
# Assessment of Earthquake Early Warning Methods for Complex Fault Ruptures

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## ABSTRACT

Earthquake early warning systems typically operate based on the early seismic arrivals to maximize the notification time. However, the accuracy of shaking intensity estimates are as important as the warning lead time. In this study, we assess alternative early warning techniques in terms of evolutionary accuracies of estimated source parameters and shaking intensities based on the playback of seismic data recorded during the 2016 M7.85 Kaikoura, New Zealand earthquake, one of the most complex ruptures ever recorded. We explore potential improvements in conventional early warning approaches by integration of ground-motion based methods.

Keywords: earthquake early warning, rapid magnitude estimation, ground motion prediction

## INTRODUCTION

Earthquake early warning (EEW) systems establish an important component of seismic loss mitigation programs. They provide advance notifications of on-going events before the arrival of damaging seismic waves. Such notifications allow recipients (e.g., utility/lifeline operators, system control centers, emergency response teams and public) to react and prepare before the arrival of destructive seismic waves. With recent technological and scientific advances, today's early warning systems can go much beyond this basic function, providing estimates of shaking intensity and potential damage for implementation of post-disaster response plans.

An effective EEW system requires a robust seismic network infrastructure, a fast communication system and a rapid event/ground-motion characterization algorithm. This algorithm automatically detects seismic radiations in real-time and estimates the shaking intensity of not-yet-arrived strong waves (Figure 1.a). Most EEW algorithms operate on a common concept, in which key attributes of early P arrivals are used to characterize the approaching strong shaking for maximized warning time. EEW systems can provide seconds to minutes of advanced warning depending on the distance to the event (Figure 1.b).

EEW systems are grouped into three main categories: on-site and regional and hybrid. The on-site EEW systems uses P-wave arrivals at an instrumented site for estimation of shaking intensity locally. As the warning is issued based on local measurements, it does not require estimations of event location and magnitude. However, the advance warning time for on-site EEW systems is constrained by the S- and P-wave arrival time difference. In other words, an on-site EEW system cannot recognize an on-going event until the P waves reach to the site. The regional approach, on the other hand, benefits from very first detections by front-line stations for maximized warning time. Event magnitude and location determined from early arrivals are used for estimation of shaking intensities at distant sites based on a regional ground motion prediction equation (GMPE). The downside is that potential inaccuracies in event magnitude and location estimates can propagate into intensity predictions. The hybrid EEW systems takes advantage of both approaches by assimilating on-site predictions into the regional approach for accurate and timely warnings.

It is the accuracy and timeliness of issued warnings that yield a truly reliable EEW system. To this end, the EEW system should successfully distinguish seismic radiations from noise to avoid false alarms, detect all events larger than the minimum magnitude of interest, and take into account the regional source, attenuation and site attributes. The timeliness and accuracy of issued warnings generally trade-off with each other due to growth of seismic data with time. This trade-off adds further challenges to achieve reliable early warning systems, particularly for complex fault ruptures.

In this study, we investigate alternative early warning approaches to identify their strengths and limitations with focus on complex fault ruptures. The evolutionary accuracies of estimated source parameters and shaking intensities are assessed based on pseudo real-time data playbacks. We explore potential improvements in conventional early warning approaches by integration of ground-motion based EEW approaches.

