Earthquake Early Warning: Recent Advances and Perspectives

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Abstract

Earthquake early warning (EEW) is a relatively new strategy for reducing disaster risk and increasing resilience to seismic hazard in urban settings. EEW systems provide real-time information about ongoing earthquakes, enabling individuals, communities, governments, businesses and others located at distance to take timely action to reduce the probability of harm or loss before the earthquake-induced ground shaking reaches them. Examples of potential losses mitigated by EEW systems include injuries and infrastructure downtime. These systems are currently operating in nine countries, and are being/have been tested for implementation in 13 more. This paper reviews state-of-the-art approaches to EEW around the world. We specifically focus on the various algorithms that have been developed for the rapid calculation of seismic-source parameters, ground shaking, and potential consequences in the wake of an event. We also discuss limitations of the existing applied methodologies, with a particular emphasis on the lack of engineering-related (i.e., risk and resilience) metrics currently used to support decision-making related to the triggering of alerts by various end users. Finally, we provide a number of suggestions for future end-user-orientated advances in the field of EEW. For example, we propose that next-generation EEW systems should incorporate engineering-based, application-specific models/tools for more effective risk communication. They should operate within robust probabilistic frameworks that explicitly quantify uncertainties at each stage of the

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analysis, for more informed stakeholder decision-making. These types of advancements in EEW systems would represent an important paradigm shift in current approaches to issuing early warnings for natural hazards.

Key Words

earthquake early warning; risk communication; engineering-related risk prediction; decision-making under uncertainty; resilience promotion

1 Introduction

Early warning consists of a set of procedures and tools for disseminating actionable information in advance of a threatening circumstance, to reduce the potential risks involved (Basher et al., 2006). Early warning systems are increasingly considered an important and effective way to mitigate the effects of natural hazards (United Nations, 2006). It is therefore not surprising that they are frequently used to send alerts related to floods (e.g., Krzysztofowicz et al., 1994), tornados (e.g., Simmons and Sutter, 2009), avalanches (e.g., Rheinberger, 2013), glacier lake outbursts (e.g., Bründl and Sturny, 2014), landslides (e.g., Medina-Cetina and Nadim, 2008), debris flows (e.g., Sättele et al., 2015), and tsunamis (e.g., Blaser et al., 2011). In this paper, we focus specifically on their application to earthquakes.

Earthquake early warning (EEW) systems are primarily based on two concepts that enable alerts to be sent ahead of the occurrence of earthquake-induced ground shaking at target locations (on the order of seconds to minutes): (1) Information travels faster than seismic (i.e., mechanical) waves; and (2) most of the energy of an earthquake is carried by the S- and surface waves, which arrive after the faster, lower amplitude P-waves. This warning time, although short, can reduce the impacts of an earthquake on many sectors of society (Strauss and Allen, 2016). Individuals can "drop, cover and hold on" or (if there is sufficient time) evacuate hazardous buildings/move to safer locations within a building, mitigating injuries or fatalities. Automated actions can be taken, including the stopping of elevators at the nearest floor and opening the doors to avoid injuries, the slowing of high-speed trains to reduce accidents, the shutting down of gas pipelines to prevent fires, and the switching of signals to stop vehicles from entering vulnerable structures such as bridges and tunnels, etc. This is not an exhaustive list but rather a snapshot of critical applications that could benefit from EEW.

The idea of using early warning for earthquakes was first considered by J.D. Cooper in November 1868 (Nakamura and Tucker, 1988); he proposed the installation of seismic sensors near Hollister, California, that would send an electric signal via telegraph to San Francisco once an earthquake was detected. EEW was not practically implemented until the 1960's however, when the Japanese National Railways authority developed an EEW system to avoid derailments of high-speed trains (Nakamura and Saita, 2007). The concept was further enhanced by members of the U.S. Geological Survey (USGS) in the 1960's and 1970's, when they developed a seismic monitoring system for central California that facilitated rapid estimation of earthquake location and magnitude (Kanamori, 2005; Stewart, 1977). Today, EEW systems are operating in the USA (Given et al., 2018), Japan (Hoshiba et al., 2008), Mexico (Cuéllar et al., 2017), Romania (Mârmureanu et al., 2011), Turkey (Alcik et al., 2009), Taiwan (Hsiao et al., 2009), South Korea (Dong-Hoon et al., 2017), China (Ji et al., 2019), and India (Kumar et al., 2014). They are also being tested for use in Italy (Zollo et al., 2016), Switzerland (Cua et al., 2009), Chile (Crowell et al., 2018b), Israel (Nof and Allen, 2016), Nicaragua (Strauch et al., 2018), Spain (Pazos et al., 2015), Slovenia and Austria (Picozzi et al., 2015a), Greece, New Zealand and Iceland (Behr et al., 2016), as well as in Costa Rica and El Salvador (Allen and Melgar, 2019). It is encouraging for developers of EEW systems to note that they are generally viewed as positive measures by relevant stakeholders (Suárez et al., 2009; Hoshiba, 2014).

This paper is written in the format of a "traditional or narrative literature review" (e.g., Cronin et al., 2008). Using Satriano et al. (2011c), Zollo et al. (2014), and Allen and Melgar (2019) as a basis, we first discuss state-of-the-art approaches and recent developments in EEW (Section 2). We specifically focus on the algorithms that have been developed for various components of the real-time calculations of source parameters, ground shaking at a target site, and potential consequences. We then identify some limitations to current approaches (Section 3); for example, although it is clear from Figure 1 that EEW has significant opportunity to reduce seismic risk in regions where it is applied, few (if any) implemented EEW systems make decisions to trigger alarms based on explicit engineering-related damage and loss predictions or resilience metrics, eventually accounting for end-user preferences in an explicit fashion. Finally, we discuss a number of suggestions for mitigating these limitations through the development of next-generation, end-user-orientated EEW systems (Section 4).

2 Current Approaches and Recent Developments in EEW

2.1 Background

EEW involves four main steps (Figure 2): (1) Detecting an event and estimating its location; (2) estimating the event magnitude; (3) estimating ground shaking at various distances conditional on the specific event occurrence and features (i.e., its location and magnitude); and (4) using all of the gathered information to determine whether or not to trigger an alarm, which may involve further processing of the available data. (Alerts are then communicated to relevant stakeholders through various technological means, including radio, television, emails, websites, SMS messages, and smartphone applications.) Each step involves a degree of uncertainty, due to the rapid real-time calculations involved in EEW models/methods and the traditional uncertainties associated with probabilistic seismic hazard analysis (PSHA; Cornell, 1968). EEW systems can be broadly divided into "regional", "on-site", and "hybrid" categories, based on their approach to the first three steps above and the complex EEW trade-off between warning time and prediction accuracy. Note that this paper focuses on "conventional" EEW systems, which make use of data measured with traditional seismic instruments (e.g., high-quality seismometers). It is important to mention that alternative approaches to EEW are beginning to be developed, which harness the ever-increasing density of mobile computing and instead use smartphone sensors as a seismic network (Kong et al., 2016; Bossu et al., 2019). However, there are currently many challenges to overcome before these types of systems become a realistic viable replacement to conventional approaches, including sensor quality issues and notification latency (Allen et al., 2019).

Regional EEW systems consist of a network of seismic sensors located within the expected epicentral area or area of high seismicity in a region, for estimating the source parameters of Steps 1 and 2. These estimates are used to predict ground shaking (Step 3) at sites located further away from the event (Satriano et al., 2011c). This type of EEW system can be further categorised as either "point-source" (which simplistically

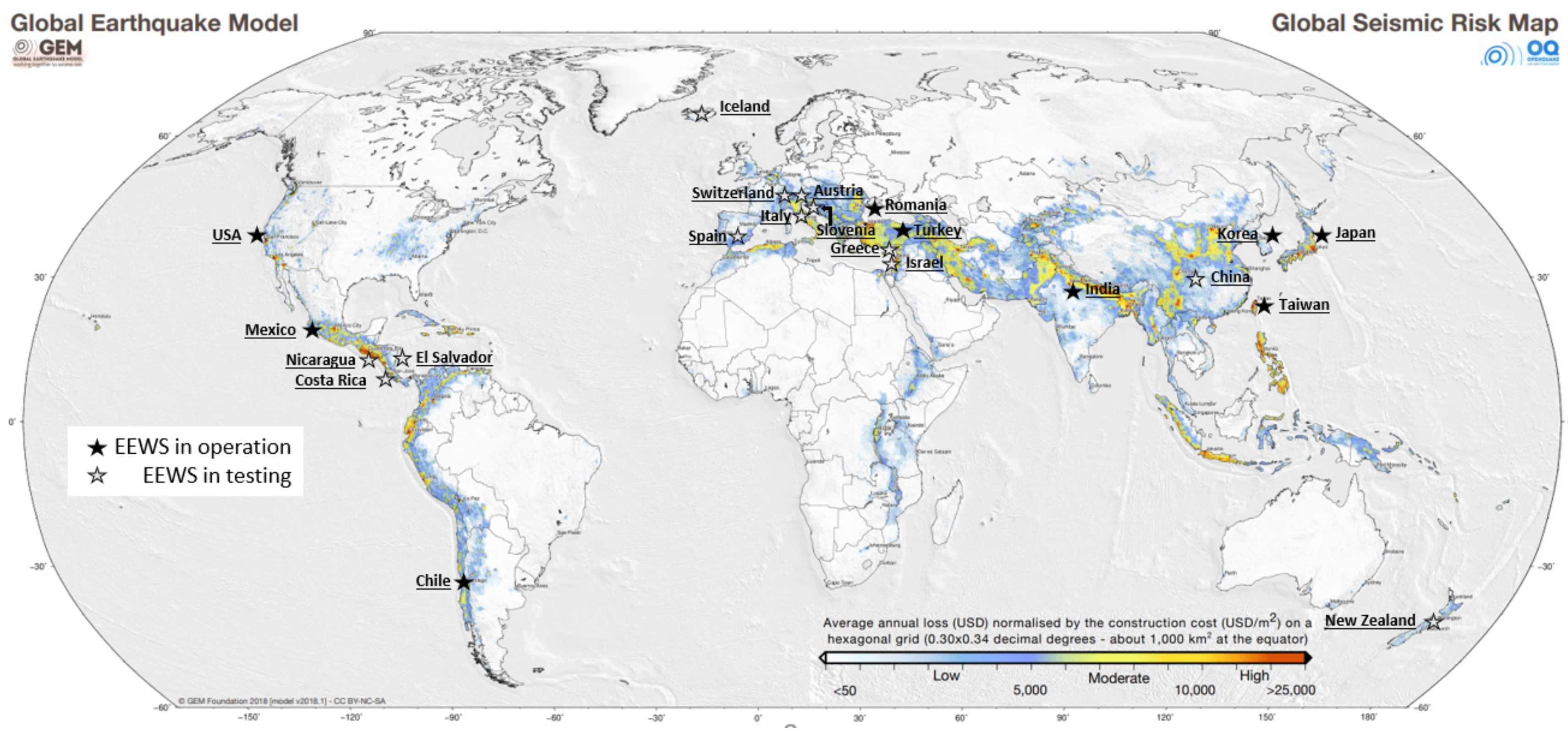

Figure 1: Earthquake early warning system development across the world, overlaying a global seismic risk map that is expressed in terms of annual average losses normalised by construction cost (Silva et al., 2018). It can be seen that EEW systems are typically applied to regions that have significant seismic risk.

represent the source as a concentrated volume) or "finite-fault" (which involve a more complete characterisation of the source). While finite-fault approaches are more accurate than point-source approaches, they require observations from many sites and are therefore slower (e.g., Allen and Melgar, 2019).

On-site EEW systems consist of a limited set of seismic stations located at (for site-specific systems) or near (for front-detection systems) particular target sites/infrastructure of interest. They estimate both source parameters and ground shaking directly based on characteristics of the seismograms recorded within the system (Zollo et al., 2014). Regional EEW systems yield more accurate estimates of the source parameters, but on-site EEW systems result in faster warning times for near-source targets (Kanamori, 2005). Hybrid EEW systems (Zollo et al., 2010; Colombelli et al., 2012a) combine the capabilities of regional and on-site systems, by incorporating evolving information on the source parameters from a regional network (Steps 1 and 2), with ground motion estimates at the target site (Step 3).

We now summarise and discuss the various state-of-the-art methodologies (algorithms) that underpin EEW systems across the world, specifically discussing whether/how they deal with the uncertainty involved in each step. Analyses of real-time algorithm performance with respect to physical EEW network constraints (such as station location and density) is outside the scope of the current review. However, interested readers should note that many previous studies have already focused on this issue (e.g. Kuyuk and Allen, 2013; Auclair et al., 2015; Ogweno et al., 2019).

