

Reply to comment by P. Rydelek et al. on “Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records”

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[1] Based on the analysis of Mediterranean, near-source, strong motion records Zollo *et al.* [2006] (hereinafter referred to as ZLN) showed that peak displacement amplitudes of initial P- and S-wave seismic signals scales with the earthquake size in the moment magnitude range $4 < M_w < 7.4$. Similar evidence have been also reported for southern California [Wu and Zhao, 2006] and Taiwan [Wu *et al.*, 2006] using only P-wave arrivals up to 100 km distance on mostly short period and broadband waveform data.

[2] As discussed by ZLN, these observations may be of potential use for earthquake early warning applications but also provide important insights on the physical processes which control the early stage of earthquake rupture nucleation and propagation.

[3] In their comment on ZLN paper, Rydelek *et al.* [2007] (hereinafter referred to as RWH) argue against the exportability of ZLN results to Japanese earthquakes and rule out the feasibility of earthquake early warning using the information carried out by the initial P-wave signal. We present here the analysis of a large strong-motion waveform data set extracted from the same data-bases of RWH (K-Net and Kik-Net), to which we applied the distance-magnitude selection criteria, the data processing tools and the regression methodologies of ZLN. The results of our study can be resumed as follows:

[4] (1) Peak displacement amplitudes in the 2-sec window of initial P waves show an excellent correlation with magnitude up to about $M = 6.5$, consistently with observations from southern California, Taiwan and Mediterranean data. For higher magnitudes, up to $M = 7.1$, our analysis reveals a possible saturation effect but this appears at a higher magnitude threshold than the one ($M = 5.5$) inferred by RWH.

[5] (2) Extending the observation window to 4-sec after the initial P, we found a good correlation up to magnitude 7.1, although magnitude bins for M about 7 are poorly sampled.

[6] (3) Peak displacement amplitudes measured in the 1- and 2-sec windows after the initial S-wave show an excellent correlation with magnitude in the whole considered magnitude range. This implies the existence of a different source and/or propagation mechanism controlling the initial P and S wave amplitudes on Japan earthquake records.

[7] Below we discuss our results on the Japanese data in relation with the issues raised by RWH. For clarity, we prefer to separate the issues regarding earthquake rupture mechanics from those regarding the potential for early warning.

[8] We analyzed strong-motion records from 256 Japanese crustal events (maximum depth = 50 Km) with magnitude ranging from 4 to 7.1 distributed over the entire Japanese archipelago, grouped in magnitude bins of width 0.3. A total of 2640 records, with hypocentral distances $HD < 60$ Km have been extracted from the K-Net seismic network; 68 records from the KiK-Net network were added for events with $M > 6.1$.

[9] In Figure 1 we report data distribution vs. magnitude and hypocentral distance. Note that the distance distribution of analyzed events for Japan (Figure 1) is clearly different from that for the Mediterranean (MED) earthquakes given by ZLN. Whereas most of MED records occur at an $HD < 25$ km, most Japanese records are at $HD > 40$ km.

[10] At odds with RWH, we did not apply any cut-off at $M = 5.5$ on hypocentral distance for small and moderate events; indeed this may introduce a bias on the estimation of attenuation law parameters retrieved from both small and large earthquakes records. We follow the ZLN procedure involving among others sensitivity correction, P and S phase identification, double integration, filtering in a frequency band (0.075, 3 Hz). Peaks are read on the modulus of displacement expressed in meters. Starting from the P-wave and S-wave picked arrivals, we measure peaks within a 2 second window. For the P arrival, we also test the method with 4 second windows.

[11] The distance attenuation effect is corrected for by assuming a simple log-linear model [Wu and Zhao, 2006; ZLN]; the amplitudes are normalized to a reference distance of 10 Km (i.e., the same as for ZLN in the Mediterranean study, to facilitate comparison). Though RWH show data normalized at a distance of 20 km (ZLN, Figures 2a and 2b), the use of a different normalization distance does not change the slope of the *log(peak) vs Magnitude* relationships and thus does not alter the graphical interpretation.

[12] In Figure 2 we show the relation between the logarithm of distance normalized, peak displacement for P and S waves in different time windows vs final magnitude of the events (following ZLN, statistical significance was

