Real-Time Estimation of Earthquake Magnitude for Seismic Early Warning

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Abstract

A prototype system for earthquake early warning and rapid shake map evaluation is being developed and tested in southern Italy based on a dense, wide-dynamic seismic network (accelerometers + seismometers) under installation in the Apenninic belt region (Irpinia Seismic Network). It can be classified as a regional Earthquake Early Warning Systems consisting of a wide seismic sensor network covering a portion or the entire area which is threatened by quake's strike.

The real time magnitude estimate will take advantage from the high spatial density of the network in the source region and the wide dynamic range of installed instruments. Based on the offline analysis of high quality strong-motion data bases recorded in Italy , several methods envisaged, using different observed quantities (peak amplitude, dominant frequency, square velocity integral, . . .) to be measured on seismograms, as a function of time, either on on P and early-S wave signals.

Results from the analysis of the italian strong motion data-base, point out the possibility of using low-pass filtered displacement and velocity peak amplitudes measured in time windows lasting less than 3-4 sec after the first P or S wave arrivals. These parameters show to be robustly correlated with moment magnitude.

keywords: seismic early warning – real time - moment magnitude estimation

1 Introduction

Over the last few decades, the experimentation of seismic early-warning systems is ongoing in several active seismic areas of the world. Prototype systems have been developed and implemented in Taiwan, Japan, USA and Mexico where alert signals from dense seismograph networks in the earthquake source area are sent to nearby urban settlements.

Early warning systems (EWS), based on real-time automated analysis of ground motion measurements, may play a role in reducing regional resiliency by actions which affect exposition of built environment and lifelines. The early information, provided by EWS when the seismic waves are still propagating, can be used, to activate different types of security measures, as shut down of critical systems, stop of transportations systems and shut-off of lifelines. Depending on the network geometry and configuration around the potential seismic source and/or target area, the early warning systems can be distinguished in [*Kanamori*, 2005]:

- regional (dense seismic network deployed on the potential earthquake source area)
- on-site (single instrument or array of instruments deployed at the target site, which is distant from the earthquake source area)

For regional EEW systems the earthquake warning window begins at the time of first P-wave detection at the network deployed in the earthquake source area and . lasts a few to several tens of seconds depending on the distance between the source and the target area lasts a few to several tens of seconds depending on the distance between the source and the target area.

For on-site EEW systems the lead time is given by the difference between the recorded first P-wave motion at the target site and the late arrival of energetic amplitudes (carried by primary S-waves, secondary body waves or surface waves), also depending on the distance from the epicentral area..

In both cases, fully automated, robust and reliable real-time estimates of the main earthquake parameters (location and magnitude) must be obtained in an evolutionary, updated form, to be used for alarm purposes, or to simulate realistic shake maps, helpful for emergency preparedness and management

With about 6 million of inhabitants, and a large number of industrial plants, the Campania region, is highly exposed to the seismic risk, related to a moderate to large magnitude seismicity originated by active fault systems in the Apenninic belt. The 1980, M=6.9 Irpinia earthquake was the most recent destructive earthquake occurred in the region causing more than 3000 causalties, huge and widespread damages to buildings and infrastructure on the whole regional territory. In the frame of an ongoing project financed by the Regional Department of Civil Protection, a prototype system for earthquake early warning and rapid shake map evaluation is being developed and tested in southern Italy, based on a dense, wide-dynamic seismic network (accelerometers + seismometers) under installation in the Apenninic belt region (Irpinia Seismic Network) (Figure 1).

It can be classified as a regional Earthquake Early Warning (EEW) System consisting of a wide seismic sensor network covering a portion or the entire area which is threatened by quake's strike. A potential application of an early warning system in the Campania region based on the Irpinia network, should consider an expected time delay to the first energetic S-wave train varying between 14-20 sec at 40-60 km distance to 26-30 sec at about 80-100 km, from a shallow crustal earthquake occurring in the source region. The latter is the typical time window available for mitigating earthquake effects through early warning in the city of Naples (about 2 million of inhabitants including suburbs).

Considering a warning window ranging from tens of seconds before to hundred of seconds after an earthquake, several public infrastructures and buildings of strategic relevance (hospitals, gas pipelines, railways, railroads, ...) of the Regione Campania can be considered as potential test-sites for experimenting innovative technologies for data acquisition, processing and transmission.

