12 Earthquake Early Warning and Engineering Application Prospects

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Abstract

The foreseeable future of Earthquake Early Warning Systems (EEWS) is their use as a tool for real-time seismic risk management and mitigation. The applicability potential of EEWS seems to be more related to the immediate activation of safety measures for critical systems rather than as a massive alert to the public. Evacuation of buildings requires warning times which are unlikely to be available in many urbanized areas threatened by seismic hazard, whereas the protection of critical systems may still significantly help to reduce the losses subsequent to a catastrophic event and to increase the resiliency of communities to earthquakes.

Real-Time Seismology (RTS), which consists of methods and procedures for the rapid estimation of earthquake and ensuing ground motion features based on measurements made on the first few seconds of the P-waves, is the focus of a great deal of research. In principle, it may boost the potential of regional seismic sensor networks for site-specific applications, in other words: *hybrid* EEW. Thus the next challenge of early warning and earthquake engineering is geographically distributed seismic networks for the protection of several critical systems and lifelines at the same time. The key issue is related to uncertainty in the estimation of the event's features. Therefore, the performance target and feasibility factor of such an EEWS is no longer only to maximize the warning time but also calibrate, in a full probabilistic approach, the alarm thresholds and the decisional rules in order to maximize loss reduction following the decision. This paper reviews and discusses some issues raised for hybrid EEWS in the light of performance-based earthquake engineering (PBEE) for risk reduction applications.

12.1 Specific vs. Regional EEWS

The basic elements of an Earthquake Early Warning System (EEWS) 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 end users (Heaton 1985) to initiate personal or automatic security measures. An EEWS is considered to be an attractive and moderately costly solution for risk mitigation, the attractiveness being related to the reduction in total losses produced in a large region or for very critical facilities.

EEWS may be distinguished by the configuration of their seismic network as *regional* or *site-specific* (Kanamori 2005). Regional EEWS 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 the *blind zone* (Kanamori 2005), the alarm may rarely be issued before the ground motion hits. Regional systems are mainly devoted to applications such as *shake maps* (Wald et al. 1999), which are territorial distributions of ground shaking available immediately after the event for emergency management for example, aiding in directing rescue teams in the zones which are expected to be subjected to the largest shaking and are therefore expected to suffer the highest losses. In this case the system works in near-real-time as a *Rapid Response System* (Wieland 2001) introducing another classification of the EEWS by 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 only a few cases will 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, such that 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. The seismic alert system is an EEWS for large earthquakes which have their source in the subduction zone of the Pacific coast. The seismic sensors network consists of 12 digital strong motion field stations located along a 300 km stretch of the Guerrero coast. Each field station includes a computer that continually processes seismic activity which occurs within a 100 km radial area around each station. The transmission infrastructure consists of a central radio relay station and three relay stations located between the coast and Mexico City. Two seconds are required for the information on an event to reach Mexico City. Data received are processed automatically to estimate the magnitude of the event and to issue a public alert (4.4 million people are potentially covered by the system). The system disseminates the warnings to the public and to specific entities via commercial radio stations and audio alerting mechanisms via specially designed receivers.

While regional systems directly improve the resiliency of communities to earthquakes, site-specific EEWS are devoted to enhancing in real-time the safety margin of specific critical engineered systems such as nuclear power plants, lifelines or transportation infrastructures, mitigating the seismic risk by reducing the exposure of the facility by automated safety actions. The networks for specific EEW are much smaller than those of the regional type, only covering the surroundings of the system creating like 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. Although, the knowledge of the seismic parameters is desirable it is not essential for issuing the alarm in critical facilities. This is because the latter is time-consuming and also because the uncertainty related to the propagation of seismic waves is generally moderate since the path between the network and the site is limited. Errors in the alerting decision are not considered much of an issue since the risk of system failure is always assumed to be greater than the losses related to a false alarm. Incidentally, it is worth recalling that if an EEWS is required intrinsically this means that the missed alarms are more important than the false alarms.

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 up of six stations that are installed at a distance of 30 km from the power plant (Fig. 12.1). An earthquake with an epicenter outside the fence of stations may trigger an alarm about 4 to 8 seconds before the ground motion reaches the reactor. As the required time to insert the control rods is 2 seconds, the reactor could be secured before the earthquake arrives.

