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A R T I C L E I N F O

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A B S T R A C T

During their postseismic interventions, Urban Search and Rescue (USAR) teams are particularly exposed to the risk of collapse of buildings due to aftershocks. Risk reduction requires the capacity building of rescuers to anticipate incoming ground motions and to quickly protect themselves, which makes the concept of earthquake early warning (EEW) particularly interesting. In parallel to the recent scientific advances in EEW, it is crucial to understand what are the real expectations and needs of USAR teams in terms of protection against this risk, and to what extent EEW solutions could meet them. In this study, we conduct a survey to collect insights from 104 USAR rescuers (32 teams represented from 11 countries). Results highlight that aftershocks are a major concern for rescuers, and that the current tools and procedures do not allow an effective protection. 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. Depending on the time available, the perceive benefits range from simply reducing the surprise effect to moving teams into safe areas and stopping dangerous operations. Combined with the opportunities offered by the miniaturization of seismic monitoring means and by the high level of interoperability of USAR teams on an international scale, this study also 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.

1. 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 [1–3]. In fact, most survivors are found within the first 72 h, 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.

In practice, the first response is community-based, thanks to citizens who intervene spontaneously in the immediate aftermath of a collapse [4], followed by the organized first-response of local emergency services within minutes [5], assisted by specialized Search & Rescue (SAR) reinforcements within hours. When the situation requires it, international reinforcements may be needed, mobilized through bilateral mutual aid agreements between countries or international civil protection mechanisms, such as the European Civil Protection Mechanism (EUCPM), and which arrive in a staggered manner over several days. Over time, the response becomes more intense and effective, and often continues beyond the period during which the probability of finding survivors is significant.

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 [6]. In addition, USAR activities must contend with particularly large "barrier effects" that can delay access for rescue teams, such as street blockage by rubble, or crowds of people [7].

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1.1. 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 [6,8]. 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), with the initial objective of formalizing and developing local initiatives to improve coordination following the destructive earthquakes in Mexico in 1985 and Armenia in 1988. Under the auspices of the UN Office for the Coordination of Humanitarian Affairs (OCHA), it now brings together more than 90 countries and/or organizations around the world, and its mission is to strengthen the effectiveness and coordination of international assistance in the USAR.

INSARAG’s work has led to the development of procedures and standards (INSARAG guidelines), the development of the concept of the On-Site Operations Coordination Centre (OSOCC) which designates both a methodology and a physical location for on-site emergency response and coordination, and the development of an external INSARAG classification system (IEC) for USAR teams. This IEC procedure allows the classification of USAR teams into 3 levels according to their size and capabilities: Light, Medium and Heavy teams.

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. In 2010, the INSARAG Hyogo Declaration encourages USAR teams operating internationally to follow the IEC process, and affected states requiring reinforcements to give priority to the IEC classified teams [9].

1.2. 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. Indeed, the period following the occurrence of a major earthquake is characterized by a period of increased probability of aftershocks [10,11]. Thus, the probability of occurrence of at least one aftershock of magnitude (Ma) greater than or equal to that of the mainshock (Mm) minus 1 (Ma $\geq$ Mm-1) is on the order of 60% during the first 15 days during which the life-saving phase is concentrated [12]. 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. [13] 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 (New Zealand’s Darfield earthquake in 2010) to a few weeks (California’s Loma-Prieta earthquake in 1989 and Northridge earthquake in 1994, Nepal’s Gorkha and Dolakha earthquakes in 2015). A quick analysis of the major earthquakes in Europe since 2000 that have resulted in USAR operations shows that the occurrence of aftershocks causing relatively high levels of shaking in the area affected by the mainshock is frequent (Fig. 1). In particular, if one considers that, for partially collapsed buildings inside which USAR teams are searching for victims, a risk of collapse may appear from a macroseismic intensity level of VI (or even V-VI for very unstable ruins: [14,15], 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 (see Fig. 6). 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 [6].

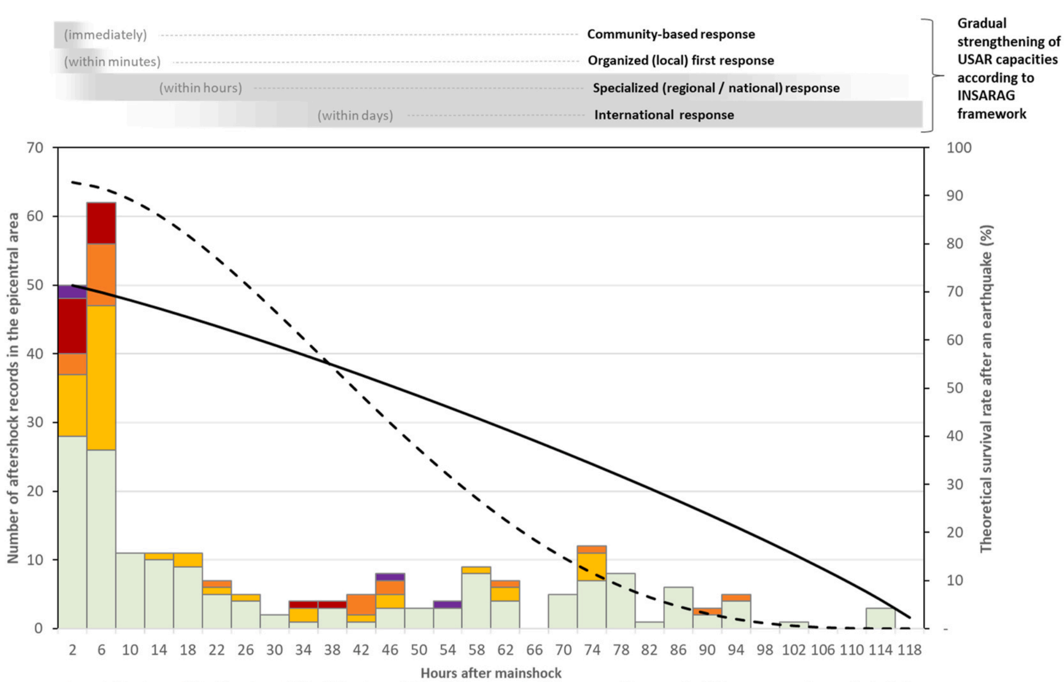


Fig. 1. Intensity values (deduced from PGA thanks to the Ground motion to intensity conversion equation from Ref. [36] of aftershocks recorded over the first 5 days after the main European earthquakes that have occurred since 2000 at seismological stations located in the epicentral area (data coming from the European Engineering Strong-Motion Database: ESM - https://esm-db.eu/#/home). Also shown is an assessment of the survival rate of people stranded in rubble masonry & concrete buildings, according to the model from Reinoso et al. [3]; as well as the schematic timing of the ramp-up of USAR capabilities.