Specifically concerning the real-time magnitude eatimation for EEW purposes, a number of methods have been proposed in the very recent past based on measurements of dominant frequency/period and/or peak ground motion amplitudes measured in a narrow time window (between 3 and 4 seconds) extending just after the first P-wave arrival [*Allen and Kanamori*,2003; *Wu and Teng*,2004;*Wu and Kanamori,*2005,). In particular the methods based on real-time magnitude estimation from the predominant period parameter have been validated and calibrated for regional recordings of velocity ground motion acquired by seismographic station equipped with vertical short-period seismometers..

Due to the high dynamic range, high density of the seismic network under installation in the seismogenetic area of the Campania Region, in this article we want to investigate the possibility of measuring different observed quantities on real-time signals acquired by the seismic network, including the dominant period parameter, to be used as magnitude-moment estimators. Assuming a moderate to large potential event occurring at shallow crustal depths (<20 km) underneath the seismic network, signals from the first P and S waves are expected to be detected within 1.5-3.5 sec and 2.6-6 sec respectively, after the origin time. These rather short time windows provide the opportinuti to integrate P with early-S wave information either for fast earthquake location and magnitude estimation.

In the present study we analyze the italian strong motion data-base whose data type is more closely related to what is expected to be recorded by the Campania Region EEW system either from the instrumental and seismo-tectonic point of views. Based on exixting information about the event location and moment magnitude we investigated the correlation pictures of peak strong motion parameters and dominant frequency parameter as a function of magnitude for incresing time windows initiating at first-P and S-arrivals.

This study represent a basic strong motion data analysis which should lead to the calibration, validation and testing of the algorithm to be used for real-time estimation of magnitude from the Campania Region seismic network.

2 Strong Motion Data Analysis

2.1 The Italian strong motion data base

Due to the high-density, high-dynamic range of the EEW seismic network under construction in the Campania Region, peak amplitude and dominant period information from unsaturated early P- and S-signals can be jointly used for magnitude estimation. With the aim of searching for correlation between observed parameters and magnitude we analyzed the three component records from the European strong motion data base (ESD)[*Ambraseis et al.* 2000],), relative to small to large earthquales occurred in Italy during the last three decades.

The European Strong Motion Data Base has been created as the outcome of an European Project in the framework od the 5th framework program. It is an internet searchable data-bank spanning the period 1972-1999. It collects, archives and freely distributes more then 3,000 acceleration time histories from earthquakes in Europe and adjacent areas. More than 2,000 acceleration time histories are archived in the databank as uncorrected and corrected record together with the corresponding elastic response spectra. The main source parameters (location, moment magnitude) for each recorded earthquake are also available in the data-base after validation, and if necessary re-calculation or re-estimation of seismological-, instrumental- and site-specific parameters.

The strong motion records of the Italian earthquakes occurred during 1976-1998 represent a consistent part of the data bank and have been acquired for the most by the ENEL -ENEA strong-motion network consisting of 300 accelerograph stations installed all over Italy. This network is now operated by the Italian Civil Protection Department (DPC) through the National Seismic Service (SSN). Data from other local or regional italian networks are also contained in the data bank. We refer to Ambraseys et al [2000] for a complete description of participating networks, instruments and methods for building the data bank.

Most of strong motion records for past italian earthquakes have been acquired by using Kinemetrics SMA-1 analog accelerographs. The SMA-1 are threshold-based instruments which recorded the ground motion in the form of either a photographic trace on film or paper, or a scratch trace on waxed paper. The threshold level is usually set to 0.005 to 0.01g in the vertical direction so that very frequently, they do not record the whole earthquake signal but a portion of the signal starting after the first P-wave train which is able to trigger the strong motion recording for optimal conditions of event distance and magnitude. The processing of SMA-1 data contained in ESD involve digitization, sensitivity correction, linear base-line correction and filtered in the frequency band 0.25-25 Hz using an eighth order elliptical bandpass filter [*Sunder & Connor*, 1982] after visual inspection of samples of displacements and velocity records obtained by double and single integration of acceleration time series, we deciced to apply an additional high-pass 2 poles, zero-phase shift Butterworth filter with a corner frequency of 0.075 Hz for a more suitable base-line and long-period trend correction.

