In-depth analysis of practitioners' perceptions about seismic early warning prior to aftershocks: the point of view of the USAR community

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ABSTRACT

Urban Search and Rescue (USAR) teams are particularly exposed to the risk of collapse of buildings due to aftershocks, making concept of earthquake early warning (EEW) particularly interesting. In addition to scientific advances in EEW, it is crucial to understand what are the real expectations and needs of USAR teams, and to what extent EEW solutions could meet them. In this study, we conduct a survey to collect insights from USAR rescuers: it highlights that aftershocks are a major concern for them. In this context, we find that the concept of EEW is very favorably received by the respondents, who consider different types of possible actions upon receipt of an early warning. This study provides a basis for the functional specifications of future solutions of EEW useful to all USAR teams, as well as for the definition of their modalities of engagement on the field.

Keywords

Earthquake early warning, aftershock, search and rescue, USAR, INSARAG.

INTRODUCTION

After the occurrence of a destructive earthquake, the immediate priority is to rescue the victims. While "visible" victims can usually be treated very quickly by the usual rescue services, those trapped under the rubble are much more difficult to find, reach and then extract - or provide first aid directly on site under the rubble. Yet, the probability of finding survivors among the ruins of collapsed buildings after an earthquake decreases very rapidly over time, becoming almost zero after less than a week (Reinoso et al., 2018). In fact, most survivors are found within the first 72 hours, which for this reason are called the "golden hours" due to the greatest chance of saving lives. Thus, it is a real race against time to try to rescue as many people as possible.

Among SAR operations, urban ones (called USAR) are the most common in the event of an earthquake, since most rescue operations are conducted in the ruins of buildings. Compared to other SAR fields such as marine, mountain, or rural operations, USAR is particularly time-consuming and technically demanding because operations are spread over very large, often densely populated areas, with structural complications related to the interlocking of buildings in older - and most vulnerable - city centers (Statheropoulos et al., 2015).

International interoperability of USAR practices

For maximum efficiency, it is therefore essential that USAR teams - sent in large numbers to the epicentral area - are able to work together according to "standardized" and interoperable procedures. This is true for the national teams that intervene from the first hours after an earthquake, but all the more for the international teams that are very often sent as reinforcements (Statheropoulos et al., 2015; Okita et al., 2021). It was in response to this challenge that the International Search and Rescue Advisory Group (INSARAG) was created in 1991 on the initiative of the United Nations (UN). Over time, INSARAG has standardized USAR practices throughout the world with a high level of requirements, and has allowed a certain interoperability of international teams that reinforce local search and rescue resources after each major earthquake.

Exposure of USAR teams to aftershocks

By nature, USAR operations take place in a degraded and dangerous environment. Therefore, the primary concern of USAR teams is the safety of their personnel. Aftershocks are a major risk for USAR teams, who must operate in severely damaged buildings, parts of which may collapse even with relatively small ground movements (structural collapses of damaged buildings can even occur in some cases under static conditions, i.e. in the absence of any ground-motion). Indeed, the period following the occurrence of a major earthquake is characterized by a period of increased probability of aftershocks (Omori, 1894). Although this risk is well known to USAR teams, to date they have few means to protect themselves from it, with practices that appear to vary from country to country.

Pointing to this exposure, Schäfer et al. (2017) list a dozen earthquakes for which interruptions in relief operations were observed following the occurrence of aftershocks, for a period ranging from a few hours to a few weeks. In particular, if one considers that, for partially collapsed buildings inside which USAR teams are searching for victims, a risk of collapse may appear for relatively low levels of shaking, the threat is very high. This risk situation is unsurprisingly greatest in the first few hours after the main tremor, but it remains significant in the days (or even weeks) following, when USAR operations take place. In particular, the "Golden Hours" are characterized by a high risk of aftershock collapse. Therefore, ensuring the safety of USAR teams is at the top of the priority list during a rapid search and rescue operation (Statheropoulos et al., 2015).

Overview of USAR team practices for aftershock management

In terms of procedures, some countries explicitly define a way to account for aftershocks, based primarily on Omori's law, which describes the typical decay of aftershock rate as approximately inversely proportional to the time since the mainshock (Omori, 1894). Thus, U.S. and New Zealand teams appear to use simple rules to estimate the level of likely aftershocks that may occur during their USAR operations (McVerry et al., 2005). In practice, while this approach is valuable in acculturating USAR teams to the reality of the risk presented by aftershocks, it remains poorly activatable because even a high level of risk of aftershocks cannot justify preemptively shutting down USAR operations for several days.

Guaranteeing the safety of rescuers is one of the highest priorities for USAR operations (Statheropoulos et al., 2015). One way to ensure this safety is to equip teams with tools that enable an automated monitoring of their ever-changing work environment, including the risk of collapsing ruins. To do this, many USAR teams use stability monitors, but all these systems have the same limitation of detecting only the movements of the structure, and not the ground shaking itself, making the alarm useless in case of sudden collapse due to aftershocks. A system detecting seismic waves themselves and predicting the shaking strength so that teams can apply safety measures makes sense in this context: that is the main goal of Earthquake Early Warning (EEW) systems, which constitute the focus of this study.

FROM MAINSHOCKS TO AFTERSHOCKS EARLY WARNING

General principle of earthquake early warning

In 1868, Cooper laid the groundwork for a new tool to provide an "early" warning to San Francisco of the impending arrival of destructive waves generated by an earthquake some 100 kilometers from the city. A little over a century and a half later, Cooper's concept was carried forward into EEW systems that use the first few seconds of P-wave recordings - the fastest and least energetic - to estimate the strength of the earthquake and the intensity of subsequent shaking. They can be divided into three broad categories (Cremen and Galasso, 2020):

1. Regional EEW systems, which aim to cover large geographic areas, rely on dense seismic sensor networks to detect the occurrence of earthquakes as soon as possible after their occurrence, and then estimate their source parameters and predict ground shaking at target sites to be warned.
2. On-site EEW systems, which are designed to alert a specific target site, and which rely on instrumentation centered on that target, most often consisting of a single seismic station that continuously acquires and analyzes ground motion. On-site systems aim to directly estimate the destructive potential of incoming strong ground-motion at the target site.

Regional EEW systems generally provide more accurate estimates of source parameters, but on-site EEW systems, on the other hand, have shorter latency times due to local treatment and no off-site communication, and then provide faster warning times for targets near the earthquake epicenter by reducing the extent of the "blind zone" within which seismic shaking arrives before warning (Kanamori, 2005). In order to take advantage of both the benefits of regional and on-site systems, some authors have introduced a third type of EEW system (Zollo et al., 2010):

3. "Hybrid" EEW systems, which are regional systems in which each station of the network behaves autonomously according to the on-site approach to alert as soon as possible the assets located in its immediate environment, while contributing to the assessment of an alert with a "regional" focus.