1.3. 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 [10,11]. 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 [16,17]. 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. Following this principle, the Operational Earthquake Forecasting (OEF) approach, which evaluates an updated estimate of the probability of an earthquake occurring over a short period of time (a few days to a few weeks), remains for the same reasons inappropriate for the protection of USAR teams, although it can be very useful for the anticipation of other safeguard measures [18].

Guaranteeing the safety of rescuers is one of the highest priorities for USAR operations [6]. 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. Among these tools, the most used remains the alarm telemeter, which is based on the pointing of a laser beam towards a target structure (located at a maximum of about 40 m from the sensor). In case of a multi-millimeter displacement of this structure in the direction of the laser beam, the device emits an audible alarm. As soon as the device goes into alarm, the USAR operations must stop and the rescuers must evacuate to a clearly identified regrouping point. In practice, the installation of the device allows for sub-horizontal monitoring, and therefore limits the detection of vertical movements. While this type of device can be useful for monitoring damage to buildings that could lead to their collapse - including damage caused by ongoing operations (drilling, shoring, technical research) - or the horizontal movement of structures under the effect of wind, it is unable to detect the effects of sub-vertical incident *P*-waves in advance. Other stability controllers seem to offer good performances (see section 3.2.2), 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 the passage of seismic waves. A system detecting seismic waves themselves and predicting the shaking strength so that teams can apply safety measures makes sense in this context: that's the main goal of Earthquake Early Warning (EEW) systems, which constitute the focus of this study.

2. From mainshocks to aftershocks early warning

2.1. General principle of earthquake early warning

In 1868, Cooper [64] 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 km 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. Although other approaches exist today (some use for example real-time geodetic data: [19], most of the modern EEW systems are still based on this principle. They can be divided into three broad categories [20,21]:

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 [22,23].
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, without necessarily going through an evaluation of the source parameters [24,25].

Regional EEW systems generally provide more accurate estimates of source parameters [26], 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 [27,28]. 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 [29,30]:

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.

2.2. 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 [31]. 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 [32]. 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 s after the arrival of the P phase. The most commonly used proxy parameters are the initial displacement peak Pd (Wu & Kanamori in 2005 [33]; and the mean period τc [27].

Methods based on the on-site EEW approach such as that of Zollo et al. [29] seem relatively reliable. For example, the "SAVE" algorithm from Caruso et al. [25] presents between 72% and 81% of good prediction of the intensity class (depending on whether we analyze 1s or 3s of the *P*-wave signal), for lead-times varying between 3 and 5–6 s for targets located respectively at about 20 and 30 km from the epicenter. Interestingly, the authors report obtaining positive lead-times as soon as the target is located more than 10 km from the epicenter.

Recently, new approaches have also been proposed to advantageously bypass empirical correlation equations relating proxies to target parameters, using machine learning techniques [34,35]. 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. To this end, Hsu et al. [28] propose two automatic classification methodologies specifically adapted to on-site EEW systems, which present very good performance when the amplitude of the shaking is greater than or equal to 0.025 g, which corresponds approximately to a macro-seismic intensity of IV-V [36]. Finally, several studies suggest that on-site EEW algorithms can be applied using low-cost microelectromechanical systems (MEMS) accelerometers [37–39], 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. In fact, the suboptimal performance of EEW systems during aftershock sequences remains an open issue [40]. Indeed, it is sometimes difficult to distinguish seismic signals generated by aftershocks that occur almost simultaneously. In cases where records from different aftershocks are improperly considered to come from a single aftershock, the magnitude of this fictitious event may be greatly overestimated. Fortunately, this problem is much more critical for regional EEW systems than for on-site systems, because on-site systems consider each record individually and are primarily concerned with evaluating the intensity of the strong motion and not the parameters of the earthquake.

2.3. 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 [41] to consider the development of an “Aftershock Prediction System” as a high priority. More recently, Statheropoulos et al. [6] 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 Japanese company System and Data Research (SDR). This company is notably known to be the originator of the world’s first on-site EEW system - UrEDAS [42] -, as well as of many other models used operationally in Japan, notably in the field of public transport (high-speed rail transport, [43]; and subway, [44]. Among the EEW systems proposed by SDR, the FREQL-light portable model was designed to be easily deployed in the field [32]. 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 [45]. 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.

Although the explanations are very incomplete, it seems that a Chinese equivalent of this system exists, documented in particular by press articles, as well as by two related patents relating respectively to (i) “On-site aftershock warning apparatus for rescue” (2011)[1] and (ii) “Portable region multi-point wireless aftershock early-warning and alarm device” (2014).[2]. Finally, we can mention the initiative of the New Zealand company *Roam3* - which seems to have ceased its activity today - that has developed a prototype EEW solution for first responders. After developing a first version of their prototype in 2010, they claim to have operated a free system for USAR teams after the Christchurch earthquake of February 21, 2011 (author’s personal communication).

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 [46]. 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 [46–49]. Despite some specific lessons from previous studies (e.g. Refs. [17,46], 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.

3. Users survey

As Becker et al. [46] state, *“understanding people’s perspectives should be the first, not last, step of developing and operationalising 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” [51].

Regarding the specificity of the USAR community, some interesting insights are given to us via two studies conducted in New Zealand following the 2010 Darfield earthquake and the subsequent seismic sequence. For example, in a study dedicated to identifying information needs about aftershocks, members of New Zealand USAR teams indicated that they needed to be able to identify seismically quiet periods that were sufficiently calm to be able to tend safely to search and rescue victims [17]. This is very interesting because, in the absence of being able to identify these periods of calm during which the teams can work safely, EEW’s approach precisely takes the problem in reverse by identifying an imminent danger requiring the cessation of rescue operations. However, the perceived usefulness of early aftershock warnings is also mentioned by USAR teams, who also seem to want to be alerted for relatively low levels of shaking (macroseismic intensity around IV to V) compared to other audiences interviewed, attesting to their overexposure to the risk of collapse in the event of aftershocks [46]. While very interesting, these few insights reflect the views of only a few individuals, and are not specific enough to guide the development of a specific EEW solution.