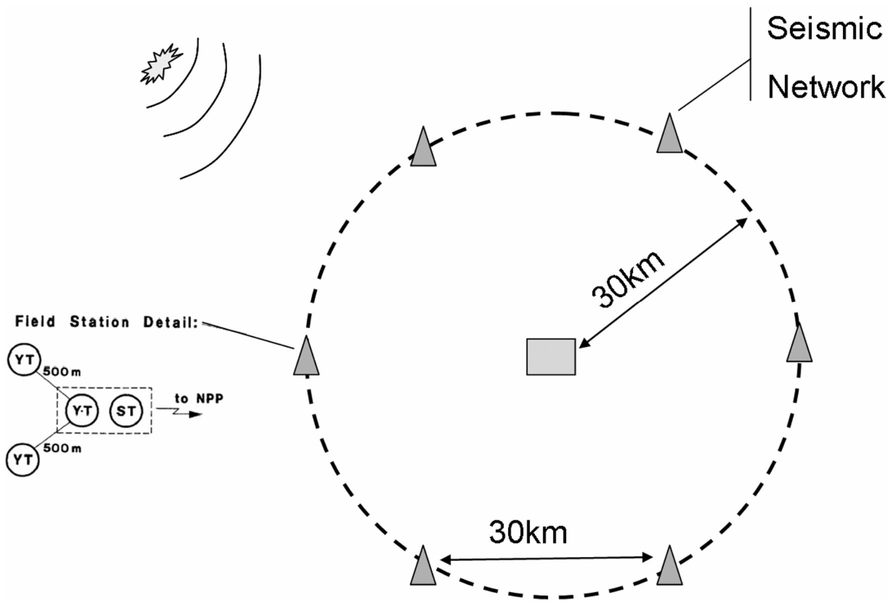

Fig. 12.1 Ignalina EEWS schematics (Wieland et al. 2000).

The alarm threshold is set at an acceleration value of 0.025 g. The decision to alert is taken by a “two out of three” logic which in statistical terms is a *partial parallel* system giving the same protection level against missed and false alarms. As discussed below, any threshold carries intrinsic false and missed alarm rates, which have to be assessed for calibration of the threshold before the seismic alert system can be used to initiate safety procedures such as control rod activation. Aspects to be considered in this respect are the acceptable losses related to both possible decisional errors. For the case of the false alarm, for example, they may be associated to the downtime of the facility.

Another example of a specific EEWS is that protecting the Thoku Shinkanzen high speed train in Japan. The fence of seismic stations is placed along the coast to protect the systems from off-shore events (Fig. 12.2). A second set of instruments, located along the track, protects the trains from inland earthquakes.

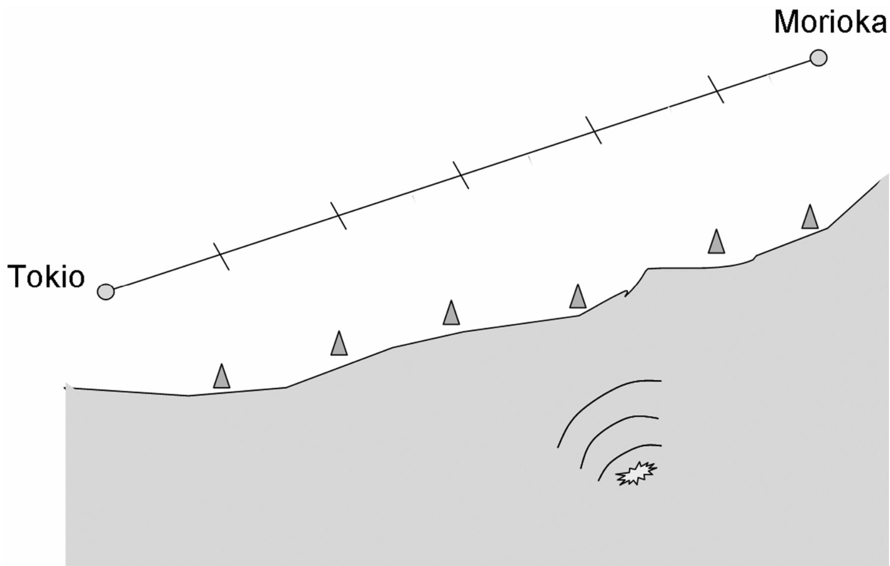

Fig. 12.2 Tohoku Shinkanzen schematics (Veneziano and Papadimitriou 1998).

