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Expected loss-based alarm threshold set for earthquake early warning systems

Iunio Iervolino[1,*,†], Massimiliano Giorgio[2] and Gaetano Manfredi[1]

[1]*Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy*
[2]*Dipartimento di Ingegneria Aerospaziale e Meccanica, Seconda Università di Napoli, Via Roma 29, 81031 Aversa, Italy*

SUMMARY

Earthquake early warning systems (EEWS) seem to have potential as tools for real-time seismic risk management and mitigation. In fact, although the evacuation of buildings requires warning time not available in many urbanized areas threatened by seismic hazard, they may still be used for the real-time protection of critical facilities using automatic systems in order to reduce the losses subsequent to a catastrophic event. This is possible due to the real-time seismology, which consists of methods and procedures for the rapid estimation of earthquake features, as magnitude and location, based on measurements made on the first seconds of the P-waves. An earthquake engineering application of earthquake early warning (EEW) may be intended as a system able to issue the alarm, if some recorded parameter exceeds a given threshold, to activate risk mitigation actions before the quake strikes at a site of interest. Feasibility analysis and design of such EEWS require the assessment of the expected loss reduction due to the security action and set of the alarm threshold. In this paper a procedure to carry out these tasks in the performance-based earthquake engineering probabilistic framework is proposed. A merely illustrative example refers to a simple structure assumed to be a classroom. Structural damage and non-structural collapses are considered; the security action is to shelter occupants below the desks. The cost due to a false alarm is assumed to be related to the interruption of didactic activities. Results show how the comparison of the expected losses, for the alarm-issuance and non-issuance cases, allows setting the alarm threshold on a quantitative and consistent basis, and how it may be a tool for the design of engineering applications of EEW. Copyright © 2007 John Wiley & Sons, Ltd.

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*Correspondence to: Iunio Iervolino, Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy.
†E-mail: iunio.iervolino@unina.it

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1. INTRODUCTION

The basic elements of an earthquake early warning system (EEWS) are: a network of seismic instruments, an unit (local or central) processing the data measured by the sensors, and a transmission infrastructure spreading the alarm to the end users [1] to initiate personal or automated security measures before the ground motion hits. EEWSs are considered to be a moderately costly solution for risk mitigation, the attractiveness is related to the reduction of total losses produced in a large region or for critical facilities. EEWSs may be distinguished by the configuration of the seismic network as *regional* or *site-specific* [2]. Regional systems consist of wide seismic station networks monitoring the region which is likely to be the source of a catastrophic earthquake, and/or the urbanized area exposed to the strike. Data recorded by the instruments are processed to retrieve information such as magnitude and/or location, faulting mechanism or spectral response. Regional systems are mainly devoted to applications such as *shake maps* [3], which are territorial distributions of ground shaking available immediately after the event for emergency management. In this case the *rapid response system*, as it is called, works in near real-time [4].

Site-specific systems are devoted to enhance in real-time the safety margin of single critical engineered systems, as nuclear power plants, lifelines or transportation infrastructures by automated security actions. The networks for specific EEW are smaller than those of the regional type and only cover the surroundings of the system in order to detect arriving 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.

Because of a large development of regional networks in recent years worldwide, the question of using these EEWS' for site-specific applications is rising. A major step may be the use of regional networks for the protection of multiple critical systems, and then a *hybrid* use of regional and on-site warning methods [2]. In fact, recently seismologists have developed several procedures to estimate the event's magnitude (M) based on limited information of the P-waves in the first few seconds of the earthquake. Similarly the location, and then the source-to-site distance (R), may be retrieved by the sequence of network stations triggered. This allows the prediction of the peak ground motion at the site [5] or, furthermore, the structural performance and consequent loss before the quake strikes. (A scheme of the hybrid application of a regional network for structure-specific earthquake early warning (EEW) is shown in Figure 1.)

The loss conditioned, in a probabilistic sense, to the real-time information of the seismic network may be of help for real-time decision making aimed at rapid risk reduction as in specific EEW systems. In fact, comparing the expected losses in the case: (a) the alarm is issued (i.e. a security action is started) to those (b) if the alarm is not launched, establishes whether it is more 'convenient' to alarm, i.e. choosing which between (a) or (b) is followed by the lower loss. This gives a consistent base for design of hybrid EEWS and implicitly optimizes the false and missed alarms rates.

In the following a methodology for determining the alarm threshold based on the estimation of the expected losses is proposed. The risk is computed adapting to a real-time case the classical approach to loss estimation [6] of the performance-based earthquake engineering (PBEE) [7]. A simple and illustrative example refers to a one-storey one-bay structure assumed to be a school building, the losses are related to the injuries to the occupants of the classroom due to both structural and non-structural failures. It is supposed that the structure is provided with a device able to spread the alarm always followed by a risk mitigation action consisting of sheltering under desks.

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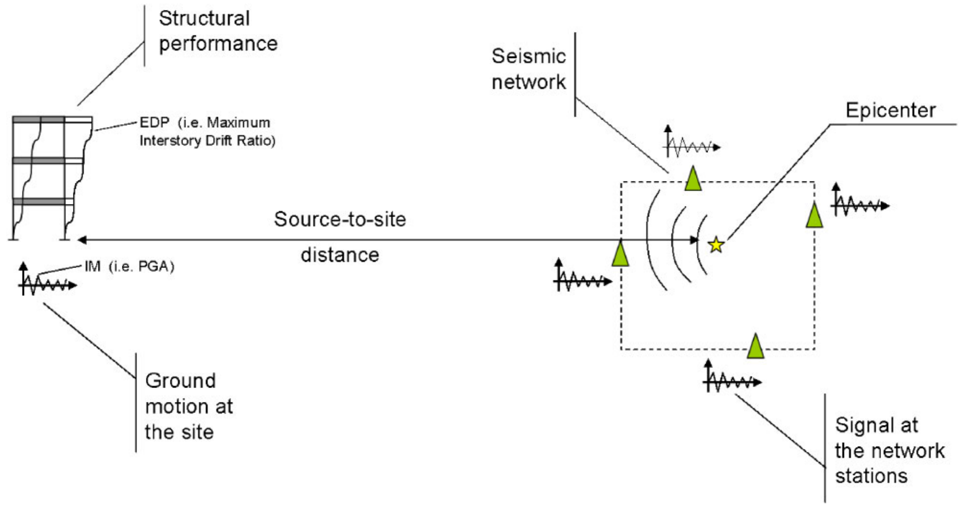

Figure 1. Regional EWWS for structure-specific applications.