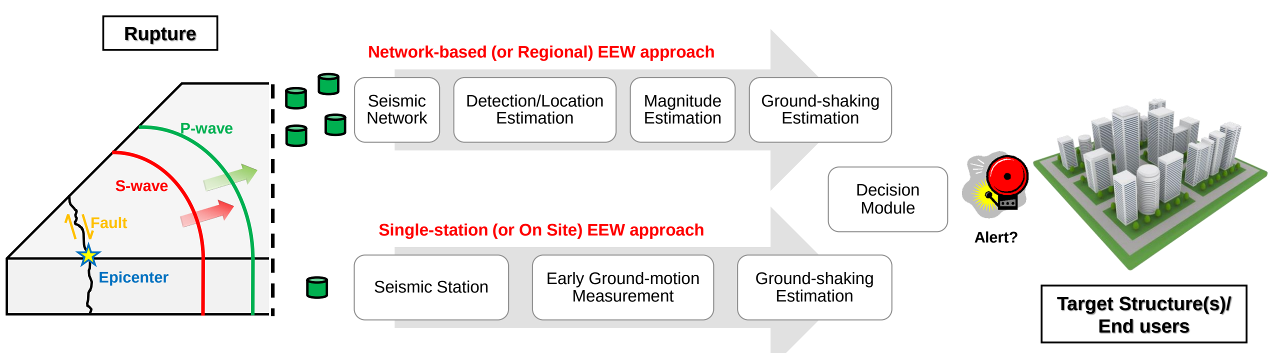

Figure 2: Conceptual outline of an EEW process. Information from an EEW system sensor network is input to an EEW algorithm to detect events and compute estimates of earthquake location, magnitude, and/or ground shaking amplitude. Select outputs of the calculations are then provided to a decision module for potentially further processing, to determine whether or not a warning should be triggered for end users.

2.2 Event Detection and Location Estimation

Tables 1 to 5 summarise the most popular current methods for event detection and EEW estimation of event locations. The procedures outlined in Tables 1 and 2 are used in point-source regional EEW systems. The method of Table 1 is conceptually straightforward and computationally efficient to implement, but it only uses information from triggered stations, which leads to less certain location estimates than those obtained from the procedure of Table 2. However, it is significantly challenging to implement the method of Table 2 in realistic seismic networks that have non-uniform station telemetry delays (Cua et al., 2009).

Tables 3 and 4 outline procedures used in finite-fault algorithms for constraining locations. While the outputs of these methods may be more accurate than those of the point source approaches in Tables 1 and 2, they typically take longer to compute. The on-site method of Table 5 is very rapid and thus useful for near-source target sites, but is significantly less accurate than the aforementioned procedures described since it relies on data from only one seismic station.

Uncertainty in the calculations are accounted for in two of the point-source algorithms included in Tables 1 and 2. PRESTo produces a normal probability density function (PDF) for hypocentre location, which is parameterised by a mean estimate and a covariance matrix that explicitly captures spatial uncertainty. Virtual Seismologist makes use of a Bayesian framework, in which location and magnitude are jointly conditioned on the available set of ground motions and the prior PDF represents an existing state of knowledge on relative earthquake probability.

Recent work has focused on improving the event detection capabilities of EEW systems, so that they are less likely to cause a false alert by misinterpreting local impulsive noise from natural or anthropogenic sources (Li et al., 2018). Hsu et al. (2016) and Meier et al. (2019) demonstrate that various machine learning algorithms (e.g. support vector classification, general adversarial network, random forest, convolutional neural network) may effectively reduce the probability of false alarms caused by non-earthquake vibration events.

Table 1: Estimating location, using only information from triggered stations

Description of Method		
Seismic arrivals at a station are detected using a picker method, such as the short-term-average/long-term-average (STA/LTA) procedure (Allen, 1978). Once a sufficient number of stations have triggered (in accordance with the underlying EEW algorithm), the location is estimated using a grid search routine to minimise the residuals between observed seismic phases and those predicted from a velocity model.		
Inputs	Outputs	Relevant Algorithms
P-wave arrival times at triggered stations; Velocity model; Seismic station locations	Epicentre/ hypocentre location estimate	ElarmS (USA, Chile, Israel); eBEAR (Taiwan); Beijing EEW system (China)
Output Uncertainty Considered?	Key References	
No	Allen et al. (2009); Wurman et al. (2007); Kuyuk et al. (2014); Chung and Allen (2019); Chen et al. (2015); Hsiao et al. (2009); Wu and Teng (2002); Peng et al. (2011)	

Table 2: Estimating location, using information from both triggered and non-triggered stations

Description of Method		
When a seismic arrival is detected at the first station, the location is initially constrained either by the geometric surface that represents the set of all locations closer to the station than any other station in the network, or characteristics of the early waveform envelope. Once two stations have triggered, location uncertainty is reduced to a conditional surface based on the time between the P-wave detections. The location can be estimated directly when the third station is triggered. Alternatively, grid search routines are used to increasingly constrain the location after the second or third trigger.		
Inputs	Outputs	Relevant Algorithms
P-wave arrival times at triggered stations; Velocity model; Seismic station locations	Epicentre/ hypocentre location estimate	JMA (Japan); Virtual Seismologist (USA, Switzerland, Costa Rica, El Salvador, Nicaragua); PRESTo (Italy, Austria, Slovenia, Spain)
Output Uncertainty Considered?	Key References	
Yes, in (1) Virtual Seismologist and (2) PRESTo	Rydelek and Pujol (2004); Horiuchi et al. (2005); Font et al. (2004); Toshikazu Odaka et al. (2003); Rosenberger (2009); Cua (2005); Cua et al. (2009); Cua and Heaton (2007); Satriano et al. (2008, 2011a); Kamigaichi (2004)	

Table 3: Estimating earthquake depth, using geodetic observations

Description of Method		
Initial estimates of earthquake depth are obtained from grid searches based on peak ground displacement (PGD) scaling relationships, using information on magnitude and pre-computed epicentral distance estimates. Final depth estimates are computed from a centroid moment tensor calculation, using static offsets from Global Positioning Systems (GPS) data.		
Inputs	Outputs	Relevant Algorithms
Epicentral distance estimates (from another EEW algorithm); GPS displacement waveforms; Green's functions	Depth estimate	G-FAST (USA, Chile)
Output Uncertainty Considered?	Key References	
No	Crowell et al. (2013); Melgar et al. (2015, 2012); Hashima et al. (2008); Crowell et al. (2016, 2018a)	

Table 4: Estimating earthquake centroid, using ground motion image-recognition techniques

Description of Method		
An image (I) of the observed spatial peak ground motion amplitude distribution is compared to theoretical templates (T), which are calculated from a ground-motion model (GMM, also known as an attenuation relationship or a ground-motion prediction equation) for line sources of varying length. The optimum T is then found by minimising the misfit between T and I, and the centroid of the corresponding line source is equivalent to the centroid of the earthquake.		
Inputs	Outputs	Relevant Algorithms
Theoretical ground motion templates, modelled from GMMs; Observed (high frequency) ground motion amplitudes; Seismic station locations	Centroid estimate	FinDER (USA, Switzerland, Chile, Costa Rica, El Salvador, Nicaragua)
Output Uncertainty Considered?	Key References	
No	Böse et al. (2012, 2015, 2018)	

Table 5: Estimating location from a single seismic station

Description of Method		
The distance is estimated from empirical equations, which include variables such as the peak P-wave amplitude and an estimate of the magnitude.		
Inputs	Outputs	Relevant Algorithms
Required parameters for empirical equations (e.g. peak P-wave amplitude);	Epicentre/Hypocentre estimate	UrEDAS (Japan); EDAS-MAS (China)
Output Uncertainty Considered?	Key References	
No	Nakamura and Saita (2007); Yutaka Nakamura (1988); Peng et al. (2013)	

2.3 Magnitude Estimation

Tables 6 to 11 summarise common procedures for estimating magnitude. The method of Table 6 is used in point-source approaches and takes advantage of regression (empirical) relationships between the magnitude of an event and characteristics of its initial P-waves (and S-waves close to the rupture in some cases). However, these relationships are found to saturate for larger magnitudes (Kanamori, 2005; Rydelek and Horiuchi, 2006; Rydelek et al., 2007; Zollo et al., 2007). The method of Table 7 is a point-source approach that makes use of longer waveform windows, in which the aforementioned relationships do not saturate.

The methods of Tables 8 and 9 are finite-fault approaches for estimating magnitude. They provide a more realistic estimate of the size of an ongoing event than the point-source approaches previously described, since they consider measurements from the entire fault plane (Zollo et al., 2014). The on-site method of Table 10 enables rapid estimations of magnitude at sites close to the epicentre, but is less reliable than other procedures due to its dependence on measurements from a single seismic station.

Uncertainties in magnitude estimates are accounted for in a number of algorithms included in the aforementioned tables. Both PRESTo and Virtual Seismologist make use of Bayesian frameworks. In PRESTo, magnitude is represented by a normal PDF; the average value is calculated from an empirical relationship between magnitude and initial characteristics of the P-wave/hypocentral distance, and the standard deviation depends on errors in the coefficients of the empirical relationship as well as uncertainty in the distance estimate. Magnitude distributions for each station and time window are combined through a likelihood product, and the prior PDF is the distribution obtained at the previous time step. In Virtual Seismologist, the joint distribution of magnitude and location is conditioned on the available set of observed ground motions as discussed in Section 2.2. Southern Iberia EEW system, G-FAST, OnSite, and EDAS-MAS account for confidence intervals on the median magnitude estimate, which are equal in width to two standard deviations of the the relevant regression relationship used to derive magnitude.

Table 6: Estimating magnitude from information in the very initial portion of seismic waveforms

Description of Method		
The magnitude is estimated from the amplitude (e.g. peak displacement) and/or the frequency content (e.g. characteristic period) of the initial few seconds of the incoming P-wave train, using empirical relationships. Estimates are typically averaged over a number of seismic stations		
Inputs	**Outputs**	**Relevant Algorithms**
Initial seismic waveform; Magnitude-ground motion empirical relationship	Magnitude estimate	ElarmS (USA, Chile, Israel); Virtual Seismologist (USA, Switzerland, Costa Rica, El Salvador, Nicaragua); REWS (Romania); eBEAR (Taiwan); KEEWS (South Korea); Beijing EEW system (China); EEW systen for Southern Iberia (Spain)
Output Uncertainty Considered?	**Key References**	
Yes, in (1) Virtual Seismologist and (2) Southern Iberia EEW system	Allen and Kanamori (2001); Tsang et al. (2007); Wurman et al. (2007); Wu and Kanamori (2008b); Wu and Zhao (2006); Festa et al. (2008); Wu and Kanamori (2008a); Cua (2005); Cua et al. (2009); Cua and Heaton (2007); Böse et al. (2007); Mârmureanu et al. (2011); Ionescu et al. (2007); Chen et al. (2015); Hsiao et al. (2009); Sheen et al. (2014); Dong-Hoon et al. (2017); Carranza et al. (2013); Peng et al. (2011)	

Table 7: Estimating magnitude from information in increasing time windows of initial seismic waveforms

Description of Method		
The method is similar to the procedure outlined in Table 6, except that the amplitude and frequency content parameters of the empirical relationships are measured over larger/increasingly expanding time windows (up to the order of minutes in some cases), and thus may also incorporate information from S-waves.		
Inputs	**Outputs**	**Relevant Algorithms**
Initial seismic waveform; Magnitude-ground motion empirical relationship	Magnitude estimate	PRESTo (Italy, Austria, Slovenia, Spain); SASMEX (Mexico); JMA (Japan)
Output Uncertainty Considered?	**Key References**	
Yes, in (1) PRESTo	Zollo et al. (2006); Colombelli et al. (2012b); Lancieri and Zollo (2008); Colombelli and Zollo (2015); Colombelli et al. (2014); Satriano et al. (2011a); Cuéllar et al. (2017); Suárez et al. (2009); Kamigaichi (2004)	

Table 8: Estimating magnitude from geodetic observations

Description of Method		
Static offsets are obtained from displacement time series that are measured using a geodetic data collection system, such as GPS or Global Navigational Satellite System (GNSS). An inversion technique recovers slip estimates from the static offsets, which are then used to calculate the magnitude.		
Inputs	Outputs	Relevant Algorithms
Fault geometry estimates; GPS/GNSS displacement waveforms; Seismic station locations; Remaining parameters of the inversion method used (e.g. Green's functions, station seismograms)	Magnitude estimate	G-larmS (USA); G-FAST (USA, Chile); BEFORES (USA); REGARD (Japan)
Output Uncertainty Considered?	Key References	
Yes, in (1) G-FAST	Crowell et al. (2009, 2012); Allen and Ziv (2011); Ohta et al. (2012); Wright et al. (2012); Zhang et al. (2014); Grapenthin et al. (2014b,a); Colombelli et al. (2013); Crowell et al. (2016, 2018a); Minson et al. (2014); Kawamoto et al. (2016, 2017)	