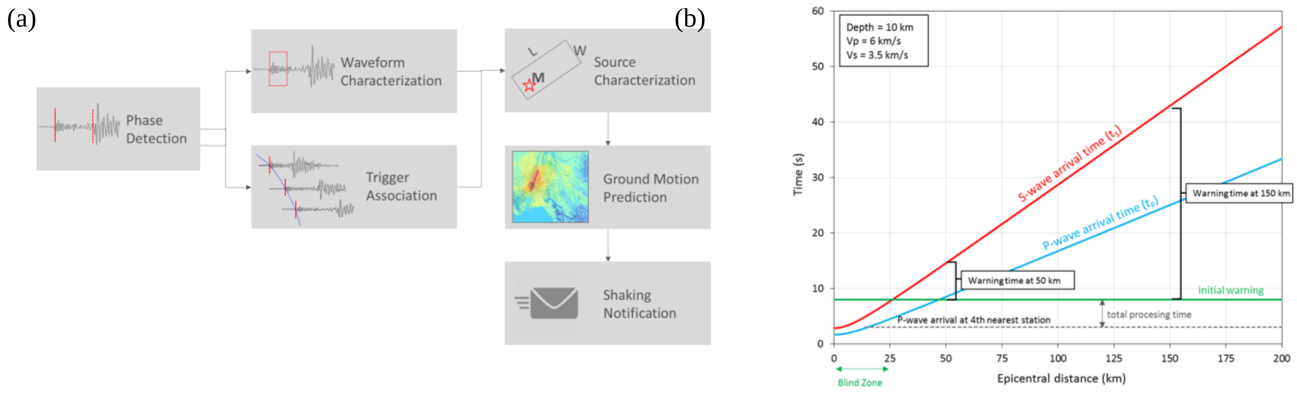


*Figure 1. (a) General workflow for a typical EEW algorithm and (b) Seismic phase arrivals as a function of distance. Warning lead time is defined as the time difference between S-wave arrival (red line) and the initial warning (green line).*

## NEW ZEALAND CASE STUDY

New Zealand is located at the Australian-Pacific tectonic plate boundary; where in the northeast, the Pacific Plate is subducted below the Australian plate, and in the south, the Australian Plate is subducted underneath the Pacific plate. The two subduction zones are linked by a series of very large fault systems that have generated several moderate-to-large crustal earthquakes and plenty of strong motion data during instrumental period.

Here, we assess alternative EEW approaches for New Zealand as a case study. To this end, waveform records of 179 crustal events with Mw>3.5 are compiled from GeoNet database [1]. Figure 2 shows the magnitude-distance distribution of the compiled dataset and the map of the selected events. Compiled waveform records are de-trended, bandpass filtered and corrected for instrument response. Their P arrivals are identified automatically by an STA/LTA triggering algorithm and the associated peak displacements ($P_d$) are determined within the first 3 s of the P onset (before the S arrival) on vertical channels. Also, peak ground velocities on vertical and horizontal components are calculated considering both P and S arrivals. These determined ground motion parameters are used for derivation of regional predictive models for New Zealand in order to facilitate the assessment of alternative EEW approaches.