2. REAL-TIME LOSS ASSESSMENT

The classical approach to the seismic risk assessment of structures aims for the estimation of the mean annual frequency of certain loss in a structure of interest. Computing such loss by the total probability theorem is the more accessible way of considering physical and economical cause-effect relationships relating the seismic hazard [8] to the risk. In fact, the expected loss may be written as

$$E[L]=\lambda \int_L \int_{\underline{\mathrm{DM}}} \int_{\underline{\mathrm{EDP}}} \int_{\underline{\mathrm{IM}}} \int_M \int_R l f(l|\underline{\mathrm{dm}})\, f(\underline{\mathrm{dm}}|\underline{\mathrm{edp}})\, f(\underline{\mathrm{edp}}|\underline{\mathrm{im}}) \times f(\underline{\mathrm{im}}|m,r)\, f(m)\, f(r)\, \mathrm{d}L\, \mathrm{d}\underline{\mathrm{DM}}\, \mathrm{d}\underline{\mathrm{EDP}}\, \mathrm{d}\underline{\mathrm{IM}}\, \mathrm{d}M\, \mathrm{d}R \tag{1}$$

where λ is the frequency of a seismic event in a certain range of magnitude; $f(l|\underline{\mathrm{dm}})$ is the probability density function (PDF) of some loss (L) given the structural and non-structural damage vector ($\underline{\mathrm{DM}}$); $f(\underline{\mathrm{dm}}|\underline{\mathrm{edp}})$ is the joint PDF of damages given the engineering demand parameters ($\underline{\mathrm{EDP}}$), proxy for the structural response; $f(\underline{\mathrm{edp}}|\underline{\mathrm{im}})$ is the joint PDF of the EDPs conditioned to a vector of ground motion intensity measures ($\underline{\mathrm{IM}}$); $f(\underline{\mathrm{im}}|m,r)$ is the distribution of the $\underline{\mathrm{IM}}$ conditioned to the characteristics of the event as magnitude and source-to-site distance, and in the case of a scalar intensity measure may be represented by a ground motion prediction relationship or *attenuation law*; finally $f(m)$ and $f(r)$ are the PDFs of M and R, respectively, reflecting the seismicity the site is subjected to. Generally $f(m)$ is retrieved by the Gutenberg–Richter's empirical relationship, and $f(r)$ depends on the level of the knowledge of the faulting system.

In the case of an EEWS, the seismic network, *via* the methods developed in the framework of real-time seismology (RTS), allows the gathering of information in the first few seconds of the event, to evaluate M and R probabilistically. In fact, for example, Allen and Kanamori [9] propose an empirical relationship between a parameter, herein called τ, measured by the P-wave signal

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and the magnitude. Similarly, in the very first seconds of the earthquake it is possible to determine, with negligible uncertainty, the hypocentral location by the sequence of stations triggered ($\underline{s}$) on the P-wave arrival. The M and R distributions conditioned to the measurements of the seismic network, $f(m|\underline{\tau})$ and $f(r|\underline{s})$, respectively, contain an higher level of information with respect to $f(m)$ and $f(r)$ because they are event-specific, and so may lead to a better estimation of the risk. Furthermore, it may be assumed that a security action, aimed at risk mitigation, is undertaken if the alarm is issued. For example, some critical systems will shut down or people in buildings may shelter themselves if the warning time is not sufficient to evacuate. More complex security measures may be related to the semi-active control of buildings [10]. The mitigation action affects the loss function if an EEWS exists and includes a security procedure in case of warning, $f^W(l|\underline{\text{dm}})$ is the loss reflecting the risk reduction; and $f^{\overline{W}}(l|\underline{\text{dm}})$ is the loss function if no alarm is issued (no security action is undertaken). Therefore, Equation (1) splits as

$$E^W[L|\underline{\tau},\underline{s}] = \int_L \int_{\underline{\text{DM}}} \int_{\underline{\text{EDP}}} \int_{\underline{\text{IM}}} l f^W(l|\underline{\text{dm}})\, f(\underline{\text{dm}}|\underline{\text{edp}})\, f(\underline{\text{edp}}|\underline{\text{im}})\, f(\underline{\text{im}}|\underline{\tau},\underline{s}) \times \mathrm{d}L\, \mathrm{d}\underline{\text{DM}}\, \mathrm{d}\underline{\text{EDP}}\, \mathrm{d}\underline{\text{IM}} \tag{2}$$

$$E^{\overline{W}}[L|\underline{\tau},\underline{s}] = \int_L \int_{\underline{\text{DM}}} \int_{\underline{\text{EDP}}} \int_{\underline{\text{IM}}} l f^{\overline{W}}(l|\underline{\text{dm}})\, f(\underline{\text{dm}}|\underline{\text{edp}})\, f(\underline{\text{edp}}|\underline{\text{im}})\, f(\underline{\text{im}}|\underline{\tau},\underline{s}) \times \mathrm{d}L\, \mathrm{d}\underline{\text{DM}}\, \mathrm{d}\underline{\text{EDP}}\, \mathrm{d}\underline{\text{IM}} \tag{3}$$

where now the expected losses in the case of warning, Equation (2), and non-warning, Equation (3), depend not only on the action following the eventual alarm, but also on the measurements made in real-time by the network (see Section 3) through the *real-time hazard*, $f(\underline{\text{im}}|\underline{\tau},\underline{s})$, expressed by the integral of Equation (4)

$$f(\underline{\text{im}}|\underline{\tau},\underline{s}) = \int_M \int_R f(\underline{\text{im}}|m,r) f(m|\underline{\tau}) f(r|\underline{s})\, \mathrm{d}M\, \mathrm{d}R \tag{4}$$

Having the capabilities to compute before the ground motion hits the site, both the expected losses in case of warning or not, means also being able to take the optimal decision—to alarm if this reduces the expected losses and to not issue any warning otherwise,

$$\text{Optimal decision:} \begin{cases} \text{to alarm if} & E^W[L|\underline{\tau},\underline{s}] \leqslant E^{\overline{W}}[L|\underline{\tau},\underline{s}] \\ \text{to not alarm if} & E^W[L|\underline{\tau},\underline{s}] > E^{\overline{W}}[L|\underline{\tau},\underline{s}] \end{cases} \tag{5}$$

In the next sections, *via* an example, it is shown how the expected loss may be computed according to Equations (2) and (3) for a structural system, and how this computation may be optimized for rapid and/or automated decision making.

3. MAGNITUDE, DISTANCE AND REAL-TIME HAZARD

The real-time hazard procedure is briefly reviewed in this section. For further details one should refer to Iervolino *et al*. [5] where it is more extensively discussed referring to the Campanian

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(southern Italy) developing seismic network, which is made of 30 seismic stations covering the Irpinian seismic zone where the 1980 earthquake occurred [11].

Allen and Kanamori [9] propose an empirical relationship between the predominant period (τ) of the first four seconds of the velocity recording of the P-waves and the magnitude of the event. Let us assume, then, that at a given instant from the earthquake origin time a number (v) of instruments of the seismic network have triggered and collected a vector $\underline{\tau}=\{\tau_1, \tau_2, \ldots, \tau_v\}$ of measurements; one measurement for each station. The distribution of magnitude conditioned on the early information, $f(m|\underline{\tau})$, may be estimated, for example, combining, *via* the Bayes theorem, historical data and real-time information:

$$f(m|\underline{\tau}) = \frac{f(\tau_1, \tau_2, \ldots, \tau_v|m)\, f(m)}{\int_{M_{\min}}^{M_{\max}} f(\tau_1, \tau_2, \ldots, \tau_v|m)\, f(m)\, \mathrm{d}M} \tag{6}$$

