FEEDFORWARD CONTROL ALGORITHMS FOR SEISMIC EARLY WARNING SYSTEMS

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Abstract

Recent impulses on the development of seismic early warning systems (SEWS) is opening the way toward innovative applications of structural control. Generally speaking, a seismic SEWS is a set of actions that can be taken from the moment when a seismic event is triggered with a significant reliability to the moment the quake strikes in a given location. This information can be very conveniently used to prevent devastating damages, by the knowledge, ahead of time, of the event that is occurring in order to decide what has to be done to the built environment to reduce the overall risk. The leading (pre-information) time can be currently estimated in the range of few seconds to dozens of seconds. Current research activities on SEWS include the anticipate estimate of peak ground acceleration and/or response spectrum. Quality and reliability of the anticipate information vary in time, being more and more accurate from the time a quake strike at the epicenter to the moment the ground motion arrives at a selected location. Possible interaction between SEWS and Structural Control is a quite recent subject still to be fully investigated. However, the possibility of knowing the incoming ground motion ahead of time opens new scenarios about the adoption of feed-forward control algorithms, so far almost neglected in the context of structural control.

Introduction

The basic elements of a Seismic Early Warning System (SEWS) are a network of seismic instruments, a station (local or central) processing the data measured by the sensors and a transmission infrastructure spreading the alarm to the end users (Heaton, 1985) to initiate personal or automatic security measures. A SEWS is considered to be attractive and moderately costly solution for risk mitigation, the attractiveness being related to the reduction of total losses produced in a large region or for very critical facilities. SEWS' may be distinguished by the configuration of their seismic network as *regional* or *site-specific* (Kanamori, 2005). Regional SEWS' consist of wide seismic networks covering a portion of the area which is likely to be the source of a catastrophic earthquake and/or the urbanized area exposed to the strike. Data recorded by the seismic instruments are further processed to retrieve information such as magnitude and/or location, faulting mechanism or spectral response. This information may be used to estimate the level of shaking in the affected area. Such processing may require significant time and in a possibly large portion of the region, called *blind zone*, the alarm may rarely be issued before the ground motion hits. Regional systems are mainly devoted to applications such as *shake maps*, which are territorial distributions of ground shaking available immediately after the event for emergency management, aiding in directing the rescue teams in zones which are expected to suffer the larger losses. In this case the system works in near-real-time as a *Rapid Response System* introducing another classification of the SEWS' by the operating time-scale. When the system can spread the alarm during the event, before the ground motion hits some sites of interest, it is operating in real-time for seismic alert purposes. In few cases only regional systems have enough time to process the data and spread the evacuation alarm. This is the case for the early warning system of Mexico City where the seismic source zone is clearly known and sufficiently far away, so that a large segments of the population can be warned by the media. In Mexico City, public schools and government agencies are directly connected with the alarm system.

While regional systems directly improve the resiliency of communities to earthquakes, site-specific SEWS' are devoted to enhance in real-time the safety margin of specific critical engineered systems as nuclear power plants, lifelines or transportation infrastructures mitigating the seismic risk by reducing the exposition of the facility by automated safety actions. The networks for specific SEWS' are much smaller than those of the regional type only covering the surroundings of the system and creating a kind of a barrier for the seismic waves. The location of the sensors depends on the lead time needed to activate the safety procedures before the arrival of the more energetic seismic phase at the site. In these Seismic Alert Systems the alarm is typically issued when the S-phase ground motion at one or more sensors exceeds a given threshold and there is no attempt to estimate the event's features. Among site specific systems, a paradigmatic example is that of the Ignalina nuclear power plant in Lithuania (Wieland *et al*., 2000). The system is designed to detect potentially damaging earthquakes and to provide an alarm before the arrival of the shear waves at the reactor. The seismic network is made of six stations that are installed at a distance of 30 km from the power plant (Figure 1). An earthquake having an epicenter outside of the fence may provoke an alarm about 4 to 8 seconds before the ground motion reaches the reactor. The required time to insert the control rods is 2 seconds, therefore the reactor can be secured before the earthquake arrives.