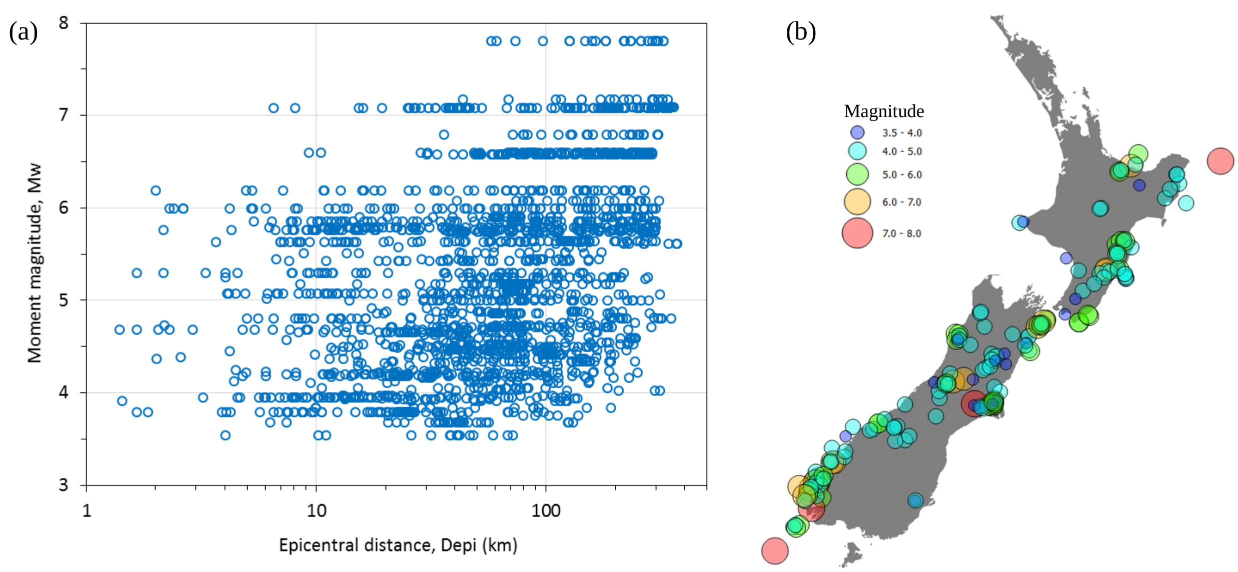


*Figure 2. (a) Magnitude-distance distribution and (b) map of earthquakes selected for this study.*

## On-Site Ground Motion Prediction

An empirical relationship between P-wave peak displacement ($P_d$) and peak ground velocity (PGV) is developed for application of on-site EEW method. This is handled in two steps. First, a predictive model between $P_d$ and vertical-component peak velocity ($PGV_Z$) is derived:

$$\log(PGV_Z) = 1.02 + 0.77\log(P_d) \tag{1}$$

Next, the relationship between horizontal-to-vertical ground motion ratios and local shear-wave velocities ($V_{S30}$) is investigated to estimate maximum horizontal velocity ($PGV_{Hmax}$) for a given $PGV_Z$:

$$\log\left(\frac{PGV_{Hmax}}{PGV_Z}\right) = \begin{cases} 0.29 - 0.23\log\left(\frac{V_{S30}}{1500}\right) & \text{if } V_{S30} < 1500 \text{ m/s} \\ 0.29 & \text{otherwise} \end{cases} \tag{2}$$

Equations (1) and (2) allow prediction of maximum horizontal velocity at an instrumented site based on locally observed P-wave peak displacement. The on-site predictions can be further incorporated into regional EEW systems to improve the accuracy of ground motion estimates at un-instrumented locations using spatial correlation of ground motions.

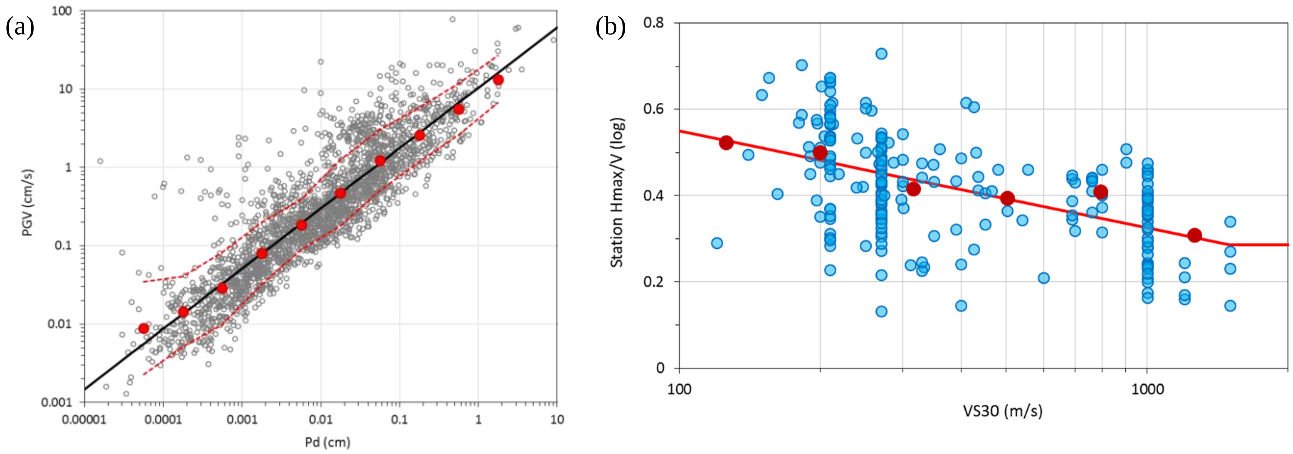


*Figure 3. (a) Relationship between P-wave peak displacement ($P_d$) and vertical peak ground velocity ($PGV_Z$), where red circles show binned mean values, dashed red lines show one standard deviation around the means, and the solid black line is the model in Eqn (1). (b) Relationship between horizontal-to-vertical ground motion ratios and local shear-wave velocities ($V_{S30}$), where red circles are the binned mean values and the red line shows the model in Eqn (2).*

## Rapid Magnitude Estimation

Event magnitude is one of the key parameters required to estimate shaking intensity in regional EEW applications. Also, the criteria to issue a warning and actions to be taken are defined in terms of staged magnitude thresholds in some EEW applications. Thus, a rapid and accurate estimation of event magnitude is crucial for achieving reliable EEW systems.