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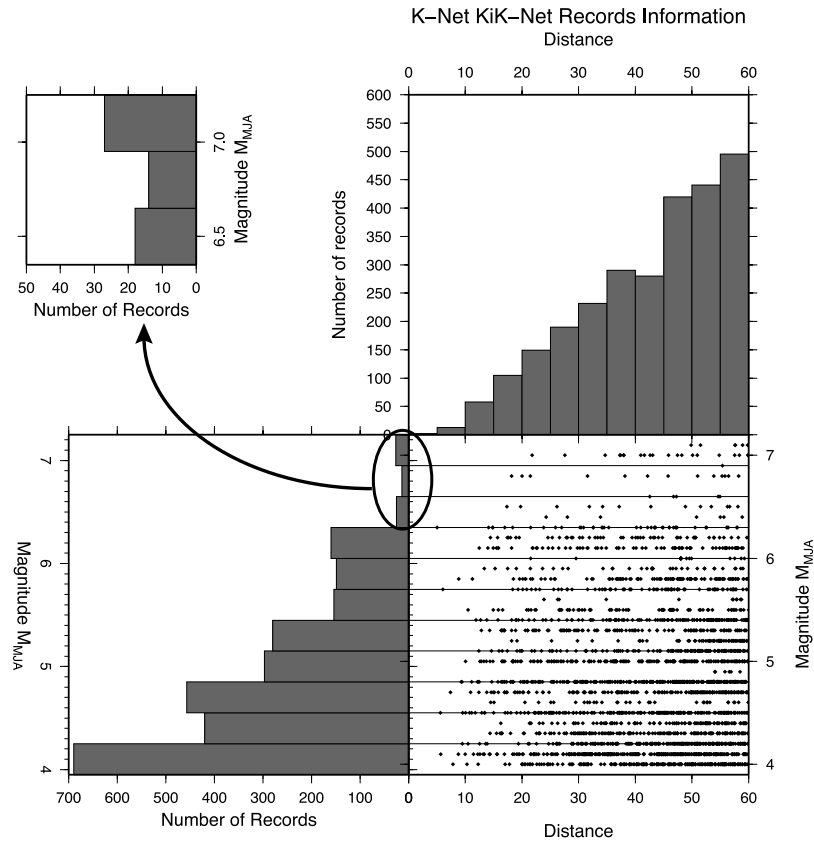


Figure 1. Data distribution vs. magnitude and hypocentral distance. (bottom left) Histogram of the number of selected strong motion records with magnitude. (bottom right) Distribution of records (diamonds) vs. distance and magnitude. (top right) Histogram of the number of selected strong motion records with distance.

verified using a chi-square test). In the 2-second window after the first P-arrival, the peak amplitudes show a linear correlation with magnitude up to $M = 6.5$, while for $M > 6.5$ the peaks appear to saturate. However we note the rather poor sampling of P-data for magnitude ranging between $M = 6.5$ and $M = 7.1$. Using a larger time window, i.e. 4 seconds after P-phase arrival, the P-peak displacements appear to correlate with magnitude over the whole magnitude range. Interestingly, the S-peaks show an excellent correlation with magnitude in the whole magnitude range for

1-sec and 2-sec windows after the first S-arrival, while no slope change is visible at $M = 6.5$.

[13] We remark that our results on Japanese data for P-peaks in the 2 second window strongly differ from what illustrated by RWH in Figures 2a and 2b. We may argue that this discrepancy could somewhat be related to RWH use of a rather different distance-magnitude selection, magnitude bin grouping and/or attenuation parameter relationship, used to correct the distance attenuation effect on peak amplitudes.

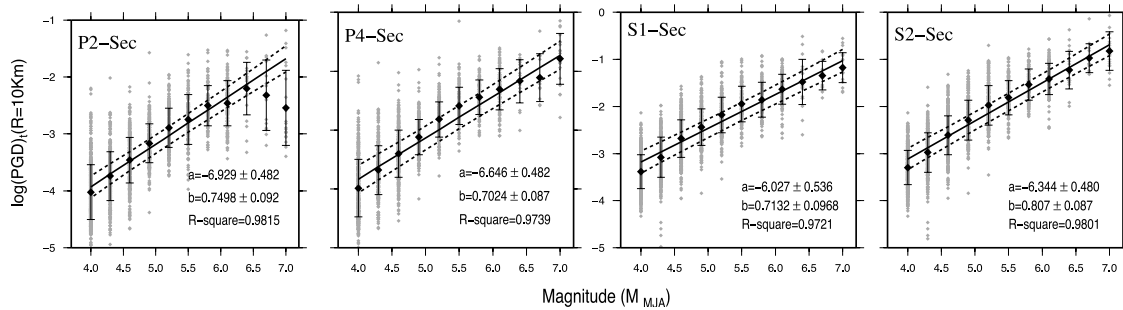


Figure 2. Correlation between low-pass filtered peak ground motion values and magnitude. The panels show the logarithm of peak ground displacement normalized at a reference distance of 10 Km as a function of M . Black diamonds represent the peak average on each magnitude bin with the associated standard deviation, while the grey dots are the peak values read on each records. The black-solid line in each plot represents the best fit line evaluated through a linear regression, whose coefficients are displayed on corresponding plot.