With the aim of investigating the correlation between real-time estimates of strong motion quantities and magnitude we selected 116 three-component strong motion records of italian earthquakes occurred in the period 1976-1998 with moment magnitude ranging between 3.5 and 7.0 and having an epicentral distances smaller than 50 km. The maximum recording distance has been chosen according to the general observation that high frequency, direct body waves radiated from extended earthquake ruptures dominate in amplitude in the near-source distance range, i.e. at distances from the source comparable with the rupture length.(*Beroza*,1996; *Zeng et al.*, 1993; Emolo and Zollo, 2005)

Figure 2a and b illustrate the location of stations and earthquake used in this study, after the selection based on the maximum distance between source and receiver.

The istogram of number of records vs magnitude is shown in Figure 3. Most of the recorded events are in the range M 4.5-6.5, while the largest event in the catalog is the M_w=7.0, 1980, Irpinia earthquake, for which 10 records are available in the considered distance range.

2.2 Measurements of strong ground motion quantities

The early warning seismic network under construction in Regione Campania is a rather dense, high dynamic seismic array so that unsaturated P and S signals can be available few seconds after the occurrence of an event whose epicentral location is within the area covered by the network.

The first analysis we have performed was to identify and pick the first S-arrival on all the selected strong motion records. The availability of first-S wave picks allowed us to calculate the origin time of the earthquake, the expected first-P arrival and the triggering time of each record, i.e. the time to be associated to the first sample of the time series. An homogeneous crustal velocity model has been assumed with $V_p = 5.5$ and $V_s = 3.2$ Km/s. This procedure is particular relevant for SMA-1 records for which the absolute time of the trace is not available. The S signal detection is based on the analysis of variation of amplitude, frequency and horizontal polarization as a function of time along low pass filtered accelerograms. The availability of first S-wave arrival times allowed us to classify the records according to the estimated S-P times (Figure 4a). Since SMA1 accelerographs generally triggers on P-wave arrivals or later, we also discriminated and classified the records for which the triggering time was later than the estimated first P-arrival (Figure 4c). For the large majority of analyzed records the S-P times are smaller than 4 second, while less than 25 records show a $T_{fs} - T_p$ greater than 4 seconds, with T_s and T_p are respectively the estimated time of the first sample and the first P-arrival time.

This rather short S-P time interval for strong-motion stations located in the near-source window, suggests the possibility of using both the information carried out by P-waves and early S-waves for the estimation of source magnitude.

Starting from the estimated first P- and S-wave arrivals on each strong motion record we considered increasing time windows low-pass filtered records, to measure the parameters Tc *[Allen & Kanamori*,2003], peak ground displacement, velocity and acceleration (Figure 5). A zero-phase shift, 2 poles butterworth filter has been used. After a series of trials using different low-pass corner frequencies, we chose a low-pass frequency of 3 Hz, which provided the best results in terms of correlation between oobserved ground motion quantities and moment magnitude. The value of 3 Hz is the same used by *Allen and Kanamori*[2003] to retrieve the τ_c vs magnitude relationship (for M> 5.5) using the Californian earthquake data base.

The selected strong motion records from the italian earthquake data-set have been processed as described in the previous paragraph and the following strong motion quantities

- PGA_t (peak ground acceleration in a time window of duration t),
- PGV_t (peak ground velocity in a time window of duration t),
- PGD_t (peak ground displacement in a time window of duration t),
- τ_c (dominant period, according to the definition of Allen & Kanamori, 2003)

have been measured within increasing time windows, with incremental time of 1 sec, starting from the estimated first-P and first S-arrivals. The vertical and the "root squared sum" of horizontal components are used for P- and S-wave measurements, respectively.

Figure 5 illustrates an example of measurements of ground motion quantities with their relative time windows performed along the whole seismogram.

Figure 6 and 7 show the plots of the logarithm of peak ground motion quantities as a function of moment magnitude (M_w) for the considered time windows after the first-P and first-S, respectively. Figure 8 show similar plots for the dominant period parameter, calculated either for P and S wave trains.

For each time slice, the unweighted earthquake-averaged logarithmic values of the strong motion quantities are used to estimate the regression line and correlation coefficient, representing the relationship between the observed ground motion quantity and moment-magnitude.