Application of the early warning principle to aftershocks

In the 1990s, when EEW technology was still in its infancy, the principle of early warning for aftershocks was proposed for California using a regional approach (Bakun et al., 1994). Nearly thirty years later, due to both the maturation of EEW techniques and the greater mobility of USAR teams, the most relevant EEW principle for the use case considered in this study is primarily the on-site one, like the FREQL-light tool (Nakamura & Saïta, 2007b). In order to estimate the impending shaking hazard, these on-site systems use proxy parameters which are computed over time windows typically ranging from 1 to 3 seconds after the arrival of the P phase.

The perspective of the use of an on-site EEW system by rescue teams also makes it essential for the system to be able to effectively discriminate signals produced by earthquakes from anthropogenic seismic noise associated with USAR operations (generator operation, displacement and drilling of concrete elements, etc.) or from ambient noise that can in some cases be loud due to the intense activity that usually prevails in impacted areas where destruction is concentrated. Finally, several studies suggest that on-site EEW algorithms can be applied using low-cost microelectromechanical systems (MEMS) accelerometers (Peng et al., 2017), paving the way for miniaturization of devices and lower costs.

Therefore, the minimum requirements for the technical feasibility of a mobile EEW solution for aftershock monitoring seem to be met. However, it is important to note that, to our knowledge, all existing EEW algorithms (both on-site and regional) have been developed primarily for mainshocks, and not specifically for aftershocks.

Current use of EEW systems by USAR teams

It seems that a few USAR teams are using dedicated EEW systems to detect aftershocks early before the strongest seismic waves have reached their work site. However, these systems are very poorly documented, and appear to be unfamiliar to the international USAR community, leading the detailed needs assessment of USAR teams conducted by Wong & Robinson (2004) to consider the development of an "Aftershock Prediction System" as a high priority. More recently, Statheropoulos et al. (2015) included this type of early warning system in their list of "candidate systems that await integration to generate significant and rapid advances in USAR capability".

The only documented EEW tool dedicated to USAR needs is developed and commercialized by the SDR Japanese company. Among the EEW systems proposed by SDR, the FREQL-light portable model was designed to be easily deployed in the field (Nakamura & Saïta, 2007). Developed in 2005, it appears that FREQL-light is now helping the Tokyo Fire Department to protect its "Hyper rescue" team personnel from the effects of aftershocks during their operations in Japan or abroad (Nakamura et al., 2011). According to information provided by the manufacturer (authors' personal communication), the FREQL-light system appears to be able to alert members responding to the site of a potentially large aftershock, who can be warned either by an audible alert sounding throughout the site or via dedicated portable receivers.

While the question of scientific and technical feasibility is important for the development of an EEW system, the question of evaluating its potential contribution to users is equally important (Becker et al., 2020a). The few existing studies aiming at this evaluation concern exclusively regional systems, via interviews or surveys carried out with actors present in the territories covered by the warning systems (Auclair et al., 2015; Becker et al., 2020a-b). Despite some specific lessons from previous studies (e.g. Becker et al., 2019 & 2020a), to our knowledge there is no such study to date to precisely investigate the perception and identification of the specific needs of USAR teams. Therefore, we set out to conduct a questionnaire survey of international USAR teams to understand what the opportunities, challenges, and contingencies would be for using a mobile EEW solution to protect them from the risk of collapse in the event of aftershocks.

USERS SURVEY

As Becker et al. (2020a) state, *"understanding people's perspectives should be the first, not last, step of developing and operationalizing a successful early warning system"*. Thus, in reference to the notion of the "last mile" which refers to the ability to issue the alert to the right users distributed over the territory, the collection and analysis of the potential users' point of view constitutes the essential "first mile" (Kelman and Glantz, 2014).

With the goal of analyzing user perspectives to guide the development of an EEW dedicated to USAR teams, the existence of a highly organized international community within the INSARAG group provides a rare opportunity facilitating comparative analysis of feedback from practitioners with relatively homogeneous operational cultures and practices.

Methodology and data

Like Becker et al. (2020.b), we chose to gather information via the conduct of a questionnaire survey. The survey data is particularly useful for quantifiably comparing the views of many participants. The main issues that inspired our questions were: respondent’s profile; respondent’s experience with USAR response activities; perception of the risk presented by aftershocks; perception of the value of an EEW; and constraints to operational deployment of an EEW.

The survey consisted of 35 questions in total, 20 quantitative (closed questions) and 15 qualitative (open questions). The survey was conducted online from April 21, 2021 to June 1, 2021. Thanks to the support of the French civil protection, the survey was sent to all operational focal points of INSARAG member countries, as well as to the focal points of their USAR teams (approximately 200 recipients). These recipients were left free to forward the link to the questionnaire to anyone they deemed relevant, opening the way for multiple returns within the same team, as well as the participation of representatives of USAR teams not affiliated with the INSARAG community.

In total, we received 104 responses to the questionnaire, 95% from active USAR team members, from 11 countries: 80.8% from the United States, 12.5% from European countries, and 6.7% from other countries (see Table 1). It is worth noting that some questions were not completed by all respondents, either in the case of non-applicable questions, or in the case of open questions that were not mandatory.

Table 1. Distribution of responses to the questionnaire by nationality, USAR team membership, and INSARAG classification level (if relevant). See section 4 for an in-depth explanation of differences between levels.

Region Country	**Affiliation to an USAR team**		**IEC classified team**			**Level**	
	No	**Yes**	**No**	**Accredited**	**Ongoing**	**Heavy (HUSAR)**	**Medium (MUSAR)**
Europe							
Czech republic	0	2	0	2	0	2	0
France	2	6	1	5	0	3	2
Germany	0	2	0	2	0	2	0
United Kingdom	0	1	0	1	0	1	0
Other				0		0	0
Australia	0	1	0	1	0	1	0
China	0	1	0	1	0	1	0
Mexico	1	1	0	0	1	0	1
New-Zealand	0	1	0	1	0	1	0

South Africa	0	1	0	1	0	1	0
United Arab Emirates	0	1	0	1	0	1	0
US				0		0	0
USA	2	82	54	28	0	28	0
Total	5	99	**55**	43	1	41	3
	104			**44**		**44**	

Analysis of results

Respondent experience

The way in which questions about protection against aftershocks (and earthquakes in general) are answered can depend to a large extent on the experience of the respondents. For this reason, 8 questions were asked in order to evaluate this experience for each of the respondents.