In the Bayesian framework [12], the distribution $f(m)$, which incorporates the information available before the experimental data are collected (e.g. before the network performs the measures, $\underline{\tau}=\{\tau_1, \tau_2, \ldots, \tau_v\}$), is called *a priori* distribution. It is a truncated exponential, Equation (7), derived by the Gutenberg–Richter recurrence relationship,

$$f(m){:}\ \begin{cases} \dfrac{\beta \mathrm{e}^{-\beta m}}{\mathrm{e}^{-\beta M_{\min}} - \mathrm{e}^{-\beta M_{\max}}} & M_{\min} \leqslant m \leqslant M_{\max} \\ 0 & m \notin [M_{\min}, M_{\max}] \end{cases} \tag{7}$$

where $\{\beta, M_{\min}, M_{\max}\}$ depend on the seismic features of the region under study and on the sensitivity of the seismic instruments in the network. The joint PDF $f(\tau_1, \tau_2, \ldots, \tau_v|m)$, which reflects all the information concerning the magnitude contained into the real-time data, is called *likelihood* function. It has been formulated assuming that, given the magnitude, the τ_i measurements are lognormal, s-independent and identically distributed random variables of parameters reported as follows:

$$\begin{aligned} \mu_{\log(\tau)} &= (M - 5.9)/7 \\ \sigma_{\log(\tau)} &= 0.16 \end{aligned} \tag{8}$$

The value of $\mu_{\log(\tau)}$ (mean of natural logs) is provided by the mentioned study by Allen and Kanamori [9], while $\sigma_{\log(\tau)}$ has been retrieved from the data reported in the same paper under the omoskedasticity hypothesis. Then the likelihood results as

$$f(\tau_1, \tau_2, \ldots, \tau_v|m) = \prod_{i=1}^{v} f(\tau_i|m) = \prod_{i=1}^{v} \frac{1}{\sqrt{2\pi}\sigma_{\log(\tau)}\tau_i} \mathrm{e}^{-\frac{1}{2}\left(\frac{\log(\tau_i)-\mu_{\log(\tau)}}{\sigma_{\log(\tau)}}\right)^2} \tag{9}$$

Due to the hypotheses listed, using the *factorization criterion* [13], it is possible to show that $\sum_{i=1}^{v} \ln(\tau_i)$ and v are jointly *sufficient* statistics for the magnitude. In fact, substituting Equations (7) and (9) into Equation (6), $f(m|\underline{\tau})$ results as in Equation (10) where it depends on data only trough $\sum_{i=1}^{v} \ln(\tau_i)$ and v. (In the following the geometric mean of the measurements' vector will be indicated as $\widehat{\tau}$.)

$$f(m|\underline{\tau}) = f\left(m \,\middle|\, \sum_{i=1}^{v} \ln(\tau_i)\right) = \frac{\mathrm{e}^{(2\mu_{\log(\tau)}\cdot(\sum_{i=1}^{v}\ln(\tau_i)) - v\mu_{\log(\tau)}^2)/2\sigma^2}\,\mathrm{e}^{-\beta m}}{\int_{M_{\min}}^{M_{\max}} \mathrm{e}^{(2\mu_{\log(\tau)}\cdot(\sum_{i=1}^{v}\ln(\tau_i)) - v\mu_{\log(\tau)}^2)/2\sigma^2}\,\mathrm{e}^{-\beta m}\, \mathrm{d}M} \tag{10}$$

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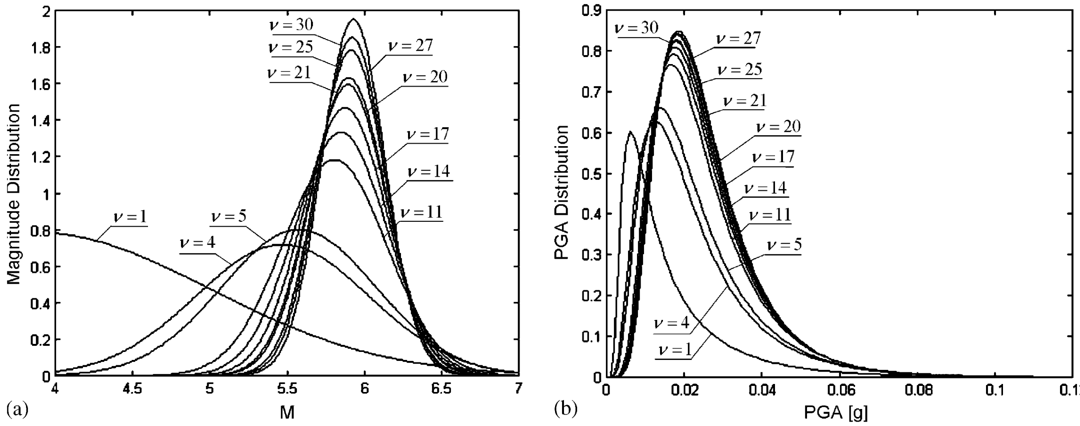

Figure 2. (a) Example of magnitude and (b) PGA distributions, for $M=6$ and $R=110\,\text{km}$, as the number of station triggered increases in the Campanian seismic network.

As just underlined, $f(m|\underline{\tau})$ depends on the number of stations triggered, v, at the time of the estimation and, consequently, on the amount of information available. As more stations are triggered, and provide measures of τ, the estimation improves. In Figure 2(a) an example of the magnitude's estimation for a M 6 event originated in the Irpinian area is shown as the number of triggered stations increases.

The real-time localization methodology considered is that of Satriano *et al.* [14] which is based on the equal differential-time (EDT) formulation. Given a geometrical configuration of a seismic network, the method allows the localization of the hypocentre based on the sequence, $\underline{s}=\{s_1, s_2, \dots, s_v\}$, of the stations triggered by the P-waves. One of the main features of the procedure is that the uncertainty related to the location become negligible within 4 s from the first trigger, at that time, according to the procedure by Allen and Kanamori [9] only the first τ measure is available. Therefore, the source to site distance may be considered deterministic during the magnitude (and loss) estimation process, and so it will be assumed in the following.

The M and R PDFs, conditioned to the real-time information, may be used to compute the distribution, or hazard curve, of a ground motion $\underline{\text{IM}}$ at the site of interest by the hazard integral of Equation (4). However, since R is virtually known, the integral may be further simplified as reported in Equation (11) where, for sake of simplicity, a scalar IM is considered. In this case $f(\text{im}|m,r)$ is given by an attenuation relationship; herein that by Sabetta and Pugliese [15].

$$f(\text{im}|\underline{\tau}) = \int_M f(\text{im}|m, R)\, f(m|\underline{\tau})\, \mathrm{d}M \tag{11}$$

It is worth noting that: (1) the λ term does not apply (or $\lambda=1$) since the event is occurring at the time of the estimation; (2) the hazard curve is also dependent on the number of stations triggered, because of the magnitude, as shown in the example of Figure 2(b) where the considered IM is the peak ground acceleration (PGA) for an M 6 event occurring within the Campanian network; the epicentral distance is 110 km which may correspond to a site in the city of Naples (Figure 3(a)).