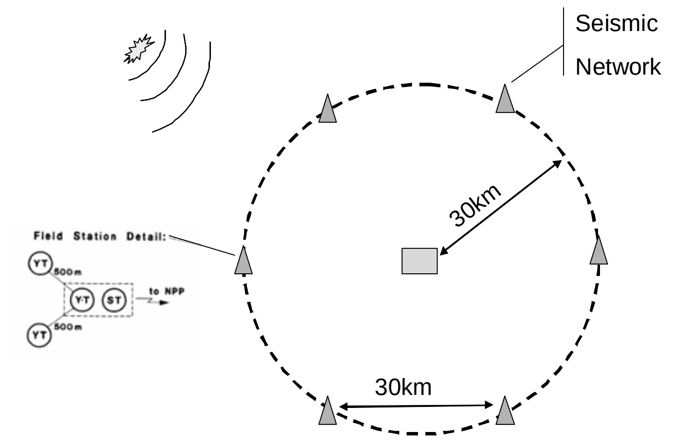

Figure 1. Ignalina EEWS schematics (Wieland et al., 2000)

Another example of specific SEWS is that protecting the Thoku Shinkanzen high speed train in Japan. The fence of seismic station is placed along the coast to protect the systems from off-shore events. A second set of instruments, located along the track, protects the trains from inland earthquakes. The system prevents the train from running on viaducts or in tunnels potentially damaged by the earthquake, which may cause catastrophic derailment.

Due to a large and rapid development of regional networks in recent years worldwide, the question of using SEWS' for structure-specific applications is raising. Even if the "early" information provided by the regional SEWS in the first seconds of the event can be still used, in case of alarm, to activate the different types of security measures described before, SEWS' predictions may also be used for the real time set-up of active or semi-active structural control. In this case the ground motion Intensity Measure (IM) of interest has to be estimated far from the sensor network's recordings and cannot be measured at the site. A scheme of the hybrid application of a regional network for structure-specific earthquake early warning is shown in Figure 2.

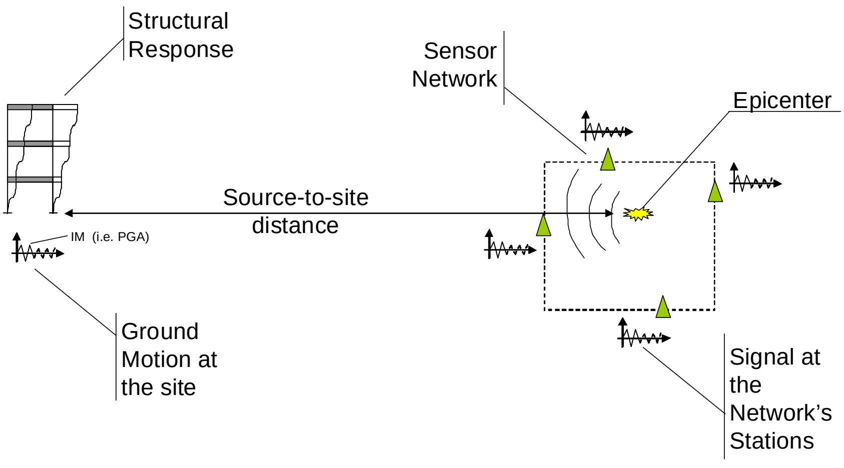

Figure 2. Regional SEWS for structure-specific applications

At the moment, feasible implementations of structural control rely substantially on semi-active devices. Technological and reliability-based issues prevent in most cases the adoption of fully active control systems (Occhiuzzi and Spizzuoco, 2005). Furthermore, in the context of seismic analysis, (Inaudi, 2000) has shown that the adoption of fully active control system leads to marginal improvement of the structural response compared to the case of optimally tuned semi-active control. So far, a semi-active control device has been typically intended as a “smart” passive device able to self-adjust its own mechanical properties in almost real time according to properly selected control algorithms, which represent the operational logics driving the device’s instantaneous behaviour on the base of the structural response and/or the external dynamic excitation. The ability of modifying the parameters of a device provides a semi-active control system the capability to produce a temporary variation of the stiffness and/or damping characteristics of the structure in order to maximize the dissipated energy and to eliminate the possibility of resonance. In practice, a semi-active control device is able to apply even large reactive control forces with a much smaller energy supply compared to fully active control. Furthermore, being typically small and compact, it can be simply installed in a structure pretty much like a passive control device and, due to its reactive behaviour, it cannot drive the hosting structure to dynamic instability, making the controlled system highly reliable. Finally, its maintenance is much easier compared to active control devices such as force actuators.