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 (see section 1.1) provides a rare opportunity facilitating comparative analysis of feedback from practitioners with relatively homogeneous operational cultures and practices.

3.1. Methodology and data

Like Becker et al. [50]; we chose to gather information via the conduct of a questionnaire survey, following a deductive approach [52]. 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) - (Table 1). The survey was conducted online via the Microsoft Forms tool from April 21, 2021 to June 1, 2021. Thanks to the support of the INSARAG French operational focal point, 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 2). It is worth noting that some questions were not completed by all respondents, either in the case of non-applicable questions (e.g., respondents who had never participated in a postseismic USAR mission

[1] Patent CN202404715U (https://patents.google.com/patent/CN202404715U/en).

[2] Patent CN105185045B (https://patents.google.com/patent/CN105185045B/en).

Table 1
Presentation of the constituent questions of the questionnaire, as well as the number of responses obtained to each of them.

Section	Question		Possible answers	Nb. answers
Profile	1	Entity	*Open question*	104
	2	Your function within your entity	*Open question*	104
	3	Do you belong to an urban search and rescue team (USAR)?	Yes/No	104
	4	Which USAR team do you belong to?	*Open question*	99
	5	Is your team INSARAG affiliated?	Accredited/Ongoing/No	99
	6	What is the classification level of your national team?	Heavy (HUSAR)/Medium (MUSAR)/Light (LUSAR)	42
	7	What is the accreditation level of your international team (either already obtained, or applying to)?	Heavy (HUSAR)/Medium (MUSAR)	2
	8	What is your role within the team?	*Open question*	99
	9	What is your expertise related to USAR operations?	*Open question*	5
Experience	10	Have you ever felt earthquakes?	Yes/No	104
	11	How many times have you already intervened for USAR operations after earthquakes?	Once/Twice/More than twice/Never. I have only participated to exercises/Never. I have participated in USAR operations for disasters other than earthquakes	104
	12	Can you tell us in which countries and after which earthquakes each of these missions took place?	*Open question*	48
	13	How long after the earthquake did your team arrive on site?	<12 h/12–24 h/24–48 h/3–5 days/> 5 days	48
	14	How long did the mission last?	1–5 days/6–10 days/11–15 days/> 15 days	48
	15	During these missions, in what types of environment did your team intervene? - Total ruins of buildings no longer at risk of collapse - Severely damaged structures with a significant risk of collapse (partial or total) - Damaged structures with a moderate risk of collapse (partial or total) - Structures not presenting a risk of collapse	Very frequently/Frequently/Occasionally/Rarely/Never	48
	16	Did any aftershocks disrupt USAR operations?	Yes/No/Don't know	47
	17	Can you specify the nature of these disturbances (if applicable)?	*Open question*	29
Risk of aftershocks	18	In your opinion, what is the level of risk represented by the occurrence of aftershocks for post-seismic USAR interventions? - For your team members - For search dogs - For intervention equipment	Very high/High/Moderate/Low	103
	19	According to you, what could be the consequences of these aftershocks for your team during its interventions?	*Open question*	96
	20	Within your team, do you have procedures adapted/specific to the risk represented by the occurrence of aftershocks (monitoring, reflex action, etc.)?	Yes/No/Don't know	103
	21	Can you describe them?	*Open question*	68
	22	Within your team, do you have tools or equipment adapted/specific to the risk represented by the occurrence of aftershocks (early warning, stability controller, etc.)?	Yes/No/Don't know	103
	23	Can you describe them?	*Open question*	49
Utility of aftershocks early warning	24	In your opinion, would it be useful to have an early warning of the imminent occurrence of strong motions related to aftershocks? - Less than 2 s before the arrival of shaking - Between 2 & 5 s before the arrival of shaking - Between 5 & 10 s before the arrival of shaking - Between 10 & 20 s before the arrival of shaking	Useless/Not very useful/Quite useful/Very useful	104
	25	What do you think would be the possible actions upon receipt of a 2 s early warning (ex. stopping delicate operations such as drilling/lifting, evacuate the buildings, etc.)? What are the expected benefits of	*Open question*	92

(continued on next page)

Table 1 (*continued*)

Section	Question		Possible answers	Nb. answers
		these actions (e.g. enhanced protection of team members)?		
	26	What do you think would be the possible actions upon receipt of a 5 s early warning (ex. stopping delicate operations such as drilling/lifting, evacuate the buildings, etc.)? What are the expected benefits of these actions (e.g. enhanced protection of team members)?	*Open question*	94
	27	What do you think would be the possible actions upon receipt of a 10 s early warning (ex. stopping delicate operations such as drilling/lifting, evacuate the buildings, etc.)? What are the expected benefits of these actions (e.g. enhanced protection of team members)?	*Open question*	94
	28	What do you think would be the possible actions upon receipt of a 20 s early warning (ex. stopping delicate operations such as drilling/lifting, evacuate the buildings, etc.)? What is the expected utility of these actions (e.g. enhanced protection of team members)?	*Open question*	92
	29	In your opinion, what would be the impact of a false alarm (i.e. early warning but no shaking) in terms of … ? - Waste of time (stoppage of operations) - Loss of confidence in the system	Very low/Low/Moredate/High	104
	30	Could you be more precise?	*Open question*	78
Deployment of the system and dissemination of the alert	31	How important are the following functionalities to you? - Make configurable the threshold of expected level of shaking intensity for which to issue an alert - Announce the time remaining before the onset of shakings	Not important at all/Not very important/Important/Very important	104
	32	How important are the following characteristics to you? - Minimal size - Minimal weight - Autonomous in energy (battery operated) - Mobile system easy and quick to deploy - Mobile system easy and quick to configure	Not important at all/Not very important/Important/Very important	104
	33	In order to improve the reliability of the early warning system, do you think it possible to … ? - Network your device with compatible ones from other USAR teams (under the coordination of the UCC for example)? - Have a system made up of several devices to be deployed around the intervention site?	Yes/No/Don't know	104
	34	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)? - From 20 to 50 m - From 50 to 100 m - More than 100 m	Yes/No/Don't know	104
	35	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	104

did not complete questions #12 to #17), or in the case of open questions that were not mandatory.