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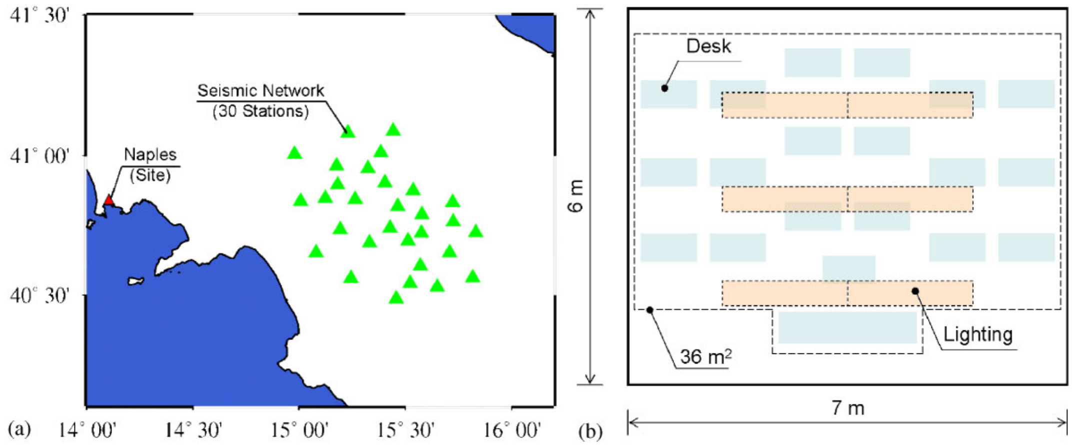

Figure 3. (a) The Campanian EEWS and (b) the plan view of the classroom considered.

4. STRUCTURAL RESPONSE, DAMAGE AND LOSS

Given the seismic hazard analysis conditioned to the EEWS information, to compute the expected losses following the event, models for seismic response as well as for structural and non-structural damages need to be established. This corresponds to have $f(\underline{\text{edp}}|\underline{\text{im}})$ and $f(\underline{\text{dm}}|\underline{\text{edp}})$ available. Since these functions are strictly dependent on the specific building which is under analysis, as for illustrative application, herein a school building is considered. It is assumed that the occupants are exposed to: (i) the risk of structural collapse; (ii) possible injury due to the collapse of some non-structural elements. The real-time action to reduce the seismic risk, initiated after the alarm *via* a light/ringer device activated by the EEWS, is the sheltering of individuals under the desks. For the sake of simplicity, the building is modelled as a one storey/bay structure hosting a single classroom. It is supposed to be made of two frames each of those modelled to behave as a $T = 0.6$ s single degree of freedom (SDOF) with an elastic-perfectly-plastic behaviour and a yielding moment of 300 kNm. According to the Italian code for school constructions [16] the class may contain 19 students and one teacher on a area of $42\,\text{m}^2$ (Figure 3(b)). The non-structural components considered to possibly cause injury are the six lamps of the lighting system.

4.1. Engineering demand parameters and structural/non-structural damages

The EDP parameter related structural collapse is considered to be the interstorey drift ratio (IDR) as a function of the first mode spectral acceleration (Sa) ($T = 0.6$ s). To this aim an incremental dynamic analysis (IDA) [17] has been performed. The seismic input is made of a set of 20 records identified as $I_D 14$ in Iervolino *et al*. [18]. Results of IDA are given in Figure 4(a).

Since the considered non-structural elements are sensitive to the inertia forces they are subjected to, the appropriate EDP is the peak floor acceleration (PFA) at the roof of the structure. Then, the (IDA) has been also retrieved, with the same record set as an input, for the PFA as a function of the PGA (Figure 4(b)) because Sa may be *insufficient* to PFA [19], e.g. PFA may not be conditionally independent of event's magnitude and distance given Sa.

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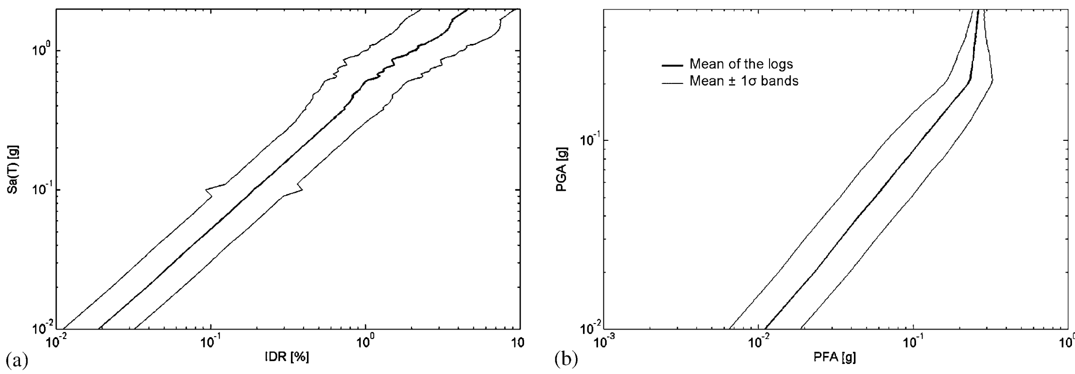

Figure 4. Incremental dynamic analysis results in terms of: (a) IDR and (b) PFA.

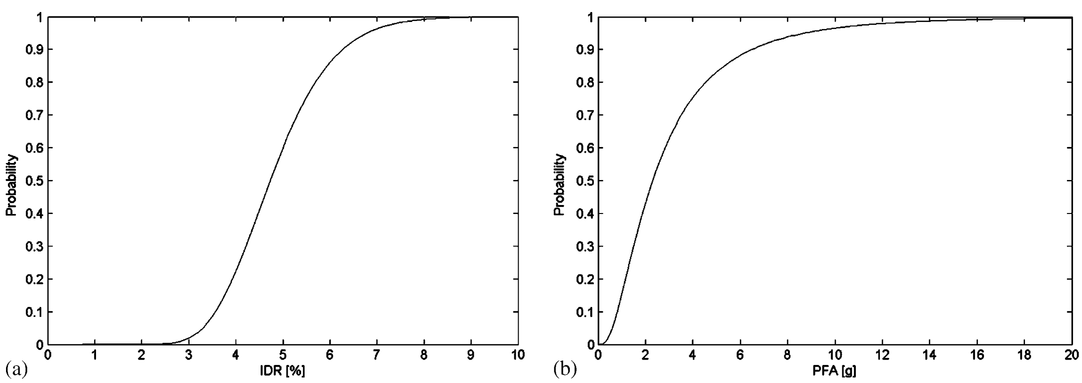

Figure 5. (a) Probability of structural collapse as a function of IDR and (b) probability of non-structural collapse as a function of PFA [20].

The structural damage probability refers to the collapse of at least one of the four columns of the two frames. The global failure probability has been obtained as $1-[1-P_{\mathrm{col}}(\mathrm{IDR})]^4$, where $P_{\mathrm{col}}(\mathrm{IDR})$ is the fragility of a single column [20]. The resulting fragility has a lognormal distribution with parameters: median IDR = 4.73%, $\sigma_{\ln(\mathrm{IDR})}=0.22$ and it is given in Figure 5(a). The failure of the ceiling panel where the lighting is anchored (one lamp per panel) has been considered as a proxy for the collapse of the lighting. Moreover, the failures of these elements are considered s-independent (i.e. in the case of collapse of one panel the failure probability of the others does not change). The fragility of a panel is lognormal [20] of parameters: median PFA = 2.3 g; $\sigma_{\ln\mathrm{PFA}}=0.81$ as reported in Figure 5(b).