Table 9: Estimating magnitude from rupture length

Description of Method		
The magnitude is estimated from an empirical magnitude-rupture length equation (e.g., Wells and Coppersmith, 1994).		
Inputs	Outputs	Relevant Algorithms
Rupture length estimate	Magnitude estimate	FinDER (USA, Switzerland, Chile, Costa Rica, El Salvador, Nicaragua)
Output Uncertainty Considered?	Key References	
No	Böse et al. (2012)	

Table 10: Estimating magnitude from initial characteristics of a single seismic waveform

Description of Method		
The magnitude is estimated from the amplitude (e.g. peak displacement) and the frequency content (e.g. the predominant period) of the initial few seconds of the incoming P-wave train, using empirical relationships.		
Inputs	Outputs	Relevant Algorithms
Required amplitude and frequency parameters	Magnitude estimate	OnSite (USA); UrEDAS (Japan); EDAS-MAS (China)
Output Uncertainty Considered?	Key References	
Yes, in (1) OnSite and (2) EDAS-MAS	Kanamori (2005); Böse et al. (2009); Yutaka Nakamura (1988); Nakamura and Saita (2007); Peng et al. (2013)	

2.4 Ground-Shaking Estimation

Regional EEW systems generally estimate ground shaking in terms of ground-motion intensity measures (IMs) from an empirical attenuation relationship (e.g. an existing GMM), using estimates of the earthquake location and magnitude obtained from the procedures outlined previously (Table 11). IMs quantify the damage potential of an earthquake-induced ground motion with respect to a specific engineering system (e.g., a structure), and can be used to predict the associated seismic response of the system (Baker and Cornell, 2005). Typical IMs predicted by EEW systems include peak ground acceleration (PGA) and peak ground velocity (PGV). In less common cases, regional systems instead estimate IMs by interpolating spatially distributed maps of recorded ground shaking (Tables 12 and 13). On-site/hybrid systems typically obtain rapid (and less accurate) PGV estimates, using only information on the characteristics of P-waves recorded at one seismic station (Table 14).

Ground-shaking estimation explicitly accounts for most of the uncertainty involved in the first three steps of EEW (Iervolino, 2011). Uncertainties in ground shaking estimates are considered in a number of algorithms. The majority of these algorithms (i.e. PRESTo, G-FAST, OnSite, and EDAS-MAS) account for uncertainty by considering a confidence interval on the estimate with width equivalent to two standard deviations of the empirical relationship used to derive ground shaking, assuming most likely/modal (or measured) values for the source-related variables. Virtual Seismologist accounts for the full lognormal PDF of ground shaking from the relevant attenuation equation, which also incorporates the propagated source parameter uncertainty quantified in Sections 2.2 and 2.3. It is also worth mentioning that several methods of reducing ground-shaking estimation uncertainty for EEW have been proposed in the literature. For example, de Matteis and Convertito (2015) developed a procedure for updating the PGA parameters of a GMM (and hence reducing its associated standard deviation) to account for the specific features of a seismic source and propagation medium, which uses real-time maximum acceleration amplitudes recorded during an event at one-second intervals. Wang et al. (2017) proposed a technique for replacing initial PGV estimates from a GMM with more certain real-time amplitude predictions calculated using recorded seismogram envelopes and wave propogation (i.e., radiative transfer) modelling.

Table 11: Estimating ground shaking from attenuation equations

Description of Method		
Source distances to target sites of interest are first computed based on earthquake location estimates. Empirical attenuation relations (e.g. GMMs) are then used in combination with these distances and the magnitude estimate, to calculate spatial estimates of ground shaking.		
Inputs	Outputs	Relevant Algorithms
Magnitude estimate; Location estimate; Remaining parameters of the attenuation relationship used (e.g. site condition)	Ground motion amplitude estimates	ElarmS (USA, Chile, Israel); PRESTo (Italy, Austria, Slovenia, Spain); Virtual Seismologist (USA, Switzerland, Costa Rica, El Salvador, Nicaragua); JMA (Japan)
Output Uncertainty Considered?	Key References	
Yes, in (1) Virtual Seismologist and (2) PRESTo	Allen et al. (2009); Satriano et al. (2011a); Cua (2005); Kamigaichi (2004)	

Table 12: Estimating spatially distributed ground shaking from ground motion recordings

Description of Method		
Recorded ground motion estimates are translated into spatially distributed maps of ground shaking, using interpolation procedures or information on ground motion spatial correlation.		
Inputs	Outputs	Relevant Algorithms
Ground motion recordings; Seismic station locations	Ground motion amplitude estimates	FinDER (USA, Switzerland, Chile, Costa Rica, El Salvador, Nicaragua), ElarmS (USA, Chile, Israel)
Output Uncertainty Considered?	Key References	
No	Iervolino (2011); Böse et al. (2012, 2018); Allen et al. (2009)	

Table 13: Estimating ground shaking from initial characteristics of multiple seismic waveforms

Description of Method		
A first image of the seismic wavefield is obtained from the initial seismic waveforms recorded, using interpolation (i.e. data assimilation) techniques. This image is input to a physics-based wave propagation model to forecast final ground motion amplitudes.		
Inputs	Outputs	Relevant Algorithms
Spatially distributed seismic waveforms; Remaining parameters of the wave propagation model (e.g. Green's functions)	Ground motion amplitude estimates	PLUM (Japan)
Output Uncertainty Considered?	Key References	
No	Hoshiba and Aoki (2015); Kodera et al. (2018, 2016)	

Table 14: Estimating ground shaking from initial characteristics of a single seismic waveform

Description of Method		
PGV is estimated from the amplitude (e.g. peak displacement) of the initial few seconds of the incoming P-wave train, using empirical relationships.		
Inputs	Outputs	Relevant Algorithms
Initial seismic waveform	PGV estimate	OnSite (USA); PRESTo^{Plus} (Italy); EEW system for Southern Iberia (Spain)
Output Uncertainty Considered?	Key References	
Yes, in (1) OnSite and (2) EEW System for Southern Iberia	Böse et al. (2009); Wu and Kanamori (2008a, 2005); Colombelli et al. (2015); Zollo et al. (2010, 2016); Carranza et al. (2013)	

2.5 Decision Module for Alert Notification

Decisions to trigger alerts in current EEW systems may be based on estimates of magnitude only (Table 15), magnitude and epicentral distance of target sites (Table 16), or ground motion amplitude estimates (Table 17). The most common decision variable used is seismic intensity (Table 18). This measures the observed effects of ground shaking, such as the degree to which it is felt or the extent of damage experienced by household contents, and is measured using a scale (e.g., Wood and Neumann, 1931).

Damage- and loss-orientated approaches to EEW decision-making have also been proposed in the literature but have not been implemented in any of the existing EEW systems around the world. For example, Le Guenan et al. (2016) developed a multi-criteria decision-making (MCDM) methodology to select a trigger threshold for a bridge that was derived from a critical probability of bridge damage. Wu et al. (2016) used the framework of Wu et al. (2013) to investigate an EEW system that triggers an alert based on losses quantified as casualties due to people trapped in elevators. Further examples of damage-driven EEW studies include Mitrani-Resier et al. (2016); Fabozzi et al. (2018), and Salzano et al. (2009), while additional examples of loss-driven EEW studies are Wang et al. (2012), Picozzi et al. (2013), as well as the performance-based EEW (PBEEW) approach proposed in Manfredi and Zollo (2006), Iervolino et al. (2007), and Iervolino (2011).

Table 15: Triggering alerts based on magnitude

Description of Method		
A warning is triggered if the magnitude estimate exceeds a certain threshold.		
Inputs	Outputs	Relevant Algorithms
Magnitude estimate	Warning trigger (yes/no)	SASMEX (Mexico); KEEWS (Korea); EDAS-MAS (China); Beijing EEW system (China)
Key References		
Suárez et al. (2009); Cuéllar et al. (2017); Dong-Hoon et al. (2017); Sheen et al. (2014); Peng et al. (2013, 2011)		

Table 16: Triggering alerts based on magnitude and epicentral distance

Description of Method		
Epicentral distances to target sites of interest are first computed based on earthquake location estimates. The magnitude and distance estimates are compared with magnitude-epicentral distance maps of predicted damage; if they lie within the portion of the map where damage is predicted, a warning is triggered.		
Inputs	Outputs	Relevant Algorithms
Magnitude estimate; Location estimate	Warning trigger (yes/no)	UrEDAS (Japan)
Key References		
Nakamura and Saita (2007); Yutaka Nakamura (1988)		

Table 17: Triggering alerts based on ground motion amplitude

Description of Method		
Warnings are triggered based on potentially damaging levels of ground motion amplitude, which can be measured in various ways e.g. PGA or cumulative absolute velocity (i.e. the time integral of the absolute acceleration over the duration of the earthquake record).		
Inputs	Outputs	Relevant Algorithms
Ground motion amplitude estimate (e.g. PGA)	Warning trigger (yes/no)	OnSite (USA); PRESTo; Virtual Seismologist (USA/Switzerland); Compact UrEDAS (Japan); IEEWS (Turkey)
Key References		
Böse et al. (2009); Satriano et al. (2011b); Cua and Heaton (2007); Cua (2005); Nakamura and Saita (2007); Erdik et al. (2003); Oth et al. (2010); Alcik et al. (2009)		

Table 18: Triggering alerts based on calculated seismic intensity

Description of Method		
Seismic intensity is calculated from characteristics of the event waveform (e.g. peak ground motion amplitude) observed at seismic stations, using empirical equations. Warnings are triggered in a region if the estimated seismic intensity exceeds a certain value on the corresponding seismic intensity scale.		
Inputs	Outputs	Relevant Algorithms
Ground motion/seismic waveform information (e.g. PGV)	Seismic intensity estimate; Warning trigger (yes/no)	ElarmS (USA, Chile, Israel); PRESTo^{Plus} (Italy); JMA (Japan); PLUM (Japan); eBEAR (Taiwan); REWS (Romania)
Key References		
Zollo et al. (2010, 2016); Minson et al. (2018); Allen and Melgar (2019); Liu and Yamada (2014); Hoshiba et al. (2008); David J. Wald and Kanamori (1999); Meier (2017); Auclair et al. (2015); Allen et al. (2009); Picozzi et al. (2015b); Colombelli et al. (2012a); Ruhl et al. (2019); Colombelli et al. (2013); Kubo et al. (2011); Wurman et al. (2007); Kamigaichi (2004); Chen et al. (2015); Böse et al. (2007)		

3 Limitations of the State-of-the-Art

It should be clear from the summary tables of Section 2 that the most cutting-edge innovations in current EEW applications concern the seismological aspects of the system (i.e. Steps 1-3 of the EEW process described in Section 2.1). For this reason, we concentrate on the decision-making component of EEW systems in this section, specifically through an end-user lens. While definitions of early warning explicitly refer to its potential to mitigate damage/loss/harm (Table 19), it is obvious from Section 2.5 that decisions to trigger EEW alerts are not currently made with risk-related metrics. The closest proxies for risk used are the ground-motion amplitude and macroseismic intensity measures, which both capture the effects of ground shaking. However, the considered threshold values in terms of those parameters are not calibrated based on explicit damage/loss analysis. More generally, there are a number of limitations associated with end-user-decision-making based on this type of metric.

Table 19: Risk-related terms included in definitions of early warning for natural hazards

Words Included	Key References
"risk"	Thomas Heaton (1985); Picozzi et al. (2015c); Emolo et al. (2016); Bründl and Sturny (2014); Medina-Cetina and Nadim (2008); Villagran de Leon et al. (2013); Pate-Cornell (1986); Sättele et al. (2016); Iervolino et al. (2007)
"damage"	Satriano et al. (2011c); Sättele et al. (2015); Krzysztofowicz et al. (1994); Minson et al. (2019); Zollo et al. (2014); Colombelli and Zollo (2016); James D. Goltz (2002); Kong et al. (2016); Minson et al. (2019); Allen and Melgar (2019)
"loss"	UNISDR (2009); Satriano et al. (2011c); Sättele et al. (2015); Wang et al. (2012); Convertito et al. (2008)
"harm"	UNISDR (2009); Strauss and Allen (2016); Pittore et al. (2014)
"vulnerability"	Emolo et al. (2016); Manfredi and Zollo (2006)

Firstly, there is an explicit assumption that a given level of ground shaking will result in a specific degree of damage. In reality however, the relationship between ground shaking and damage at a target site is highly uncertain (e.g., Cremen and Baker, 2019). In addition, regional EEW-system decision-making (e.g., by a highway authority) based on ground shaking does not account for varying levels of fragility across the affected area, i.e. the fact that damage probability and severity for a given level of ground motion is not the same across different types of structure/infrastructure/systems. Failure to account for uncertainty in damage may lead to a miscalculation in false (or missed) alarm potential.

