A uniform representation in the calculation of seismic radiation efficiency and rupture speed^{*}

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Abstract

According to energy partition principle, we have derived a generalized formula used to calculate the radiation efficiency. It overcomes the numerical errors involved in the estimation of radiation efficiency caused by the uncertainties owe to the different frictional mechanisms which is used to describe the earthquake faulting. Using real seismic data published in the previous studies, we have recalculated the radiation efficiency with associated to the different frictional mechanisms, and compared with previous results lack of consideration of frictional mechanism. The results indicate that, based on the new formula, the radiation efficiency we have estimated is always less than 1, and the unphysical conclusion of radiation efficiency greater than 1 is avoided completely.

Key words: apparent stress; static stress drop; partial stress drop; undershoot; overshoot; radiation efficiency; rupture speed

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Introduction

In observational seismology, precisely estimating of earthquake source parameters, such as apparent stress σ_a , static stress drop $\Delta\sigma_s$, rupture speed v , and seismic radiation efficiency η_R can provide us insight into the fault rupture process. With the advance of modern instrument and acquisition of high-quality seismic data, the accuracy in estimating the source physical and geometrical parameters also get improved greatly. The accuracy of estimated value of E_S (the radiated seismic energy) for large earthquakes, for example, has been controlled within the same order of magnitude, and even its premier numbers probably within a gap of only 2~3 (McGarr and Fletcher, 2002) in virtue of high-quality seismic data. Therefore, a quantitative investigation of the earthquake source rupture process with associated physical mechanism has become available based on the seismological measurements.

In recent study, Kanamori and Brodsky (2004) proposed a specific relation between radiation efficiency and rupture speed on the base of slip weakening frictional mechanism and self-similar crack model. The relation usefully serves to quantitatively map the radiated seismic energy with

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associated rupture speed on the fault. The concept of radiation efficiency η_R in an earthquake was first introduced by Hussein and Randall (Hussein and Randall, 1976; Hussein, 1977). Recently, with the acquisition of high-quality seismic data, the radiation efficiency has been used to determine some of fault ruptures characteristics for large earthquakes (Venkataraman and Kanamori, 2004). As we know, the radiation efficiency quantitatively represents the ratio of the radiated seismic energy to the fracture energy required to keep rupture propagation on the fault. In fact, there exists a common relation between radiation efficiency η_R and other macroscopic field measurement, like apparent stress σ_a and static stress drop $\Delta\sigma_s$. According to the simplified slip weakening frictional mechanism without a consideration of dynamic frictional overshoot or undershoot, the relation can be expressed as (Kanamori and Brodsky, 2004):

$$\eta_R = \frac{2\sigma_a}{\Delta\sigma_s} \quad (1)$$

where $\sigma_a = \mu E_S / M_0 = E_S / UA$ is known as apparent stress, where μ is shear modulus on the fault; E_S and M_0 are the radiated seismic energy and scalar seismic moment, respectively; and U is the averaged slip displacement over the fault area A . It denotes the radiated energy (E_S) measured in far field when per unit area in the fault plane occurs per unit slip. The static stress drop $\Delta\sigma_s = \sigma_1 - \sigma_2$ is the difference of the shear stresses on the fault before and after earthquake faulting.

According to the Savage and Wood inequality (1971),

$$\sigma_a = \frac{1}{2}(\sigma_1 - \sigma_2) - (\bar{\sigma}_r - \sigma_2) = \frac{1}{2}\Delta\sigma_s - (\bar{\sigma}_r - \sigma_2) \quad (2)$$

where the average friction stress $\bar{\sigma}_r$ is defined as $\bar{\sigma}_r = \int_0^U \sigma_r(u) du / U$, and $\sigma_r(u)$ is the dynamic

friction stress during fault rupture. With respect to the description of dynamic friction on the fault motion, three frictional models are stated as follows. ① A total stress drop model (Orowan, 1960; Brune, 1970), that is, the dynamic frictional stress is equal to the final shear stress on the fault as shown in Figure 1, $\sigma_a = \Delta\sigma_s / 2$, $\bar{\sigma}_r = \sigma_2$; ② A partial stress drop model or frictional undershoot model (Brune, 1970, 1976; Housner, 1955), and $\sigma_a > \Delta\sigma_s / 2$, $\bar{\sigma}_r < \sigma_2$; ③ A frictional overshoot model (Savage and Wood, 1971), and $\sigma_a < \Delta\sigma_s / 2$, $\bar{\sigma}_r > \sigma_2$. As to the three frictional models described above and the assumption of neglecting fracture energy E_G , equation (1) itself cannot but lead to an overestimation or underestimation of the radiation efficiency. In this paper, we put our emphasis on the derivation of a uniform formula for the radiation efficiency considering the energy partitioning principle and slip weakening