4.2. Loss functions

The possible events assumed to cause a loss are: (1) structural collapse; (2) injury after collapse of at least one of the six components of the lighting system (which excludes structural collapse); (3) neither the structure nor the lighting system collapse but the warning is issued (false alarm) and

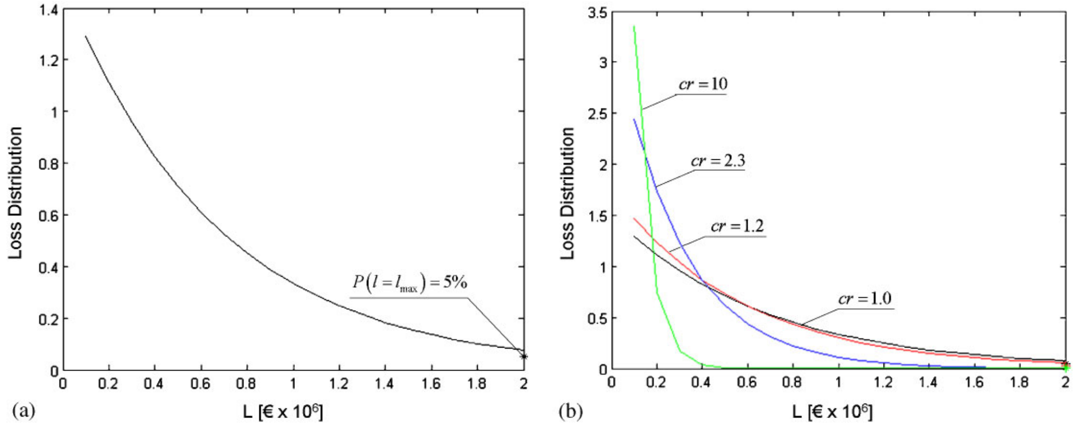

Figure 6. Loss function: (a) in the case of no warning and (b) in the case of warning and following security measure for several reduction coefficient (cr) values.

then the loss following the alarm, or downtime, occurs. In the case of event (1), it is assumed that nobody would survive the structural collapse, and therefore the loss is independent of the decision to alarm or not and it is given by the loss of life of all the occupants. To quantify the latter, which is the maximum loss possible, it is conventionally assumed $l_{max} = 2 \times 10^6$ euros per person, although some authors prefer to refer to the *cost per life saved* [21], which avoids the delicate question of evaluating the monetary value of a human life. For an event of type (2), a loss follows the collapse of the lighting system and consequent injury. To model different grades of injury the loss function is, arbitrarily, defined as an exponential in $[0, l_{max}[$, plus a concentrated probability mass at the maximum value of the loss. This is given in Equation (12) where h indicates the event of an occupant hit by the lighting. The θ value has been chosen in a way that 5% of the area below is associated to the maximum value of the loss, which corresponds to the death of the hit person (Figure 6(a)).

$$f^{\overline{W}}(l|h) = \begin{cases} \theta e^{-\theta l} & l \in [0, l_{max}[\\ e^{-\theta l} & l = l_{max} \\ 0 & l \notin [0, l_{max}] \end{cases} \tag{12}$$

To quantify the reduction of expected loss due to the security action following the possible alarm it is assumed that the effect of the EEWS is summarized by a reduction coefficient (cr), Equation (13). Figure 6(b) shows the loss function for possible cr values.

$$f^{W}(l|h) = \begin{cases} \theta \mathrm{cr} e^{-\theta \mathrm{cr} l} & l \in [0, l_{max}[\\ e^{-\theta \mathrm{cr} l} & l = l_{max} \\ 0 & l \notin [0, l_{max}] \end{cases} \tag{13}$$

In the case (3) when neither the structure nor the non-structural elements collapse, the loss due to the seismic risk is virtually zero; however, if the warning is issued by the EEWS there is a cost associated to the security action. The cost following the alarm (ca) reflects the operational costs of the mitigation action and/or the cost of the downtime because of the alarm. For example, in the case of the EEWS for a power plant, a transportation system, or a lifeline, the shut down after a warning has significant direct and indirect costs also if a damaging ground motion did not follow the alarm; this is known as the *cry wolf* issue. In the example the loss following the action is supposed to be related to the disruption of school ordinary activities: it is conventionally assumed that a false alarm causes an interruption, with a cost $\mathrm{ca} = 5 \times 10^2$ euros per class. In the example it is also assumed that the security action is always undertaken after the alarm, which means that the cost of the action occurs every time the warning is issued. Furthermore, it is assumed that the security action is taken (e.g. the cost is sustained) even if the alarm is not issued but the ground motion is felt anyway in the building.

5. EXPECTED LOSS

The expected loss may be computed *via* the total expectation theorem, Equation (14), which may be derived by the total probability theorem.

$$E[L|\hat{\tau}] = E[L|\mathrm{DS}, \hat{\tau}]P(\mathrm{DS}|\hat{\tau}) + E[L|\mathrm{DNS}, \overline{\mathrm{DS}}, \hat{\tau}]P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau}) + E[L|\overline{\mathrm{DNS}}, \overline{\mathrm{DS}}, \hat{\tau}]P(\overline{\mathrm{DNS}}, \overline{\mathrm{DS}}|\hat{\tau}) \tag{14}$$

In Equation (14) DS indicates the structural damage (e.g. collapse of, at least, one columns of the structure), DNS is the collapse of at least one of the elements in the lighting system, while $\overline{\mathrm{DS}}$ and $\overline{\mathrm{DNS}}$ are their complementary (negated) events. $E[L|\mathrm{DS}, \hat{\tau}]$, $E[L|\mathrm{DNS}, \overline{\mathrm{DS}}, \hat{\tau}]$, and $E[L|\overline{\mathrm{DNS}}, \overline{\mathrm{DS}}, \hat{\tau}]$ are the expected losses conditioned to the occurrence of events (1), (2) or (3), described in Section 4.2, respectively. The dependence on $\hat{\tau}$ means that the assessment is performed on the basis of the measurements of the seismic network. In what follows Equation (14) will be synthesized as Equations (15) and (16) for the cases of alarm and no warning, respectively. Moreover, the total loss will be computed only considering those costs affecting the threshold and neglecting the others.

$$E^{W}[L|\hat{\tau}] = E^{W}_{\mathrm{DS}}[L|\hat{\tau}] + E^{W}_{\mathrm{DNS},\overline{\mathrm{DS}}}[L|\hat{\tau}] + E^{W}_{\overline{\mathrm{DNS}},\overline{\mathrm{DS}}}[L|\hat{\tau}] \tag{15}$$

$$E^{\overline{W}}[L|\hat{\tau}] = E^{\overline{W}}_{\mathrm{DS}}[L|\hat{\tau}] + E^{\overline{W}}_{\mathrm{DNS},\overline{\mathrm{DS}}}[L|\hat{\tau}] + E^{\overline{W}}_{\overline{\mathrm{DNS}},\overline{\mathrm{DS}}}[L|\hat{\tau}] \tag{16}$$

5.1. *Structural collapse*

In the case of structural collapse it is assumed that nobody would survive the failure of the building. Then, the expected loss is given by the total number of occupants times the loss associated to one individual scaled by a factor which is the probability of occurrence of such structural collapse given the early warning information. The computation of the expected loss conditioned to DS should also include the cost, say cds, of downtime due to structural damages, which may be comparable to that related to loss of life

$$E^{W}_{\mathrm{DS}}[L|\hat{\tau}] = E^{\overline{W}}_{\mathrm{DS}}[L|\hat{\tau}] = (20 l_{\max} + \mathrm{cds}) P(\mathrm{DS}|\hat{\tau}) \tag{17}$$

However, in the case of structural collapse the risk mitigation action does not have any effect, then the expected loss is independent of the warning decision. Therefore, the value of cds does not affect the set of alarming threshold, which is the scope of the application, and it could be neglected. Herein, it has been set equal to ca, a lower bound, that will also be considered in computing the other contributions to the expected loss.