To illustrate this, we take Figure 1A in Minson et al. (2019), which depicts the performance of an EEW system that triggers alerts for ground motions exceeding 10%g when the expected ground motion is 20%g. In keeping with convention (Porter et al., 2007), the fragility function (i.e. the probability of damage conditioned on ground motion amplitude) associated with a target structure is assumed to be a lognormal cumulative distribution function. We assume that the median of the function is the expected ground motion of 20%g. The dispersion is taken as 0.6, which is in line with values used for real-life structural fragility functions (FEMA, 2012). We have superimposed this fragility function on the probability distribution of ground shaking values from Minson et al. (2019) in Figure 3. The red shading refers to potentially observed ground motion values that would lead to a false alert according to Minson et al. (2019) (i.e. that are below the 10%g threshold), and the green shading indicates ground motion values that would lead to a correct alert. Hatched areas in the figure identify values that may result in an opposite alert to that determined in Minson et al. (2019), when uncertainty in damage is also considered. It is particularly interesting to note that the red hatched area, which refers to the probability of no damage (i.e. false alert) across ground motion values that were originally labeled as returning a correct alert, is significant. For this hypothetical case, it is clear that the probability of false alarm is notably higher than that obtained from ground motion predictions alone, when uncertainty in damage is also considered. Failure to accurately predict false alert probability is an important limitation of ground motion-based decision metrics, as false alarms can have substantial economic impacts (e.g. due to business interruption) and/or affect large communities (e.g. due to an emergency lifeline stoppage), and their frequent occurrence can significantly decrease the value of warning information (Fritz et al., 2008).

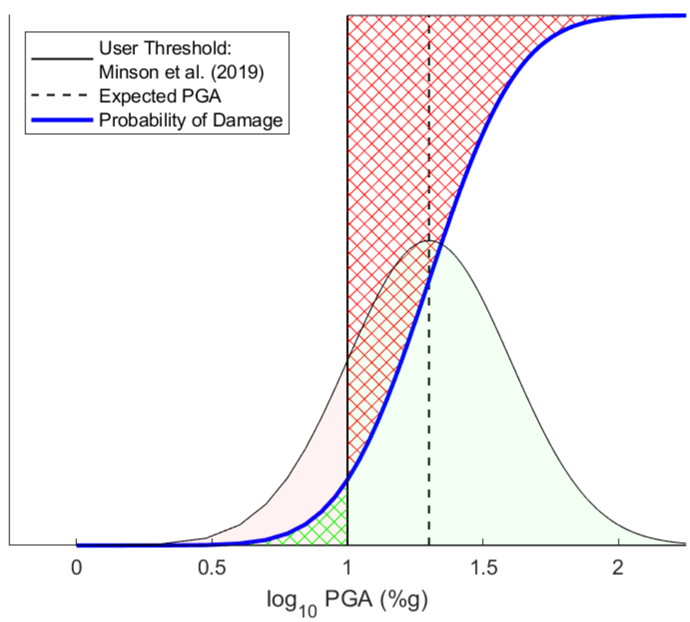

Figure 3: Illustration of potential false alarm miscalculation when ground shaking amplitude is used as an EEW decision metric, using data from Figure 1A of Minson et al. (2019). Red and green shaded areas respectively indicate false and correct alerts identified by Minson et al. (2019). Red and green hatched areas refer to these alerts when a hypothetical fragility function for the target site is also accounted for.

Another notable limitation of ground shaking-related decision metrics is their failure to explicitly consider losses, which are additionally uncertain with respect to damage (e.g., Martins et al., 2016). Accounting for losses as well as damage would therefore further amplify the potential miscalculation of false alarms from ground shaking found in Figure 3. Distinction between losses is also important for optimal decision-making. For example, a business owner may be more interested in measuring the value of an alert based on its ability to mitigate building downtime (business interruption) than the cost of repair after an event; ground shaking decision-based metrics are not useful in this instance.

Finally, descriptions of an event in terms of magnitude/ground motion/macroseismic intensity are difficult for the public to understand (Allen and Melgar, 2019). Confusion in the meaning of an alert makes the public less likely to take preventative action (James D. Goltz, 2002), which decreases the value of a warning. To maximise the benefits of alerts, they should be paired with robust messaging (Cochran and Husker, 2019), which is best achieved using risk-orientated decision metrics (e.g., consequences).

4 Suggested Future End-User-Orientated Advances

The discussion in Section 3 suggests that there is a strong need to develop next-generation end-user-orientated EEW systems that significantly advance the state-of-the-art in EEW decision support. These systems should trigger alerts based on interpretable probabilistic risk-based estimates that are optimised for the needs of - and are understandable to - a given end user, so that clear preventative actions can be taken to mitigate the impact of the event. Using earthquake engineering expertise, fragility and vulnerability/damage-to-loss models for target structure/infrastructure components should be combined with ground motion amplitude predictions from the scientific entity responsible for EEW, to determine end-user-focused estimates of damage and loss (Figure 4). Since the engineering models represent a static piece of information (with respect to the EEW-based seismic hazard estimates), these combinations can be conveniently pre-computed offline for all possible ground motion amplitude estimates and then simply retrieved in real-time for rapid decision-making, following Iervolino (2011).

For well-informed decision-making on EEW triggering, we suggest that next-generation EEW systems be developed based on a robust end-to-end theoretical framework that explicitly tracks uncertainties at each stage of the EEW process, such as the PBEEW approach mentioned in Section 2.5. This framework utilizes the concept of real-time PSHA (RTPSHA), where the PDF of an IM is conditioned on real-time seismic measurements that are related to the probability distributions of the source parameters. (Note that

RTPSHA could easily be adapted to include additional conditional information, such as updated estimates of source parameters from operational earthquake forecasting calculations). This type of probabilistic approach is rarely used in current EEW applications. From Section 2.4, Virtual Seismologist is the only existing algorithm that propagates uncertainties in the source parameters through to ground shaking estimation (although its estimations may be too slow for real-time applications; Chung and Allen, 2019). RTPSHA is mathematically extended to a performance-based framework, to also quantify expected dollar losses in terms of the source-dependent real-time seismic measurements.

We suggest combining PBEEW with an EEW-adapted version of the MCDM methodology presented in Caterino et al. (2008, 2009). This methodology evaluates a group of alternative actions ($\{A_i\}$) for seismic structural retrofitting, based on a set of criteria ($\{I_j\}$) that are weighted ($\{w_j\}$) in importance according to end-user preferences. The explicit consideration of such preferences would improve the current dollar loss-based decision-making procedure of PBEEW. The proposed approach would also remove the requirement for criteria to be exclusively expressed in monetary terms. We now demonstrate integration of both PBEEW and MCDM for the case of a hypothetical school. Potential end users in this case include children, their parents, the headteacher, and local public officials.

The alternative set of actions for EEW-focused MCDM are: A_1: "Trigger an EEW Alarm" and A_2: "Don't Trigger an EEW Alarm". The school-specific criteria for assessing the feasibility of each action can be measured using the indicators shown in the last column of the decision framework presented in Figure 5. Note that since this is a hypothetical framework, the criteria included are not exhaustive. For example, the cost of installing/maintaining the EEW is neglected for simplicity; however this may be an important consideration for school stakeholders in a realistic scenario. We can represent the values of the indicators (for each criterion) associated with each action in the form of a consequence matrix, as demonstrated in Table 20.

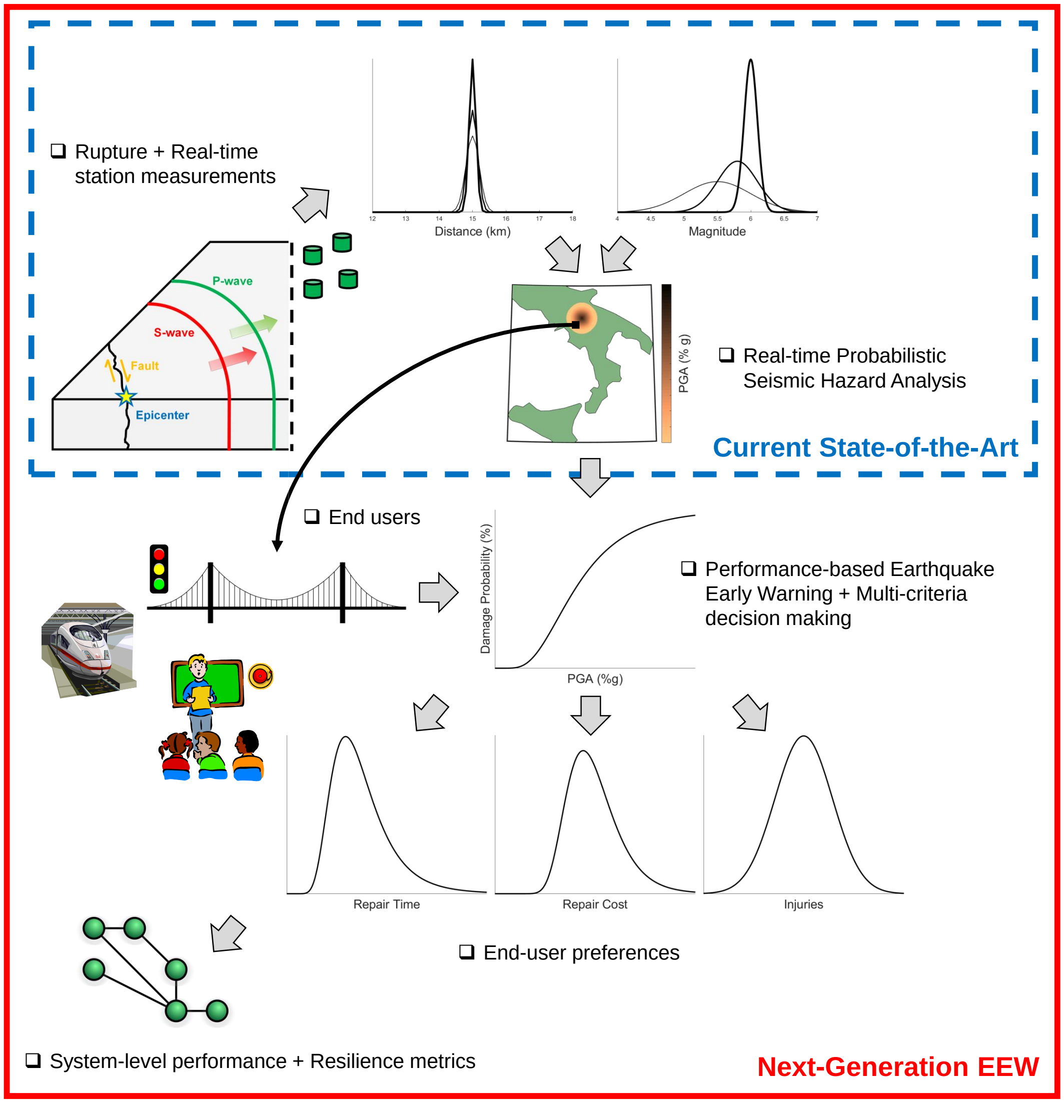

Figure 4: Conceptual overview of a suggested next-generation EEW system for a given end user (e.g., highway operator). Leveraging earthquake engineering expertise, this type of system translates ground motion amplitudes predicted by the scientific entity responsible for EEW (i.e. the current state-of-the-art) to damage and various loss metrics, using application-specific fragility functions and vulnerability functions or damage-to-loss models. This facilitates risk-orientated decision-making that satisfies the needs of the end user and results in robust messaging that enables clear preventative actions to be taken. These systems are underpinned by a probabilistic end-to-end theoretical framework that explicitly tracks uncertainties at each stage of the EEW process. For EEW applications to network-based components (e.g. roads), system-level consequences and resilience metrics are captured by accounting for interdependencies in losses across individual target sites.

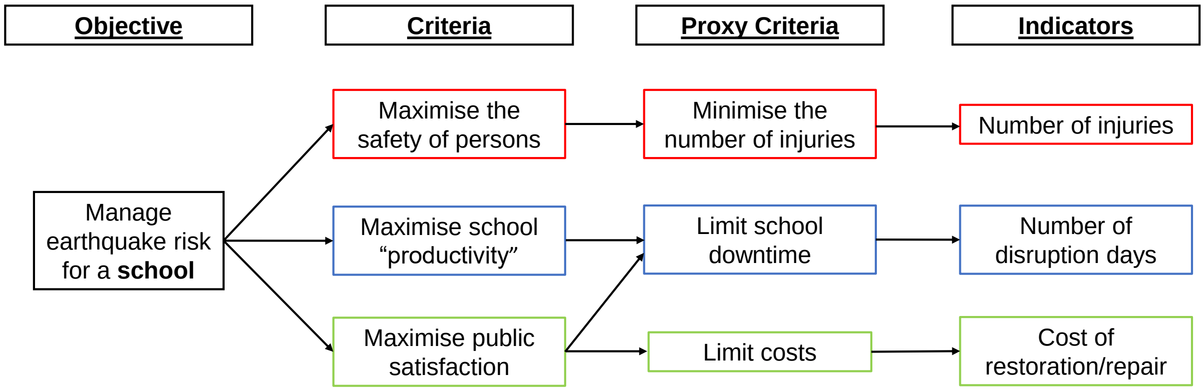

Figure 5: A suggested decision framework for determining end-user criteria of interest to the application of EEW systems in schools.