Figure 1 A simple graphic representation of the energy budget during a fault slip in the total stress drop model

E_S , E_G , and E_H are the radiated seismic energy, fracture energy and heat, respectively. D_c is the critical slip displacement, $\Delta\sigma_c = \bar{\sigma}_r - \sigma_2$ is the difference between average friction stress and actual sliding friction stress ($E_G = \Delta\sigma_c AU$)

frictional mechanism with self-similar crack model, rather than the physical causation of these frictional behaviors. Finally, we recalculated the radiation efficiency and the rupture speed associated for several typical earthquake events occurred worldwide.

1 Energy partition principle

Supposing a closed surface S_0 (external boundary) around the earthquake fault (internal boundary $\Sigma^- + \Sigma^+$) with a characteristic scale Σ at a distance, r , much larger than the source dimension, part of seismic energy is carried by seismic waves through S_0 when the faults interact each other during sliding (Figure 2). The radiation energy in the far field (Rudnicki and Freund, 1981) is equivalent to:

$$E_S = \int_{t_0}^{t_1} \int_{S_0} \rho [\alpha (\dot{u}_j n_j)^2 + \beta (\dot{u}_i - \dot{u}_j n_j n_i)^2] dS dt \quad (3)$$

Figure 2 Schematic illustration of fault Σ surrounded by a closed surface S_0

where ρ is the material density, α and β are the P- and S-wave speeds, respectively. u_i is the displacement, $\dot{u}_i$ is the particle velocity and n_j is the unit vector normal to S_0 pointing outwards, and i, j are spatial indexes. t_0 is a reference time before the earthquake and t_1 is a time after the earthquake when any movement has ceased within S_0 .

On the other hand, if $r \gg \Sigma$, it is shown that the radiated seismic energy (only including S-wave) induced by the change of the potential energy before and after earthquake can be calculated as (Kostrov, 1974; Dahlen, 1977)

$$E_S = \frac{1}{2} \int_{\Sigma} (\sigma_{ij}^1 + \sigma_{ij}^2) \Delta u_i v_j dS - \int_{\Sigma} 2\gamma_{\text{eff}} dS - \int_{t_0}^{t_1} dt \int_{\Sigma(t)} \sigma_{ij} \Delta \dot{u}_i v_j dS \quad (4)$$

σ_{ij} represents the stress tensor at any time, σ_{ij}^1 and σ_{ij}^2 are the initial and final stress tensor. This expression can be further simplified by defining $\Delta u_i = u_i^+ - u_i^-$, which is the displacement discontinuity from one side of the fault to the other, and letting u_i^+ and u_i^- collapse to a single open surface Σ^+ and Σ^- whose normal vectors are $\mathbf{n}_+$ and $\mathbf{n}_-$, respectively. Then the normal vector of the fault plane Σ is $\mathbf{v} = \mathbf{n}_+ = -\mathbf{n}_-$. γ_{eff} is the effective fracture energy (Kostrov, 1974). Comparing equation (3) with (4), observed data on the ground can be served to evaluate the dynamic rupture parameters in the fault plane. Further discussion could be referred to Rivera and Kanamori's (2005) work.