The results show that 85.6% of the respondents indicate that they have already experienced an earthquake, which is a much higher proportion than those who have already taken part in real life to USAR post-seismic interventions, which is only 37.5%. One the other hand, 35.6% have experience of real life engagement for situations other than earthquakes, while the remaining 14.4% have only participated in exercises. Analysis of the responses from 52 respondents having experience in postseismic USAR operations conducted to identify the main international earthquakes in which they have participated. Unsurprisingly, these were primarily the major earthquakes over the past decade that required international USAR reinforcements via INSARAG, including earthquakes that occurred in 2010 in Haiti and New Zealand, in 2011 in Japan, and in 2015 in Nepal. Thus, it is possible to analyze the responses either in aggregate or to extract a specific analysis for each of the four aforementioned earthquakes for which we have sufficient data.

It appears that, overall, 43% of the responses reported the arrival of USAR teams within the first 24 hours after the earthquake occurred, and 84% within the first 48 hours. In terms of the duration of the missions in which the respondents took part, these were relatively long, most often lasting from 11 up to 15 days (43%). These elements confirm that the conduct of USAR responses is very much affected by aftershocks, which are most likely to occur during the first few days after the earthquake (one respondent reported feeling up to 70 aftershocks per day during his 2011 mission in New Zealand). The responses to another question confirm that this high exposure to aftershocks results in a high risk for USAR team members, 77.1% of whom report frequently to very frequently working in heavily damaged buildings with a high risk of collapse (Figure 1).

Therefore, it is not surprising to find that aftershocks disrupted USAR operations in 70% of the postseismic missions in which the respondents participated (Figure 2). Responses to an open question provide more details on the nature of these disruptions. Most of the responses emphasize reflex actions of sheltering in place or evacuating the operational rescue area to limit the risk to the safety of the rescuers. Several respondents indicate that these frequent interruptions remain mostly short, but that resuming afterwards the rescue activities requires the realization of a new diagnosis to assess the security level of the buildings and the re-evaluation of the possible evacuation itineraries:

"Aftershocks required us to temporarily halt rescue operations, move to a designated safe zone or evacuate the structure."

Some respondents also report actual aftershock-induced damage, sometimes even resulting in new victims being injured or trapped under the rubble:

"Violent aftershocks resulting in persons trapped and injured"

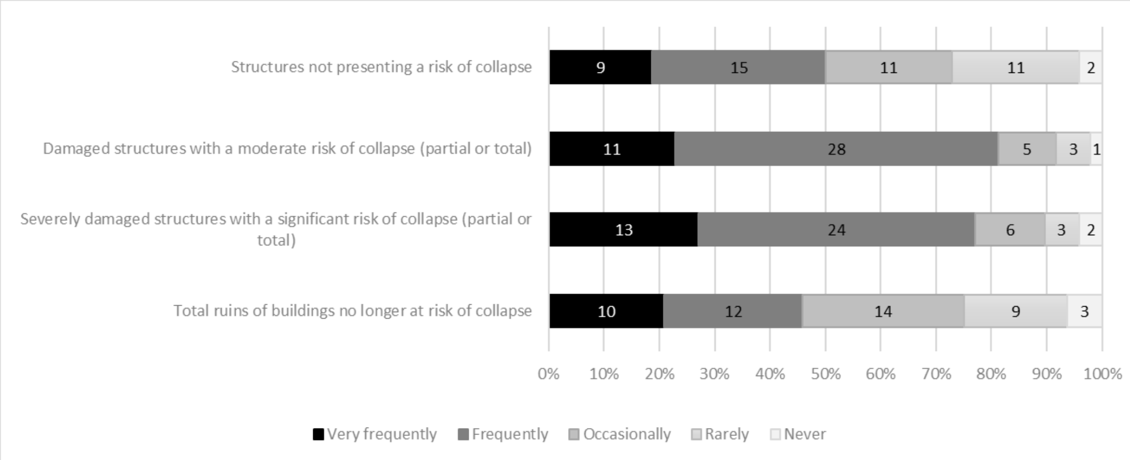


Figure 1. Answers to question "During these missions, in what types of environment did your team intervene?"

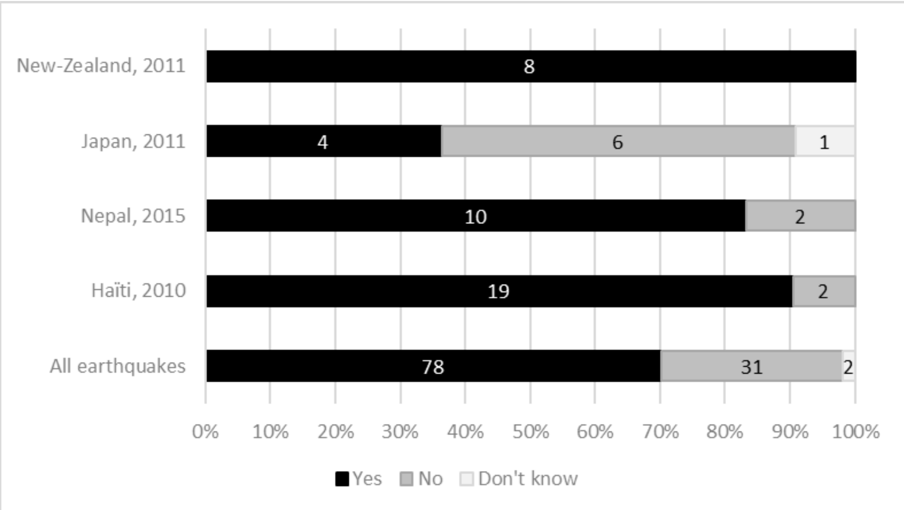


Figure 2. Answers to question "Did any aftershocks disrupt USAR operations?"

Perception and management of aftershock risk

The next group of questions aimed to establish the perception of respondents and to identify the means available to them to protect themselves from this risk.

