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Fast characterization of the rupture duration and earthquake magnitude using the P-wave peak displacement

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ABSTRACT
In the present study, the P-wave peak displacement (Pd) is evaluated to rapidly estimate the magnitude and duration of the earthquake source time function, for application to Earthquake Early Warning (EEW) systems. To this regard, we average the logarithm of the normalized Pd by hypocentral distance over all available stations at any time windows (LPDT), starting from the P-phase onset. Mathematically, the LPDT curve increases with time until it reaches a constant value (plateau), which is related to the magnitude of the earthquake. From the obtained observations, the corner time of the LPDT at the beginning of the plateau can be considered as a proxy of the source duration/length of the earthquake. This approach has been applied and tested using the recent earthquakes occurred in central Italy, with magnitude range 3.5-6.5.

Keywords: Earthquake Early warning parameters, peak displacement, earthquake source duration/length, magnitude.

INTRODUCTION
Together with the advancement of Earthquake Early Warning (EEW) systems, automatic and rapid methodologies to estimate the earthquake location, magnitude, intensity (Allen and Kanamori, 2003; Odaka et al. 2003; Colombelli et al. 2015a; Nazeri et al. 2017) and to characterize the earthquake source properties (Colombelli et al. 2014; 2015b) have been developed. The significant outcomes of these studies, i.e., being able to compute the final properties of an earthquake while the rupture is still ongoing, challenge the old ideas about the stochastic rupture process and the cascade model.
In the most recent approaches for EEW, the initial part of the P-wave plays an important role to compute the different frequency- and amplitude-based parameters, and usually a fixed time window (3 to 4 s), starting from the P-wave onset is used to compute the parameters (Zollo et al. 2006; Allen and Kanamori, 2003; Nazeri et al. 2017).
The P-wave peak displacement (Pd) is one of the most common amplitude-based parameter adopted in EEW systems to estimate the magnitude and intensity of the events (Wu and Kanamori, 2005; Colombelli et al. 2015a). However, in order to simply correlate Pd to the earthquake magnitude, an empirical correction for the hypocentral distance is needed (Zollo et al. 2006; Nazeri et al. 2017).
Colombelli et al. (2014) introduced a new methodology to follow the evolution of Pd with time. In the proposed approach, instead of considering a fix time window to compute Pd, the P-wave peak amplitude is estimated in progressively expanded time windows. They used a Japanese dataset including moderate to large events, with magnitude ranging, Mw 4.0 to 9.0. The analysis revealed that the event magnitude and the source duration/length can be automatically computed following the time evolution of Pd, which is progressively computed by normalizing Pd to the hypocentral distance, and then averaging over the stations recording the event. The resulting function is a proxy for the Moment Rate Function (MRF) as the most reliable representation of the earthquake source rupture process.
Here we evaluate this method by using a dataset of 135 events occurred in the active seismic region of Central Italy (Meletti, et al., 2016), that was recently struck by several earthquakes, such as the 2009, Mw 6.3 L'Aquila earthquake, and the 2016, Mw 6.0, Amatrice earthquake.

METHODOLOGY & DATA
Following the recent methodology introduced by Collombeli et al. (2014; 2015), here we first compute Pd^C, which represents the observed Pd normalized to a reference distance. We then evaluate the variability of the Pd^C in terms of time. Concerning the dataset that of the earthquakes occurred in Italy from August 2016 to January 2017, magnitude range of 3.5 to 6.5 including 12 events with magnitude larger than 4.7. Only vertical components of the accelerometric data recorded in a maximum epicentral distance of 100 km are used. The P-phase arrival time on all selected waveforms are picked manually. Among 135 earthquakes, those events recorded at less than 5 stations are automatically excluded from the computation. Figure 1 shows the epicentral position of the selected events, the seismic stations and the distribution in distance and magnitude classes of the available data.
For each earthquake, we obtained the displacement signals by double integrating the acceleration waveforms. A casual, 0.075 Hz high-pass Butterworth filter is also applied to remove the low frequencies after integrating to produce the displacement records. Then the average value of the logarithm of Pd^C is computed at any time steps

