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Co-defining a user-based desirable future for seismic alert systems with stakeholders: application to martinique, French west indies

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ABSTRACT

Since we cannot predict earthquakes, it is critical to better anticipate them and thus to save time in enabling timely implementation of appropriate protection measures. To this end, several types of tools based on real-time monitoring have been proposed over the past ten years, namely: Operational Earthquake (or Aftershock) Forecasting, (ii) Earthquake Early Warning and (iii) Rapid Response to Earthquakes systems. This paper assesses the opportunity to transfer these three socio-technical systems into operational tools for the territory of Martinique (French West Indies), and more generally for the Lesser Antilles regions.

The research design relies on an user-centered approach based on an in-depth three-steps consultation of stakeholders in the territory of Martinique, by implementing (i) an online survey, (ii) a targeted interview with key actors and finally (iii) a workshop bringing together all stakeholders. This sequential consultation approach enables to start from individual considerations and to progressively refine the diagnosis of the applicability of earthquake alerting tools, first for each type of entity, then for the territory as a whole. Coupled with an analysis of international experience in seismic alerting and the regional context of seismic risk governance, this leads to the elaboration of perspectives at three scales: (i) the local scale of Martinique, (ii) the regional scale of the French West Indies on one hand, and of Lesser Antilles on the other, and (iii) the international scale. In particular, the findings of this study emphasize the need for an "informational continuum" of decision support for practitioners before, during and after the occurrence of earthquakes and their aftershocks. This leads to a reconsideration of Operational Earthquake Forecasting, Earthquake Early Warning and Rapid Response to Earthquakes systems as intrinsically complementary, while not having the same level of operational applicability.

1. Introduction

The Sendai Framework for Disaster Risk Reduction (DRR) identifies the development of user-centered early warning systems as a priority [1]. This led the UN Office for Disaster Risk Reduction (UNDRR) to launch the "Early warnings for all" (EW4All) initiative in 2022, which aims to ensure that the entire world population can benefit from early warning systems by 2027 to better prepare for impending hazardous phenomena, including earthquakes, which are among the world's deadliest and most destructive natural disasters [2]. Unlike other phenomena, earthquakes are unpredictable, meaning that we cannot know where, when, and with which magnitude the next one will occur. Due to the inability to predict them, the challenge is to be able to better anticipate earthquakes

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and/or respond as quickly as possible to save precious hours/minutes/seconds, and thus minimize the risk of incurring major losses. To this end, over the last decade, the earthquake engineering community has developed three types of innovative tools based on modern real-time seismic technology for continuous, automated monitoring of seismicity: (i) Operational Earthquake Forecasting (OEF), which takes into account observed variations in regional seismic activity to provide a short-term reassessment of the seismic hazard, (ii) Earthquake Early Warning (EEW) which analyzes the first few seconds of P-wave records - the fastest and least energetic seismic waves - to assess the strength of the earthquake and the intensity of subsequent shaking, and (iii) Rapid Response to Earthquakes (RRE), which provides a rapid estimate (from a few minutes to a few tens of minutes after an earthquake occurs) of the likely impact of the earthquake in terms of shaking intensity, and even potential damage to infrastructure and people.

Each of these three types of tools can be used for both main shocks and sequences of aftershocks (for operational forecasting, we call them "Operational Aftershock forecasting" systems, or OAFs) (Fig. 1).

1.1. Operational forecasting

The principle of operational forecasting was developed in the USA in the 1980s, after the 1966 Parkfield earthquake [3–5]. Among the many models available, the "ETAS" model (for Epidemic-Type Aftershock Sequence; [6]) is currently considered to be the most reliable and is the most widely used [7]. This model is based on a few simple assumptions and well-established empirical principles concerning the triggering behavior of earthquakes, such as Omori's law for the temporal distribution of aftershocks [8], or the Gutenberg-Richter law for the frequency distribution of earthquake magnitudes.

Under the term "operational forecasting", OEF actually deals with the relative variation of the seismic hazard over a given time window, which can be more or less long (from a few days to a few months or years). As is often the case in the scientific literature [9], we will focus hereafter on short-term operational forecasting, corresponding to a period between one week (7 days) and one month (30 days) before an earthquake.

The question of the contribution of operational forecasting to decision support has only recently arisen, following the 2009 L'Aquila earthquake in Italy, and it led to the establishment of an international commission to develop recommendations on the use of operational forecasting for civil protection purposes [10]. While the OEF is in some cases able to highlight increases in seismic hazard a few days/weeks before an earthquake occurs, these estimates are mostly associated with objectively low probabilities of occurrence (less than 1/100 or 1/1000 over a week). However, the relative variation with respect to the long-term estimates given by the seismic hazard map can be very high (e.g. increase by a factor of 100). This makes the operational interpretation of these short-term forecasts very sensitive.