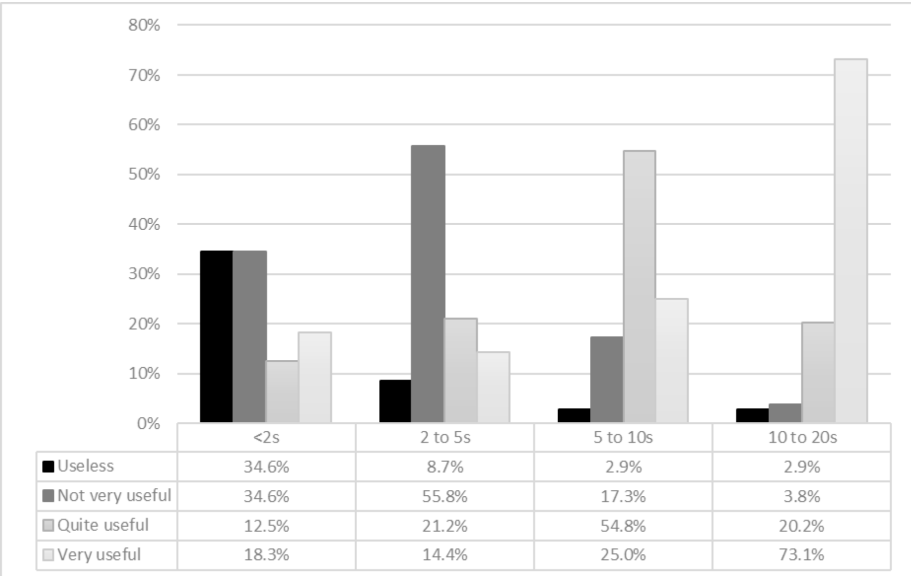
With 72.9% of responses expressing a high to very high risk, it appears first of all that the risk is perceived as maximum for the team members themselves, followed by the search dogs of the canine units, then by the intervention equipment. The most feared effect of aftershocks is the collapse of buildings that could injure or kill rescuers, or even trap them under rubble. In this case, the priority work of the USAR team would naturally become rescuing their colleague(s), to the detriment of other victims.

To face this danger, only 52.4% of the respondents report having in their team an early warning or stability control tool, a figure that reaches 61.3% among INSARAG-affiliated team members. While some respondents marginally mention the use of crack monitors or theodolites, none mention the use of an EEW. More surprisingly, almost 20% of the respondents do not know if their team is equipped with such procedures or tools, almost exclusively in teams not affiliated with INSARAG.

Utility of aftershocks early warning

The next section of the questionnaire is specific to assessing the perceived usefulness of an EEW system, without any presupposition about technical feasibility. Unsurprisingly, and in good agreement with previous work (Auclair et al., 2015; Becker et al., 2020a), it first emerges that the perceived usefulness is stronger the longer the warning time (Figure 3). In this respect, it should be noted that, with the exception of some regional EEW systems that can offer large warning times of more than 10 seconds due to specific regional configurations with a large distance between seismic sources and target areas, the characteristic performances of on-site EEW systems are generally much lower, in particular for a near field application with respect to seismic sources such as the one considered in this study. A test conducted in Italy (i.e. with a diffuse continental source configuration) suggests warning times ranging on average between 3 and 5-6 seconds for targets located respectively at about 20 and 30 kilometers from the epicenter, with values of 8-10 seconds obtained only at about 50 kilometers from the epicenter (Caruso et al., 2017). As USAR teams are working in the heart of mainshock disaster areas, it is common for them to be exposed to aftershocks occurring relatively close to the epicenter, which leads us to consider extremely short warning times of only a few seconds.

93.3% of the respondents consider an EEW to be useful to very useful for a warning time of between 10 and 20 seconds. This figure decreases to 79.8% for alert times between 5 and 10 seconds, to 35.6% for alert times between 2 and 5 seconds, and finally to 30.8% for alert times lower than 2 seconds. Although the perception of usefulness only becomes the majority when the alert time exceeds five seconds, it is interesting to examine carefully the actions envisaged by the respondents even under extremely short delays. In practice, respondents identify three types of actions that can be taken in response to receiving an EEW to reduce the level of danger: (1) immediately stop sensitive operations (e.g., stop and remove concrete saws used for drilling), (2) move into a safe position on site (e.g., remain crouched at the foot of a prop set by the USAR team), and (3) move to a safe area (outside or, failing that, inside the building). While the answers obtained clearly point out that the efficiency of these actions increases with the duration of the early warning, they are nevertheless considered by some for extremely short delays of less than 2 seconds. For such short warning times, it is also pointed out that the reduction of the surprise effect brought by an early warning would be in itself an important contribution to allow the team members to better anticipate the imminent arrival of seismic ground motions.

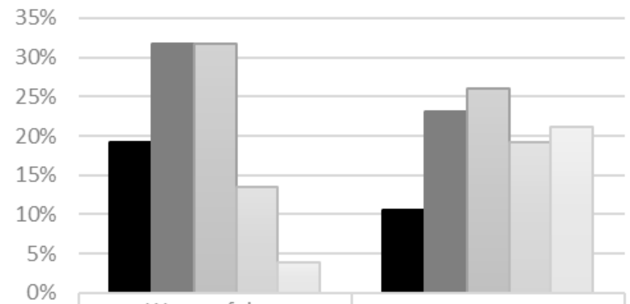


	<2s	2 to 5s	5 to 10s	10 to 20s
Useless	34.6%	8.7%	2.9%	2.9%
Not very useful	34.6%	55.8%	17.3%	3.8%
Quite useful	12.5%	21.2%	54.8%	20.2%
Very useful	18.3%	14.4%	25.0%	73.1%

Figure 3. Answers to question "In your opinion, would it be useful to have an early warning of the imminent occurrence of strong motions related to aftershocks?"

Another very important notion when considering the contribution of an EEW system to users is to evaluate the potential impact of bad predictions. Indeed, the EEW principle being by nature a "race against time", it critically highlights the duality between speed and accuracy. Thus, depending on the user's risk aversion, the trigger thresholds can be adjusted so as to avoid missed alerts (false negative), or on the contrary false alerts (false positive). We decided to address this issue with only one question related to the impact of false alarms.

Figure 4 shows that false alarms (i.e. alerts in the absence of strong motions) are mostly considered to have a low to very low impact in terms of loss of time and therefore efficiency in USAR operations (50.9%). On the other hand, only 17.3% of respondents consider this impact to be high or very high. Considering the safety gain offered by an early warning, having to preventively stop the search for victims because of a false alarm seems acceptable, especially since in this case operations can restart very quickly because it is not necessary to proceed with a new inspection of the stability of the buildings in which the search is taking place. However, it appears that these false alarms could result in a loss of confidence in the system (Figure 4). However, opinions on this point seem to be nuanced, and it is in fact more the repetition of false alarms rather than isolated false alarms that could seriously alter the confidence of the teams in the EEW system.



	Waste of time (stoppage of operations)	Loss of confidence in the system
Very low	19.2%	10.6%
Low	31.7%	23.1%
Moredate	31.7%	26.0%
High	13.5%	19.2%
Very high	3.8%	21.2%

Figure 4. Answers to question 29 – "In your opinion, what would be the impact of a false alarm (i.e. early warning but no shaking) in terms of ...?"