A regional relationship between P-wave peak displacement ($P_d$) and moment magnitude ($M_w$) is developed in order to facilitate rapid characterization of earthquakes in New Zealand:

$$M_w = 1.16\log(P_d) + 1.42\log(D_{epi}) + 5.19 \tag{3}$$

We observe that in most cases Equation 3 provides accurate magnitude within ± 0.2 of the catalog $M_w$, though there are some cases where larger discrepancy is observed in predicted $M_w$ values.

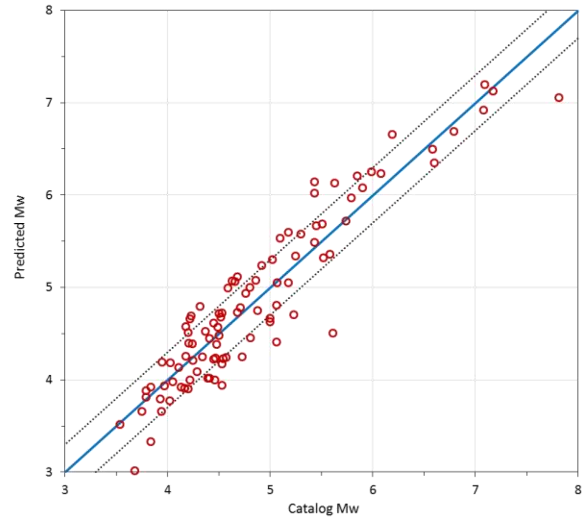


*Figure 4. Comparison of final reported (catalog) and predicted event magnitudes. Solid line represents 1:1 relationship between the two and dotted lines indicate ±0.2 magnitude unit error in predicted magnitudes*

**Regional Ground Motion Prediction**

For prediction of ground motions at un-instrumented sites and stations that have not yet been triggered, a regional ground motion prediction equation (GMPE) is developed using the generic GMPE framework [2]:

$$\ln(PGV) = F_M + F_{\Delta\sigma} + F_Z + F_\gamma + F_S + C \qquad (4)$$

where source terms are represented by the magnitude scaling term, $F_M$, and the stress parameter function, $F_{\Delta\sigma}$; the regional attenuation is captured by the geometric spreading model and the anelastic attenuation term, $F_Z$ and $F_\gamma$ respectively; effects of site characteristics are accounted for by the site amplification function, $F_S$; and any residual amplitude offsets resulting from model selection and limitations are captured by the empirical calibration factor, C. The adjusted GMPE for New Zealand provides estimates of $PGV_{Hmax}$ as a function of $M_w$, stress drop, distance and $V_{S30}$, where the stress drop is also defined as a function of $M_w$. The resulting GMPE, between-event and within-event residuals are shown in Figure 5.