Table 20: Example consequence matrix for decision-making on EEW triggering in a hypothetical school

	I_1 Injuries (Number)	I_2 Downtime (days)	I_3 Direct Cost (\$)
A_1	Expected injuries due to estimated earthquake that cannot be reduced with EEW	Expected disruption due to potential false alarm + expected downtime due to estimated earthquake that cannot be reduced with EEW	Expected restoration cost due to potential false alarm + expected repair cost due to estimated earthquake that cannot be reduced with EEW
A_2	Estimated injuries due to estimated earthquake	Expected downtime due to estimated earthquake	Expected repair cost due to estimated earthquake

Quantification of the indicators for a given action A_i is conditioned on time-dependent physical measurements from the seismic network ($\mathbf{d}$), which comprise, for instance, the vectors of information used to estimate magnitude (i.e., $\underline{\tau}$) and location (i.e., $\underline{s}$) and the resulting ground-shaking intensity, defined in Iervolino et al. (2007), i.e.:

$$E^{A_i}(I_j^{A_i}|\mathbf{d}) = \int_{I_j^{A_i}} \int_{DM} \int_{IM} I_j^{A_i} f^{A_i}(I_j^{A_i}|dm) f(dm|im) f(im|\mathbf{d})\, dI_j^{A_i}\, dDM\, dIM \tag{1}$$

This equation can be computed offline for all possible estimates of $\mathbf{d}$; thus, the only real-time activity involved is the selection of an appropriate value based on event-specific information. $E^{A_i}(I_j^{A_i}|\mathbf{d})$ is the expected value of the jth indicator for action A_i and the seismic measurements at a given time, $f(a|b)$ is the conditional probability density function of a given b, dm is the damage state of the school, and im is the considered intensity measure. $f(dm|im)$ is derived from an appropriate fragility model. $f^{A_i}(I_j^{A_i}|dm)$ is derived from an action-specific damage-to-loss (or consequence) model, where losses and consequences are broadly defined to include non-monetary considerations such as injuries and downtime. Note that models for $f^{A_1}(I_j^{A_1}|dm)$ (i.e., when the EEW alarm is triggered) are case-specific, and may be obtained from consultations with stakeholders and/or expert engineering judgement for most practical applications. They may also be equivalent to $f^{A_2}(I_j^{A_2}|dm)$ in certain situations. This is foreseeable in the case of direct cost (I_3) for example, since EEW may not be able to reduce any dollar losses associated with a given level of damage. More advanced resilience-orientated decision-making could be facilitated by deriving indicator values directly from IMs following the limit-state approach of Burton et al. (2016), which developed fragility functions that enable ground motion intensity to be translated straight to postearthquake functionality and recovery consequences. These resilience-based metrics have been successfully applied to support post-earthquake decision-making in previous studies (Burton et al., 2018, 2019).

The consequence matrix of Table 20 is translated to a decision matrix (Table 21) by accounting for importance weights $\{w_j\}$ (i.e., end-user preferences) and normalising indicator values. The values of each weight can be obtained, for instance, through an end-user pairwise comparison analysis across all criteria, according to the analytic hierarchy process (Saaty, 2008). Finally, the optimal decision can be determined based on the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method (Yoon and Hwang, 1995), in which the best action to take (at a given time) is deemed to be the one that minimises the highest number of weighted normalised values (in Table 21) across all criteria. The proposed decision-making approach results in a probabilistic dynamic decision-support system for real-time seismic risk management.

Table 21: Example decision matrix for decision-making on EEW triggering in a hypothetical school

	I_1 Injuries (Number)	I_2 Downtime (days)	I_3 Direct Cost (\$)
A_1	$\frac{E^{A_1}(I_1^{A_1}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_1^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_1^{A_2}\|\mathbf{d}))^2}}\times w_1$	$\frac{E^{A_1}(I_2^{A_1}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_2^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_2^{A_2}\|\mathbf{d}))^2}}\times w_2$	$\frac{E^{A_1}(I_3^{A_1}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_3^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_3^{A_2}\|\mathbf{d}))^2}}\times w_3$
A_2	$\frac{E^{A_2}(I_1^{A_2}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_1^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_1^{A_2}\|\mathbf{d}))^2}}\times w_1$	$\frac{E^{A_2}(I_2^{A_2}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_2^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_2^{A_2}\|\mathbf{d}))^2}}\times w_2$	$\frac{E^{A_2}(I_3^{A_2}\|\mathbf{d})}{\sqrt{(E^{A_1}(I_3^{A_1}\|\mathbf{d}))^2+(E^{A_2}(I_3^{A_2}\|\mathbf{d}))^2}}\times w_3$

A key limitation of existing damage- and loss-focused studies related to EEW is their narrow focus on one target site (and generally one target structure) of interest. However, system-level consequences are also important to consider for EEW applications to network-based components. For example, the threshold for triggering an alert to shut down a vehicular bridge should explicitly account for an indicator that measures the resulting decrease in functionality across the entire road network. Thus (where relevant), next-generation EEW systems should incorporate decision-making tools that capture interdependencies in losses. This could be achieved using mathematical tools developed for seismic engineering-related network analyses (e.g., Argyroudis et al., 2015; Lam et al., 2018).

As a significant improvement over current EEW approaches, next-generation EEW systems should consider leveraging more advanced IMs from the scientific entity in charge of EEW, such as spectral-shape-based IM or inelastic spectral acceleration values at a range of prescribed periods (e.g., Minas and Galasso, 2019), for calculating loss estimates within the PBEEW framework. This would notably enhance EEW suitability to risk-based engineering applications, as these IMs are much better correlated with structural response/damage/loss than those typically considered for EEW such as PGA or PGV (e.g., Shome et al., 1998). For example, it would enable interaction between EEW systems and structural control mechanisms that could rapidly alter the behaviour of a building in response to the forecasted spectral acceleration at the structure's fundamental period, which may reduce the structural vulnerability (and resulting losses). This would be particularly beneficial in critical buildings required to be operational for emergency management immediately after an event (such as hospitals and fire stations). Preliminary attempts to combine EEW and structural control exist in the literature (Maddaloni et al., 2011; Velazquez et al., 2017), however they rely on simplified structural models and there is poor statistical significance in the results. Future related studies should make use of more advanced (i.e. state-of-the-art nonlinear 3D) structural modelling techniques and account for proper treatment of uncertainty in the IMs via the RTPSHA framework (Convertito et al., 2008). Consideration of spectral acceleration values in PBEEW would also allow ground shaking outputs of EEW systems to be combined with information from on-site structural health monitoring systems. This could result in more accurate rapid response (and therefore damage and loss) estimates (Cremen and Baker, 2018), leading to more effective decision-making on the triggering of planned mitigation actions (e.g. controlling elevators, alerting occupants).

Up to now, evaluations of EEW systems have concentrated on the performance of magnitude predictions (e.g., Peng et al., 2013), ground shaking forecasts (e.g., Zollo et al., 2009) and macroseismic intensity estimates (e.g., Cochran et al., 2018), while optimisation of the systems have also considered the extent of the blind-zone (i.e. the size of the region that is too close to the epicentre to receive a warning in time; Kuyuk and Allen, 2013). However, next-generation EEW systems should instead be analysed with explicit consideration of the risk-based variables incorporated within the decision support system component of various end users. For example, optimisation of seismic station locations could be based on minimising different types of damage/loss uncertainty observed within the blind zone, rather than simply focusing on its size. The optimal solution could furthermore be weighted in favour of stakeholders with the most urgent needs for timely and accurate consequence estimates, such as hospital managers and high-speed railway authorities.

5 Conclusions

Earthquake early warning is a relatively new innovation in seismology/earthquake engineering, with significant potential to increase the resilience of societies to seismic risk. It is currently operating in nine countries and is being/has been tested for operation in 13 more. This paper has reviewed state-of-the-art approaches to EEW, including the various algorithms that have been developed for completing the four main steps involved, i.e., (1) detecting an event and estimating its location; (2) estimating the event magnitude, (3) estimating the resulting ground shaking; and (4) deciding whether to trigger an alarm based on the previous information.

Our review identified that modern advancements in EEW applications have been largely concentrated within the seismological aspects of the system, i.e., steps 1-3 of the previous paragraph; for example, recent notable applied EEW research efforts have focused on developing innovative finite-fault approaches for estimating magnitude that result in significantly better estimates of the size of an ongoing event than previously proposed magnitude estimation methods. On the other hand, we found that current methods for end-user-decision-making related to the triggering of alerts in EEW systems are relatively simplistic and do not explicitly account for risk. Risk-based (engineering-related) decision metrics are important to consider, since they accurately capture uncertainty in the damage and losses/consequences that result from a given level of ground shaking and can be used to provide informative, robust descriptions of an event that encourage the public to take preventative action.

We provided a number of suggestions for future advances in EEW (specifically through the lens of an end user), including the development of next-generation EEW systems that trigger interpretable alerts based on probabilistic risk-based estimates optimised for the preferences of a given stakeholder. This type of system could be designed based on the findings of the few previous studies that have focused on damage- and loss-driven EEW approaches. In particular, we suggest implementing the robust theoretical loss-based framework of PBEEW, which explicitly tracks uncertainties at each stage in EEW, and improving its decision-making capabilities by also leveraging the MCDM methodology detailed in Caterino et al. (2008, 2009). This type of decision-making approach could be integrated into future EEW algorithms to determine optimal actions, considering multiple (weighted) criteria of interest to an end user that do not necessarily need to be measured in terms of monetary value. The result would be a novel dynamic real-time decision-support/risk management system aimed at resilient structure and infrastructure. Where relevant, the decision-making approach of next-generation EEW systems should also account for interdependencies in system-level losses across a region and more engineering-orientated IMs (e.g., elastic/inelastic spectral ordinates), which would transform EEW into a more credible tool for seismic resilience assessment and promotion.

6 Acronyms

Table 22: Explanation of acronyms used throughout the paper

Acronym	Explanation
BEFORES	Bayesian Evidence-based Fault Orientation and Real-time Earthquake Slip
eBEAR	Earthworm Based Earthquake Alarm Reporting
EDAS-MAS	No explanation available in the literature
EEW	Earthquake Early Warning
ElarmS	Earthquake Alarm Systems
FinDER	Finite-Fault Rupture Detector
G-FAST	Geodetic First Approximation of Size and Time
G-larmS	Geodetic Alarm System
GMM	Ground-Motion Model
GPS	Global Positioning Systems
IM	Intensity Measure
IEEWS	Istanbul Earthquake Early Warning System
JMA	Japan Meteorological Agency
KEEWS	Korean Earthquake Early Warning System
MCDM	Mutli-Criteria Decision-Making
PBEEW	Performance-Based Earthquake Early Warning
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement
PGV	Peak Ground Velocity
PLUM	Propagation of Local Undamped Motion
PRESTo	PRobabilistic and Evolutionary early warning SysTem
REGARD	Real-time GEONET Analysis system for Rapid Deformation monitoring
REWS	Rapid Early Warning System
RTPSHA	Real-Time Probabilistic Seismic Hazard Analysis
SASMEX	Sistema de Alerta Sísmica Mexicano
UrEDAS	Urgent Earthquake Detection and Alarm System

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References

Alcik, H., Ozel, O., Apaydin, N., and Erdik, M. (2009). A study on warning algorithms for Istanbul earthquake early warning system. *Geophysical Research Letters*, 36(5).

Allen, R. M., Brown, H., Hellweg, M., Khainovski, O., Lombard, P., and Neuhauser, D. (2009). Real-time earthquake detection and hazard assessment by ElarmS across California. *Geophysical Research Letters*, 36(5).

Allen, R. M. and Kanamori, H. (2001). The Potential for Earthquake Early Warning in Southern California. *Appl. Phys. Lett*, 293(9):383.

Allen, R. M., Kong, Q., and Martin-Short, R. (2019). The MyShake Platform: A Global Vision for Earthquake Early Warning. *Pure and Applied Geophysics*.