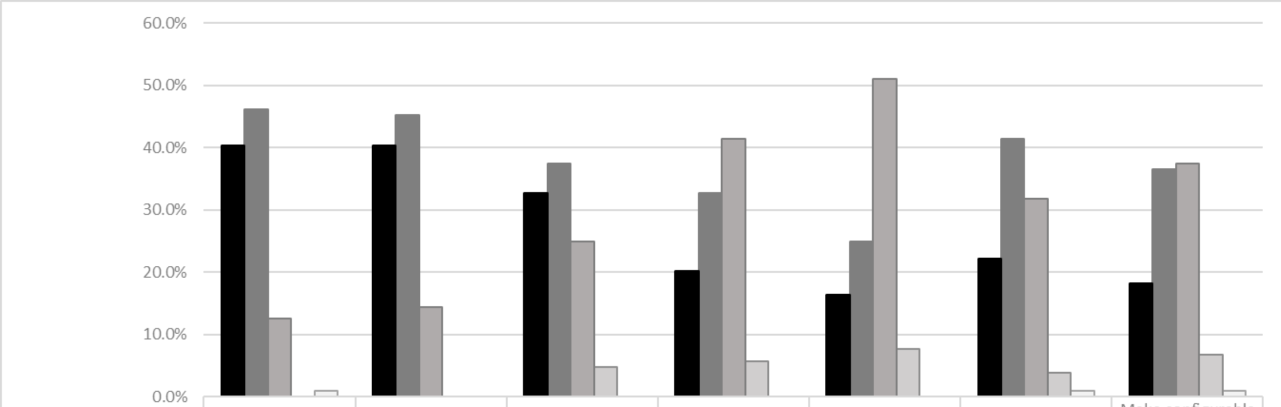
Deployment of the system and dissemination of the alert

With 5 questions, the last section of the questionnaire aimed at addressing the issue of the system design and its operational engagement conditions, in order to draw up the main lines of technical and functional specifications.

Inspired by existing EEW systems, two functionalities were proposed to be evaluated by the respondents: (1) being able to self-configure the trigger threshold in terms of predicted seismic intensity, and (2) being informed of the estimated time remaining before the arrival of shaking. Figure 5 shows that the majority of respondents consider each of these two functionalities to be important or very important in 74.0% and 73.0% of cases respectively.

Easy to implement, allowing the USAR teams to configure themselves the threshold of the alert system is indeed a way to adapt more easily to the specificities of each intervention, with for example a more sensitive threshold in case of interventions in very vulnerable and unstable buildings, and on the contrary a higher threshold in case of more stable structures with a lower level of threat for the rescuers. Being able to be warned of the time remaining before the arrival of the strong motions also presents an intuitive interest, so as to better anticipate the type of action that can be undertaken. Thus, depending on their location within the buildings, the USAR team members could decide whether to evacuate the building or to go to safety on site depending on the duration of the warning time. Contrary to parameterization of the system's triggering threshold by the users, the calculation of this time available before the arrival of the strong ground motions is however more tricky and linked to a certain uncertainty. As proposed by some EEW on-site methodologies, it is thus necessary to first estimate the epicentral distance (Odaka et al., 2003), then to deduce a time of arrival of the strong motions at the site based on the average propagation times of the "S" seismic waves.

Among the four characteristics submitted for evaluation by the respondents, the two considered most important are the ease and speed of deployment and configuration of the system, so as not to slow down or USAR operations: 85.6% and 86.6% of respondents respectively consider these characteristics very important to essential (Figure 5). Next is the need for battery operated hardware. Although also considered important, minimizing the weight and size of the system seems less critical. In fact, the size and weight of the equipment are very important parameters during the initial phase of deployment of international airborne rescue systems, but they take a back seat once in the field.



	Mobile system easy and quick to configure	Mobile system easy and quick to deploy	Autonomous in energy (battery operated)	Minimal weight	Minimal size	Announce the time remaining before the onset of shakings	Make configurable the threshold of expected level of shaking intensity for which to issue an alert
Not important at all	1.0%					1.0%	1.0%
Not very important			4.8%	5.8%	7.7%	3.8%	6.7%
Important	12.5%	14.4%	25.0%	41.3%	51.0%	31.7%	37.5%
Very important	46.2%	45.2%	37.5%	32.7%	25.0%	41.3%	36.5%
Essential	40.4%	40.4%	32.7%	20.2%	16.3%	22.1%	18.3%

Figure 5. Answers to questions "How important are the following functionalities & characteristics?"

As described previously, the hybrid EEW approach is an interesting configuration to operate either with a single station or with a set of co-located seismic stations in a small area around the target to be protected, using the concept of "warning levels" introduced by Zollo et al. (2010). In order to assess whether this type of configuration is realistic with respect to the contingencies of the USAR teams, one question aimed to identify to what extent sensor networking would be feasible. Table 2 shows that a large majority of respondents (80.8%) thinks that it would be possible to couple different devices in order to network them, whether each of these devices is operated by a given USAR team or shared between several teams.

Table 2. Answers to question "In order to improve the reliability of the early warning system, do you think it possible to …?"

	Yes	No	Don't know
Network your device with compatible ones from other USAR teams (under the coordination of the UCC for example)?	84 (80.8%)	4 (3.8%)	16 (15.4%)
Have a system made up of several devices to be deployed around the intervention site?	84 (80.8%)	9 (8.7%)	11 (10.6%)

Because EEW techniques rely on continuous processing of very low amplitude seismic waves, it is also necessary to ensure that the device allow for the acquisition of good quality data with a high signal-to-noise ratio (SNR) (Caruso et al., 2017). However, due to their activities, USAR teams can generate a relatively high level of seismic background noise because of the rubble drilling operations, but also because of the generators used to ensure the autonomy of the power supply (the regularity of this noise induced by generators can however be filtered quite easily). To reduce this seismic background noise, an effective way would be to move the sensor away from the sites to be protected. However, this is not always feasible, especially in the post-seismic urban conditions in which USAR teams operate. Respondents consider such a distance to be all the more difficult the further away it is: if a distance of 20 to 50 meters seems entirely feasible, the perception of the feasibility of a greater distance of 50 to 100 meters is less unanimous. Moving the measurement sensor more than 100 meters away from the intervention site seems difficult to envisage (Figure 6). As one of the respondents explains, to avoid the theft of equipment, it is essential that the equipment used by the USAR teams be located within a secure sector, often very close to the site where the searches are carried out.