The system prevents the train from running on viaducts or in tunnels potentially damaged by the earthquake, which may cause catastrophic derailment. Originally the system was designed, as for the Ignalina powerplant, to issue the alarm when the S-waves acceleration recorded at the coastal stations exceeded a threshold; the train can then be stopped and, eventually, the railway inspected for damage. The available lead time is about 20 seconds.

The EEWS for the Tokio-Morioka Shinkanzen required extensive study for its optimization (Veneziano and Papadimitriou 1998). The original system caused frequent delays and train cancellations due to false alarms. The study shows how an engineering approach can improve the performance of the system: optimizing the alarm thresholds by considering the seismic fragility of the track which may suffer damage during an earthquake could reduce the annual rate of false alarms by several orders of magnitude.

12.2 Real-Time Seismology and Hybrid Systems

State-of-the-art site-specific EEWS, working as seismic alarm systems, require a dedicated seismic network around the facility to protect, while regional networks monitoring a potential seismic source zone, due to the computational effort needed, are mostly used as rapid response systems, producing shake maps for emergency preparedness. Due to the considerable development of regional networks worldwide in recent years the question of using EEWS for site-specific applications is rising. A major step for the EEWS may be the use of regional networks to protect multiple critical systems and/or the community and then a *hybrid* use of regional and on-site warning methods (Kanamori 2005).

Early warning is the current focus of considerable research effort. Recently seismologists have developed several methods to estimate the event's magnitude (M) based on limited information of the P-waves, such as the first few seconds of velocity recording (Allen and Kanamori 2003). Similarly the location, and then source-to-site distance (R), may be estimated by the sequence of network stations triggered during the developing earthquake with negligible uncertainty after only some instants (Satriano et al. 2007, this issue). Therefore, it is possible to assume that real-time estimates of M and R are available. This may improve the traditional functioning of EEWS, giving additional warning time and reducing the blind zone. However, this information may also be used to design EEW engineering applications. For example, the M and R estimates can provide a prediction of the ground motion at the site, which can be performed in analogy with common Probabilistic Seismic Hazard Analysis (PSHA). It results in seismic hazard analysis reflecting real-time information.

Computing the seismic hazard *conditionally* (in a probabilistic sense) upon the EEWS allows it to account properly for all uncertainties related to both the estimates of the seismic networks and also the propagation of the seismic waves from the source zone to the sites of interest by an appropriate attenuation law. Consequently, the performance or even the losses related to a structure or engineered system of interest may be computed. Most such types of analyses may be optimized so as not to require significant additional processing time (Iervolino et al. 2007, this issue). A scheme of the hybrid application of a regional network for structure-specific earthquake early warning is shown in Fig. 12.3.

Employing *Real-Time Seismology* in an earthquake engineering framework means updating the knowledge of the seismic hazard from the data gathered by the network. This allows re-evaluation of the seismic risk conditioned to the measures of the network for risk management purposes. Indeed, virtually all the knowledge and decision-making approaches developed in the framework of Performance-Based Earthquake Engineering (PEER 2004) may be applied to early warning, helping to design such systems on a quantitative and consistent basis.