The probability of DS given $\hat{\tau}$ is computed by the integral of Equation (18) with the obvious meaning of the symbols.

$$P(\mathrm{DS}|\hat{\tau}) = \int_{\mathrm{Sa}} \int_{\mathrm{IDR}} \int_{M} P(\mathrm{DS}|\mathrm{idr}) f(\mathrm{idr}|\mathrm{sa}) f(\mathrm{sa}|m, r) f(m|\hat{\tau})\, \mathrm{dIDR}\, \mathrm{dSa}\, \mathrm{d}M \tag{18}$$

5.2. Non-Structural collapse

The loss following the non-structural failure is related to the injury of students by the lighting system. Herein non-structural collapse is intended as the failure of lighting elements without structural failure, then the probability of interest is $P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau})$. To compute this joint probability, it has to be considered that the EDPs related to structural and non-structural response, IDR and PFA, are assumed to be dependent on different IMs, Sa(T) and PGA, respectively, being s-dependent random variables [22]. This has been carried out in Equation (19), calibrating the joint PDF of the logs of $\underline{\mathrm{IM}} = \{\mathrm{PGA}, \mathrm{Sa}(T)\}$ as a bivariate Gaussian.[‡]

$$P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau}) = \int_{\underline{\mathrm{IM}}} P(\mathrm{DNS}|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau}) P(\overline{\mathrm{DS}}|\underline{\mathrm{IM}}, \hat{\tau})\, f(\underline{\mathrm{im}}|\hat{\tau})\, \mathrm{d}\underline{\mathrm{IM}} \tag{19}$$

To estimate the loss in the case of non-structural damage the basic assumptions are: (1) in case of no collapse of the structure, the number of lighting elements failed (Y) (between 0 and 6 which is the total number of elements in the classroom) is a binomial random variable of parameter $p = P(\mathrm{DNS}|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau})$ and $n = 6$; (2) given $Y = y$, assuming that one element of the lighting system can hit one occupant only, the number of individuals hit (X) is a binomial random variable of parameter $n = y$ and $p = K$, where K is the probability of a student being hit given by the ratio of the area occupied by persons ($20 \times 1.8\,\mathrm{m}^2$) and the whole area of the classroom ($42\,\mathrm{m}^2$), see Figure 3(b). The probability of having X individuals injured, conditioned to the measures of the network and to not observe structural collapse, is given by Equation (20) where the two terms described above are given as follows:

$$P(X|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau}) = \sum_{y=1}^{6} P(X|Y) P(Y|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau}) \tag{20}$$

$$P(X|Y) = \binom{y}{x} K^x [1 - K]^{y-x} \tag{21}$$

[‡]In this application it has been assumed that, for any given value of event's magnitude and distance, the logs of Sa(T) and PGA are jointly Gaussian random variables such that the two marginal distributions of the logs coincide with those of the considered attenuation law [15]. The same empirical data set used for IDA was used to test normality and to estimate the parameters of the conditional distribution of log(Sa) given log(PGA). The correlation coefficient was estimated comparing the marginal standard deviation of log(Sa) to the conditional one.

$$P(Y|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau}) = \binom{6}{y} P(\mathrm{DNS}|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau})^{y}[1 - P(\mathrm{DNS}|\overline{\mathrm{DS}}, \underline{\mathrm{IM}}, \hat{\tau})]^{6-y} \tag{22}$$

If X and L are s-independent, the expected loss is given by the product of the expected values of the loss function, $E[L]$, and of the occupants hit, $E[X] = 6P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau})K$, after integrating over $\underline{\mathrm{IM}}$. This results as in Equations (23) and (24), for the case of no alarm and when a warning is issued, respectively. Again, the loss related to the downtime is included in the case of no warning because interruption occurs anyway in this case.

$$E_{\mathrm{DNS}}^{\overline{W}}[L|\hat{\tau}] = \left[\left(\int_L l f^{\overline{W}}(l|h)\,\mathrm{d}l\right) + l_{\max} P(l = l_{\max})\right][6P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau})K] + \mathrm{ca} P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau}) \tag{23}$$

$$E_{\mathrm{DNS}}^{W}[L|\hat{\tau}] = \left[\left(\int_L l f^{W}(l|h)\,\mathrm{d}l\right) + l_{\max} P(l = l_{\max})\right][6P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau})K] + \mathrm{ca} P(\mathrm{DNS}, \overline{\mathrm{DS}}|\hat{\tau}) \tag{24}$$

5.3. *False alarm*

In the case of neither structural nor non-structural damage, the expected loss related to the exposition to the seismic risk is zero. However, it has to be considered that the information of the seismic network may lead to a warning also if the subsequent ground motion does not cause any damage, and this is a possible definition of false alarm. In this case, the loss to be sustained is related to the interruption of school activities

$$E_{\mathrm{DNS},\overline{\mathrm{DS}}}^{W}[L|\hat{\tau}] = \mathrm{ca} P(\overline{\mathrm{DNS}}, \overline{\mathrm{DS}}|\hat{\tau}) = \mathrm{ca}[1 - P(\mathrm{DNS}|\overline{\mathrm{DS}}, \hat{\tau})] P(\overline{\mathrm{DS}}|, \hat{\tau}) \tag{25}$$

In the case of no warning, it is reasonable to assume that the mitigation action is taken also if the ground motion is felt by occupants of the building. To account for this case, the expected loss is given as

$$E_{\mathrm{DNS},\overline{\mathrm{DS}}}^{\overline{W}}[L|\hat{\tau}] = \mathrm{ca}\, P(\mathrm{PGA} > \mathrm{PGA}_F|\overline{\mathrm{DS}}, \overline{\mathrm{DNS}}, \hat{\tau})[1 - P(\mathrm{DNS}|\overline{\mathrm{DS}}, \hat{\tau})] P(\overline{\mathrm{DS}}|, \hat{\tau}) \tag{26}$$

where $P(\mathrm{PGA} > \mathrm{PGA}_F|\overline{\mathrm{DS}}, \overline{\mathrm{DNS}}, \hat{\tau})$ represents the probability of the ground motion having a PGA larger than the limit value (PGA_F), which means feeling the earthquake, when no damage occur. The limit has been retrieved by Wald *et al.* [23] considering an intensity III event in the modified Mercalli scale; for sake of simplicity no uncertainty has been considered in the relationship between intensity and PGA.