Supposing that the variation of stress on the fault plane and slip displacement obey a simple slip weakening principle (Figures 1 and 3), equation (4) can be reduced as:

$$E_S = \frac{1}{2} (\sigma_1 + \sigma_2) UA - A \int_0^U \sigma_t(u) du \quad (5)$$

where the surface integral in equation (4) is transferred into one along the fault plane so that σ_{ij}^1

and σ_{ij}^2 are substituted as σ_1 and σ_2 , respectively. Owing to geometric relationship illustrated by Figures 1 and 3, we can derive:

$$\begin{cases} E_s = \frac{1}{2}(\sigma_1 + \sigma_2)UA - [E_G + E_H] \\ E_G + E_H = A \int_0^U \sigma_r(u) du \\ E_H = \sigma_f UA \end{cases} \quad (6)$$

or,

$$\begin{cases} E_s = \frac{1}{2}(\sigma_1 + \sigma_2)UA - \Delta\sigma_c UA - \sigma_f UA \\ E_G = \Delta\sigma_c UA \end{cases} \quad (7)$$

Here σ_f is the sliding frictional stress, $\Delta\sigma_c = \bar{\sigma}_r - \sigma_f$. E_G here is different from the fracture energy normally used in rupture mechanics, which depends on not only the material in both sides of fault, but also the process of faulting itself (*e.g.*, Abercrombie and Rice, 2005). For example, if faulting involves extensive off-fault cracking (Rice *et al.*, 2005; Andrews, 2005), the energy used to create off-fault cracks $\int_{\Sigma} 2r_{\text{eff}} ds$ may be included in E_G . If fault slip motion involves fluid pressurization or melting (Rice, 2005; Wibberley and Shimamoto, 2005) due to heating, the thermal energy and latent heat involved in melting and fluid pressurization can be also included in E_G . E_H is the energy dissipated as the work done against the frictional resistance on the fault plane, in general, which becomes heat energy near the crack surface, *i.e.*, frictional heating. The definition of radiation efficiency η_R is shown as follows (Kanamori and Brodsky, 2004):

$$\eta_R = \frac{E_s}{E_s + E_G} \quad (8)$$

In light of equation (7) retrospectively, the general formula of radiation efficiency from the observed data can be attained

$$\eta_R = \frac{\sigma_a}{\sigma_a + \Delta\sigma_c} \quad (9)$$

When the rupture process applies to a total stress drop model, we can reveal from Figure 1 that

$$\Delta\sigma_c = \frac{1}{2}\Delta\sigma_s - \sigma_a \quad (10)$$

In cases of undershoot (partial stress drop) and overshoot (Figures 3a and 3b) respectively, we have

$$\begin{cases} \Delta\sigma_c^u = \sigma_{us} - \sigma_a + \frac{1}{2}\Delta\sigma_s \\ \Delta\sigma_c^o = \frac{1}{2}\Delta\sigma_s - \sigma_a - \sigma_{os} \end{cases} \quad (11)$$

Substitute equation (11) into equation (9), then

Here C_R is Rayleigh wave velocity ($C_R \approx \beta$), and β is shear wave velocity. Thus, combining equations (8), (13) with (14), we can evaluate fracture energy E_G and rupture velocity V . Meanwhile, it should be noticed that the equation by Kanamori and Brodsky (2004) seems to be not the last description to actual strike earthquakes, for it is just an approximate average rupture speed. Recently some researchers proposed that supershear rupture exists in some segments of strike fault region, and especially Chen and Zhang (2004, 2006a, b; 2006) claimed that even most of strike earthquakes with ground rupture zone allow occurrence of supershear rupture. Nevertheless, the equation by Kanamori and Brodsky (2004) is rooted in the assumption of rupture speed less than S-wave speed. As a result, this equation is reliable to value average rupture speed in non-strike earthquakes and probably pose certain risks when imposed to deal with strike earthquake.

3 Case studies and discussions

1) The 2001 $M_S 8.1$ Kunlunshan earthquake, generated more than 500 km surface rupture, is one of the largest earthquakes occurred in Chinese mainland within a period of the last fifty years. The observed surface rupture zone extends about 500 km, the largest fault in the world. Seismic moment and the radiated seismic energy determined by the USGS (NEIC) are $M_0 = 1.80 \times 10^{20}$ N·m and $E_S = 3.20 \times 10^{16}$ N·m, respectively. If we choose $\mu = 3.0 \times 10^4$ MPa, the resultant apparent stress of σ_a is about 5.3 MPa. Recent study shows that the static stress drop varies distinctly as different source models. Here we would pay little attention to discuss how to choose optical source model pertinent to the estimations of η_R . According to equations (13) and (14) using the data listed in Table 1, we have estimated the radiation efficiency and the ratio of the rupture speed to the shear wave speed of this earthquake (Table 1). These average are $\eta_R = 0.85$, $V/\beta = 0.87$, respectively. This outcome suggests that the Kunlunshan earthquake has high seismic radiation efficiency and the average rupture speed is approximate to Rayleigh wave speed. Given S-wave speed $\beta = 3.7$ km/s, our gained rupture speed V is 3.2 km/s, quite near the recent result $V = 3.4$ km/s from body-wave inversion (XU and CHEN, 2004; Ozacar and Beck, 2004; Lin *et al.*, 2003)