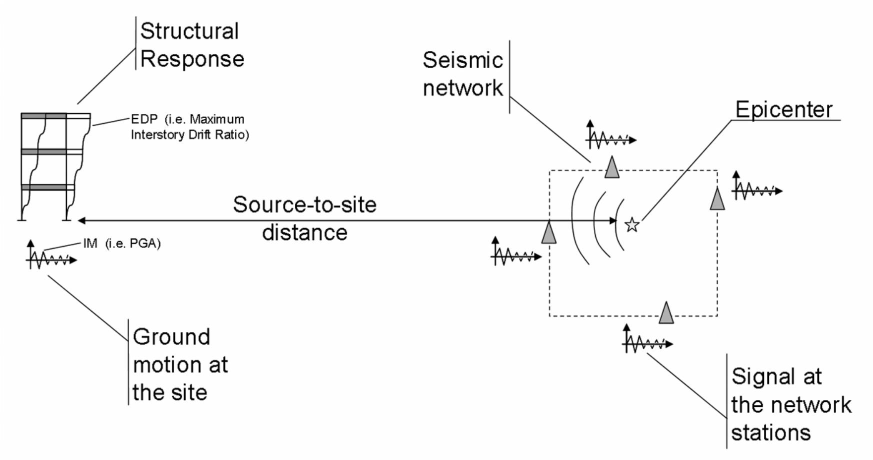

Fig. 12.3 Regional EWWS for structure-specific applications.

Obviously, the probability density function of the structural response and/or consequent expected losses, conditioned to the measures of the seismic instruments, when an event is occurring contains the highest level of information available. Real-time risk analysis in the case of hybrid EEWS, in principle, allows application of regional networks to multiple specific systems at the same time as critical systems and lifelines and possibly gives a quantitative basis for automated decision making. Contrasting with the current EEWS calibration approach, adjusting the alarm threshold by predicting the consequences is more consistent with an engineering approach to the seismic risk management.

Hybrid systems designed in this way may also overcome an intrinsic limit of existing EEWS. The latter currently help reduce the loss related to exposure (e.g. casualties in case of evacuation) but they do not help to decrease economic losses due to structural damage in buildings, infrastructures and other engineered systems. Now it seems possible to take real-time action to reduce the structural vulnerability of specific systems (to follow). For example, if real-time hazard analysis allows the response spectra at the site to be estimated before the ground motion hits, semi-active control devices, which need milliseconds to seconds to set, may change the vibrating characteristics of the structure accordingly.

12.3 Applicability Potential of EEWS

Seismic risk may be defined, whilst separating causes and effects, as the combination of: hazard, vulnerability and exposure. Risk management consists of: (1) Risk mitigation by vulnerability or exposure reduction; and (2) Emergency preparedness (Fig. 12.4). The latter is a near-real time issue; the former consists of strategies which are typically mid-term (i.e. seismic retrofit of structures and infrastructures) or long-term actions (i.e. urban land use planning or development of appropriate design standards). From the brief review given in the previous sections, it is clear that EEWS may play a role in both policies, whether in minimizing loss of lives and property or directing rescue operations (Wieland 2001).

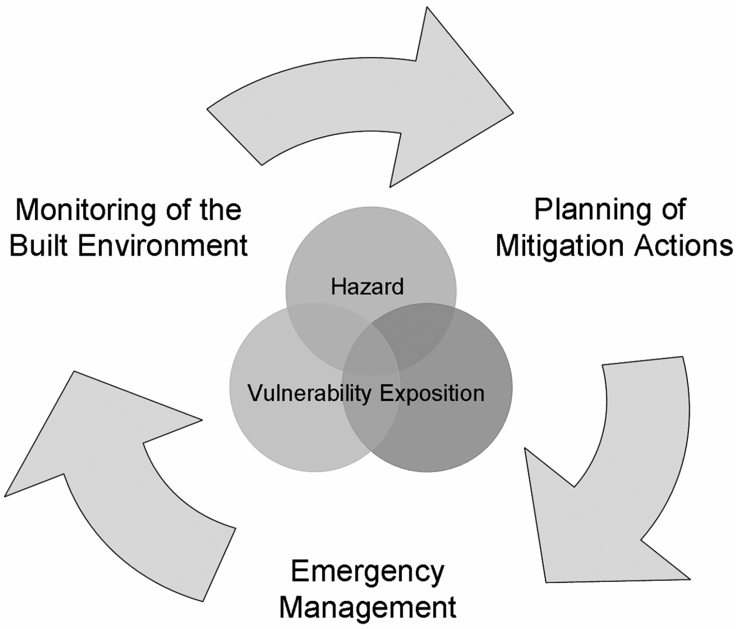

Fig. 12.4 Risk factors and risk mitigation strategies.