Allen, R. M. and Melgar, D. (2019). Earthquake Early Warning: Advances, Scientific Challenges, and Societal Needs. *Annual Review of Earth and Planetary Sciences*, 47.

Allen, R. M. and Ziv, A. (2011). Application of real-time GPS to earthquake early warning. *Geophysical Research Letters*, 38(16).

Allen, R. V. (1978). Automatic Earthquake Recognition and Timing From Single Traces. *Bulletin of the Seismological Society of America*, 68(5):1521–1532.

Argyroudis, S., Selva, J., Gehl, P., and Pitilakis, K. (2015). Systemic seismic risk assessment of road networks considering interactions with the built environment. *Computer-Aided Civil and Infrastructure Engineering*, 30(7):524–540.

Auclair, S., Goula, X., Jara, J. A., and Colom, Y. (2015). Feasibility and Interest in Earthquake Early Warning Systems for Areas of Moderate Seismicity: Case Study for the Pyrenees. *Pure and Applied Geophysics*, 172(9):2449–2465.

Baker, J. W. and Cornell, C. A. (2005). A vector-valued ground motion intensity measure consisting of spectral acceleration and epsilon. *Earthquake Engineering and Structural Dynamics*, 34(10):1193–1217.

Basher, R., Page, J., Woo, J., Davies, M. L., Synolakis, C. E., Farnsworth, A. F., and Steacey, S. (2006). Global early warning systems for natural hazards: Systematic and people-centred.

Behr, Y., Clinton, J. F., Cauzzi, C., Hauksson, E., Jónsdóttir, K., Marius, C. G., Pinar, A., Salichon, J., and Sokos, E. (2016). The Virtual Seismologist in SeisComP3: A New Implementation Strategy for Earthquake Early Warning Algorithms. *Seismological Research Letters*, 87(2A):363–373.

Blaser, L., Ohrnberger, M., Riggelsen, C., Babeyko, A., and Scherbaum, F. (2011). Bayesian networks for tsunami early warning. *Geophysical Journal International*, 185(3):1431–1443.

Böse, M., Felizardo, C., and Heaton, T. H. (2015). Finite-fault rupture detector (FinDer): Going real-time in californian shakealert warning system. *Seismological Research Letters*, 86(6):1692–1704.

Böse, M., Hauksson, E., Solanki, K., Kanamori, H., Wu, Y. M., and Heaton, T. H. (2009). A new trigger criterion for improved real-time performance of onsite earthquake early warning in Southern California. *Bulletin of the Seismological Society of America*, 99(2 A):897–905.

Böse, M., Heaton, T. H., and Hauksson, E. (2012). Real-time Finite Fault Rupture Detector (FinDer) for large earthquakes. *Geophysical Journal International Geophys. J. Int*, 191:803–812.

Böse, M., Ionescu, C., and Wenzel, F. (2007). Earthquake early warning for Bucharest, Romania: Novel and revised scaling relations. *Geophysical Research Letters*, 34(7).

Böse, M., Smith, D. E., Felizardo, C., Meier, M. A., Heaton, T. H., and Clinton, J. F. (2018). FinDer v.2: Improved real-time ground-motion predictions forM2-M9 with seismic finite-source characterization. *Geophysical Journal International*, 212(1):725–742.

Bossu, R., Steed, R., Roussel, F., Landès, M., Fuenzalida, A., Matrullo, E., Dupont, A., Roch, J., and Fallou, L. (2019). App earthquake detection and automatic mapping of felt area. *Seismological Research Letters*, 90(1):305–312.

Bründl, M. and Sturny, R. A. (2014). Bayesian Networks for Assessing the Reliability of a Glacier Lake Warning System in Switzerland. In *Interpraevent*.

Burton, H., Kang, H., Miles, S., Nejat, A., and Yi, Z. (2019). A framework and case study for integrating household decision-making into post-earthquake recovery models. *International Journal of Disaster Risk Reduction*, 37.

Burton, H. V., Deierlein, G., Lallemant, D., and Lin, T. (2016). Framework for Incorporating Probabilistic Building Performance in the Assessment of Community Seismic Resilience. *Journal of Structural Engineering*, 142(8).

Burton, H. V., Miles, S. B., and Kang, H. (2018). Integrating Performance-Based Engineering and Urban Simulation to Model Post-Earthquake Housing Recovery. *Earthquake Spectra*, 34(4):1763–1785.

Carranza, M., Buforn, E., Colombelli, S., and Zollo, A. (2013). Earthquake early warning for southern Iberia: A P wave threshold-based approach. *Geophysical Research Letters*, 40(17):4588–4593.

Caterino, N., Iervolino, I., Manfredi, G., and Cosenza, E. (2008). Multi-criteria decision making for seismic retrofitting of RC structures. *Journal of Earthquake Engineering*, 12(4):555–583.

Caterino, N., Iervolino, I., Manfredi, G., and Cosenza, E. (2009). Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. *Computer-Aided Civil and Infrastructure Engineering*, 24(6):432–445.

Chen, D. Y., Hsiao, N. C., and Wu, Y. M. (2015). The earthworm based earthquake alarm reporting system in Taiwan. *Bulletin of the Seismological Society of America*, 105(2):568–579.

Chung, A. I. and Allen, R. M. (2019). Optimizing Earthquake Early Warning Performance: ElarmS-3 ElarmS View project Building Response Using Ambient Noise View project. *Seismological Research Letters*, 90(2A).

Cochran, E. S. and Husker, A. L. (2019). How low should we go when warning for earthquakes? *Science*, 366(6468):957–958.

Cochran, E. S., Kohler, M. D., Given, D. D., Guiwits, S., Andrews, J., Meier, M. A., Ahmad, M., Henson, I., Hartog, R., and Smith, D. (2018). Earthquake early warning shakealert system: Testing and certification platform. *Seismological Research Letters*, 89(1):108–117.

Colombelli, S., Allen, R. M., and Zollo, A. (2013). Application of real-time GPS to earthquake early warning in subduction and strike-slip environments. *Journal of Geophysical Research: Solid Earth*, 118(7):3448–3461.

Colombelli, S., Amoroso, O., Zollo, A., and Kanamori, H. (2012a). Test of a Threshold-Based Earthquake Early-Warning Method Using Japanese Data. *Bulletin of the Seismological Society of America*, 102(3).

Colombelli, S., Caruso, A., Zollo, A., Festa, G., and Kanamori, H. (2015). A P wave-based, on-site method for earthquake early warning. *Geophysical Research Letters*, 42(5):1390–1398.

Colombelli, S. and Zollo, A. (2015). Fast determination of earthquake magnitude and fault extent from real-time P-wave recordings. *Geophysical Journal International Geophys. J. Int*, 202:1158–1163.

Colombelli, S. and Zollo, A. (2016). Rapid and reliable seismic source characterization in earthquake early warning systems: current methodologies, results, and new perspectives. *Journal of Seismology*, 20(4):1171–1186.

Colombelli, S., Zollo, A., Festa, G., and Kanamori, H. (2012b). Early magnitude and potential damage zone estimates for the great Mw 9 Tohoku-Oki earthquake. *Geophysical Research Letters*, 39(22).

Colombelli, S., Zollo, A., Festa, G., and Picozzi, . M. (2014). Evidence for a difference in rupture initiation between small and large earthquakes. *Nature Communications*.

Convertito, V., Iervolino, I., Zollo, A., and Manfredi, G. (2008). Prediction of response spectra via real-time earthquake measurements. *Soil Dynamics and Earthquake Engineering*.

Cornell, C. A. (1968). Engineering Seismic Risk Analysis. *Bulletin of the Seismological Society of America*, 58(5):1583–1606.

Cremen, G. and Baker, J. (2018). Quantifying the benefits of building instruments to FEMA P-58 rapid post-earthquake damage and loss predictions. *Engineering Structures*, 176.

Cremen, G. and Baker, J. (2019). A methodology for evaluating component-level loss predictions of the FEMA P-58 seismic performance assessment procedure. *Earthquake Spectra*, 55(1).

Cronin, P., Ryan, F., and Coughlan, M. (2008). Undertaking a literature review: a step-by-step approach What is a literature review? *British Journal of Nursing*, 17(1).

Crowell, B. W., Bock, Y., and Melgar, D. (2012). Real-time inversion of GPS data for finite fault modeling and rapid hazard assessment. *Geophysical Research Letters*, 39(9).

Crowell, B. W., Bock, Y., and Squibb, M. B. (2009). Demonstration of earthquake early warning using total displacement waveforms from real-time gps networks. *Seismological Research Letters*, 80(5):772–782.

Crowell, B. W., Bodin, P., Vidale, J. E., and Barrientos, S. E. (2018a). G-FAST Earthquake Early Warning Potential for Great Earthquakes in Chile From Boutique to Wholesale Seismic Monitoring: Performance Evaluation Tools to Prepare a Traditional Regional Seismic Network for Earthquake Early Warning View project Earthquake-early warning for research facilities View project. *Article in Seismological Research Letters*.

Crowell, B. W., Melgar, D., Bock, Y., Haase, J. S., and Geng, J. (2013). Earthquake magnitude scaling using seismogeodetic data. *Geophysical Research Letters*, 40(23):6089–6094.

Crowell, B. W., Schmidt, D. A., Bodin, P., Vidale, J. E., Baker, B., Barrientos, S., and Geng, J. (2018b). G-FAST earthquake early warning potential for great earthquakes in Chile. *Seismological Research Letters*, 89(2A):542–556.

Crowell, B. W., Schmidt, D. A., Bodin, P., Vidale, J. E., Gomberg, J., Hartog, J. R., Kress, V. C., Melbourne, T. I., Santillan, M., Minson, S. E., and Jamison, D. G. (2016). Demonstration of the cascadia G-FAST geodetic earthquake early warning system for the Nisqually, Washington, Earthquake. *Seismological Research Letters*, 87(4):930–943.

Cua, G., Fischer, M., Heaton, T., and Wiemer, S. (2009). Real-time performance of the virtual seismologist earthquake early warning algorithm in Southern California. *Seismological Research Letters*, 80(5):740–747.

Cua, G. and Heaton, T. (2007). The Virtual Seismologist (VS) method: a Bayesian approach to earthquake early warning by. *Earthquake Early Warning Systems*, pages 97–132.

Cua, G. B. (2005). *Creating the Virtual Seismologist: Developments in Ground Motion Characterization and Seismic Early Warning*. PhD thesis, California Institute of Technology.

Cuéllar, A., Suárez, G., and Espinosa-Aranda, J. M. (2017). Performance evaluation of the earthquake detection and classification algorithm 2 (tS-tP) of the seismic alert system of Mexico (SASMEX). *Bulletin of the Seismological Society of America*, 107(3):1451–1463.

David J. Wald, Vincent Quitoriano, T. H. H. and Kanamori, H. (1999). Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California. *Earthquake Spectra*, 15(3).

de Matteis, R. and Convertito, V. (2015). Near-real-time ground-motion updating for earthquake shaking prediction. *Bulletin of the Seismological Society of America*, 105(1):400–408.

Dong-Hoon, S. ., Jung-Ho, P., Heon-Cheol, C. ., Eui-Hong, H., In-Seub, L., Yun Jeong, S., and Jihwan, P. (2017). The First Stage of an Earthquake Early Warning System in South Korea. *Seismological Research Letters*, 88(6):1491–1498.

Emolo, A., Picozzi, M., Festa, G., Martino, C., Colombelli, S., Caruso, A., Elia, L., Zollo, A., Brondi, P., and Miranda, N. (2016). Earthquake early warning feasibility in the Campania region (southern Italy) and demonstration system for public school buildings. *Bulletin of Earthquake Engineering*, 14(9):2513–2529.

Erdik, M., Fahjan, Y., Ozel, O., Alcik, H., Mert, A., and Gul, M. (2003). Istanbul Earthquake Rapid Response and the Early Warning System. *Bulletin of Earthquake Engineering*, 1:157–163.

Fabozzi, S., Bilotta, E., Picozzi, M., and Zollo, A. (2018). Feasibility study of a loss-driven earthquake early warning and rapid response systems for tunnels of the Italian high-speed railway network. *Soil Dynamics and Earthquake Engineering*, 112:232–242.

FEMA (2012). Hazus ®-MH 2.1 Technical Manual. Technical report, Department of Homeland Security, Washington D.C.

Festa, G., Zollo, A., and Lancieri, M. (2008). Earthquake magnitude estimation from early radiated energy. *Geophysical Research Letters*, 35(22).

Font, Y., Kao, H., Lallemand, S., Liu, C. S., and Chiao, L. Y. (2004). Hypocentre determination offshore of eastern Taiwan using the maximum intersection method. *Geophysical Journal International*, 158(2):655–675.

Fritz, S., Scholes, R. J., Obersteiner, M., Bouma, J., and Reyers, B. (2008). A conceptual framework for assessing the benefits of a global earth observation system of systems. *IEEE Systems Journal*, 2(3):338–348.