3.1.1. *Limitations*

Allowing the initial recipients of the survey to distribute the link to the questionnaire, as noted above, resulted in an over-representation of American respondents (80% of the responses received), with only 2 INSARRAG classified teams out of 18 teams represented, and 3 teams with more than 10 respondents. Because of this imbalance in the sample, we conducted an analysis of the responses from the American teams, and did not find any systematic bias in the responses, with the exception of

Table 2
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**	

question 5.64% of the American respondents indicated that they did not belong to an INSARAG-affiliated USAR team, whereas, with the exception of France, where one respondent belonged to a non-INSARAG-affiliated NGO, all of the other USAR teams represented were. However, this INSARAG affiliation criterion is not discriminating, as non-affiliated teams may have significant post-seismic USAR experience.

Similarly, even though the target audience was primarily active USAR team members, the responses from 5 respondents who indicated that they did not consider themselves as active USAR members are still interesting, as all of them indicated that they had participated in USAR postseismic missions in the past. These are mostly coordinators with extensive experience. Also, with the objective of focusing more on the diversity of individual views of each respondent rather than on the institutional positioning of the USAR teams, we decided to keep this inhomogeneity of the provenance of the responses, with a case-by-case discussion of the impact this may have.

3.2. *Analysis of results*

3.2.1. *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. Having experienced aftershocks, having been confronted with frequent aftershocks during a post-earthquake response, or even having feared for one's own safety during such aftershocks necessarily affects individual perception of the risk presented by aftershocks, and of how to protect oneself effectively against them. For this reason, 8 questions (from 10 to 17) 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 (question 10), 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% (question 11). 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 (Table 3). Analysis of the responses to question 12 from the 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 (Fig. 2). Thus, for some of the following questions (13, 14, and 16), 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 h after the earthquake occurred, and 84% within the first 48 h (question 13 and Fig. 3). In terms of the duration of the missions in which the respondents took part (question 14 and Fig. 4), these were relatively long, most often lasting from 11 up to 15 days (43%).

It should be noted, however, that the answers vary greatly from one earthquake to another. For example, the deployment of USAR teams whose members responded to the survey seems at first glance to have been particularly prompt following the 2010 Haiti earthquake, with 57% of respondents arriving in the area within the first 24 h, for a relatively long commitment of over 11 days in 76% of cases. However, this trend is mainly due to the activity of two American INSARAG-certified teams (USA-01 and USA-02) whose deployment was

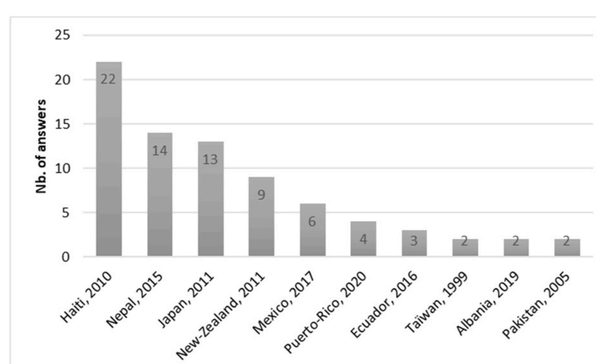


Fig. 2. Answers to question 12 – "Can you tell us in which countries and after which earthquakes each of these missions took place?"

Table 3
Answers to question 11 - "How many times have you already intervened for USAR operations after earthquakes?"

1	2	≥2	Never. I have participated in USAR operations for disasters other than earthquakes	Never. I have only participated to exercises
21 (20.2%)	3 (2.9%)	28 (26.9%)	37 (35.6%)	15 (14.4%)

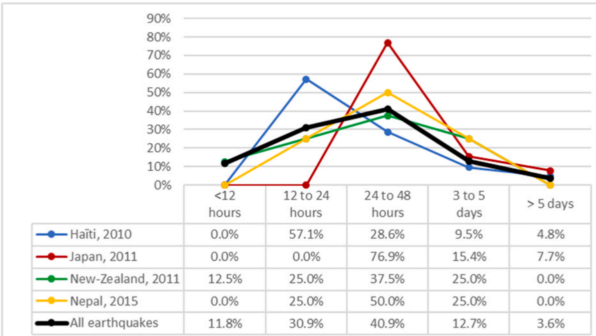


Fig. 3. Answers to question 13 – "How long after the earthquake did your team arrive on site?"

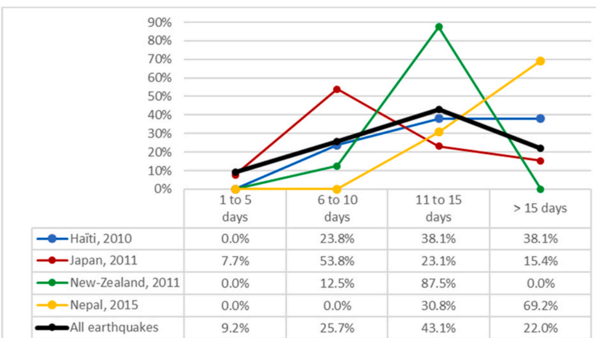


Fig. 4. Answers to question 14 – "How long did the mission last?"

particularly quick due to the geographical proximity between the two countries. On the other hand, the arrival of the teams represented in the survey reveals a later arrival following the 2011 Japanese Tohoku earthquake (77% of the arrivals between 24 and 48 h after the earthquake), for relatively short missions of less than 10 days in 62% of cases. This can be explained first by the longer time it takes to get to the site due to the fact that the respondents are mostly located far from Japan, but it also reveals more complex dynamics that combine the USAR capacities of the affected countries (i.e. weak USAR self-capacities in Haiti and strong in Japan), and international diplomacy issues that can in some cases delay the request for international assistance.

Above all, 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 question 15 also 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. This figure rises to 81.2% for interventions in buildings with a moderate risk of collapse (Fig. 5).

Therefore, it is not surprising to find that aftershocks disrupted USAR operations in 70% of the postseismic missions in which the respondents participated (Fig. 6). Responses to open question #17 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."