Table 1 Static stress drops from different source models of of $M_W 8.1$ Kunlunshan earthquake, the corresponding estimated radiation efficiency of seismic wave and rupture velocity

Source	$\Delta\sigma_s$ /Mpa	η_R		V/β	
		Eq.(13)	Eq.(1)	Eq.(14-a)	Eq.(14-b)
XU and CHEN (2004)	4.0	0.81	2.6	0.85	—
CHEN (2005)	1.5	0.92	7.1	0.89	—
Antolik <i>et al</i> (2004)	3.75	0.82	2.65	0.86	—

Note: Because the Kunlunshan earthquake is a typical strike-slip earthquake, it is not feasible to evaluate its parameters by the model-III crack formula. So the lines in Table 1 are on behalf of no calculation.

2) The 2004 $M_W 9.3$ Sumatra-Andaman earthquake which aroused catastrophic tsunami and brought tremendous economic and life loss is the largest earthquake until now in this century. Kanamori's (2006) research indicates that the rupture zone of this earthquake, subdivided into three segments, extends 1 300 km around. Table 2 provides the source parameters of three main shock from body-wave inversion.

Using equations (13) and (14), we obtain the radiation efficiency and ratio of rupture speed to shear speed of three segments (Table 3). Our results are quite near and a little larger than Kanamori's (2006). In addition, low radiation efficiency and rupture speed imply that the Suma-

tra-Andaman earthquake faults subjected to large-scale relative displacements (overshoot) in the rupture process, which is consistent with the mechanism of earthquake-induced tsunami (Kanamori, 2006).

Table 2 Source parameters of $M_W 9.3$, 2004 Sumatra-Andaman earthquake (Kanamori, 2006)

Fault Segment	L/km	W/km	D_c/m	$\Delta\sigma_s/\text{MPa}$	σ_a/MPa
Andaman (1)	570	120	2.8	2.7	0.32
Nicobar (2)	325	128	7.8	7.0	0.19
Sumatra (3)	420	180	5.8	3.8	0.40
Sumatra-Andaman (4)	1315	141	4.9	3.8	0.32

Table 3 Radiation efficiency η_R and average rupture speed V ($\mu = 7.0 \times 10^4$ MPa) of $M_W 9.3$, 2004 Sumatra-Andaman earthquake

Fault Segment	η_R	V/β		η_R (Kanamori, 2006)	V/β (Kanamori, 2006)	
		Model-II	Model-III		Model-II	Model-III
1	0.28	0.41	0.32	—	—	—
2	0.083	0.14	0.09	0.053	0.09	0.05
3	0.26	0.39	0.30	0.21	0.32	0.23
4	0.22	0.33	0.24	0.16	0.25	0.17

3) Zúñiga (1993) noted that most of earthquake source rupture processes obey partial stress drop model in California. In accordance with Zúñiga's (1993) inversion results (Figure 4), we also calculate radiation efficiencies and average rupture speeds of these earthquakes and compare with the results from equation (1) (Figures 4 and 5). Our conclusions avoid the unphysical result $\eta_R > 1$ (Figure 4) commonly derived from equation (1). Moreover, the radiation efficiencies of overshoot from equation (13) become a bit higher (Figure 5). It has shown in Figure 6 that the earthquake faults where undershoot occur, comparing with overshoot's case, have a relative higher rupture speed in general. It agrees with the fore-mentioned model (Figure 3a) where high radiation efficiency is correlated with high rupture speed usually (Figure 6).