The traditional approach to risk mitigation by EEW deals with those facilities and processes where rapid response can contribute to the reduction in the *value* exposed. For example, operations of critical facilities and processes are stopped, trains are slowed down, traffic lights are switched to red on critical infrastructure tracks such as bridges, valves in gas and oil pipelines in hazardous industrial facilities are closed, and power plants are secured. Personal protective measures are undertaken at home and in the workplace, including getting under desks and moving away from dangerous equipment or materials. All the listed actions following an EEW reduce losses following damage (exposure) of the engineered systems but do not prevent such damage (vulnerability). However, EEWS are now capable of providing, from a few seconds to a few tens of seconds before the arrival of strong ground shaking, a prediction of the ground motion or the seismic demand on structures caused by a large earthquake in a fully probabilistic way. Therefore the question raised now is how such early warning information may be used to take real-time action for vulnerability reduction in the light of real-time seismic risk management and effective damage mitigation.

Several studies discussed, as an engineering application of EEWS, the semi-active control of structures (Grasso et al. 2005) such that the building can change its dynamic properties within a few seconds to better withstand the predicted ground motion features. A semi-active control device is a passive system which has controllable properties which may change the dynamic properties of the structures it is applied to. For example, the magneto-rheological dampers use fluids which contain micro-sized iron particles that, if a magnetic field is applied, form chains increasing the viscosity. The intensity of the magnetic field may be regulated to adjust the viscosity; this may change the structural damping. How to change the damping in the semi-active control strategies is dependent on the response spectra which reflect the hazard at the site. Then, although EEWS development for such applications will require a dedicated and reliable infrastructure that can utilize the information and operate very rapidly and automatically, integration with an EEWS in the light of real-time structural control now seems feasible since it is possible to have the expected, or the full probabilistic distribution, of the spectral ordinates in real time. On the other hand, it seems harder to integrate the EEW with active control strategies requiring the full waveform prediction to operate.

An application of semi-active control implementing some of these concepts, albeit for a traditional site-specific EEWS, is that under development by ENEA in Italy to protect Michelangelo's David displayed at the Uffizi museum (Florence). The system is made of a seismically isolated stand, which in non-earthquake conditions is tightly secured to the floor to prevent accidental movement, while in the case of an early warning alarm the locks are automatically released, isolating the statue from the floor motion.

Although interaction of EEW and semi-active control is a real-time application and quite innovative, there is another engineering application which has received considerable attention, namely integration with structural monitoring systems. Structural health monitoring is used to represent the evolution of structural conditions during service life. By contrast, performance-based earthquake engineering methodologies employ structural-response information to estimate probabilistic losses related to seismic performance. It seems quite straightforward to combine these capabilities to automatically estimate in near-real-time the probabilistic performance of an instrumented building after the hit of the strong motion (Porter et al. 2004). This application of EEW may enhance the potential of the system in the light of the rapid response to catastrophic events. Indeed, in the case of critical systems, which have to be operable for emergency management purposes such as hospitals, fire stations or even lifelines, rapid damage assessment may provide a useful picture of the situation of such important resources available during the emergency.

Finally, another possible evolution of near-real-time applications of EEW for the implementation of a rapid response system is the evolution of shake maps into *damage maps*. Research is being conducted on the fragility functions for classes of buildings, which are probabilistic distributions of structural damage conditioned to a seismic intensity measure (spectral acceleration for instance) retrieved on an analytical or empirical basis. Then, if the spatial distribution of the inventory of any category of buildings is available, it is possible to retrieve in near-real-time maps of the structural damage, which is more informative for emergency management rather than the distribution of the shaking level. This holds particularly for those countries where the building stock is very heterogeneous and structures in the same region may be old masonry constructions, reinforced concrete frames whether seismically designed or pre-code, pre-cast and even steel structures. Thid happens, for example, in Europe and in Mediterranean countries, where the shaking maps are not the best proxy for damage since the listed categories are very differently sensitive to the ground motion level.