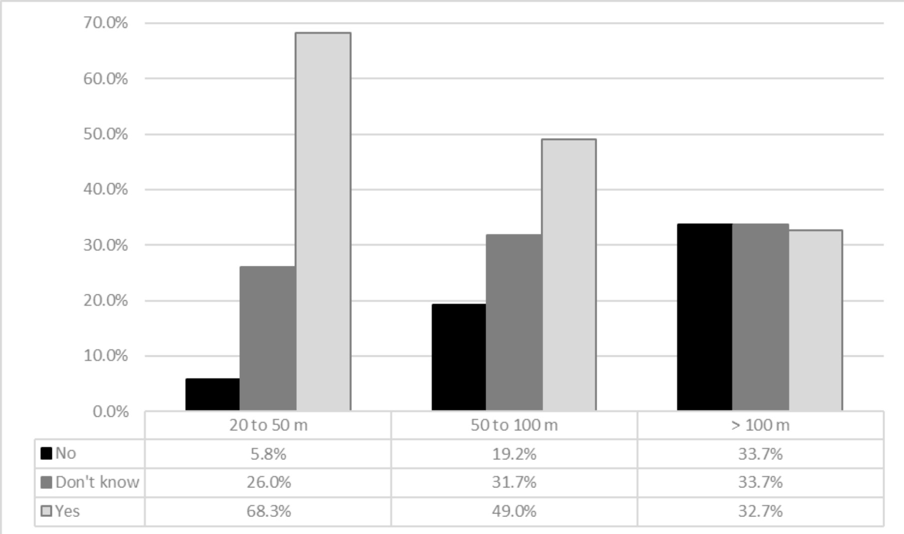


Figure 6. Answers to question "In order to reduce interference from the seismic wave recording sensor, do you think it possible to move the monitoring device away from the intervention site (away from generators in operation and drilling operations)?"

Finally, the last question concerned the identification of the most appropriate modalities for disseminating early warning to the USAR members. The preferred modality is clearly the broadcasting of an audible alert that can be heard by everyone on the intervention site, far ahead of the possibility of equipping each member with portable receivers. Some respondents thought that it would be interesting to combine the two approaches (i.e. an audible alert for all supplemented by an alert received by each member on his own receiver) (Table 3).

Table 3. Answers to question "In your opinion, what would be the most suitable way to broadcast the early warning (a few seconds) of arriving strong motions within your team?"

Alarm that can be heard anywhere on the intervention site	**Reception of the alert via individual wearable receivers**	**Both**	**Other**
69 (66.3%)	25 (24.1%)	4 (3.8%)	6 (5.8%)

DISCUSSION

Based on the responses received, it is possible to outline what an EEW system for aftershocks should look like to meet the specific needs of USAR teams. It is worth noting that, contrary to what one might intuitively think, respondents' experience has relatively little influence on their perception of the usefulness of an EEW system. This strengthens the analysis of the results presented in this article. On the other hand, it is very clear that the more experienced the respondents are, the more information they provide in their qualitative responses to the open-ended questions.

Following the representation proposed by Becker et al. (2020a), Figure 8 schematically represents a summary of the actions considered by survey respondents that could be undertaken by USAR team members based on available warning time. These actions attest to a capacity of rescuers to leverage EEWs to better anticipate the imminent arrival of seismic shaking, and reduce their exposure to over-damage of building ruins in which they respond.

Moreover, it appears that some of the actions listed in Figure 8 are exclusive, and that the main criterion for prioritizing them is the time available before the arrival of the strong motions. This is the case, for example, for the safety actions of the rescuers, with a choice between an option consisting of moving to safety in the immediate vicinity if the time available is very short, and another option consisting of moving to a more distant safety zone if time permits. As a result, and as indicated by respondents, it seems essential to include a system capability to estimate the time available before the arrival of the strongest tremors, similar to some regional EEW systems that even perform a countdown of this time.

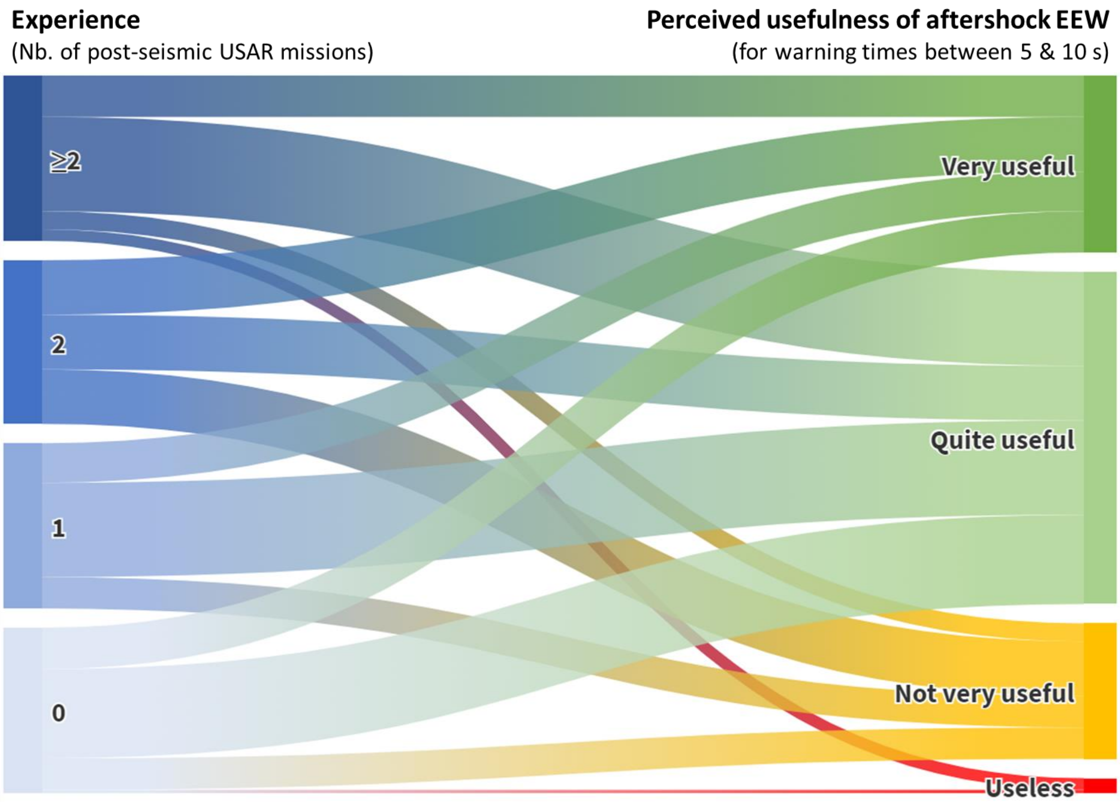


Figure 7. Dependence of perceived usefulness of an EEW system (for a warning time between 5 & 10 seconds) on respondents' experience in terms of postseismic USAR missions. The thickness of the lines is proportional to the number of answers after normalization so that each "Experience" category is equal.