Furthermore, not all mainshocks are preceded by an increase in seismicity, which means that OEF systems cannot anticipate all earthquakes. However, this approach is particularly efficient for assessing the potential evolution of aftershock sequences that generally follow main shocks, hence the sub-concept of "OAF".

Several regions around the world now have OE(A)F systems in testing phase, including the US [11], Italy [12–14], Iceland [15], New Zealand [16], Japan [17] and Israel [18]. Some of these pilots are part of the international initiative of the *Collaboratory for the Study of Earthquake Predictability* [19], which aims to rigorously evaluate large-scale experiments of OEF.

Consequently, in addition to the performance of the forecasts provided by the OE(A)F, the question of the use of these forecasts is also raised. Among the many potential applications of operational forecasting, we can mention [20]: factual information and preparation of the population; intensification of preventive actions, verification of the proper functioning of critical equipment, ensuring business continuity, etc.

In particular, OEF can provide authoritative, scientific information that can objectify communication to the public ([10]; [21]). In the context of increasingly judicial societies, this OEF-based information could prevent situations such as the famous L'Aquila trial, in which Italian civil protection officials were charged with endangering the population following a communication emphasizing the absence of imminent earthquake risk [20]. Moreover, given the difficulty of imposing restrictive protective measures at the collective level in the face of low – but significant – probabilities of imminent earthquakes, Woo and Marzocchi [22] argue for bringing decision making down to the individual level (e.g. checking and replenishing individual/family emergency kits, securing heavy objects/furniture, etc.), so that everyone can adjust their behavior according to their own appropriation of risk. To this date, however, few of these theoretical measures have been tested in real-life situations, highlighting the difficulty of turning them into an operational tool.

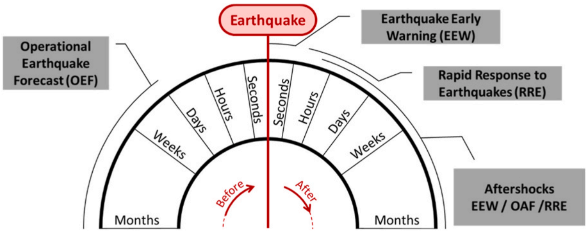

Fig. 1. Temporal positioning of OE(A)F, EEW and RRE tools before, during and after the occurrence of an earthquake and its aftershocks (figure adapted from the European RISE project - https://www.rise-eu.org/).

1.2. Early warning

Several recent review articles outline the EEW systems available worldwide [23,24]. Among these systems, "regional" ones – which cover entire territories that can be very large – generally provide more accurate estimates of source parameters (Zollo et al., 2014), while "on-site" systems - dedicated to warning specific sites - offer faster warning times for targets close to the epicenter, by reducing the extent of the "blind zone" within which seismic shocks arrive before the warning is received (Kanamori, 2005; Hsu et al., 2016). In practice, and depending on the configuration considered, warning times vary from a few seconds to about 20 s, with potentially better performance for strong earthquakes occurring at sea than for more shallow earthquakes on land (Allen, 2020).

Among the many potential areas of application for EEW are: broadcasting alerts to individuals (population, employees or public/visitors) so that they take reflex self-protection measures; automatically activating control systems to secure equipment and/or isolate parts of critical processes or stop vehicles; broadcasting alerts to on-call personnel so that they manually take emergency measures and/or activate intervention plans. Currently being deployed in California [25], many of these potential applications have already been implemented in Japan, including automatic shutdown of high-speed trains, control of vehicles, population alerting, and control of industrial equipment and processes (e.g. Tokyo's gas distribution network) ([26]; Doi, 2011).

In terms of the potential impact of EEW on risk reduction, the expected reduction in mortality from the dissemination of early warnings to the population is in the order of 10–30 %, and the reduction in the number of injuries is in the order of 20–50 % [27]. However, these estimates depend critically on the actual behavior of the population upon receiving the alert, which in turn depends on the population's level of preparedness. Furthermore, the notions of performance and reliability are related to what we consider to be system failure. It is interesting to note that populations covered by EEW systems appear to be more tolerant of false alarms (i.e. alerts issued for ground motions of lower intensity than expected) than of missed alarms (i.e. no alert but ground motions of high intensity) ([28,29]). Finally, it is worth noting that, due to the very short lead times they offer, EEW systems should able to automatically identify the optimal action to be taken immediately (automatically or not) by stakeholders [30].

1.3. Rapid response

RRE systems are conceptually different from OEF and EEW ones, insofar as they come into action when the effects of the earthquake are no longer to be avoided, but have already occurred and need to be managed. This means that we move from the logic of "forecasting" potential losses, to that of "estimating" these losses before they are properly described. In this way, RRE systems aim to provide rapid impact assessments, rather than detailed estimates that necessarily require a lengthy synthesis of feedback from the field [31]. In doing so, they contribute to situational awareness by providing a "common operational picture" of the situation on which to base an operational response.

