tremors to the largest subduction megathrust earthquakes.

The first objective of this paper is to show how the resulting τ_a – M_0 scaling depends on the assumed earthquake model dynamics and geometry. The second aim is to demonstrate that the seismic

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state equation based on the proposed triangle pulse model is more consistent with the available real data than its homogeneous crack alternative. The complementary M_0 – A relations are systematized in the next section. Two seismic state equations are introduced in Section 3. The resulting τ_a – M_0 scalings are presented in Section 4. The real data are analyzed in Section 5. Discussion and Conclusions end the paper.

2. Seismic moment versus rupture area scaling

Seismic moment is expressed in terms of mean slip displacement, $\bar{D}$, and rupture area, A , as

$$M_0 = \mu \bar{D} A,$$

where μ is shear modulus. To obtain M_0 – A scaling, dependence of $\bar{D}$ on rupture geometry is needed. In static, homogeneous crack models, $\bar{D}$ depends on the characteristic dimensions of rupture: its length, L , width, W , or area, A (Kanamori and Anderson, 1975; see also Shearer, 2011). If the characteristic dimension is $\bar{L}$, the static stress drop can be expressed as

$$\Delta\sigma = C\mu \frac{\bar{D}}{\bar{L}} = C \frac{M_0}{A\bar{L}}, \quad (1)$$

where C is a constant. For a circular crack-like model, the characteristic source dimension is its radius, $\bar{L} = R$. For a rectangular source model, the characteristic dimension is the smaller one of two: W or L . From Eq. (1), geometrical and physical similarities of seismic sources, $L \propto W$ and $\bar{D} \propto L$, respectively (Aki, 1967; Prieto et al., 2004) imply that $\Delta\sigma = \text{const}$, which is consistent with observations (e.g., Allmann and Shearer, 2009).

Two earthquake classes are distinguished. For small to moderate earthquakes, such that $W < W_0$ (W_0 is the maximum rupture width related to seismogenic layer depth), geometrical similarity is assumed, $L = fW$ (f is a geometrical factor), so the rupture grows both in W and L . For large earthquakes, where $W = W_0$, the rupture grows only in L .

Examples of M_0 – A scalings obtained for different source models are listed in the left part of Table 1.

- (A) In the L model, slip displacement is controlled by rupture length,

$$\bar{D} = \alpha L,$$

where α is a constant (Scholz, 1982). This scaling agrees with empirical results showing that slip displacement continues to grow even after the rupture width reaches the seismogenic fault depth, $W = W_0$. Consequently, the static stress drop given by the homogeneous crack solution,

$$\Delta\sigma = \mu \bar{C} \bar{D} / W,$$

grows with increasing L for large events with $W = W_0$. According to Scholz (1982), however, such events do not represent a crack, but the last unbroken asperity failure, so the right scale length, which involves a deeper, aseismic fault patch, is L , i.e.,

$$\Delta\sigma = \mu \bar{C} \bar{D} / L.$$

In this interpretation, the L model is consistent with the constant stress drop assumption. For small to moderate events, the seismic moment scales with L and A as $M_0 \propto L^3$ and $M_0 \propto A^{3/2}$, respectively. For large events, the scalings are $M_0 \propto L^2$ and $M_0 \propto A^2$.

- (B) According to the W model, slip displacement is controlled by rupture width,

$$\bar{D} = \alpha W$$

(Romanowicz, 1992; Romanowicz and Ruff, 2002), so it predicts that both $\bar{D}$ and $\Delta\sigma$ remain constant for large events. The W model is consistent with the constant stress drop assumption. For small to moderate events, the seismic moment scales with L and A as in the L model. For large events, the scalings are, respectively, $M_0 \propto L$ and $M_0 \propto A$. Most studies suggest that earthquakes follow rather the W than L model (e.g., Manighetti et al., 2007). However, it is also admitted that $\bar{D}$ somehow continues to grow with L after the fault seismogenic depth, W_0 , is reached.

- (C) Shaw and Scholz (2001); (see also Shaw, 2009) combined both the L and W models. They assumed that

$$\bar{D} = \alpha \begin{cases} L/2 & \text{for } L < 2W_0 \\ [(1/L) + (1/2W_0)]^{-1} & \text{for } L > 2W_0 \end{cases}$$

Consequently, $\bar{D}$ scales with L for small events and tapers off at large L . The model predicts constant static stress drop for both small and large earthquakes. For small earthquakes the seismic moment scales with L and A in the same way as in the L and W models. For large earthquakes the relations are, respectively, $M_0 \propto L^2/[1 + (L/2W_0)]$ and $M_0 \propto A^2/[1 + (A/2CW_0^2)]$. Manighetti et al. (2007) used that model to explain large stress drop variability, reflected by the α factor, in terms of fault segmentation and its structural maturity.

Next three models go beyond the homogeneous crack-like rupture view.

- (D) Dynamic, pulse-like rupture models assume that slip duration at a point, i.e., rise time, is shorter than earthquake duration, $t_R < T$ (Heaton, 1990). Such a slip velocity pulse can be modeled as a continuous dislocation distribution moving along a fault (e.g., Weertman and Weertman, 1980). The difference between stresses before and after rupture front passage, i.e., stress drop, scales with the slip to pulse length ratio, $\Delta\sigma \propto \bar{D}/L_p$ (e.g., Senatorski, 2008). Consequently, the constant stress drop assumption implies the

$$\bar{D} = \alpha L_p$$

scaling. For small to moderate events, the seismic moment scales with L and A as $M_0 \propto L^2 L_p$ and $M_0 \propto A L_p$, respectively. For large events, the scalings are $M_0 \propto L L_p$ and $M_0 \propto A L_p$. It should be noticed that though $\bar{D}$ does not directly depend on the final rupture dimensions, it can depend on L somehow. This is because larger slip velocity pulses are expected to propagate farther (Scholz, 1982; Heaton, 1990; Liu-Zeng et al., 2005; Mai and Beroza, 2000). Larger pulses concentrate higher stresses ahead of rupture fronts, therefore they are less likely to be arrested by barriers randomly distributed along fault planes.

- (E) Liu-Zeng et al. (2005) modeled a heterogeneous slip function as the stochastic fractional Brownian process, obtaining the

$$\bar{D} = \alpha L^\gamma$$

scaling, where exponent γ depends nonlinearly on a parameter that describes spatial smoothness of slip. Ruptures with smooth slip functions produce $\bar{D}$ that is linearly proportional to L ($\gamma = 1$), and exponent γ gradually decreases for rougher

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