Possible interactions between SEWS and structural semi-active control has not been fully explored so far. However, it is reasonable to utilize the possibility of knowing some kind of information about the incoming ground motion in order to take a series of actions to reduce the seismic hazard. As a first step, it should be noticed that we are not thinking to a conventional open-loop control scheme: to do so, there would not need of a SEWS, being sufficient an accelerometer at the base of the structure to protect. Actual operating possibilities depend on the quality of pre-arrival information provided by the SEWS. If just an alarm signal can be issued by a SEWS, then control could mean a series of safety measures needed to shut off some relevant devices. For instance, all the elevators of a building could be forced to reach the nearest floor, to open the doors and to stop within the pre-arrival (leading) time provided by the SEWS. Similarly, the leading time could be long enough to shut down an hazardous plant or to stop a train, as discussed earlier. This is the simplest implementation of SEWS to reduce the seismic hazard, that we call “level 0”. Issues related to false and missed alarms are discussed in (Grasso et al., 2005). However, even this simple prediction scheme can be analyzed from a structural perspective. As a first example, we consider a frame structure equipped with semi-active magnetorheological (MR) dampers. These devices can be thought as the combination (in parallel) of a viscous and a friction damper, where the threshold level of the friction component can be adjusted through a magnetic field induced by a pretty weak current (Occhiuzzi et al., 2003). To avoid power outages typical during an earthquake, it is likely that such a current could be provided by a battery; however, should the battery be always on, it would last a really short time. Therefore, the control devices should be always switched off, but in selected time interval, correspondent to a seismic strike. The SEWS could therefore provide the switch on command signal within the leading time.

A different scenario can be thought of when a SEWS is able to provide, with a given leading time, some information on the intensity of the forthcoming quake. If the intensity measure is a forecast of the peak ground acceleration expected, or some statistics of its probability distribution, a series of structural-like countermeasures can be made. Similarly, should the SEWS be able to forecast the expected spectral acceleration, a semi-active control system could be set up within the leading time so as to optimize the expected structural response.

Level 1: activating a passive, but adjustable, control device

In this section we assume that an estimate of an intensity measure of the incoming ground motion, for istance the peak ground acceleration (PGA) at a selected site, is available tens of seconds before the quake strikes. To fix ideas, consider the simple continous span bridge shown in Figure 3. The bridge is seismically isolated from the substructure, but the motion of the deck and of the substructure is coupled by a set of dampers whose dynamic properties can be slowly varied. Assume that the damping constant *c(t)* can be varied so as the global damping ratio can vary from a value close to 0 to a significant fraction of the critical damping and therefore the level of seismic isolation may vary in a fairly wide range. If the damping constant is set to its lowest value c_{min}, the bridge structure is almost completely isolated from the substructure, but its overall damping ratio is low; on the contrary, when the damping constant is set to its maximum value c_{max}, the level of isolation reduces and the global damping increases. It is reasonable to assume that the value of c_{min} correspond to a design-basis earthquake (DBE) in order to achieve an optimum value of seismic isolation of the bridge compatible with the allowable horizontal displacement of the deck, whereas the value of c_{max} is designed to prevent structural collapse under the maximum credible earthquake (MCE) expected at the site. Therefore, if $\mathrm{PGA}_{\mathrm{SEWS}}$ is an estimate of the peak ground acceleration provided by the SEWS tens of seconds before the arrival of the ground motion, the corresponding value of the damping constant can be expressed as:

$$c(t) = c_{\min} + (c_{\max} - c_{\min}) \frac{\mathrm{PGA}_{\mathrm{SEWS}} - \mathrm{PGA}_{\mathrm{DBE}}}{\mathrm{PGA}_{\mathrm{MCE}} - \mathrm{PGA}_{\mathrm{DBE}}} \tag{1}$$