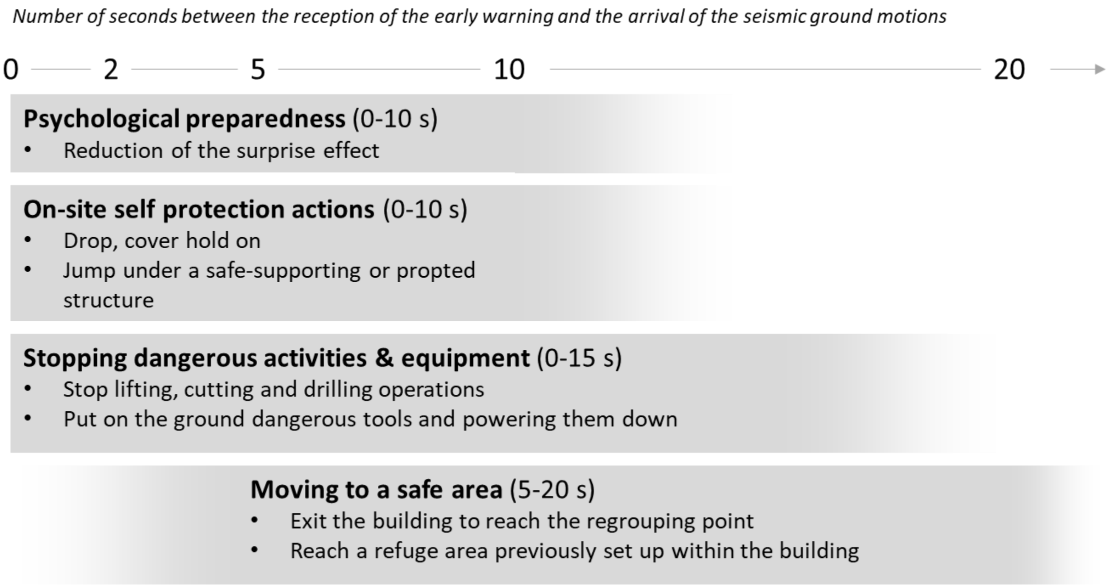


Figure 8. Typical actions that can be taken by USAR team members based on available alert time

While all USAR teams seem to share the need to protect themselves from aftershocks, their ability to operate an EEW system may differ depending on their size, expertise, and skills. Thus, it is worth considering the three levels introduced by IEC process for USAR teams based on their minimum standard operational capabilities (INSARAG Guidelines, 2020):

1. Light USAR teams (LUSAR): can be activated quickly, are highly mobile in the field, and are very effective in the initial phase of the disaster when access is difficult for the search for victims on the surface. With a single rescue team and light equipment, they can work on one site at a time, 12 hours a day, for seven consecutive days;

2. Medium USAR teams (MUSAR): with heavier and more important means than the previous ones, allowing to carry out more technical operations, they are projectable and autonomous. With two rescue teams taking turns on a regular basis, they are capable of managing a site 24 hours a day, for seven consecutive days.
3. Heavy USAR teams (HUSAR): also projectable and autonomous, their contract is to ensure the simultaneous management of two sites far from each other, 24 hours a day for 10 consecutive days. To do this, they have four rescue teams working in pairs.

Since one of the basic rules for USAR teams is that they must be completely self-sufficient in their response, it is necessary that the EEW system be designed to support and be operated by a single team. However, while LUSAR and MUSAR teams only need to operate at one site and can therefore rely on a single site-specific EEW system, HUSAR teams may need to employ personnel simultaneously at two potentially remote sites. In this case, the EEW solution must either be able to manage the multi-site, or be acquired in duplicate by the HUSAR teams.

Concerning its use, the EEW solution must be as compact as possible, in order to respect the strong constraints of transporting the equipment on site. Moreover, it must also be easy and quick to deploy and configure, without requiring any seismological skills. It could for example be operated under the coordination of the Safety & Security Officer present in each USAR team, whose mission is to ensure the safety of the team, and who must know and use the available tools and protective equipment. The security officer could also be supported by the communications specialist (specific position within the MUSAR and HUSAR teams) for aspects related to data transmission and possible networking of EEW devices.

Most of the technical specifications aforementioned seem to be already met by the FREQL-light system (personal communication), whose real performances remains to be proven. Another interesting alternative seems to be the development of ad hoc solutions based on the use of low-cost MEMS sensors, which offer three particularly interesting advantages in the context of USAR operations: low cost, low weight/size, low power consumption. A recent study by D'Allessandro et al. (2020) confirms that these sensors are suitable for the specific case of on-site EEW.

Close examination of how USAR teams operate in the field also allows us to imagine different modes of deployment of EEW solutions (Figure 9):

- EEW solution specific to each USAR team:
    a) Solution based on a single sensor located in close proximity to the USAR site to be alerted;
    b) Solution based on the networking of several sensors located in the immediate vicinity of the USAR site to be alerted;
    c) Solution based on the networking of one or more sensors located in the immediate vicinity of the USAR site to be alerted, supplemented by a fixed sensor located at the base of operations (BoO).
- Solution shared by networking the equipment of each USAR team:
    d) Solution based on the networking of all the sensors deployed in the field by the different USAR teams involved.
- Configuration *a* is the one that most easily satisfies all the technical specification criteria. By multiplying the sensors and networking them together, configurations *b*, *c* and *d* would necessarily lead to a bulkier equipment and a greater deployment complexity; on the other hand, they would theoretically allow a significant gain in reliability.

Although offering more efficiency in terms of early warning potential, it is noteworthy that configurations *c* and *d* must be considered taking into account the fact that the BoO is often very far from the worksites. In addition, USAR teams can work in areas far apart from each other during the successive levels of *Assessment*, *Search and Rescue* – ASR (INSARAG Guidelines, 2020). Moreover, configuration *d*, which would allow the implementation of a regional EEW mini-system respecting the essential principle of autonomy of the USAR teams (i.e. each team must deploy its own equipment), could be operated under the responsibility of the entity that coordinates all the USAR teams deployed, called "UCC" (USAR coordination cell).