Figure 4 Radiation efficiency in different magnitudes calculated from equation (1) $\eta_R = 2\sigma_a/\Delta\sigma_s$, $\eta_R \geq 1$ means undershoot occurs on the fault [data from Zúñiga (1993)]

Figure 5 Radiation efficiencies derived from equation (13) $\eta_R \approx \sigma_a/(\sigma_a + 0.3\Delta\sigma_s)$ compared with those in Figure 4

4) On July 20, 1995, an earthquake of $M_L 4.1$ occurred in Huailai basin, which is followed by a series of small shocks mostly taking place in the north and south edges of this basin. Si-

no-European cooperative Huailai Digital Seismograph Network with some small-aperture and 3-component field stations, recorded and precisely located the earthquake series. They provided epicenter coordinates 40.3260°N, 115.4480°E, the focal depth 5.5 km at 12:51 24.0 (GMT). XU *et al* (1997; 1999) used P-wave first-motion data from each station to gain the fault-plane solution of focal mechanism and in virtue of empirical Green's function inversed source parameters of main shock, including source time process, direction of crack propagation, rupture length and speed *etc.* CHEN *et al* (2005) presented that the main shock applies to partial stress drop model, while other of 28 aftershocks obey overshoot model. In light of our new resultant formulas of radiation efficiency and rupture speed, we quantitatively analyze dynamic rupture speeds and energy partition of this earthquake again.

Figure 7 illustrates that the ratios of apparent stress drop to static stress drop of M_L 4.1 main shock and 28 aftershocks. In view of the inequality (equation 2) proposed by Savage and Wood (1971), we can reach a conclusion that the main shock obeys partial stress drop model, and all of aftershocks do overshoot model. A comparison between the outcomes from equations (13) and (1) for the main shock and aftershocks is displayed in Figure 8. Obviously, it is conflicting with the physical meaning that the radiation efficiency of main shock is larger than 1 using equation (1), whereas η_R from equation (13) should be always smaller than 1. This shows that our modified formula is valid and considerable. The outcomes of aftershocks suggest that the radiation efficiencies before modification are clearly smaller than ones after modification. In another words, the modified radiation efficiencies make the differences between efficiencies of main shock and aftershocks smaller, owing to proper consideration of dynamic frictional overshoot in our estimation. The rupture speeds resulted from equations (13) and (14) account for that the ratio of rupture speed of main shock to shear wave speed is 0.85β , while the speeds of aftershocks are as quite small as $0.1\sim 0.3\beta$ mostly. It is in accordance with low radiation efficiency shown in Figure 8.

Figure 6 Rupture speeds from equation (14) corresponding to the outcomes shown in Figure 5

Figure 7 Apparent stresses and static stress drops of the 1995 M_L 4.1 Shacheng, Hebei, China, earthquake sequence

4 Conclusions

According to energy partition principle, we have reached a generalized formula for the radiation efficiency. If $\Delta\sigma_c \propto \Delta\sigma_s$, equation (13) is independent of the choice of dynamic friction mechanisms. On second thoughts, if source rupture process obey self-similarity crack extension

model, the size of radiation efficiency depends on rupture speed on the fault plane. Hereby, The outcomes estimated by the radiated energy of seismic wave and seismic moment presented by NEIC of USGS indicate that the 2001 M_S 8.1 Kunlunshan earthquake has a radiation efficiency 0.85 and rupture speed $V=0.87\beta$ close to shear wave speed, the 2004 M_W 9.3 Sumatra-Andaman earthquake is a low-efficiency one with average efficiency $\eta_R \sim 0.22$ and rupture speed $V \approx 0.3\beta$ much smaller than S-wave speed. In term of large, middle and small earthquakes in California, most of earthquakes with source process where partial stress drop occurs have high radiation efficiency and high rupture speed. Our derived formulas ensure the resultant efficiency radiation $\eta_R \leq 1$ and avoid the unphysical conclusion $\eta_R > 1$ estimated by the previous formulas.

Figure 8 A comparison of different methods for estimation of radiation efficiencies of the 1995 M_L 4.1 Shacheng, Hebei, China, earthquake sequence

The circles are modified radiation efficiencies from equation (13), and the stars are unmodified ones from equation (1).

Figure 9 Rupture speeds of the 1995 M_L 4.1 Shacheng, Hebei, China, earthquake sequence by model-II crack extension model

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