(LPDT curves), starting from the P-wave arrival time and stopping at the expected arrival of the S-wave, which is computed through an empirical relationship between the S-P travel time window and the hypocentral distance. At each time step, those waveforms possibly contaminated by the S-wave are automatically excluded and the average value of the logarithm of Pd^C is computed by using a minimum number of available stations (that should be equal to 5). Figure 2a shows the average of logarithm of Pd^C in terms of time. The origin of time axis refers to the P-wave arrival time.
To model the curves and compute the relevant parameters, we used a fitting function, defined as:

$$y = P_L(1 - e^{-\frac{t}{T_L}}) + y_0 \quad (1)$$

where P_L represents the plateau level of the curve, T_L is a proxy of the beginning time of the plateau, and y_0 presents the intercept of the plot with the y-axis. Figure 2b and c show the variation of these parameters as a function of magnitude of the events. The least-square fit to both parameters with magnitude is calculated as:

$$P_L\ (cm) = 1.14\, M - 4.41\ \pm 0.14 \quad (2)$$

$$\log T_L\ (s) = 0.28\, M + 1.45\ \pm 0.16 \quad (3)$$

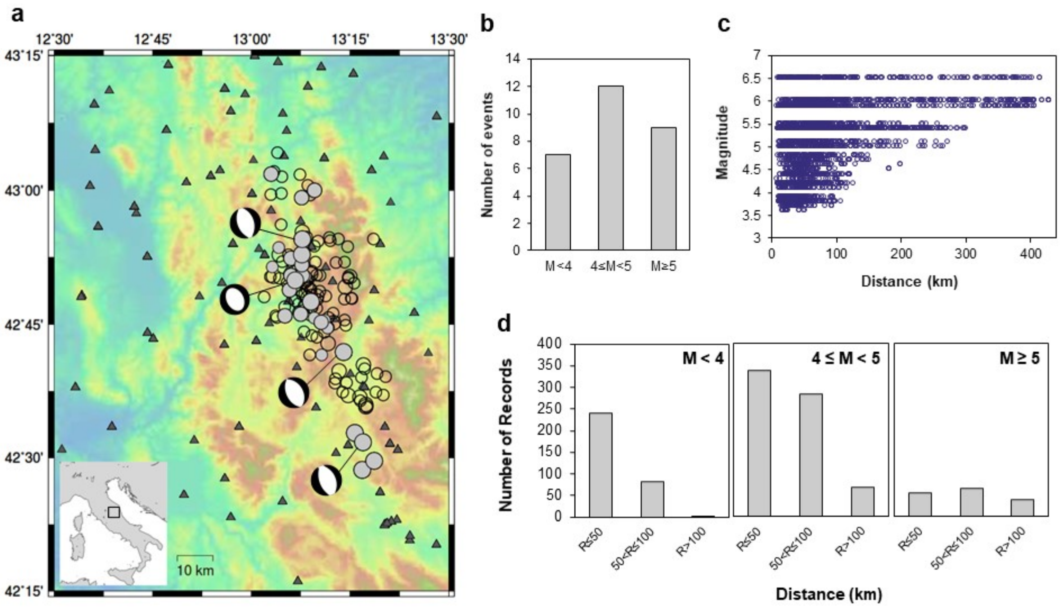

Figure 1. (a) Map shows the distribution of the epicenter of the selected dataset (circles) and the seismic stations (triangles). (b) Histogram of the number of events in terms of different magnitude classes. (c) Distribution of the magnitude versus the hypocentral distance (km). (d) Number of records in different categories of the magnitude in terms of the hypocentral distance (km).