12.4 Beyond the False Alarms: the Loss Estimation Approach to Early Warning

In hybrid EEWS the warning time is not the only parameter to optimize: estimation of event features by real time seismology is a process based on empirical relationships and carries significant uncertainty. Moreover, ground motion prediction, structural response, damage and loss relationships further introduce uncertainty in the prediction at the site. The uncertainty may lead to errors in alerting decisions. Alerting or not alerting both have a cost: in the case of not alerting the loss is associated to an earthquake striking without any countermeasure taken; in the case of alerting, preparedness interventions have a cost (social and/or economic) which may transform into loss if the actual ground motion does not require such action. As discussed by Goltz (2002), false alarms are important for alerts to the community because they can result in a reduction of credibility (the "cry wolf") with even legal liability. In automated decision making for engineering applications costly risk reduction measures must not be taken if not strictly needed. For example, the downtime of lifelines may be costly and has to be limited. It has to be kept in mind that the real-time actions featuring the larger risk mitigation potential often also require the larger warning time. Also, the cry wolf phenomenon does not have the same importance for every intervention category: its impact depends on the extent of the systems the alarm affects, and on the cost of downtime (Fig. 12.5).

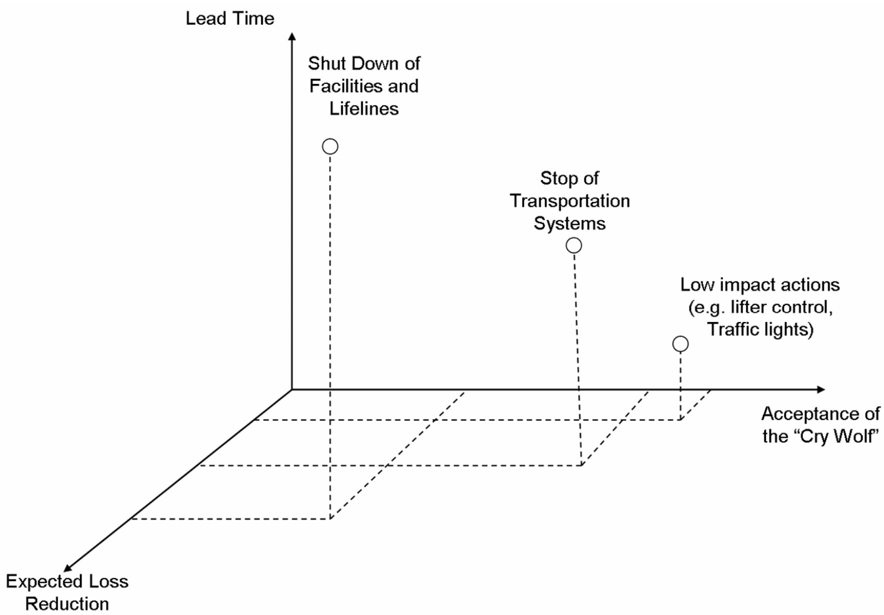

Fig. 12.5 Impact of missed/false alarms for categories of EEW applications.

Any decisional rule and alarm threshold have intrinsic false and missed alarm probabilities which constitute a trade-off. Indeed, the reduction in false alarms by adopting high warning thresholds is dangerous since it would intrinsically increase the chance of a missed alarm. These error rates may be effectively adjusted only by improving the estimation method of the parameters the decision is based on (acceleration, for example). Moreover, the false and missed alarm rates also change with time, therefore the decision of issuing the alarm may be taken in advance with some probability of errors which may change if more data are available. This is another crucial trade-off in the design of seismic early warning applications because the uncertainty only decreases when more information is collected by the seismic instruments, and then only when the available lead-time is reduced. Estimation of missed and false alarm probabilities associated to an alarm threshold is one way to understand the implications of a decision based on that threshold. Computation on an empirical basis should consist of post-event analysis of EEWS predictions and would require a large strong-motion waveform database both for the network and the site where the structure is located. Since such databases are very rarely available, especially for large earthquakes, the I and II type errors may be approximated in a simulation framework using appropriate characterizations of the uncertainties involved in the prediction.

Estimation of false missed alarm rates is a first approach to test performance of a hybrid early warning system. A more sophisticated way to calibrate design of an EEWS for automated decision making may be based on the minimization of expected losses. Let us say that two actions are possible, based on the data from the seismic instruments: (1) alarm; (2) no alarm. Consider that the decision to alert should be made if a statistic of the measures (decision variable) made by the network exceeds a given threshold. To establish which threshold should be set, the expected losses following action (1) or (2) have to be computed conditionally upon any value of the decision variable. The decision associated to the lower expected cost indicates which action should be taken for that value of the decision variable. This approach also leads to the definition of the threshold value.