The statistical significance of log(parameter) vs magnitude correlation has been tested by applying the “correlation test” method [*Taylor*, 1997]. Given the data number an expected significance level, the correlation test provide a threshold of the correlation coefficient above which the obtained linear relationships can be considered statistically significant with an error of type I defined by the assigned significance level. For each selected time window after the first P and first S arrival, figure 9 show the measured correlation coefficient for each measured ground motion quantity, along with the *correlaton test* threshold for the assigned significance level. Since correlation coefficients are much higher for S-wave measurements than for P-waves we chose two different significance level of the test rof the two data types, 0.5 % and 5% respectively. This means that, denoting α the test significance level, if the correlation coefficient is larger than α, the probability of making an error of type I (i.e, accepting the hypotesis of linear relationship between the log(parameter) and magnitude) is smaller than α.

For sake of clarity, the gray shaded panels in figures 6,7 and 8 correspond to data which did not pass the correlaton test.

The results of the correlation analysis between ground motion quantities and moment-magnitude show that 3Hz low-pass filtered displacement and velocity peak quantities can be considered good magnitude estimator on strong motion records, when measured on time windows 2-3 sec wide, after the initial P- and S-wave arrivals. The τ_c parameter appears rather well correlated with magnitude on S-wave records at t> 3 sec , while for P-waves an acceptable correlation is found only in the t=3 sec time window.

3 Discussion and Conclusions

Based on 116 strong motion records of italian eartquakes occurred during the period 1976-1998 and acquired at epicentral distances smaller than 50 km, we have investigated the correlation between several observed ground motion quantities and moment-magnitude within an increasing time window starting from the first-P and S- arrivals.

This work has been motivated by the need of implementing a real time procedure for magnitude estimation on the earthquake early warning system under construction for the Campania Region in southern Italy.

The regression analysis of log (parameter) vs M_w indicates that 3 Hz, low-pass filtered peak ground velocity (PGV_t) and displacement parameters (PGD_t) measured in time windows witn $t \geqslant 2$ sec after the initial P and S waves are well correlated with moment-magnitude. In particular, the parameters of the retrieved regression lines are stable for the different time windows and are associated to statistically significant correlation coefficients.

This is not the case for peak ground acceleration parameter (PGA_t) which shows rather scattered and uncorrelated log-values with moment-magnitude.

The regression analysis applied to the predominant period parameter introduced by *Allen & Kanamori*(2003) shows less stable results than PGV_t and PGD_t in the post-P wave windows (acceptable correlation is found only in the 3 sec time window), while it shows significant correlation with magnitude on S-wave strong motion records for time windows larger then 3 sec.

This analysis indicates that combining magnitude estimations obtained by different ground motion quantities measured at different stations as a function of time from the first P wave detection at a strong motion dense network could significantly improve the reliability and robustness of the earthquake size estimation in real-time procedures.

A high-density, high-dynamic network around the epicentral area of expected moderate to large earthquakes will also allow for the real-time use of early S-wave information in addition to P-waves. The ntegration of different wave type information is expected to reduce the uncertainty on the magnitude estimation as a function of time or of the number of triggered stations. The latter aspect is fundamental in case of earthquake early warning applications providing the automatic activation of security measures, as shut down of critical systems, higly exposed to the earthquake risk. The possibility to release as a funtion of time, upgraded estimations of source parameters (location and magnitude) along with their uncertainties is a basic requirement for a reliable EEW system. Infact any control system interfaced with the EEW system can use this information to predict step by step the peak ground acceleration, intensity or in general the required engineering demand parameter for the target structure and automatically evaluate the opportunity of activate the security measures based on a probabilistic estimation of false/missed alarms (*Iervolino et al.*, ,this issue).

The basic scientific question originating from this and other similar studies on the correlation between magnitude and ground motion quantities measured in the very early stage of recorded earthquake signals is about what earthquake physics and rupture mechanism can explain the paradox of being able to estimate the earthquake size using few seconds of signals from the first-P arrival, i.e. while the rupture itself is still propagating and the whole rupture process is not yet achieved. This is specially true for M>7 shallow crustal earthquakes for which the total rupture times are expected to be in the range 10-15 seconds, depending on the average rupture velocity.

In a recent review dedicated the issues of real-time seismology, *Kanamori*[2005] discusses and debates different hypotheses and observations concerning the rupture nucleation problem and possible correlation of early P-wave dominant period with magnitude.

The present analysis of near-source strong motion records primarily shows that low-frequency peak velocity and displacement parameters measured in a rather short time window (2-3 sec) after the inital P and S waves well correlate with earthquake size.

If we consider a M> 6.5 earthquake and assume a reasonable value for rupture velocity (close to the S-wave velocity), the small surface the rupture can attain during the initial 2-3 seconds cannot explain the observed correlation between peak ground motion quantities and moment-magnitude.