The algorithm of eq. (1) relates the control actions $c(t) \cdot \left(\dot{x}_{deck}(t) - \dot{x}_{pier}(t) \right)$ not only to the state of the structural system, but also to some characteristic of the external action. In this sense, eq. (1) shows an unconventional, mixed feedback-feedforward algorithm. The damping devices considered herein should be set to the desired level of *c(t)* just once before the ground motion. This, in turn, corresponds to a simple technology, which can be considered ready and available on the market.

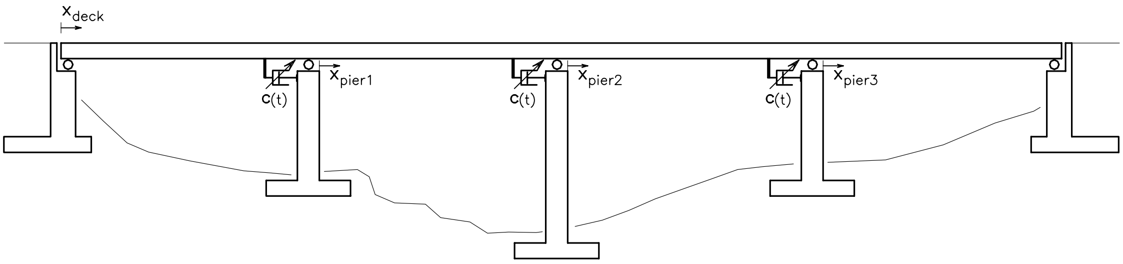

Figure 3. Isolated viaduct with variable-constant dampers

Level 2: activating a semi-active control system

Recent developments of real time seismology (Iervolino et al., 2006 a-b) are opening new possibility on the use of pre-arrival information in structural control systems. As detailed in the following, information coming from a modern early warning network can be exploited to get an estimate of the response spectra. Consider the schematic structural frame in Figure 4, whose braces are linked to the corresponding beams through MR dampers. By exploiting the properties of the MR dampers, each link can be thought as "soft" if the friction threshold f_y is kept low or "stiff" otherwise. In other words, if i_{min} and i_{max} are the extreme values of the current feeding the coils inside the dampers, by considering a simple bang-bang control approach, the structural system has 4 possible dynamic configurations, summarized in table 1.

Configuration #	f_y – upper damper	f_y – lower damper	natural period	eq. damping ratio
1	$i_{min} \Rightarrow f_{y,min}$	$i_{min} \Rightarrow f_{y,min}$	T_1	ζ_1
2	$i_{max} \Rightarrow f_{y,max}$	$i_{min} \Rightarrow f_{y,min}$	T_2	ζ_2
3	$i_{min} \Rightarrow f_{y,min}$	$i_{max} \Rightarrow f_{y,max}$	T_3	ζ_3
4	$i_{max} \Rightarrow f_{y,max}$	$i_{max} \Rightarrow f_{y,max}$	T_4	ζ_4

Table 1. Dynamic configurations

In general, it is $T_1 > T_2 > T_3 > T_4$ and $\zeta_1 < \zeta_2 < \zeta_3 < \zeta_4$. Assuming that acceleration spectra of the incoming earthquake are available ahead of time for each equivalent damping value, the selection of the more appropriate configuration can be made (Figure 5) according the following law:

$$i(t): S_a(i) = \min\{S_a(T_1,\zeta_1); S_a(T_2,\zeta_2); S_a(T_3,\zeta_3); S_a(T_4,\zeta_4)\} \qquad (2)$$

Again, the damping devices considered herein should be set to the desired level of *i(t)* just once before the ground motion. The control law expressed by eq. (2) is based on the characteristic of the external action S_a and is, therefore, of the feedforward type, although unconventional. The logical beyond this control algorithm is to make the structure "escape" the predominant frequency of the incoming ground motion. A similar concept, but based on the instantaneous structural response and therefore in a feedback control framework, was used in the first real application of structural control (Kobori et al., 1993).