> "Search elements inside collapsed structure took a tactical pause to evaluate escape possibilities during an aftershock."

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

> "Falling objects from floors and roof, weakening of the building severely cracked."

> "Violent aftershocks resulting in persons trapped and injured"

In this regard, it is noteworthy that the 2011 Tohoku earthquake visibly results in a lower proportion of USAR operation suspensions due to aftershocks (36% - Fig. 6). This illustrates perfectly that aftershocks following powerful, devastating earthquakes that occur offshore (especially in subduction zones) present a lower risk to USAR teams, as the associated seismic ground motions are usually strongly attenuated when

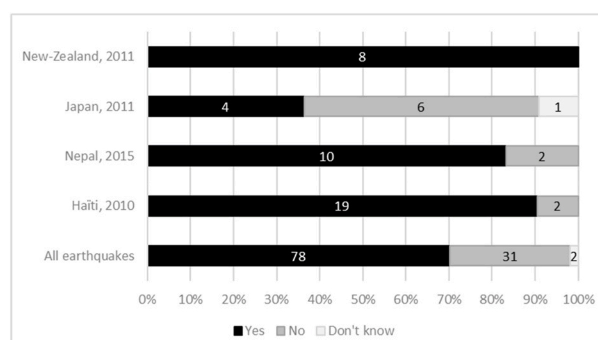


Fig. 6. Answers to question 16 – "Did any aftershocks disrupt USAR operations?"

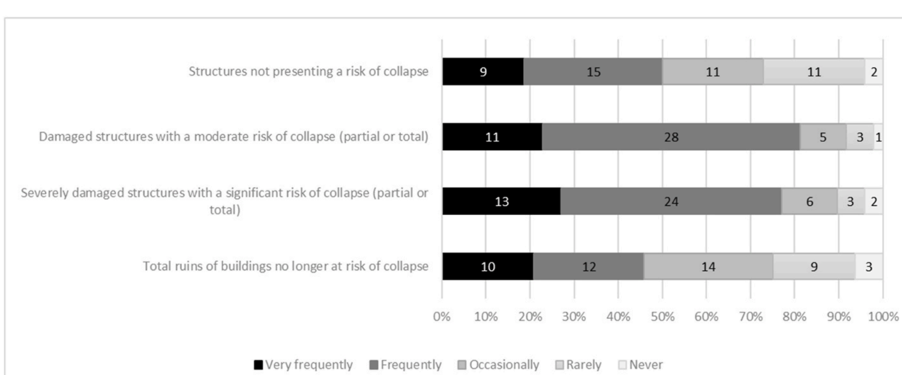


Fig. 5. Answers to question 15 – "During these missions, in what types of environment did your team intervene?"

reaching the coast.

3.2.2. Perception and management of aftershock risk

While the description of the conditions of engagement of USAR teams reported in section 3.2.1 shows a significant exposure of USAR teams to the risk of collapse of structures following aftershocks, 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 (67.0%), then by the intervention equipment (49.5%) (Table 4). Once again, answers to open question #19 about possible consequences of aftershocks are very instructive. For example, one respondent points out that assessing the actual level of collapse of a ruined building in the event of an aftershock is difficult, and sometimes underestimated:

> "We know that many partially damaged buildings do not often show how close to collapse they actually are and that rescue teams could be operating in buildings that could experience a total collapse."

The responses to question 19 essentially reflect the fact that 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:

> "Team members could be trapped under the rubbles, injured or killed specifically when they drive difficult operations like cutting or breaching concrete under the rubble in small space in order to access to the victim."

> "If necessary, operations would be shifted to rescue and recover trapped rescue personnel."

> "Team members can become trapped injured or killed as a result of aftershocks. It could delay the rescue operation resulting in more casualties. It may decrease the functional capability of the team or even disqualify it from being operational. If members become killed, it will have a significant impact on physical and psychological state of its members."

The level of risk linked to aftershocks also seems in some cases unacceptable for some rescuers, in view of the missions to be accomplished. Indeed, if the primary mission of USAR teams is to rescue victims who are still alive in the first hours to days after the earthquake, this mission often evolve with time into identifying and sometimes extracting victims who are already dead, as the probability of finding survivors decreases:

> "Some team members quit because they felt the reward (recovering bodies) did not justify the risk."

Here are some other interesting comments made by respondents:

- Equipment needed for USAR operations is also vulnerable and can be damaged or lost: *"We can also lose a part of our equipment during evacuation of the worksite."*
- Escape capabilities of buildings can be altered or eliminated by aftershocks: *"Depending on safety zones in the building, there may be limited escape possibilities if a secondary collapse were to occur."*

- Frequent aftershocks can create stress for teams, which can result in an impairment of their operational capacity: *"The threat or presence of aftershocks either inhibit the team engagement, or place the members in high risk situations while engaged."*

To face this danger, 68.9% of the respondents indicate that they have either adapted or developed specific procedures for aftershocks (Table 5). This figure increases significantly among members of INSARAG-affiliated teams to 95.5%, which is not surprising since INSARAG gives very clear instructions in this matter (Appendices B17 and B18 of volume III of the INSARAG guidelines). As the answers to open question 21 indicate, such procedures usually consist of:

- If available (see below), continuous monitoring of building stability;
- Procedure and means for issuing an audible alert throughout the site;
- Evacuation of all team members from the work site to a pre-determined safe zone, where a head count of team members can be performed to check that no one is missing;
- For any trapped team members, take refuge in an identified "safe zone" within the building:

  "During breaching operations within a building (long tunneling operations) a safe zone is created within the structure through the use of cribbing. This zone is for members inside the structure who are unable to exit the building."

- Reassessment of the vulnerability of buildings by the structural engineer.

On the other hand, only 52.4% of the respondents report having in their team an early warning or stability control tool (Table 5), a figure that reaches 61.3% among INSARAG-affiliated team members. The two most commonly used types of tools are the alarm telemeters already mentioned in section 1.3, and the so-called Warning Alarm Stability Protection Device (WASP), which are very sensitive stability controllers specifically designed for the needs of USAR teams, and which are positioned directly on the structures to be monitored. We can quote here one of the answers to question 23 which allows us to better understand how these tools are used:

> "We use laser telemeters pointed at different angles of the building to appreciate the slightest movement of the structure. These devices have a powerful audible alarm. In addition, a team member staying outside the building to monitor the stored equipment observes the environment to give the alert if necessary with a foghorn."