In the perspective of using this type of EEW system within a national civil protection organization (and not in the case of international reinforcements), this principle of networking of single EEW devices could also include the seismic sensors deployed by the teams in charge of monitoring the aftershocks, so as to strengthen the ability to detect incoming strong motion as early as possible. Such an arrangement would improve the overall reliability of early warning at each site, which would particularly benefit USAR teams without such a tool. On the other hand, this would require compatibility of all individual EEW systems (same type of equipment or interoperable solutions), as well as the ability to network the different components of the system in environments where communication infrastructures are likely to be heavily damaged. This also raises questions regarding data processing, either via a centralized system that is cumbersome to implement in the field and probably not compatible in terms of processing speed, or more realistically in a distributed manner at the level of each unit.

It is worth noting that networking EEW sensors would also increase the complexity of the deployment (setting up a distributed network beforehand, establishing communications and verifying them, testing the proper functioning of network-based detection tools), while the size of the devices would be bigger with less battery life and more prone to failure if not properly designed, as well as probably much more expensive. In addition, networking constraints imply that field teams include a specialist or that they be specifically trained to operate this kind of equipment. Finally, legal considerations may also pose practical problems in bringing and operating equipment emitting radio waves for communication in foreign countries.

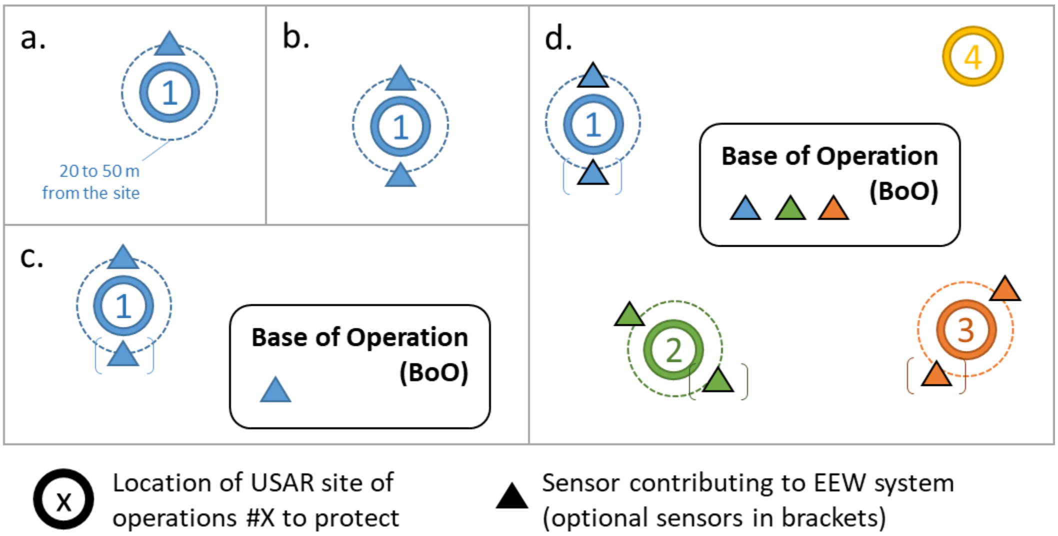


Figure 9. Schematic representation of the different configurations proposed for the deployment of an on-site aftershock EEW solution for USAR teams.

CONCLUSION AND PERSPECTIVES

This study uses the results of a questionnaire survey of 104 USAR team members from 11 different countries, structured to identify the extent to which an EEW system could address the need for protection of rescuers from the high risk of collapse of ruins (in which they operate) due to aftershocks. Although relatively limited, this panel is particularly interesting because it is composed exclusively of specialists in the USAR field. We note that the responses come from international teams scrupulously following the international USAR standards defined in the INSARAG guidelines, as well as from teams with various organizational and response references (national teams and NGOs). The individual respondents had varying levels of experience with post-earthquake USAR missions in real conditions. Aware that this wide variety of respondent profiles is likely to affect the responses collected, we made sure to analyze them in a contextual manner so as to put the results obtained into perspective with the varied practices of USAR teams. Furthermore, as shown in Figure 7, respondents' experience appears to have only a second-order impact on the perceived usefulness of an EEWS.

First, we found that USAR team members were highly exposed to the risk of collapse of vulnerable structures due to their destabilization by aftershocks. This risk results from the prolonged exposure of these first-responders within ruined buildings in the post-seismic period during which the probability of strong aftershocks is the highest. Furthermore, it is interesting to note that the respondents have a clear perception of this risk, and that they measure the critical need for them to protect themselves from it. Thus, the field experience of many rescue workers confirms that USAR operations conducted after destructive earthquakes are frequently interrupted due to the occurrence of aftershocks.

Therefore, it is not surprising to note a very positive and enthusiastic response from respondents to the prospect of being able to react in anticipation thanks to an EEW system capable of issuing an alert a few seconds before the arrival of strong ground motions at the site. With warning times often less than ten seconds, the perceived benefits of these early warnings range from simple psychological preparation to reduce the surprise effect for extremely short alerts, to the possibility of reducing one's exposure to risk by moving to a safe position, going to a safe zone, or stopping dangerous activities when time permits. It is also interesting to note that, contrary to other sectors of activity whose criticality makes false alarms unacceptable and the EEW principle almost inoperative, the impact of isolated false alarms on USAR activities seems relatively limited, which makes it possible to take full advantage of the potentialities of EEW systems by configuring very sensitive triggering thresholds maximizing rescuers' safety.

Finally, this research also provides answers to the rarely addressed question of how the system can be deployed and used operationally. While conventional regional EEW systems are based on fixed perennial seismic instrumentation, the use case considered here implies a capacity for rapid deployment in degraded conditions and on a territory potentially unknown to the responders (in the case of international reinforcements). This turns into strong constraints in terms of weight and size, as well as ease of deployment and configuration.

As the study shows, although USAR practices remain heterogeneous from one country to another, the UN INSARAG group is tending to structure the international USAR community in a profound and lasting way, by proposing guidelines and a certification system aimed at guaranteeing the interoperability of international reinforcements mobilized after the most devastating earthquakes. This is a strong opportunity to go further in the development of EEW solutions for USAR teams. Indeed, beyond the fact that this may constitute a market sector sufficiently homogeneous to motivate the involvement of specialized industrialists, the INSARAG community can facilitate the appropriation of such tools.

Moreover, if this organizational interoperability of USAR teams is coupled with a high-level technological interoperability, it is also possible to consider the exploitation of the principle of hybrid EEW system to improve the early warning performances by networking on-site EEW devices.

Last but not least, it is important to point out that this type of EEW systems would not be able to prevent collapses occuring under static conditions. The risk of collapse therefore remains and must in any case be dealt tactically and operationally (structural monitoring) by the USAR teams.

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