6. RESULTS AND DISCUSSION

The total losses in the cases of alarming or not, Equations (15) and (16), respectively, are given by the contribution of the terms discussed in the previous section. $E^{W}[L|\hat{\tau}]$ and $E^{\overline{W}}[L|\hat{\tau}]$ have been

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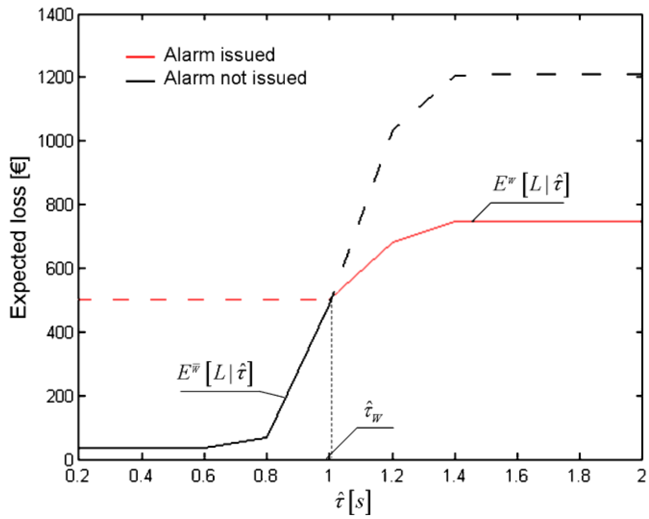

Figure 7. Expected loss for the warning and no warning cases as a function of the statistics of the network measurements for the building supposed located at 110 km from the epicentre.

computed, for the example under exam, for 10 equally spaced $\hat{\tau}$ values in the range between 0.2 and 2 s as suggested by the relation between τ and the magnitude of 'high-magnitude events' in Allen and Kanamori [9]. For the sake of brevity, it is assumed that all stations in the Campanian system are triggered ($v = 30$), then the evolution in time of the loss estimation is not illustrated, although it would be straightforward.

Since the localization method gives a deterministic value of distance after 4 s for an event within the network, then the R value has been fixed to 110 km which is a possible distance of a building in Naples for an event having its epicentral location in the Irpinian region. The reduction coefficient is cr = 10. In Figure 7 the trends of the expected losses in the two cases are given, the dark curve (dashed and solid) corresponds to the non-issuance of the alarm, the light colour one refers to the issuance.

It is possible to observe that the intersection of the two curves separates the $\hat{\tau}$ domain in two regions; if the statistic of the measurements is below the intersection value ($\hat{\tau}_W$) the expected loss is lower if the warning is not issued, otherwise, if $\hat{\tau} > \hat{\tau}_W$, the *optimal decision* is to alarm since it minimizes the expected loss. Moreover, since the loss estimations accounts for false and missed alarms, the threshold optimizes also the tradeoff between these events.

If the alarming decision is taken based on the $\hat{\tau}_W$ value, then the *total expected loss curve* is given by the envelope of $E^{\overline{W}}[L|\hat{\tau}]$ and $E^{W}[L|\hat{\tau}]$ minimizing the loss, then by the combination of the two solid lines of Figure 7. This may be used to compute the loss reduction implied by the installation of an EEWS. In fact, considering the $E_{\overline{W}}[L|\hat{\tau}]$ curve in Figure 7 as the expected loss without the EEWS, the reduction of loss may be computed by comparing the marginal values in respect of $\hat{\tau}$, for both the warning and non-warning case, as follows: where $f(\hat{\tau}|m)$ and $f(m)$ are those discussed in Section 3:

$$E[L] = \int_{\tau} \int_{M} E[L|\hat{\tau}] f(\hat{\tau}|m) f(m) \, \mathrm{d}\hat{\tau} \, \mathrm{d}M \tag{27}$$

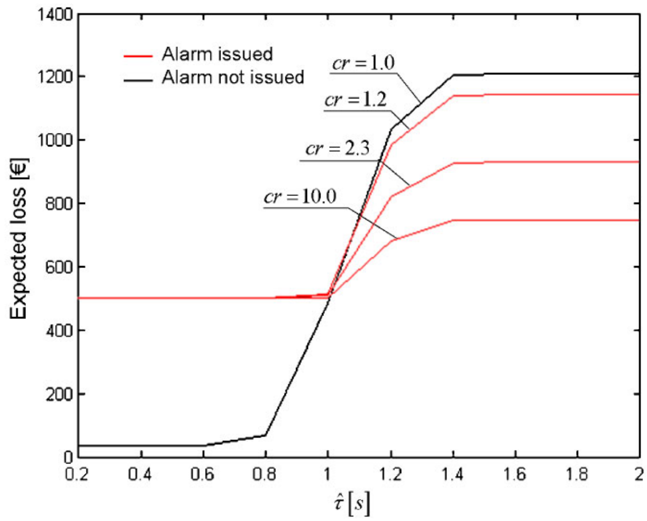

Figure 8. Effect of cr on the expected loss for the building supposed located at 110 km from the epicentre.

For a single event with $R = 110$ km, the loss without EEWS is 179 euros, and 162 euros in the case the system is installed (∼10% reduction). For a lower epicentral distance, i.e. 50 km, the losses without and with EEWS are 710 euros and 524 euros, respectively (26% reduction). These are expected losses per single event and classroom; the reductions would be amplified in a life-cycle analysis for a building with more classrooms. Finally, in the following a simple parametric analysis is conducted to see how the expected loss curves are sensitive to some parameters assigned in the example.

6.1. Effect of reduction coefficient and cost of mitigation action

The cr coefficient directly links to the effectiveness of the security measures following the alarm since it changes the loss function. To see how the reduction coefficient affects the expected loss it has been varied in a range from 1 to 10 (Figure 8). All other parameters, such as the epicentral source-to-site distance and the cost of the interruption are kept constant to 110 km and 500 euros, respectively. Note also that the curve of the expected loss in case of no alarm may be considered as having cr = 1.

The cost following the alarm considered in the example refers to a conventional cost of temporarily stop of didactic activity after the alarm. No operating cost of the EEWS is included since the security action is the personal protection. Such cost may have to be included if the action is costly itself, i.e. activating semi-active structural control to change the dynamic properties of a structure to better withstand the ensuing ground motion. Figure 9 shows the effect of ca on the expected loss for various cases. Converse to what happens for cr, the cost of the action affects both the loss if the alarm is issued or not.

6.2. Effect of distance

The distance has been considered as deterministically known during the whole loss assessment process. This reflects the real-time localization methods, which although associates an uncertainty

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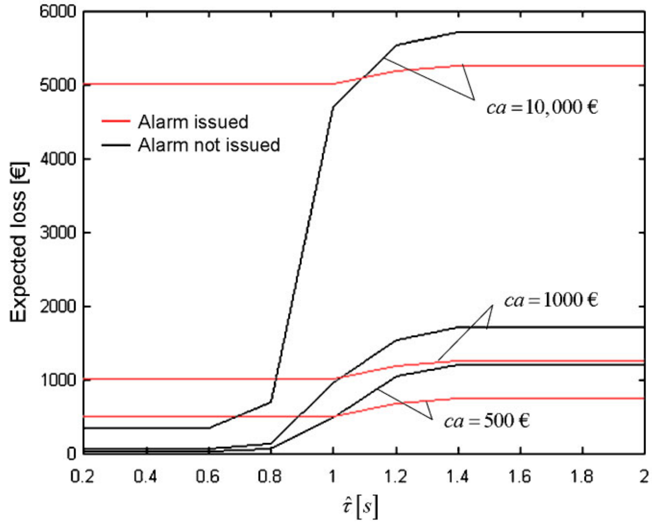

Figure 9. Effect of ca on the expected loss for the building at 110 km from the epicentre (cr = 10).