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

Table 4
Answers to question 18 – "In your opinion, what is the level of risk represented by the occurrence of aftershocks for post-seismic USAR interventions?"

	Very high	High	Moderate	Low	Very low
For your team members	39 (37.9%)	36 (35%)	19 (18.4%)	5 (4.9%)	4 (3.9%)
For search dogs	32 (31.1%)	37 (35.9%)	20 (19.4%)	12 (11.7%)	2 (1.9%)
For intervention equipment	19 (18.4%)	32 (31.1%)	38 (36.9%)	9 (8.7%)	5 (4.9%)

Table 5
Answers to questions 20 & 22 "Within your team, do you have procedures or tools adapted/specific to the risk represented by the occurrence of aftershocks (monitoring, reflex action, etc.)?"

	Yes	No	Don't know
Procedures	71 (68.9%)	12 (11.7%)	20 (19.4%)
Tools	54 (52.4%)	30 (29.1%)	19 (18.4%)

with INSARAG.

3.2.3. *Utility of aftershocks early warning*

The next section of the questionnaire, which consists of 7 questions, 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 [46,47], it first emerges that the perceived usefulness is stronger the longer the warning time (Fig. 7). 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 s due to specific regional configurations with a large distance between seismic sources and target areas (e.g., the Mexico City EEW system that is far from the Guerrero seismic zone - [53] - or Budapest that is far from the Vrancea seismic zone - [54], 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 s for targets located respectively at about 20 and 30 km from the epicenter, with values of 8–10 s obtained only at about 50 km from the epicenter [25]. 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 to question 24 consider an EEW to be useful to very useful for a warning time of between 10 and 20 s. This figure decreases to 79.8% for alert times between 5 and 10 s, to 35.6% for alert times between 2 and 5 s, and finally to 30.8% for alert times lower than 2 s. Although the perception of usefulness only becomes the majority when the alert time exceeds 5 s, it is interesting to examine carefully the actions envisaged by the respondents in the different hypotheses (answers to questions 25 to 28), 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 s. 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.

However, it is interesting to note that there are also a large number of parameters that can critically affect the effectiveness of early warning. For example:

- Ability of the teams to hear the alert (in the case of an audible alert):

  "[ndlr. Difficult] to even register the warning due to high ambient noise during operations"

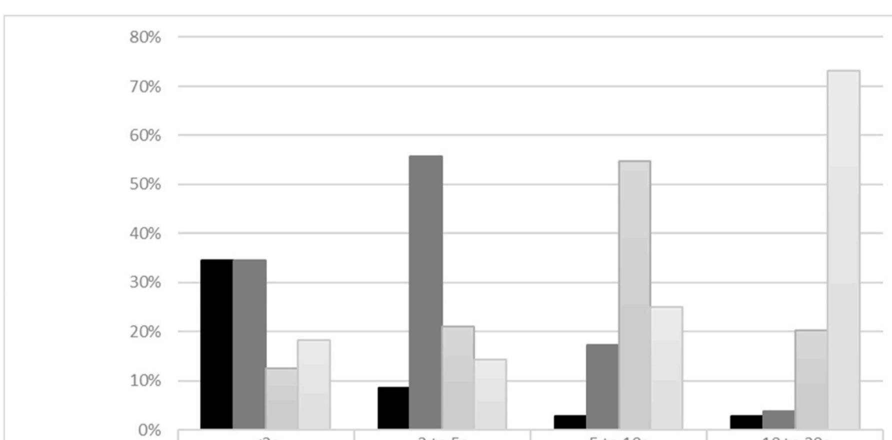
- Rescuers' reaction time:

  "In general, people need time to understand what is going on. This time increases when people are tired after several hours of operations."

- Specific intervention configurations within damaged buildings:

  "From my experience, while tunneling through a rubble in the multi-story pancake collapse building, sandwiched between two floors where it is hard to take a deep breath [...] stopping the operation will not prevent aftershocks and evacuating to a safe area would be impossible."

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). Although this is a notable limitation to the completeness of our survey, we decided to address this issue with only one question (#29) related to the impact of false alarms. This choice was motivated by previous discussions between the authors of this study and USAR experts who pointed out that USAR teams do not hesitate to stop operations in case of doubt - thus presenting a "risk averse" profile (personal communication). While we did not investigate the question of the impact of missed alerts, we argue that this



	<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%

Fig. 7. Answers to question 24 – "In your opinion, would it be useful to have an early warning of the imminent occurrence of strong motions related to aftershocks?"

simplification of the questionnaire avoided the risk of confusion between falsed/missed alerts by focusing on the most important element for our use-case.

Fig. 8 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, with 40.4% of respondents judging the impact to be high to very high, compared to 33.7% who judged it to be low to very low (Fig. 11). 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, as shown by some of the answers to the open question #29:

> "A system that would have a false alarm would simply be the price to pay for safety. Unless there were multiple false alarms, rescuers would appreciate the safety measure."

> "As long as the warning system only gives the occasional false alarm, there won't be a big impact. In fact, it can focus awareness on planning for the aftershock that will eventually come."

> "If the system delivers very frequent false alerts, it will get turned off. If a few false alarm are given, but it also alerts to real events, the impact would be acceptable."

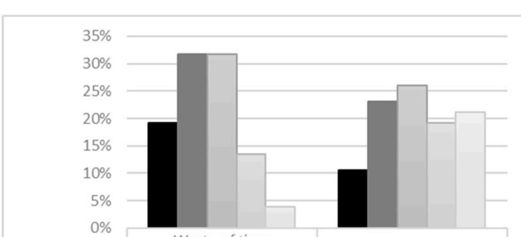
> "I would rather have a warning and keep people safe, whether you need it or not, than to never have waring at all"

> "Life safety for the rescuers safety must be paramount in this process, erroring on the side of safety should be our philosophy."

3.2.4. *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 (question 31): (1) being able to self-configure the trigger threshold in terms of predicted macroseismic intensity, and (2) being informed of the estimated time remaining before



	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%

Fig. 8. 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 … ?"

the arrival of shaking. Fig. 9 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. It should also be noted that 35.6% of respondents consider both of these two features as being important or very important.