For example, in the case of the methodology suggested by Allen and Kanamori (2003) the alarm threshold could be set at the predominant period of the first few seconds of the P-waves (τ_c) because this parameter is correlated to the magnitude of the event and, together with an estimation of source location, it may be used to predict ground motion, structural performance or economic losses for a system of interest. Considering no risk mitigation action, it is possible to compute the expected value of losses in the case of not issuing the alarm. Similarly, in the case of a protective action being taken, the expected losses may be computed if the alarm is issued. Estimating these two losses conditionally upon any possible value of τ_c will lead to sub-divide the space of τ_c into two regions: (1) the region where the expected losses in the case of no alarm is lower than the expected losses if any action is taken; (2) the region where there are expected losses if the alarm is issued are lower than if the alarm is not issued. The limiting value of τ_c separating these two regions is the optimal threshold to set. This approach overcomes the false and missed alarm approaches to establishing the alarm threshold since the decision always minimizes the expected loss (Iervolino et al. 2006).

12.5 Concluding Remarks: Future Prospects of Seismic Early Warning Engineering

EEWS may be regional or site-specific. Currently the regional warning method using a network of stations can provide more detailed but less rapid information about the ground motion. In contrast, the on-site method provides a more rapid warning, but the information coming from the on-site warning is limited to relatively simple parameters. A hybrid use of a regional and on-site warning may enhance the usefulness and reliability of an EEWS.

Real-Time Seismology may help to overcome some of the limitations of the EEWS developed or implemented so far which only provide warnings regarding the severity of impending earthquakes. Now information regarding the characteristics of the ground motion, at least on the response spectrum, may be given from the first few seconds of the event. The integration of real-time seismology with performance-based earthquake engineering allows the EEWS to be capable of providing the real-time predictions of those information which are useful for design of engineering applications with a quantification of the uncertainty related as a function of time.

Current EEW projects worldwide are chiefly of the regional type, since they rely on the development of national or regional seismic networks. Hence the question of using such EEWS for engineering applications has arisen. Indeed, several countries are developing regional seismic networks aiming to have RTS capabilities. For example, Japan, Turkey, Romania, Greece, United States (California) and Italy have several earthquake early warning projects (see also www.seismolab.caltech.edu/early.html). However, few of them are ready to implement a prototypal system of real-time earthquake engineering, even though all the projects set this as a major goal.

All the projects and current EEWS tend to reduce exposure of critical systems. However, it seems a natural development of EEWS to reduce damage, i.e. to mitigate seismic risk by reducing structural vulnerability. It seems possible with the application of real-time seismology as an input to semi-active structural control. To this aim the interaction of real-time engineering seismology and real-time earthquake engineering is required to develop design guidelines for engineering EEWS applications.

This is the foreseeable future of EEWS. Whether this kind of application is feasible depends on the lead time provided but also on the failure rate of the prediction. There is extensive discussion on early warning systems as to how the alarm threshold should be set. In many EEWS, typically site-specific but also regional, in some cases, this threshold is set on a ground motion level, i.e. the acceleration recorded by the seismic network. In general, the threshold should be set on the parameter the seismic stations record as a proxy for the features of the event. Although false/missed alarm rates may now be estimated, calibration of the seismic early warning system and set-up of an alarm threshold should be done in a loss estimation approach, i.e. the action to be taken to reduce the risk is that which minimizes the expected losses.

Among its requisites, EEWS for real-time engineering applications should have a network able to measure parameters of use for RTS, rapid processing capabilities and a reliable, then redundant, dedicated transmission infrastructure. In the case of real-time vulnerability reduction, as for semi-active structural control, the system to protect should also be supplied with an automatic system able to operate the devices or initiate any other security measure in case of an alarm. These kinds of applications most likely will require the development of new technologies specific to real-time earthquake engineering, which may be a critical issue for the development of hybrid EEWS.

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