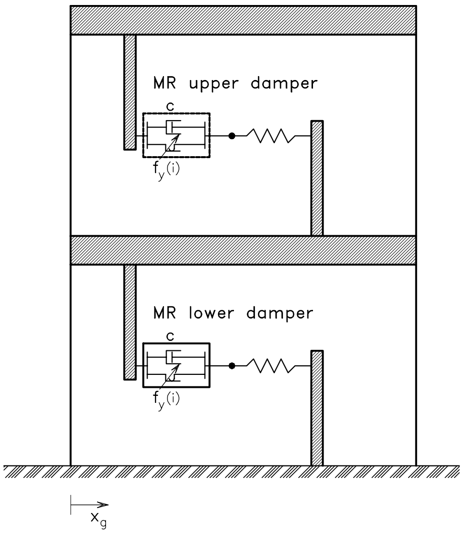

Figure 4. Frame with MR dampers

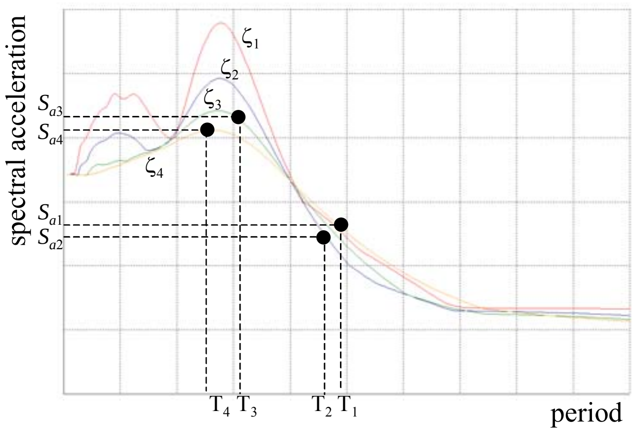

Figure 5. Control strategy

Many of such examples can be thought of. The viaduct of Figure 3, for istance, could be equipped with variable damping devices individually controllable. An appropriate model of seismic resistant structure should consider a dissipative mechanism at the base of the piers. However, according to the intensity of the upcoming strike, one or more piers could be selected to collaborate to the horizontal resistant structure. At a very high level of base motion, even the abutment could be activate in order to resist horizontal actions. Again, this selection could be implemented by a variable friction threshold of MR dampers linking the deck to the supporting elements (piers and abutment). The inclusion in the control laws of the main characteristics of the incoming ground motion, however, is heavily dependent on the quality of such estimate that real time seismology can actually provide. On one hand, therefore, the examples described represents only some first ideas on the way to utilize pre-arrival information in control algorithm, on the other this kind of algorithms can be significantly enhanced depending on the type of data coming from the SEWS and on the amount of the leading time.

Real time estimate of pseudo-acceleration/displacement spectra

Recently, seismologists have developed several methods to estimate the event's magnitude M based on limited information of the P-waves (e.g., the first few seconds of velocity recording) for real-time applications. Similarly, as briefly described in the following, the source-to-site distance R may be predicted by the sequence of network's stations triggered by the developing earthquake. Therefore, since it is possible to assume that at given instant estimates of M and R are available, the prediction of the ground motion at the site can be performed in analogy with Probabilistic Seismic Hazard Analysis (PSHA) (Cornell,1968). This results in a seismic hazard analysis conditioned (in a probabilistic sense) to the real-time information given by the SEWS. In fact, let's assume that at a given time *t* from the earthquake's origin time, the seismic network can provide estimates of M and R. These probability density functions (PDFs) are intrinsically conditioned to a vector of measures of the seismic instruments, say $\{\tau_1, \tau_2, ..., \tau_\nu\}$ where ν is the number of instruments at which the measure of interest is available. Then the PDF of M has to be indicated as $f_{M|\tau_1,\tau_2,...,\tau_\nu}(m \mid \tau_1, \tau_2, ..., \tau_\nu)$; similarly the PDF of R, which, according to the method used, only depends on the sequence of stations triggered, will be referred as $f_{R|s_1,s_2,...,s_\nu}(r \mid s_1, s_2, ..., s_\nu)$, where $\{s_1, s_2, ..., s_\nu\}$ is such sequence. Thus it is possible to compute the probabilistic distribution (or hazard curve) of a ground motion Intensity Measure (IM), for instance the Peak Ground Acceleration (PGA) at the site:

$$f_\nu(im) = \int_M \int_R f(im \mid m, r)\, f_{M|\tau_1,\tau_2,...,\tau_\nu}(m \mid \tau_1, \tau_2, ..., \tau_\nu)\, f_{R|s_1,s_2,...,s_\nu}(r \mid s_1, s_2, ..., s_\nu)\, dr\, dm \quad im \in [0, +\infty] \tag{3}$$

where the conditioned PDF in eq. (3) is given by an attenuation relationship as in the ordinary PSHA. The subscript ν indicates that the computed hazard curve refers to a particular set of triggered stations and changes when a large amount of data is included in the process. The integral given in eq. (3) requires the distribution of magnitude estimated on the basis of data provided by the network at a given time. For example, (Allen and Kanamori, 2003) provides the relationship between the magnitude of the event and the log of the predominant period $\tau_{P,max}$ (simply τ herein) of the first four seconds of the P-waves for the TriNet network. It has been assumed that the distributions of τ, conditioned to the magnitude of the event $f_{\tau|M}(\tau \mid m)$ are lognormal (Iervolino *et al*., 2006a). These distributions enable to compute the estimation of magnitude, $f_{M|\tau_1,\tau_2,...,\tau_\nu}(m \mid \tau_1, \tau_2, ..., \tau_\nu)$, in a Bayesian approach. In fact, if at a given time only one station is triggered measuring τ_1 from the first four seconds of the signal, the sought distribution of magnitude, conditioned to such measurement, $f_{M|\tau_1}(m \mid \tau_1)$, is the *posterior* of eq.(3):

$$f_{M|\tau_1}(m \mid \tau_1) = \frac{f_{\tau_1|M}(\tau_1 \mid m)\, f_M(m)}{\int_{M_{MIN}}^{M_{MAX}} f_{\tau_1|M}(\tau_1 \mid m)\, f_M(m)\, dm} \tag{4}$$

where $f_M(M)$ is the *a priori* magnitude's PDF, from the Gutenberg-Richter's recurrence relationship for the region of interest, and the denominator is the marginal distribution of τ, $f_{\tau_1}(\tau_1)$. As time flows the number of stations which may be included in the magnitude estimation increases, new data are therefore available, then the posterior distribution may be updated. At the time when a number ν of station have measured τ, eq.(4) can be generalized as:

$$f_{M|\tau_1,\tau_2,\ldots,\tau_\nu}\left(m\,|\,\tau_1,\tau_2,\ldots,\tau_\nu\right)=\frac{f_{\tau_1,\tau_2,\ldots,\tau_\nu|M}\left(\tau_1,\tau_2,\ldots,\tau_\nu\,|\,m\right)f_M\left(m\right)}{\int_{M_{MIN}}^{M_{MAX}} f_{\tau_1,\tau_2,\ldots,\tau_\nu|M}\left(\tau_1,\tau_2,\ldots,\tau_\nu\,|\,m\right)f_M\left(m\right)dm} \tag{5}$$

Assumed that, conditionally to M, the τ measurements are stochastically independent, it results $f_{\tau_1,\tau_2,\ldots,\tau_\nu|M}\left(\tau_1,\tau_2,\ldots,\tau_\nu\,|\,m\right)=\prod_{i=1}^{\nu} f_{\tau_i}\left(\tau_i\,|\,m\right)$ which is the product of known terms. Therefore eq.(5) may be rewritten as eq. (6) which, applied for all the values of $m\in\left[M_{\min},M_{\max}\right]$, gives the full magnitude PDF to be plug into the PSHA integral:

$$f_{M|\tau_1,\tau_2,\ldots,\tau_\nu}\left(m\,|\,\tau_1,\tau_2,\ldots,\tau_\nu\right)=\frac{\left(\prod_{i=1}^{\nu} f_{\tau_i}\left(\tau_i\,|\,m\right)\right)f_M\left(m\right)}{\int_{M_{MIN}}^{M_{MAX}}\left(\prod_{i=1}^{\nu} f_{\tau_i}\left(\tau_i\,|\,m\right)\right)f_M\left(m\right)dm} \tag{6}$$