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 [55], 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 (question 32), 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 (Fig. 9). 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.

As described in section 2, 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. [29]. In order to assess whether this type of configuration is realistic with respect to the contingencies of the USAR teams, question 33 aimed to identify to what extent sensor networking would be feasible. Table 6 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.

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) [25]. 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. Answers to question 34 (Fig. 10) clearly show that the respondents consider such a distance to be all the more difficult the further away it is: if a distance of 20–50 m seems entirely feasible (92% without taking into account the people who have no opinion on the question), the perception of the feasibility of a greater distance of 50–100 m is less unanimous (71.8% of positive answers). Moving the measurement sensor more than 100 m away from the intervention site seems difficult to envisage (49.3% of positive responses). 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

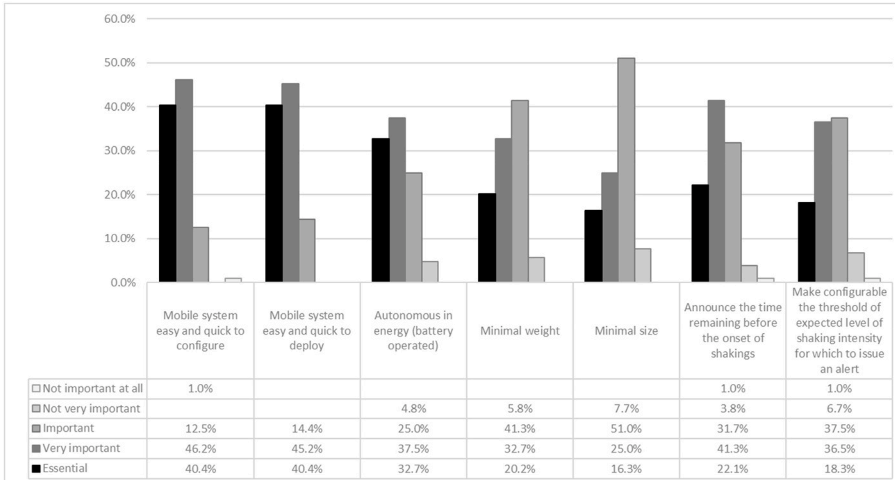


Fig. 9. Answers to questions 31 & 32 - "How important are the following functionalities & characteristics?"

Table 6

Answers to question 33 – "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%)

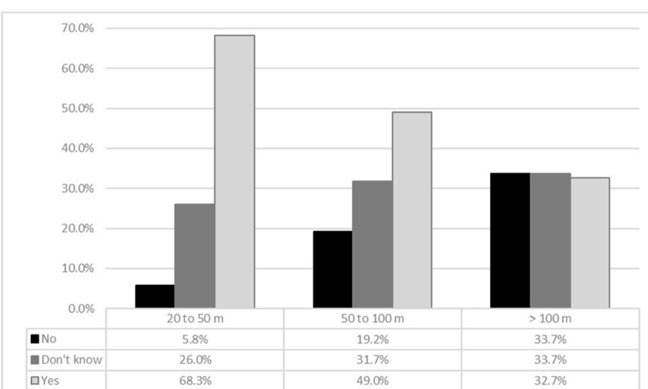


Fig. 10. Answers to question 34 – "In order to reduce interference from the seismic wave recording sensor, do you think it possible to move the monitoring device away from the intervention site (away from generators in operation and drilling operations)?"

sector, often very close to the site where the searches are carried out.

Finally, the last question concerned the identification of the most appropriate modalities for disseminating early warning to the members of a USAR teams. The preferred modality is clearly the broadcasting of an audible alert that can be heard by everyone on the intervention site (66.3% of responses), far ahead of the possibility of equipping each member with portable receivers (24.1%). 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 7).

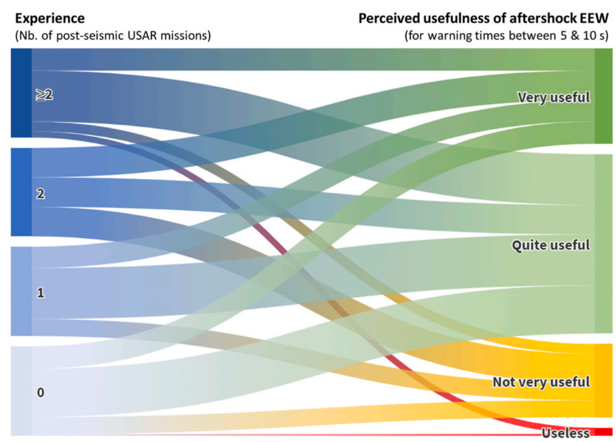


Fig. 11. Dependence of perceived usefulness of an EEW system (for a warning time between 5 & 10 s - question #24) on respondents' experience in terms of postseismic USAR missions (question #11). The thickness of the lines is proportional to the number of answers after normalization so that each "Experience" category is equal.

Table 7

Answers to question 35 – "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%)

4. Discussion

Based on the responses received presented in section 3.2, 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 is illustrated in Fig. 11 for warning times ranging between 5 and 10 s, but the answers given for the other classes of warning times (i.e. less than 2 s, 2–5 s, and 10–20 s) confirm this trend. 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. [46]; Fig. 12 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 Fig. 12 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 [56].

It is important to underline that we have chosen to question rescuers only on their perception of the impact of positive warning times. In doing so, we did not address the case of negative warning times (i.e. strong motion arriving before the warning), with the risk of maintaining the misconception that EEW systems always provide positive warning times [57]. This choice is justified by our desire to not confuse respondents so that they can focus on listing actions that seem for them useful and feasible in response to receiving positive warning times, which were some of the main pieces of information we wanted to identify through this survey.

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 [58]:

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 h 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 h 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 h 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 (volume and weight reduction), 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 Officer present in each USAR team (specific position within the LUSAR, MUSAR and HUSAR teams), 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. Thus, the main technical specifications of this EEW dedicated to the USAR teams are reported in Table 8.