To better illustrate the meaning of the T_L parameter, first we evaluate the circular fault model of Sato & Hirasawa (1973) to have an estimate of the expected rupture duration and length. Figure 2d shows the computed half time (HT) of the source time function as a function of T_L and the least-square fit is calculated as:

$$\log HT\ (s) = 1.05\ \log T_L\ (s) + 0.68\ \pm 0.03 \quad (4)$$

CONCLUSION

Here we tested and tried to optimize the straightforward approach of Colombelli et al. (2014; 2015) to estimate the earthquake magnitude, seismic moment (M_0) and source properties by using a dataset of earthquakes ($3.5 \leq M \leq 6.5$) occurred in Central Italy and including accelerometric data recorded at an epicentral distance less than 100 km.
We measured the P-wave displacement in different time steps after the P-phase onset and compute the LPDT curves for each event. We found that the LPDT curves increase with time, up to a final constant value. The plateau level, P_L, and the time related to the corner of the plateau derived from the T_L value, are two relevant parameters of these curves.
According to our observations, both P_L and T_L parameters show a similar trend to the earlier studies by using the Japan's dataset. The plateau level of the LPDT curves is linear increasing with the magnitude of the event, so that the larger the magnitude the higher the P_L value (Figure 2a and b). Therefore, M_0 can be easily estimated

from the empirical relationship of the Kanamori moment-magnitude scale without using the displacement spectral and following the complex process.

Finally, after computing the source length and duration using the circular source model of Sato & Hirasawa, we fund that the computed T_L parameter from the LPDT curves is related to the source duration of the rupture (Figure 2d), so that a rapid estimation of the source duration and extension can be obtained from the plateau time of LPDT curves.

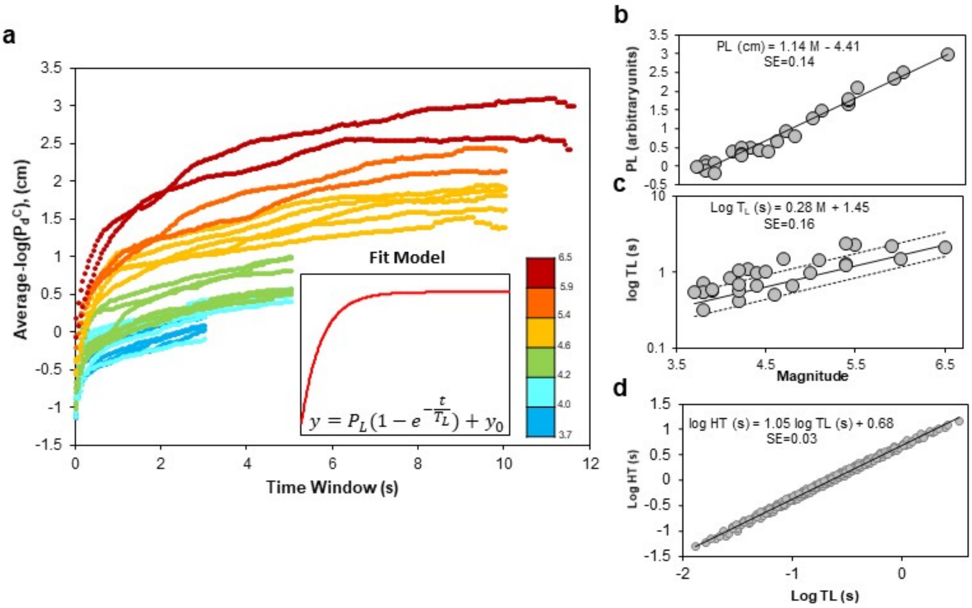

Figure 2. (a) LPDT curve: Average-logarithm of Pd^C in terms of different time windows exactly after the P-wave onset. (b) Plot shows the plateau levels of the LPDT curved versus magnitude. (c) The time related to the beginning of the plateau in terms of magnitude. (d) Comparison between the half-time of the rupture computed from Sato & Hirasawa (1972) model and T_L.

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