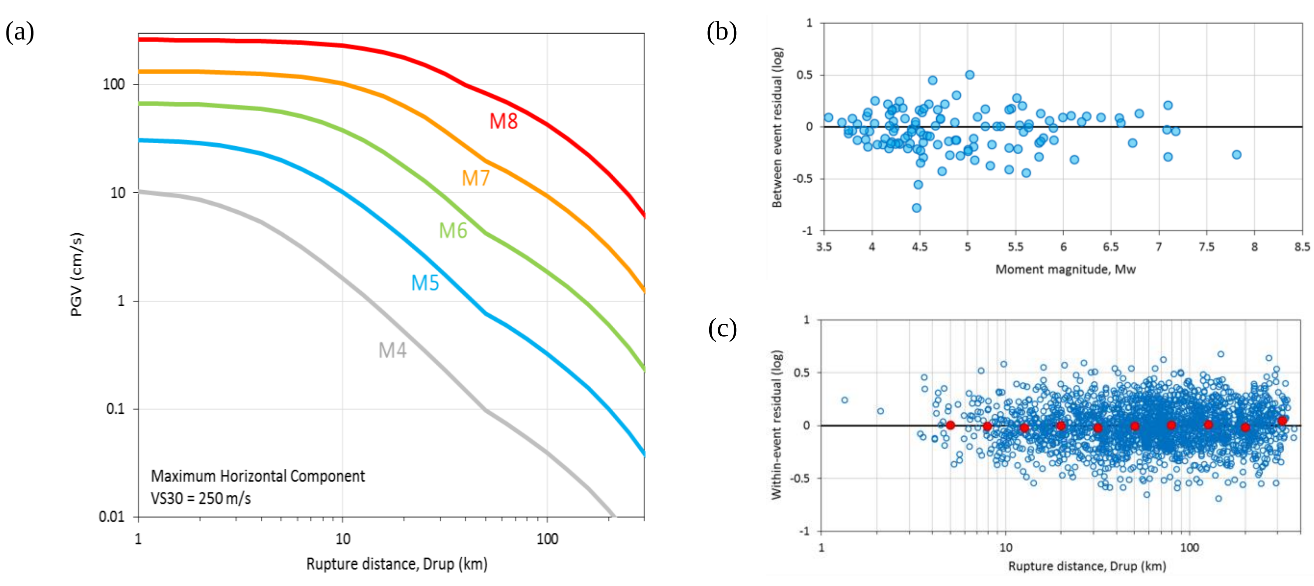


*Figure 5. (a) The empirically calibrated generic ground motion prediction equation for New Zealand evaluated up to 300 km for $M_w$ 4 – 8 for a $V_{S30}$=250m/s. (b) Between-event residuals as a function of moment magnitude and (c) within-event residuals as a function of distance, where open blue circles show individual source, path and site corrected ground motion observations and closed red circles show logarithmically-spaced means.*

## 2016 KAIKOURA EARTHQUAKE

A M7.85 earthquake occurred about 60 km south-west of the town of Kaikoura in South Island, New Zealand on November 13, 2016. It has been described as one of the most complex multi-fault ruptures ever recorded. From the 15 km deep hypocenter, the rupture propagated at 2 km/s in the NE direction for more than 170 km, along at least 12 major faults and including possible slip along a subduction interface [3]. The complex sequence of ruptures lasted for about two minutes. The majority of the seismic energy was released 60 seconds after the origin time, at 120 km distance to the NE of the epicenter (Figure 6).

(a) (b)