Most of these specifications 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. Moreover, the improving resolution of these strong-motion sensors now allows to obtain good recordings, including for low magnitude earthquakes recorded at short distance (which is the case for aftershocks presenting a danger for USAR teams), allowing a satisfactory extraction of the spectral response [59]. A recent study by D'Allessandro et al. [60] confirms that these sensors are suitable for the specific case of on-site EEW. Finally, these MEMS-sensors can be easily controlled via microcontrollers (such as open-source Arduino solutions) allowing a total miniaturization of the early warning solution [61]. That said, it is important to note that such solutions must be "hardened" and incorporated into robust casings to be useful under operational

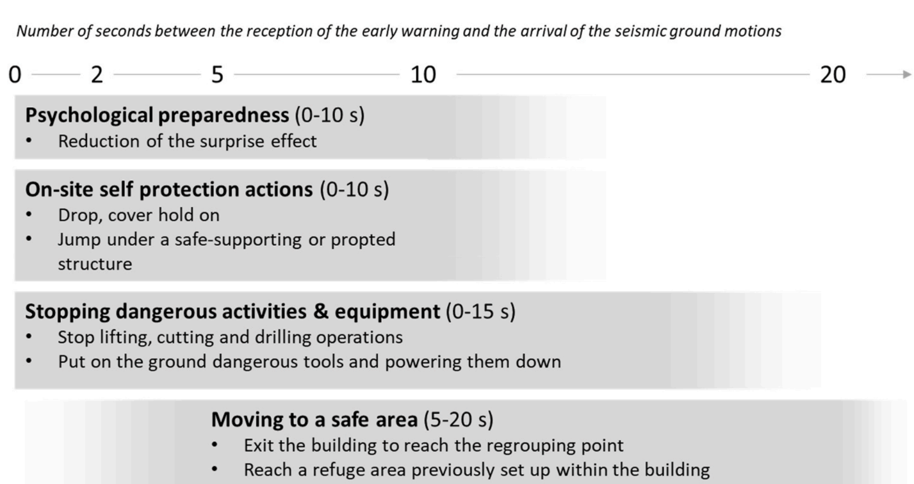


Fig. 12. Typical actions that can be taken by USAR team members based on available alert time.

Table 8
Technical specifications for a mobile aftershock EEW system for USAR teams.

Specifications	USAR needs	Consequence for the EEW solution
Material characteristics	Minimum size	Reduce the weight and volume of the EEW device as much as possible
	Stand-alone solution not dependent on third-party tools	EEW system based on the "on-site" stand-alone approach
	Eventually: possibility to network with EEW solution from other teams	*Develop a system that can operate according to the so-called "hybrid" stand-alone/network-based EEW approach*
	Solution that can run on battery power, or alternatively be powered by a generator	Due to the seismic noise induced by diesel generators, it is better to operate the EEW device on batteries, limiting its power consumption and excluding lithium batteries because of air transportation restrictions according to IATA rules
	Mobile solution easy and quick to deploy and configure	Facilitate the use of the system by non-specialists
Functionalities	Early warning of imminent shaking of a given intensity	Make configurable the level of intensity to be predicted in order to issue an early warning adapted to the level of vulnerability of the structures
	Quantify the time between the warning and the arrival of strong motion	Allow the assessment of the lead-time
	Immediately broadcast of the alert to all team members	To emit an audible alert powerful enough to be heard and understood without delay by all rescuers present on the site, outside and inside the structures, doubled if necessary by the sending of the alert on portable receivers (watch, bracelet)

conditions by USAR teams, in such a way that they can withstand operation in degraded configurations.

Close examination of how USAR teams operate in the field also allows us to imagine different modes of deployment of EEW solutions (Fig. 13):

- 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 listed in Table 8. 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.

It is noteworthy that 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 center). 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. However, recent wireless networking geophone arrays for

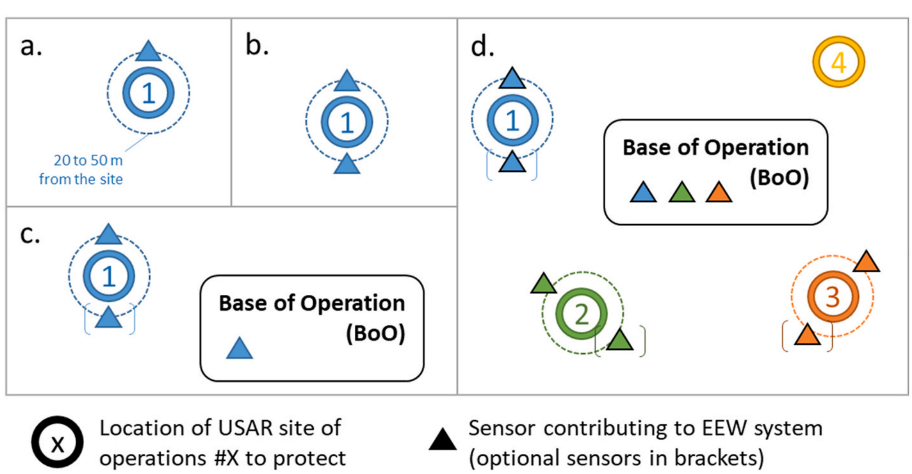


Fig. 13. Schematic representation of the different configurations proposed for the deployment of an on-site aftershock EEW solution for USAR teams.

microseismic monitoring show that the cost of an EEW system with networking capabilities may still be reasonable [62], although R&D is needed to develop a prototype suitable for specificities of postseismic interventions.

5. 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 the particularly high proportion of American respondents compared to other nationalities, and on the contrary the very low participation of some regions (Asia, Middle East, Africa). Furthermore, 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 Fig. 11, 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. In the absence of a tool that would allow them to anticipate the imminence of seismic strong motions, the members of USAR teams act in reaction to the perception of these motions, with the primary objective of getting to safety with respect to the residual risk (potential new seismic shocks in the near future or collapses delayed in time), then to take stock of the situation (to ensure the integrity of the rescuers, their search dogs, and the intervention equipment), if necessary to rescue injured members or those trapped under the rubble, and finally to ensure that the resumption of USAR operations can be done safely.

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 10 s, 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 (e.g. nuclear power plants - [63], 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 [57]. 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. At the European level, the decision taken in 2019 by the European Commission to provide the European Civil Protection Mechanism (EUCPM) with a new European reserve of resources (the "rescEU reserve"), reinforces this desire to make civil protection resources interoperable, both from a practical and material point of view. Thus, if new tools were developed to protect USAR teams from seismic aftershocks, they could quickly benefit all European Member States.

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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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