Given, D. D., Allen, R., Baltay, A. S., Bodin, P., Cochran, E. S., Creager, K., deGroot, R. M., Gee, L. S., Hauksson, E., Heaton, T. H., Hellweg, M., Murray, J. R., Thomas, V. I., Toomey, D., and Yelin, T. S. (2018). Revised Technical Implementation Plan for the ShakeAlert System-An Earthquake Early Warning System for the West Coast of the United States. Technical report, U.S. Geological Survey.

Grapenthin, R., Johanson, I., and Allen, R. M. (2014a). The 2014 M w 6.0 Napa earthquake, California: Observations from real-time GPS-enhanced earthquake early warning. *Geophysical Research Letters*, 41(23):8269–8276.

Grapenthin, R., Johanson, I. A., and Allen, R. M. (2014b). Operational real-time GPS-enhanced earthquake early warning. *Journal of Geophysical Research: Solid Earth*, 119(10):7944–7965.

Hashima, A., Takada, Y., Fukahata, Y., and Matsu'ura, M. (2008). General expressions for internal deformation due to a moment tensor in an elastic/viscoelastic multilayered half-space. *Geophysical Journal International*, 175(3):992–1012.

Horiuchi, S., Negishi, H., Abe, K., Kamimura, A., and Fujinawa, Y. (2005). An Automatic Processing System for Broadcasting Earthquake Alarms. *Bulletin of the Seismological Society of America*, 95(2):708–718.

Hoshiba, M. (2014). Review of the Nationwide Earthquake Early Warning in Japan during Its First Five Years. In *Earthquake Hazard, Risk and Disasters*. Academic Press.

Hoshiba, M. and Aoki, S. (2015). Numerical shake prediction for earthquake early warning: Data assimilation, real-time shake mapping, and simulation of wave propagation. *Bulletin of the Seismological Society of America*, 105(3):1324–1338.

Hoshiba, M., Kamigaichi, O., Saito, M., Tsukada, S., and Hamada, N. (2008). Earthquake Early Warning Starts Nationwide in Japan. *Eos*, 89(8):73–80.

Hsiao, N.-C., Wu, Y.-M., Shin, T.-C., Zhao, L., and Teng, T.-L. (2009). Development of earthquake early warning system in Taiwan. *Geophysical Research Letters*, 36(2):L00B02.

Hsu, T. Y., Wu, R. T., and Chang, K. C. (2016). Two Novel Approaches to Reduce False Alarm Due to Non-Earthquake Events for On-Site Earthquake Early Warning System. *Computer-Aided Civil and Infrastructure Engineering*, 31(7):535–549.

Iervolino, I. (2011). Performance-based earthquake early warning. *Soil Dynamics and Earthquake Engineering*, 31(2):209–222.

Iervolino, I., Giorgio, M., and Manfredi, G. (2007). Expected loss-based alarm threshold set for earthquake early warning systems. *Earthquake Engineering and Structural Dynamics*, 36(9):1151–1168.

Ionescu, C., Bose, M., Wenzel, F., Marmureanu, A., Grigore, A., and Marmureanu, G. (2007). An early warning system for deep Vrancea (Romania) earthquakes. In *Earthquake Early Warning Systems*, pages 343–349. Springer.

James D. Goltz (2002). Introducing earthquake early warning in California - A summary of social science and public policy issues. Technical report, Governor's Office of Emergency Services, Pasadena, California.

Ji, J., Gao, Y., Lü, Q., Wu, Z., Zhang, W., and Zhang, C. (2019). China's early warning system progress.

Kamigaichi, O. (2004). JMA EARTHQUAKE EARLY WARNING. *Journal of Japan Association for Earthquake Engineering*, 4(3).

Kanamori, H. (2005). REAL-TIME SEISMOLOGY AND EARTHQUAKE DAMAGE MITIGATION. *Annu. Rev. Earth Planet. Sci*, 33:195–214.

Kawamoto, S., Hiyama, Y., Ohta, Y., and Nishimura, T. (2016). First result from the GEONET real-time analysis system (REGARD): the case of the 2016 Kumamoto earthquakes. *Earth, Planets and Space*, 68:190.

Kawamoto, S., Ohta, Y., Hiyama, Y., Todoriki, M., Nishimura, T., Furuya, T., Sato, Y., Yahagi, T., and Miyagawa, K. (2017). REGARD: A new GNSS-based real-time finite fault modeling system for GEONET. *Journal of Geophysical Research: Solid Earth*, 122(2):1324–1349.

Kodera, Y., Saitou, J., Hayashimoto, N., Adachi, S., Morimoto, M., Nishimae, Y., and Hoshiba, M. (2016). Earthquake early warning for the 2016 Kumamoto earthquake: performance evaluation of the current system and the next-generation methods of the Japan Meteorological Agency. *Earth, Planets and Space*, 68:202.

Kodera, Y., Yamada, Y., Hirano, K., Tamaribuchi, K., Adachi, S., Hayashimoto, N., Morimoto, M., Nakamura, M., and Hoshiba, M. (2018). The Propagation of Local Undamped Motion (PLUM) Method: A Simple and Robust Seismic Wavefield Estimation Approach for Earthquake Early Warning. *Bulletin of the Seismological Society of America*, 108(2).

Kong, Q., Allen, R. M., Schreier, L., and Kwon, Y. W. (2016). MyShake: A smartphone seismic network for earthquake early warning and beyond. *Science Advances*, 2(2).

Krzysztofowicz, R., Kelly, K. S., and Long, D. (1994). RELIABILITY OF FLOOD WARNING SYSTEMS. *Journal of Water Resources Planning and Management*, 120(6):120.

Kubo, T., Hisada, Y., Murakami, M., Kosuge, F., and Hamano, K. (2011). Application of an earthquake early warning system and a real-time strong motion monitoring system in emergency response in a high-rise building. *Soil Dynamics and Earthquake Engineering*.

Kumar, A., Mittal, H., Chamoli, B., Gairola, A., Jakka, R. S., and Srivastava, A. (2014). Earthquake Early Warning System for Northern India. In *15th Symposium on Earthquake Engineering*, Roorkee.

Kuyuk, H. S. and Allen, R. M. (2013). Optimal seismic network density for earthquake early warning: A case study from California. *Seismological Research Letters*, 84(6):946–954.

Kuyuk, H. S., Allen, R. M., Brown, H., Hellweg, M., Henson, I., and Neuhauser, D. (2014). Designing a network-based earthquake early warning algorithm for California: ElarmS-2. *Bulletin of the Seismological Society of America*, 104(1):162–173.

Lam, J. C., Adey, B. T., Heitzler, M., Hackl, J., Gehl, P., van Erp, N., D'Ayala, D., van Gelder, P., and Hurni, L. (2018). Stress tests for a road network using fragility functions and functional capacity loss functions. *Reliability Engineering and System Safety*, 173:78–93.

Lancieri, M. and Zollo, A. (2008). A Bayesian approach to the real-time estimation of magnitude from the early P and S wave displacement peaks. *Journal of Geophysical Research: Solid Earth*, 113(12).

Le Guenan, T., Smai, F., Loschetter, A., Auclair, S., Monfort, D., Taillefer, N., and Douglas, J. (2016). Accounting for end-user preferences in earthquake early warning systems. *Bulletin of Earthquake Engineering*, 14(1):297–319.

Li, Z., Meier, M. A., Hauksson, E., Zhan, Z., and Andrews, J. (2018). Machine Learning Seismic Wave Discrimination: Application to Earthquake Early Warning. *Geophysical Research Letters*, 45(10):4773–4779.

Liu, A. and Yamada, M. (2014). Bayesian approach for identification of multiple events in an early warning system. *Bulletin of the Seismological Society of America*, 104(3):1111–1121.

Maddaloni, G., Caterino, N., and Occhiuzzi, A. (2011). Semi-active control of the benchmark highway bridge based on seismic early warning systems. *Bulletin of Earthquake Engineering*, 9(5):1703–1715.

Manfredi, G. and Zollo, A. (2006). REAL-TIME RISK ANALYSIS FOR HYBRID EARTHQUAKE EARLY WARNING SYSTEMS. *Journal of Earthquake Engineering*, 10(6):867–885.

Mârmureanu, A., Ionescu, C., and Cioflan, C. O. (2011). Advanced real-time acquisition of the Vrancea earthquake early warning system. *Soil Dynamics and Earthquake Engineering*.

Martins, L., Silva, V., Marques, M., Crowley, H., and Delgado, R. (2016). Development and assessment of damage-to-loss models for moment-frame reinforced concrete buildings. *Earthquake Engineering and Structural Dynamics*, 45(5):797–817.

Medina-Cetina, Z. and Nadim, F. (2008). Stochastic design of an early warning system. *Georisk*, 2(4):221–234.

Meier, M. A. (2017). How "good" are real-time ground motion predictions from Earthquake Early Warning systems? *Journal of Geophysical Research: Solid Earth*, 122(7):5561–5577.

Meier, M. A., Ross, Z. E., Ramachandran, A., Balakrishna, A., Nair, S., Kundzicz, P., Li, Z., Andrews, J., Hauksson, E., and Yue, Y. (2019). Reliable Real-Time Seismic Signal/Noise Discrimination With Machine Learning. *Journal of Geophysical Research: Solid Earth*, 124(1):788–800.

Melgar, D., Bock, Y., and Crowell, B. W. (2012). Real-time centroid moment tensor determination for large earthquakes from local and regional displacement records. *Geophysical Journal International*, 188(2):703–718.

Melgar, D., Crowell, B. W., Geng, J., Allen, R. M., Bock, Y., Riquelme, S., Hill, E. M., Protti, M., and Ganas, A. (2015). Earthquake magnitude calculation without saturation from the scaling of peak ground displacement. *Geophysical Research Letters*, 42(13):5197–5205.

Minas, S. and Galasso, C. (2019). Accounting for spectral shape in simplified fragility analysis of case-study reinforced concrete frames. *Soil Dynamics and Earthquake Engineering*, 119:91–103.

Minson, S. E., Baltay, A. S., Cochran, E. S., Hanks, T. C., Page, M. T., McBride, S. K., Milner, K. R., and Meier, M. A. (2019). The Limits of Earthquake Early Warning Accuracy and Best Alerting Strategy. *Scientific Reports*, 9(1).

Minson, S. E., Meier, M.-A., Baltay, A. S., Hanks, T. C., and Cochran, E. S. (2018). The limits of earthquake early warning: Timeliness of ground motion estimates. *Science Advances*, 4(3).

Minson, S. E., Murray, J. R., Langbein, J. O., and Gomberg, J. S. (2014). Real-time inversions for finite fault slip models and rupture geometry based on high-rate GPS data. *Journal of Geophysical Research: Solid Earth*, 119(4):3201–3231.

Mitrani-Resier, J., Wu, S., and Beck, J. L. (2016). Virtual Inspector and its application to immediate pre-event and post-event earthquake loss and safety assessment of buildings. *Natural Hazards*, 81(3):1861–1878.

Nakamura, Y. and Saita, J. (2007). UrEDAS, the Earthquake Warning System: Today and Tomorrow. In *Earthquake Early Warning Systems*, chapter 13. Springer.

Nakamura, Y. and Tucker, B. (1988). *Japan's Earthquake Warning System: Should it be Imported to California?* National Emergency Training Center.

Nof, R. N. and Allen, R. M. (2016). Implementing the elarms earthquake early warning algorithm on the Israeli seismic network. *Bulletin of the Seismological Society of America*, 106(5):2332–2344.

Ogweno, L. P., Withers, M. M., and Cramer, C. H. (2019). Earthquake Early Warning Feasibility Study for the New Madrid Seismic Zone. *Seismological Research Letters*, 90(3):1377–1392.

Ohta, Y., Kobayashi, T., Tsushima, H., Miura, S., Hino, R., Takasu, T., Fujimoto, H., Iinuma, T., Tachibana, K., Demachi, T., Sato, T., Ohzono, M., and Umino, N. (2012). Quasi real-time fault model estimation for near-field tsunami forecasting based on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (M w 9.0). *Journal of Geophysical Research: Solid Earth*, 117(2).

Oth, A., Böse, M., Wenzel, F., Köhler, N., and Erdik, M. (2010). Evaluation and optimization of seismic networks and algorithms for earthquake early warning-the case of Istanbul (Turkey). *J. Geophys. Res*, 115:10311.

Pate-Cornell, M. E. (1986). Warning Systems in Risk Management. *Risk Analysis*, 6(2).

Pazos, A., Romeu, N., Lozano, L., Colom, Y., López Mesa, M., Goula, X., Jara, J. A., Cantavella, J. V., Zollo, A., Hanka, W., and Carrilho, F. (2015). A regional approach for earthquake early warning in South West Iberia: A feasibility study. *Bulletin of the Seismological Society of America*, 105(2):560–567.