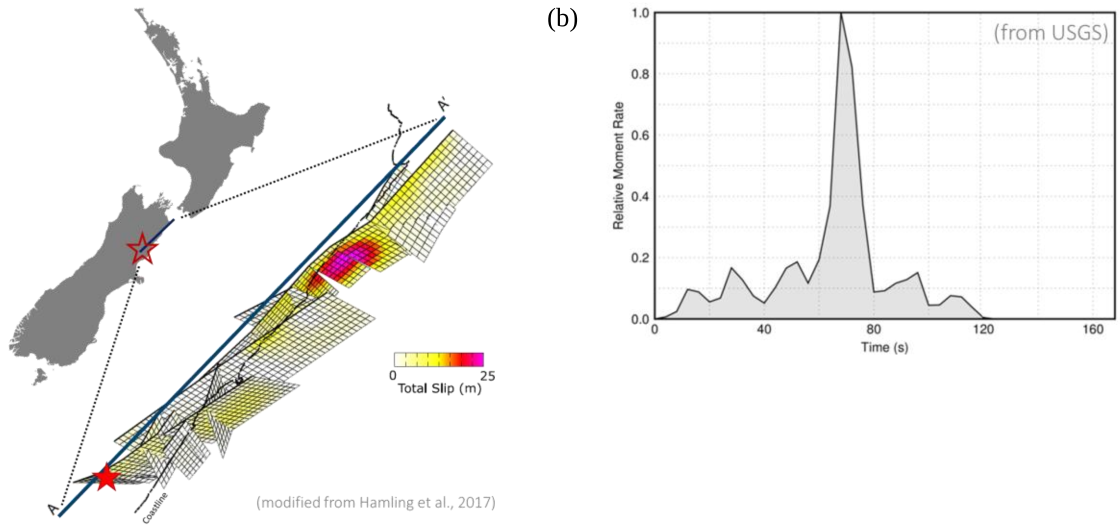


*Figure 6. (a) Finite fault rupture model of 2016 Mw7.85 Kaikoura, New Zealand earthquake (modified from Hamling et al., 2017 [3]), and (b) relative moment release as a function of rupture time (adopted from USGS [4])*

### Pseudo Real-Time Playback

We playback waveform data obtained from the Kaikoura earthquake in a pseudo real-time to assess the performance of derived models within EEW context. Figure 7 shows the evolutionary growth of predicted final event magnitude based on Eqn 3 in comparison to that of true magnitude as a function of time since the rupture initiation. In a preliminary assessment, it was realized that using only the first 3 seconds of the P-window is insufficient to characterize source parameters accurately for complex events where the majority of seismic energy is radiated at later stages of growing rupture. Therefore, we allow the peak displacement to be measured using the entirety of the P-window that is captured up to a given point in time (prior to the S arrivals). This method estimates final event magnitude accurately and forecasts event magnitude to exceed Mw7.5 about 35s before the true event magnitude reach that level.

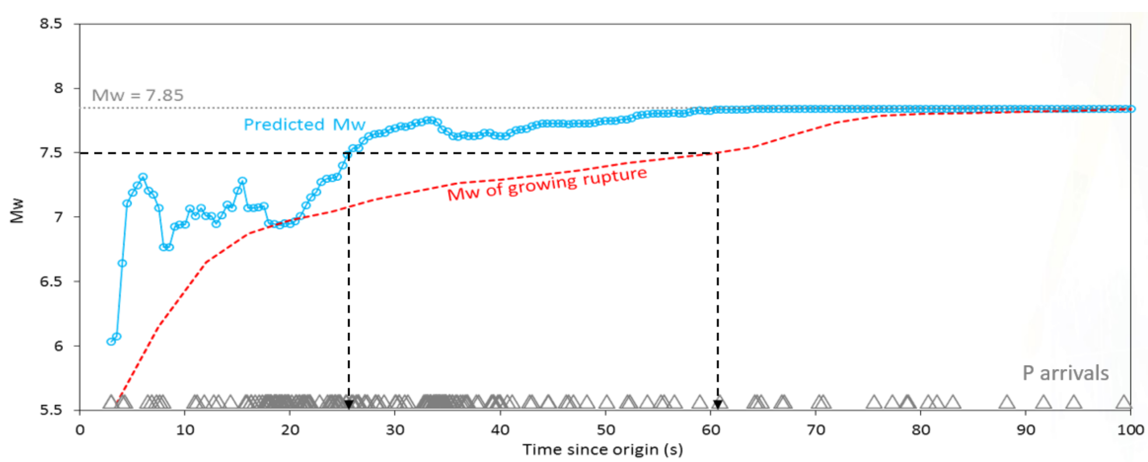


*Figure 7. The evolution of $M_w$ estimates based on Eqn (3) using $P_d$ values measured from the entirety of the P-window that is captured up to a given point in time.*

Figure 8 shows evolution of shaking intensity estimates across the region as more data becomes available with time, and their comparison with the final shaking intensity. Intensities at triggered stations at a given time are estimated based on on-site approach (Eqns 1 and 2). Intensities at un-instrumented locations as well as at stations that have not yet been triggered are estimated based on the predicted event magnitude at the given time (Figure 7) using regional GMPE (Eqn 4). The on-site predictions are then incorporated into regional estimated using data assimilation technique [4]. This hybrid approach breaks the circular pattern of intensity estimates due to point source assumption, providing higher intensity estimates in the direction of rupture as similar to the final intensity distribution. The non-uniform distribution of shaking intensity can provide some promising constraints on the orientation of the rupture for implementation finite-source predictions in EEW context.