Several real time approaches are available for the real-time location of hypocenter. One of the more recent is that of (Satriano *et al*, 2006) which is based on the Equal Differential-Time (EDT) formulation. It allows to assign, to each point in the region of interest, a probability of containing the hypocenter based on the triggering sequence of the seismic instruments detecting the earthquake. Consequently, the estimate of the epicentral distance, $f_{R|s_1,s_2,\ldots,s_\nu}\left(r\,|\,s_1,s_2,\ldots,s_\nu\right)$, may be retrieved by a geometrical transformation assigning, to any particular distance value, a probability which is the sum of the probabilities of all points of the grid with the same epicentral distance to the site. This method locates the seismic event within 3 seconds, and after that time the uncertainty on the location becomes negligible in respect to uncertainties in the magnitude estimation and attenuation law. Therefore the distance estimate can be considered exact in the computation of eq. (3).

In Figure 6 (left) an example of probabilistic magnitude estimation is given for an M 6 event in the Campanian region (southern Italy). Different distributions corresponds different numbers of triggered stations during the developing seismic event. In Figure 1 (right) the real time hazard (in terms of PGA) is given for an M 6 event with an epicentral location 91 km far from the considered site. Again, several curves corresponds to the triggered stations.

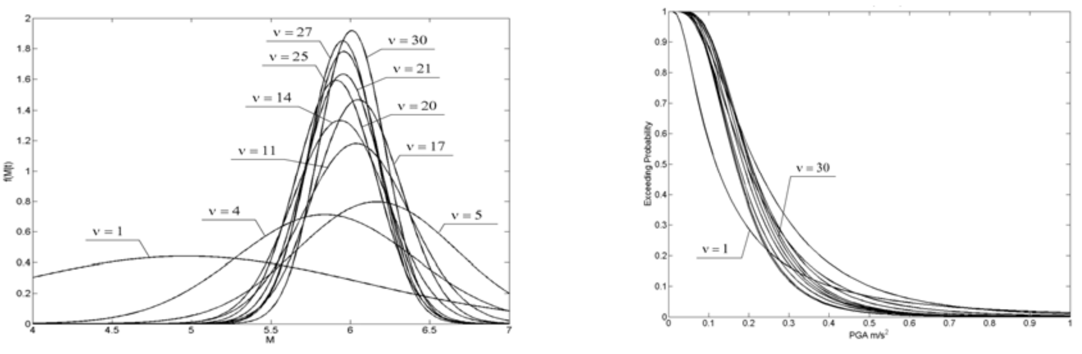

Figure 6: Magnitude distribution (left) and EWWS conditioned seismic hazard (right) as the number of stations increases for an M 6 event 91 km distant from the site

The adoption of the described methodology can be utilized also to estimate elastic spectra, also at various levels of equivalent damping. If the considered ground motion intensity measure of eq. (3) is the spectral acceleration and the attenuation law is available for such IM in a range of period of interest for the structural control, then the real-time distributions of spectral ordinates at each period may be computed by eq. (3). Once these distributions are known, by selecting the same probability level s for these hazard curve, say the level corresponding to the expected value, the expected spectrum or any other uniform hazard spectrum may be obtained.

Conclusions

Developments of real time seismology may open new scenarios in the context of structural control. The possibility of knowing some pre-arrival information about an incoming earthquake suggest to look at control algorithms from a different perspective. The paper shows some preliminary ideas about how to exploit this information, but the corresponding path is still to be followed. Control algorithms based in the external excitation belongs to the feed-forward family, even if the classical open-loop is hardly visible in this case. The efficiency of the proposed, preliminary algorithms is still to be assessed, but the feasibility of the corresponding control system, once a SEWS is set up, is straightforward.

Acknowledgements

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