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地震のリアルタイムモニタリングと情報の利活用

地震破壊の自己相似的および決定論的性質：M 決定方法の即時性向上

Self-similar and deterministic properties of earthquake rupture: Improvement of the speed of *M* determination

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Rapid determination of earthquake magnitude (*M*) is essential for Earthquake Early Warning (EEW). To do this, some methodologies have been proposed, such as the τ_p or τ_c method [e.g., Allen and Kanamori, 2003; Wu and Kanamori, 2005], combination of the peak displacement and a ground motion prediction equation (GMPE) [e.g., Odaka et al., 2003; Wu and Zhao, 2006], and measurement of the time from the onset of body wave to the arrival time of the peak amplitude (T_{op}) [e.g., Noda et al., 2016; Colombelli and Zollo 2015]. Because the ultimate aim of EEW is not to determine *M* but to issue the distribution of ground motion radiated from the source, Hoshiba and Aoki [2015] proposed a method to infer the seismic wave field without the hypocentral parameters. However, these methodologies, except the τ_p and τ_c methods, must wait for the arrival of the peak amplitude to estimate the final size of earthquakes or the ground motion distribution associated with the final *M*. This typically requires 1.5 s, 3 – 4 s, 10 s following the P onset respectively for *M* 5, *M* 6, and *M* 7, which are consistent with typical source durations [e.g., Kanamori, 2005].

To investigate this problem, we use K-NET data from 150 events with $4.5 \leq Mw \leq 9.0$ and hypocentral distance (*R*) less than 200 km. The data are binned by 0.1 magnitude unit and by 25 km in *R*. We analyze the average of absolute displacement (AAD) in each bin as a function of time, and find that there is no statistical difference in AAD between smaller and larger earthquakes for early times (< 0.2 s), suggesting that the observed P wave begins in a similar way. However, we also find that the AAD for smaller events departs from the similarity sooner than large events. The departure time (T_{dp}) from the similarity is identified in such a way that the "departure delay" (defined as a period of the first decreasing absolute displacement after the P onset) exceeds a pre-defined threshold, *DPD*. As a result, we introduce a scaling relation between T_{dp} and *M*w in a range of $4.5 \leq M_W \leq 7$ using *DPD* = 0.05 s, $M_W = 2.29 \times \log T_{dp} + 5.95$. T_{dp} are about 0.4 s, 1.1 s, and 2.9 s respectively for *M* 5, *M* 6, and *M* 7, demonstrating that T_{dp} is significantly shorter than typical source duration (i.e., T_{op}) shown above.

We consider that the physical background of the scaling relation may be explained by the cascade model of rupture growth [Ellsworth and Beroza, 1995], and conclude that this scaling relation can be consistent with and even explain the results shown by several previous studies. For example, Uchide and Ide [2010] suggested that the self-similar growth stage ended later for larger events, and Zollo et al. [2006] and Lancieri et al. [2011] found that the maximum displacement of initial P or S wave significantly correlated with the final *M* even though the time windows to measure them were much shorter than typical source durations. In addition, it confirms the limitation as well as the performance of the τ_p or τ_c method. That is, if the time window to measure the frequency content is shorter than T_{dp}, the estimates will saturate [e.g., Lancieri et al., 2011]. In contrast, if the time window is too long compared to

T_{dp}, the measurements could bottom out [Kuyuk and Allen, 2013b]. However, for suitable time windows, this methodology should be able to determine *M*. We consider this is the reason why the frequency content can scale with the final *M* before the rupture is completed, which was discussed by Olson and Allen [2005] and Rydelek and Horiuchi [2006]. See Noda and Ellsworth [2016] for more details.

Even though the physical background of the scaling relation has not yet been demonstrated, importantly for EEW as an engineering approach to mitigate earthquake loss, it is not necessary to wait for the completion of rupture to determine the final *M* because the scaling relation suggests that there is a characteristic that depends on the final size at T_{dp}. Based on this finding, we propose a new method that uses a GMPE to determine *M* for EEW. In this study, we employ a simple form of GMPE, $\log Dis_c = \log Dis + \alpha \times \log R = \beta \times M + \gamma$, where *Dis* is displacement amplitude, Dis_c is displacement amplitude corrected by distance, *R* is hypocentral distance and α, β, and γ are coefficients determined for the relation. Although the coefficients are constant in the conventional approach, we propose to set the intercept, γ, a function of time in order to consider the scaling relation. That is, to determine $\gamma(T)$ at each time *T*, we use only earthquakes that have passed T_{dp}. For example, when we determine $\gamma(1.00\ \mathrm{s})$, M_W is 5.95 for $T_{dp} = 1$ s, so that we use only the maximum displacements from events of magnitude less than M_W 5.95.

Consequently, our result demonstrates that the proposed GMPE is able to determine the final *M* even for early times up to about M_W 7 without loss of the estimation accuracy, while the conventional approach provides significantly underestimated *M*. We conclude that the proposed method is useful for EEW to gain longer lead time as well as to reduce the blind zone [e.g., Kuyuk and Allen, 2013a], and that it is required to determine hypocentral parameters in order to issue the fastest alert.

References

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