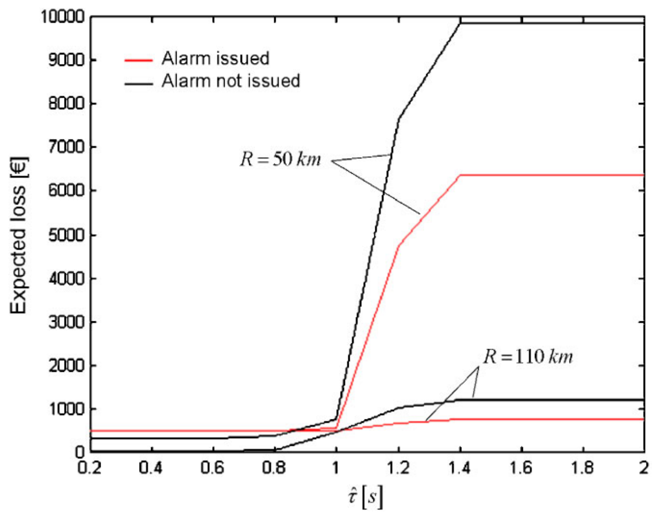

Figure 10. Effect of distance on the expected loss for the case under exam when ca = 500 and cr = 10.

to the hypocentral location of the event, the latter is negligible in respect to other variability involved, above all that of the attenuation relationship. In Figure 10 the expected losses for an epicentral distance of 50 km are compared to the $R = 110$ km case. As it may be anticipated, the expected losses increase more than linearly, this is because, due to the attenuation features the shortest distances are likely to be associated to larger damages. From the figure it is also possible to note that the shorter the distance the larger the reduction of the expected losses if the warning

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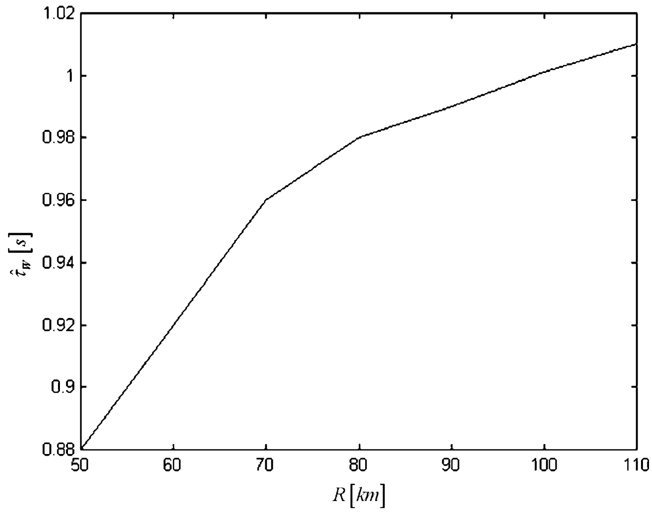

Figure 11. Trend of the optimal alarm threshold as a function of distance (ca = 500 euros; cr = 1.2).

is issued, then the better the EEWS is performing. When considering the distance, however, it has also to be kept in mind that shorter distances correspond to reduced warning times. Therefore, not all applications are feasible at short distances, where triggering many stations to have a good estimate of magnitude requires a larger portion of the available the lead time, and then the time to take the security measure is crucial.

The personal protection under a desk, although easily applicable, may be time consuming (herein it has been assumed that about 10 s are needed to complete the sheltering for trained students). On the other hand, other automatic simple actions, such as the shut down of some critical system or more complicated measures as the real-time power up and configuration of a semi-active control system, in many cases, require negligible time in respect to the available lead time, and the technology to implement seems to be readily available.

The distance also has a significant effect on the optimal threshold. In fact, given the magnitude and an isotropic attenuation relationship, with a shorter distance the building is more exposed to the loss, then the optimal decision is most likely to alarm even for smaller events characterized by a lower $\hat{\tau}$. To clearly picture the effect of distance on the alarm threshold, the latter has been plotted in Figure 11 *versus* the epicentral distance for R equal to 60, 70, 90 and 110 km. The curve is obtained by linear interpolation of these points.

7. CONCLUSIONS

This paper presented a procedure to set the optimal warning threshold and to assess the performance of an EEWS on the basis of the expected loss. The method takes advantage of the classical loss assessment procedure transferring it to the real-time case. The modifications to the risk integral affect the event's occurrence probability and magnitude and distance distributions. Also the loss functions change if a safety action is taken after the alarm is issued.

The presented, and merely illustrative, example refers to a classroom equipped with an EEWS eventually initiating a personal protection action, although the procedure, developed within the PBEE framework, is suitable for more advanced EEW applications, such as those in which the structural response is modified in real-time to better withstand the ensuing ground motion. Computing and comparing the expected losses, conditioned to the real-time information coming from the seismic network, in the case of alarming or not allows: (1) the determination of the alarm threshold above which is convenient to issue the warning according to the *maximum optimality criterion*; (2) the assessment of the average loss reduction determined by the EEWS, and then allows the evaluation of the efficiency and feasibility of such a system; (3) the provision of a quantitative framework and tool for design. Other advantages given by the approach are (a) it minimizes the *cry wolf* issues reducing the probability of false and missed alarms thanks to the threshold optimization; (b) the threshold is set on a statistic (i.e. the summation of the logs) of seismic network measurements, which has been shown to be *sufficient* to the magnitude dramatically reducing the required computational effort for real-time decision making.

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ERRATUM

Expected loss-based alarm threshold set for earthquake early warning systems *Earthquake Engng Struct. Dyn.* 2007 (DOI: 10.1002/eqe.675)

Iunio Iervolino*,†, Massimiliano Giorgio and Gaetano Manfredi

The above article (DOI: 10.1002/eqe.675) was published online on 15 February 2007 in Wiley Interscience (www.interscience.wiley.com). A number of imperfections were subsequently identified and have been corrected below. The print publication will incorporate the amendments identified by this erratum notice.

Equation (10) has been corrected as follows:

$$f(m|\underline{\tau}) = f\left(m \left| \sum_{i=1}^{\nu} \ln(\tau_i)\right.\right) = \frac{e^{(2\mu_{\log(\tau)}\cdot(\sum_{i=1}^{\nu}\ln(\tau_i)) - \nu\mu_{\log(\tau)}^2)/2\sigma_{\log(\tau)}^2} e^{-\beta m}}{\int_{M_{\min}}^{M_{\max}} e^{(2\mu_{\log(\tau)}\cdot(\sum_{i=1}^{\nu}\ln(\tau_i)) - \nu\mu_{\log(\tau)}^2)/2\sigma_{\log(\tau)}^2} e^{-\beta m}\, \mathrm{d}M} \tag{10}$$

References [11, 13, 14] and [18] have been corrected as follows:

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*Correspondence to: Iunio Iervolino, Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli Federico II, Via Claudio 21, 80125 Napoli, Italy.
†E-mail: iunio.iervolino@unina.it