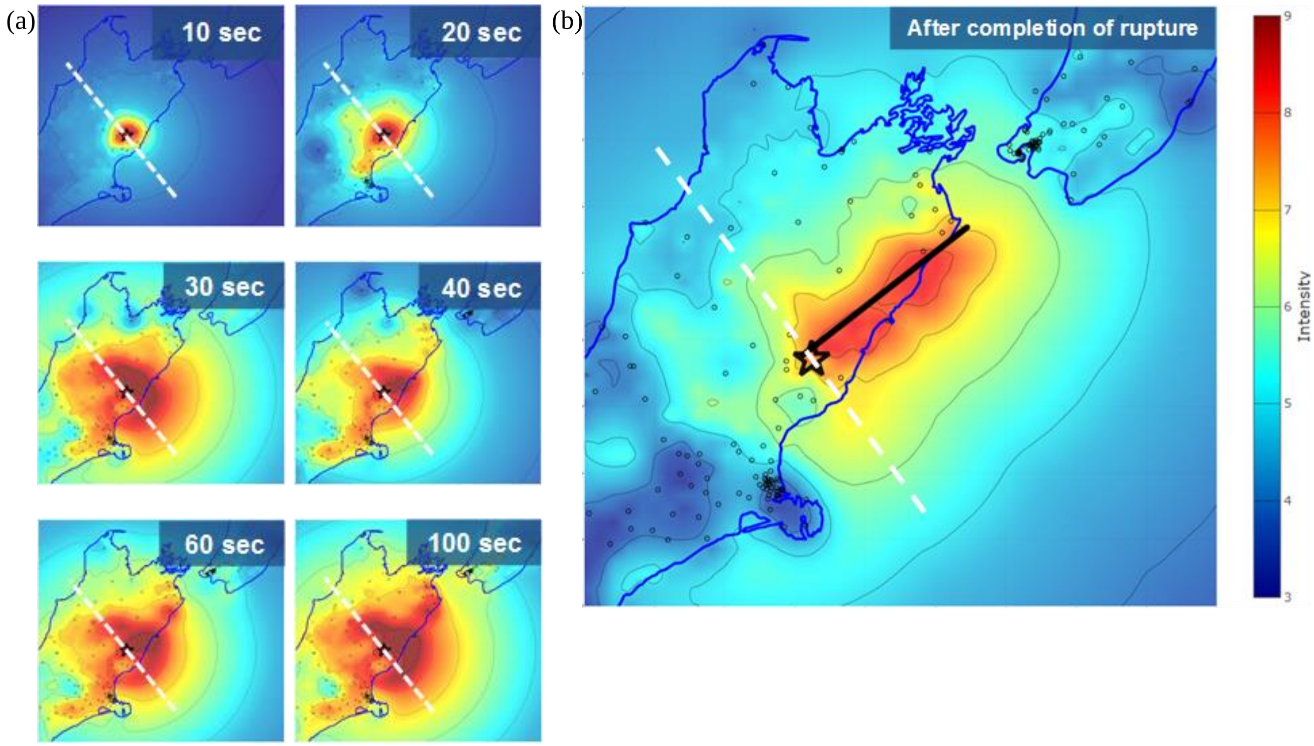


*Figure 8. Evolution of the shaking intensity estimates based on assimilation of on-site predictions into regional GMPE predictions at a given time since the rupture initiation.*

## CONCLUSIONS

The evolutionary accuracy of estimated magnitude and shaking intensity are examined for alternative source and ground motion characterization techniques. Using available P-wave window at a given time (rather than a fixed width of 3s) allows contributions from late P arrivals in $P_d$ calculations. This can be helpful to accurately characterize the event magnitude from large and complex ruptures. Additionally, assimilation of on-site intensity estimates into regional approach can capture rupture directionality effects. Intensity distribution can be used to constrain the rupture orientation in real time.

## ACKNOWLEDGMENTS

The financial support provided by Nanometrics Inc. for the conducted research is gratefully acknowledged.

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