[14] Although the comment of RWH is mainly focussed on the implications for earthquake early warning of ZLN results, they also briefly argue against the deterministic nature of the fault rupture based on the geological evidences reported by Wesnousky [2006]. We stress that ZLN never invoked a deterministic nature of earthquakes but interpreted the results of the data analysis in terms of probability and basic rupture dynamic concepts: the larger the fracture energy released in the initial propagation of rupture, the larger is the probability the earthquake can reach a bigger size. This interpretation is valid on a statistical base (rather than a deterministic one).

[15] While other mechanisms may be at play, either related to fracture mechanics or not, the observation remains that initial peak motion for P and S waves does scale with magnitude, within a large magnitude range, though the exact position of its upper bound remains somewhat debatable.

[16] As quoted by RWH, Wesnousky [2006] offers an interpretation where rupture length, and thus, earthquake magnitude, are essentially determined by structural features in the fault geometry (jogs, steps, bends) that stop rupture propagation. We agree with this interpretation but we believe that it does not prevent the existence of a scaling between initial rupture and final magnitude. Indeed, while geometrical barriers are likely to stop rupture, they are also likely to yield in the presence of fractures that release a very large elastic potential energy.

[17] As a consequence fracture propagation to large areas will result from a probabilistic combination of a particular fracture energy with a particular, and mostly unknown a priori fault strength distribution. In addition, Wesnousky study indicates that large faults, where large magnitude earthquakes are likely to be generated, may have a different, finer-scale structure than small faults, owing to the large strain history that they were subjected to. In such case the radiation and type of fracture may be detectably different on large faults from the very initial phases of the rupture, as commented by Dolan [2006].

[18] According to Kanamori [2005], real-time estimates of earthquake location and magnitude are needed for regional early warning systems (EEWS), i.e., dense seismic networks covering all or portion of an area of interest. However the alarm decision in an early warning system is rather based on the prediction, with quantified confidence, of a ground motion intensity at a distant target site (where a sensitive structure is located). This problem needs an evolutionary (i.e., time-dependent) and probabilistic frame where pdfs for earthquake location, magnitude and attenuation parameters are combined to perform a real-time probabilistic seismic hazard analysis [e.g., Iervolino *et al.*, 2006].

[19] Just considering the peak displacement amplitude measured in the early portion of P-waves, results from ZLN and from the present work on Japanese data, show that suitable probability density functions for the magnitude parameter can be constructed even including the possible effect of saturation for $M > 6.5 - 7$. For instance, for larger magnitude events, a threshold-based probabilistic approach for early warning as the one suggested by Iwata *et al.* [2005], could benefit of a combined use of the magnitude-frequency relation and magnitude estimates based on initial peak displacement measurements as suggested by ZLN.

[20] We disagree with RWH arguments against the use of S-waves for early warning, especially in view of the excellent correlation that S-peak show with magnitude up to about $M = 7$. Dense accelerometric networks now operating in Japan and other seismic regions in the world can provide a sufficient number of records at distances smaller than 20–30 km from potentially damaging crustal earthquakes so that S-P times are expected to be smaller than 2–3 sec. A magnitude estimation using S-waves could be therefore available 4–5 sec after the first P-wave is recorded, which is still useful for sending an alert to distant target sites.

[21] In addition, let us remark that EEWS have potential to mitigate the effects of moderate size earthquakes ($M = 6 - 7$), which can produce severe damages in densely urbanized areas and places where old structures were not built to current standards. This has been the case for a significant number of earthquakes occurred in the Mediterranean basin during last decades: the 1976 Friuli ($M = 6.5$) and 1997 Colfiorito ($M = 6$) in Italy, 1999 Athens ($M = 5.9$) in Greece, 2002 Nahrin, in Afghanistan ($M = 6.1$), 2003 in Algeria ($M = 6.7$), 2003 Bam ($M = 6.3$) in Iran, 2004 in Morocco ($M = 6.4$). For moderate size events, early warning systems could also mitigate earthquake effects in terms of infrastructure operability (e.g., hospitals, firehouses, telecommunication hubs) during the post-event emergency phase and rescue operations.

[22] At odds with RWH, we confirm the previous ZLN statement that both P and S wave early phases have potential for real time estimation of magnitude up to about $M 7$, based on the analysis of the Japan and Mediterranean earthquake records. The possible saturation effect at about $M = 6.5$ for P measurements in 2 sec windows vanishes with 4 sec windows. The scaling of displacement peak with magnitude, instead, appears at even shorter (1 sec) time lapses after the first S-arrival.

[23] While these observations may bring insights on the physics of earthquake rupture, we believe that their applicability to early warning still needs to be validated through massive experimentation where the system performances are carefully evaluated downstream of its engineering application. The actual goal is the probabilistic assessment of expected loss reduction through triggered security action, rather than the accurate estimation of the final earthquake size.

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