On the other hand one can hypothesize that peak seismic radiation from large earthquake ruptures is mainly controlled by the local slip-rate amplitude, rather than by the extension of the ruptured surface.

The observed correlation would therefore imply that a/ slip-rate amplitudes do not vary too much along the fault during the rupture propagation and b/ the average slip-rate values scales with earthquake size, i.e. large average slip-rate values are associated to large earthquakes .

The earthquake slip rate distribution on a fault is generally obtained through the kinematic inversion of strong-motion and/or teleseismic waveforms (references). Unfortunely, this is a quite difficult task, due to the bias on data between the slip duration (or rise-time), slip amplitude and rupture velocity which all concur to modify the amplitude and shape of the observed seismic radiation.

Based on the analysis of a large number of well constrained kinematic source models retrieved from different large size earthquakes *Heaton*[1990] observed that the slip duration is weakly variable on the fault surface, being generally independent on the final rupture dimension and so, of the total rupture time. According to these observations he proposed the so called "slip-pulse" model for which the slip, during rupture propagation, only affect a narrow band around the rupture front, whose width depends on the rise-time parameter. According to Heaton' model, the slip-rate amplitude is therefore mainly controlled by the local slip amplitude.

The inversion of final slip distribution on the fault from strong motion records of recent M>7 earthquakes consistently show moderate variation along the fault surface of the ratio between maximum and average slip (in the range 1.5-2.5)(Kobe,1975, M=6.9, *Sekiguchi et al.*, [1996]; Imperial Valley, M_L=6.6, *Archuleta*[1989]; Loma Prieta, 1989, M=7.1, *Beroza*[1996]; Landers,1992,M=7.3, *Cotton and Campillo*[1995]).

The moderate variation of slip-rate on the fault would therefore explain why local slip-related quantities as PGV_t and PGD_t correlate with moment-magnitude, even when measured in the initial portion of the P and S-wave windows. A change in slip amplitude of factor of two imples a moment-magnitude change of 0.3, which is largely smaller than the scatter of data used for retrieving the PGV_t,PGD_t vs M_w relationships of fig 6 and 7.

Concerning the scaling of slip-rate with earthquake size, if we still assume the "pulse" model of Heaton, this would imply a scaling of average slip with magnitude which is infact a rather well known scaling law of earthquakes inferred from a large number of geological and seismological observations (*Wells and Coppersmith*[1994], *Madariaga and Perrier*,[1998]).

In conclusion, we consider the observations and ideas developed in this work as a first, important step toward the development of a robust and reliable procedure for real-time estimation of magnitude for seismic early warning applications. Nevertheless a more refined study is planned for the next future, providing the integration of data covering uniformly the investigated magnitude range and to further explore the implications on the earthquake source physics which could derives from the confirmation of results of the present study.

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4 Figure Captions

Figure 1 Map of the EEW network and seismicity in Campania Region

Figure 2 Map of strong motion stations(a) and earthquakes(b) used in this study. The size of symbols is proportional to the event magnitude

Figure 3 Istogram of number of records per magnitude

Figure 4 (a) Istograms of number of records vs S-P times. (b) Number of events vs T_{sf}-T_p (T_{fs} and T_p are respectively the estimated time of the first sample and the first P-arrival time) relative to the selected strong motion data-set.

Figure 5 Example of strong motion record analysis. Top. Tc vs time. Bottom: Peak ground velocity vs time. Time windows increase from 1 to 5 sec after the initial P- and S-wave arrivals. The vertical and the root squared sum of horizontal components are used for P- and S-wave measurements, respectively.

Figure 6 Plot of PGA,PGV and PGD vs magnitude for each considered time window, and for P- wave records. Black dots represents event-averaged measures. Shaded panels show low-correlated data according to the statistical test(Fig.11).

Figure 7 As in Figure 6 but for time windows after the estimated first S-arrivals. .

Figure 8 Plot of τ_c vs magnitude for each considered time window after the first P- and S-wave arrivals. Black dots are event-averaged measures. Shaded panels show low-correlated data according to the statistical test (Fig.9).

Figure 9 The correlation test. The calculated correlation coefficients are plotted for each considered time window both for P and S wave measurements. The horizontal segments give the corr. coeff. threshold above which the measured value indicate a statistically significant correlation between parameter and magnitude.