Peng, C., Zhu, X., Yang, J., Xue, B., and Chen, Y. (2013). Development of an integrated onsite earthquake early warning system and test deployment in Zhaotong, China. *Computers and Geosciences*.

Peng, H., Wu, Z., Wu, Y. M., Yu, S., Zhang, D., and Huang, W. (2011). Developing a prototype earthquake early warning system in the Beijing capital region. *Seismological Research Letters*, 82(3):394–403.

Picozzi, M., Bindi, D., Pittore, M., Kieling, K., and Parolai, S. (2013). Real-time risk assessment in seismic early warning and rapid response: A feasibility study in Bishkek (Kyrgyzstan). *Journal of Seismology*, 17(2):485–505.

Picozzi, M., Elia, L., Pesaresi, D., Zollo, A., Mucciarelli, M., Gosar, A., Lenhardt, W., and Živcíc, M. (2015a). Trans-national earthquake early warning (EEW) in north-eastern Italy, Slovenia and Austria: First experience with PRESTo at the CE3RN network. *Advances in Geosciences*, 40:51–61.

Picozzi, M., Emolo, A., Martino, C., Zollo, A., Miranda, N., Verderame, G., Boxberger, T., Elia, L., Del Gaudio, S., Colombelli, S., Amoroso, O., Brondi, P., De Risi, M. T., Parolai, S., Bindi, D., Boxberger, T., Miranda, N., Buonaiuto, L., and Amelia, A. (2015b). Earthquake early warning system for schools: A feasibility study in southern Italy. *Seismological Research Letters*, 86(2A):398–412.

Picozzi, M., Zollo, A., Brondi, P., Colombelli, S., Elia, L., and Martino, C. (2015c). Exploring the feasibility of a nationwide earthquake early warning system in Italy. *Journal of Geophysical Research: Solid Earth*, 120(4):2446–2465.

Pittore, M., Bindi, D., Stankiewicz, J., Oth, A., Wieland, M., Boxberger, T., and Parolai, S. (2014). Toward a Loss-Driven Earthquake Early Warning and Rapid Response System for Kyrgyzstan (Central Asia). *Central Asia).-Seismological Research Letters*, 85:1328–1340.

Porter, K., Kennedy, R., and Bachman, R. (2007). Creating fragility functions for performance-based earthquake engineering. *Earthquake Spectra*, 23(2):471–489.

Rheinberger, C. M. (2013). Learning from the past: Statistical performance measures for avalanche warning services. *Natural Hazards*, 65(3):1519–1533.

Rosenberger, A. (2009). Arrival-Time Order Location Revisited. *Bulletin of the Seismological Society of America*, 99(3).

Ruhl, C. J., Melgar, D., Chung, A. I., Grapenthin, R., and Allen, R. M. (2019). Quantifying the Value of Real-Time Geodetic Constraints for Earthquake Early Warning Using a Global Seismic and Geodetic Data Set. *Journal of Geophysical Research: Solid Earth*, 124(4):3819–3837.

Rydelek, P. and Horiuchi, S. (2006). Is earthquake rupture deterministic? *Nature*, 442(7100).

Rydelek, P. and Pujol, J. (2004). Real-Time Seismic Warning with a Two-Station Subarray. *Bulletin of the Seismological Society of America*, 94(4):1546–1550.

Rydelek, P., Wu, C., and Horiuchi, S. (2007). Comment on "Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records" by Aldo Zollo, Maria Lancieri, and Stefan Nielsen.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences*, 1(1):83–98.

Salzano, E., Garcia Agreda, A., Di Carluccio, A., and Fabbrocino, G. (2009). Risk assessment and early warning systems for industrial facilities in seismic zones. *Reliability Engineering and System Safety*.

Satriano, C., Elia, L., Martino, C., Lancieri, M., Zollo, A., and Iannaccone, G. (2011a). PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives. *Soil Dynamics and Earthquake Engineering*, 31(2):137–153.

Satriano, C., Elia, L., Martino, C., Lancieri, M., Zollo, A., and Iannaccone, G. (2011b). PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives. *Soil Dynamics and Earthquake Engineering*.

Satriano, C., Lomax, A., and Zollo, A. (2008). Real-Time Evolutionary Earthquake Location for Seismic Early Warning. *Bulletin of the Seismological Society of America*, 98(3):1482–94.

Satriano, C., Wu, Y. M., Zollo, A., and Kanamori, H. (2011c). Earthquake early warning: Concepts, methods and physical grounds. *Soil Dynamics and Earthquake Engineering*, 31(2):106–118.

Sättele, M., Bründl, M., and Straub, D. (2015). Reliability and effectiveness of early warning systems for natural hazards: Concept and application to debris flow warning. *Reliability Engineering and System Safety*, 142:192–202.

Sättele, M., Bründl, M., and Straub, D. (2016). Quantifying the effectiveness of early warning systems for natural hazards. *Natural Hazards and Earth System Sciences*, 16(1):149–166.

Sheen, D. H., Lim, I. S., Park, J. H., and Chi, H. C. (2014). Magnitude scaling relationships using P waves for earthquake early warning in South Korea. *Geosciences Journal*, 18(1):7–12.

Shome, N., Cornell, C. A., Bazzurro, P., and Carballo, J. E. (1998). Earthquakes, Records, and Nonlinear Responses. *Earthquake Spectra*, 14(3):469–500.

Silva, V., Amo-Oduro, D., Calderon, A., Dabbeek, J., Despotaki, V., Martins, L., Rao, A., Simionato, M., Vigano, D., Yepes, C., Acevedo, A., Horspool, N., Crowley, H., Jaiswal, K., Journeay, M., and Pittore, M. (2018). Global Earthquake Model (GEM) Seismic Risk Map (version 2018.1).

Simmons, K. M. and Sutter, D. (2009). False alarms, tornado warnings, and tornado casualties. *Weather, Climate, and Society*, 1(1):38–53.

Stewart, S. W. (1977). REAL-TIME DETECTION AND LOCATION OF LOCAL SEISMIC EVENTS IN CENTRAL CALIFORNIA. *Bulletin of the Seismological Society of America*, 67(2):433–452.

Strauch, W., Talavera, E., Tenorio, V., Ramírez, J., Argüello, G., Herrera, M., Acosta, A., and Morales, A. (2018). Toward an earthquake and tsunami monitoring and early warning system for Nicaragua and central America.

Strauss, J. A. and Allen, R. M. (2016). Benefits and costs of earthquake early warning. *Seismological Research Letters*, 87(3):765–772.

Suárez, G., Novelo, D., and Mansilla, E. (2009). Performance evaluation of the seismic alert system (SAS) in Mexico City: A seismological and a social perspective. *Seismological Research Letters*, 80(5):707–716.

Thomas Heaton (1985). A model for a seismic computerized alert network. *Science*, 228(4702):987–990.

Toshikazu Odaka, b., Ashiya, K., Tsukada, y., Sato, S., Ohtake, K., and Nozaka, D. (2003). A New Method of Quickly Estimating Epicentral Distance and Magnitude from a Single Seismic Record. *Bulletin of the Seismological Society of America*, 93(1):526–532.

Tsang, L. L., Allen, R. M., and Wurman, G. (2007). Magnitude scaling relations from P-waves in southern California. *Geophysical Research Letters*, 34(19).

UNISDR (2009). 2009 UNISDR Terminology on Disaster Risk Reduction. Technical report, UN International Strategy for Disaster Risk Reduction (UNISDR), Geneva, Switzerland.

United Nations (2006). Global Survey of Early Warning Systems: An assessment of capacities, gaps and opportunities towards building a comprehensive global early warning system for all natural hazards. Technical report, United Nations.

Velazquez, O., Galasso, C., and Duffour, P. (2017). A loss-based control algorithm for magnetorheological dampers combined with earthquake early warning. In *16th World Conference on Earthquake Engineering*, Santiago.

Villagran de Leon, J. C., Pruessner, I., and Breedlove, H. (2013). *Alert and warning frameworks in the context of early warning systems a comparative review*. UNU-EHS.

Wang, J. P., Wu, Y. M., Lin, T. L., and Brant, L. (2012). The uncertainties of a Pd3-PGV onsite earthquake early warning system. *Soil Dynamics and Earthquake Engineering*.

Wang, T., Jin, X., Wei, Y., and Huang, Y. (2017). Real-time numerical shake prediction and updating for earthquake early warning. *Earthquake Science*, 30(5-6):251–267.

Wells, D. L. and Coppersmith, K. J. (1994). New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement. *Bulletin of the Seismological Society of America*, 84(4):974–1002.

Wood, H. O. and Neumann, F. (1931). MODIFIED MERCALLI INTENSITY SCALE OF 1931. *Bulletin of the Seismological Society of America*, 21:277–283.

Wright, T. J., Houlié, N., Hildyard, M., and Iwabuchi, T. (2012). Real-time, reliable magnitudes for large earthquakes from 1 Hz GPS precise point positioning: The 2011 Tohoku-Oki (Japan) earthquake. *Geophysical Research Letters*, 39(12).

Wu, S., Beck, J. L., and Heaton, T. H. (2013). ePAD: Earthquake probability-based automated decision-making framework for earthquake early warning. *Computer-Aided Civil and Infrastructure Engineering*, 28(10):737–752.

Wu, S., Cheng, M. H., Beck, J. L., and Heaton, T. H. (2016). An Engineering Application of Earthquake Early Warning: EPAD-Based Decision Framework for Elevator Control. *Journal of Structural Engineering (United States)*, 142(1).

Wu, Y. M. and Kanamori, H. (2005). Rapid assessment of damage potential of earthquakes in Taiwan from the Beginning of P waves. *Bulletin of the Seismological Society of America*, 95(3):1181–1185.

Wu, Y.-M. and Kanamori, H. (2008a). Development of an Earthquake Early Warning System Using Real-Time Strong Motion Signals. *Sensors*.

Wu, Y.-M. and Kanamori, H. (2008b). Exploring the feasibility of on-site earthquake early warning using close-in records of the 2007 Noto Hanto earthquake. *LETTER Earth Planets Space*, 60:155–160.

Wu, Y.-M. and Teng, T.-L. (2002). A Virtual Subnetwork Approach to Earthquake Early Warning. *Bulletin of the Seismological Society of America*, 92(5):2008–2018.

Wu, Y. M. and Zhao, L. (2006). Magnitude estimation using the first three seconds P-wave amplitude in earthquake early warning. *Geophysical Research Letters*, 33(16).

Wurman, G., Allen, R. M., and Lombard, P. (2007). Toward earthquake early warning in northern California. *Journal of Geophysical Research: Solid Earth*, 112(8).

Yoon, K. P. and Hwang, C.-L. (1995). *Multiple attribute decision making: an introduction.* Sage Publications.

Yutaka Nakamura (1988). On the urgent earthquake detection and alarm system (UrEDAS). In *Ninth World Conference on Earthquake Engineering*, Tokyo.

Zhang, Y., Wang, R., Zschau, J., Chen, Y. T., Parolai, S., and Dahm, T. (2014). Automatic imaging of earthquake rupture processes by iterative deconvolution and stacking of high-rate GPS and strong motion seismograms. *Journal of Geophysical Research: Solid Earth*, 119(7):5633–5650.

Zollo, A., Amoroso, O., Lancieri, M., Wu, Y.-M., and Kanamori, H. (2010). A threshold-based earthquake early warning using dense accelerometer networks. *Geophys. J. Int*, 183:963–974.

Zollo, A., Colombelli, S., and Emolo, A. (2016). An Integrated Regional and On-Site Earthquake Early Warning System for Southern Italy: Concepts, Methodologies and Performances SHEER-Shale gas Exploration and Exploitation induced Risks-An EU Horizon 2020 Project View project. In *Early Warning for Geological Disasters*, chapter 7. Springer.

Zollo, A., Festa, G., Emolo, A., and Colombelli, S. (2014). Source Characterization for Earthquake Early Warning. In *Encyclopedia of Earthquake Engineering*, pages 1–21. Springer Berlin Heidelberg.

Zollo, A., Iannaccone, G., Lancieri, M., Cantore, L., Convertito, V., Emolo, A., Festa, G., Gallovič, F., Vassallo, M., Martino, C., Satriano, C., and Gasparini, P. (2009). Earthquake early warning system in southern Italy: Methodologies and performance evaluation. *Geophys. Res. Lett*, 36:0–07.

Zollo, A., Lancieri, M., and Nielsen, S. (2006). Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records. *Geophysical Research Letters*, 33(23).

Zollo, A., Lancieri, M., and Nielsen, S. (2007). Reply to comment by P. Rydelek et al. on "Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records".