For the purposes of this study, we consider only rapid response tools covering the critical first few hours, leaving aside remote sensing-based systems that are already operational and cover the entire globe, such as products from the European COPERNICUS-EMS system (Labiano et al., 2021) or from the International Charter "Space and Major Disasters" [32]. RRE systems covering the first few hours after the occurrence of an earthquake must therefore be able to perform two main tasks: (i) the evaluation of the severity of the seismic ground motions and (ii) the assessment of the losses resulting from these shakings (damage to buildings and infrastructures, human losses, even functional and financial losses, etc.). It should be noted that there are RREs that assess impacts at different scales, from individual buildings/facilities (e.g. ShakeCast tool: [33]) to the global scale of the event (PAGER tool: [34,35]), including estimates at different administrative scales. Erdik et al. [36] and Guérin-Marthe et al. [37] provide detailed overviews of the main technical components of RRE and inventories of the main existing systems.

Among the many potential applications of RRE are: immediate operational response sizing; reconnaissance prioritization; itinerary selection; identification of risk factors (e.g. induced or NaTech effects).

From a reactivity point of view, RRE systems are very robust in their ability to provide estimates very quickly, between a few minutes and a few hours after the occurrence of an earthquake. Compared to OEF and EEW, which are associated with high uncertainties in the likely severity of earthquakes, rapid response is more accurate because it can be calibrated on the fly with seismological field measurements. On the other hand, the seismic intensity of certain events remains difficult to characterize rapidly, such as those due to very strong earthquakes associated with rupture of large fault segments (Goldberg et al., 2023), or to very shallow earthquakes [38]. In addition, the loss assessment based on seismic intensity parameters is subject to a significant degree of uncertainty. As a result, loss assessment ultimately remains uncertain and should therefore be perceived by users for what it is, i.e. indications of orders of magnitude of earthquake impact rather than precise estimates. It is therefore imperative that the way in which these assessments are presented make the associated uncertainties explicit, so that users do not over-interpret them [39]. Furthermore, there is a striking contrast between the sophistication of models for estimating the shaking intensity and the resulting damage to infrastructure, and the rusticity with which population exposure is often consider in modelling human losses, which are most often represented statically from census data (Freire and Aubrecht, 2012).

1.4. From feasibility to opportunity to deploy new earthquake alerting systems

Each of the three tools presented in the previous sections has its own limitations. Some of these are inherent to the principle of each approach and are difficult to reduce, such as the high uncertainty associated with "operational forecasts". Others are related to deployment conditions and can be reduced by densifying the earthquake monitoring networks (e.g. increasing the density and azimuthal coverage of an accelerometer network can reduce the extent of blind-zone of an EEW system, or reduce the uncertainty in the seismic intensity assessment of an RRE system).

If these limitations and the question of the scientific and technical feasibility of modern seismic alerting tools are crucial, so is the question of assessing their potential contribution to users [40,41]. As Tan et al. [42] point out, it is necessary to understand the social aspects associated with these tools, paying particular attention to their implementation and use. Thus, for example, some studies have been conducted to assess the interest in some of these tools through interviews or surveys with potential users, taking into account OE(A)F systems [20,43,44], regional EEW ([45]; Becker et al., 2020 [40,46–49]) and site-specific EEW [43] systems, or RRE systems (Auclair et al., 2023; [39]). We should also mention the review studies specifically dedicated to the social aspects of EEW systems [42,50]. Last but not least, Scolobig et al. [51] provide a list of criteria to be taken into account in order to improve the relationship between the author and the recipients of alerts, in order to allow for appropriate decision making.

Key findings include the following.

- In the case of OE(A)F systems, it is clear that end-users have difficulty in understanding and interpreting forecast information and translating them into action [10,44]. As a result, it is necessary to involve end-users in co-designing ways of presenting results to turn this operational forecast into actionable information [52]: the same approach is also desirable for EEW [47] and RRE [39] tools.
- Whatever tool is considered, there is a risk that users will turn away from it in case of repeated false alarms [41,44], which makes it necessary to accurately assess user acceptability and work with them to define optimal trigger thresholds [53].
- There is a need to identify, sector by sector, the opportunities for the development of a given system. In this regard, Oliveira et al. [49] provide some very interesting insights into the main vulnerability factors of critical systems that constitute an industrial complex, as well as possible actions with early warnings, including valuable insights on electricity (production and distribution), gas distribution, water distribution, refining activities and port infrastructures.
- To be effective, a warning message should include the information elements related to hazard, impact, location, time, guidance, and source [51].

Despite many other useful lessons that can be drawn from these studies, it remains very difficult to extrapolate them from one region to another, as the perception of the usefulness of a tool depends on numerous factors such as the hazard context (type of seismogenic structure, level of hazard, potential for local site and induced effects), the type of territory considered (e.g. continental VS insular), the nature and vulnerability of the exposed assets, the robustness of emergency plans, the ability to invest in protection systems, etc. Furthermore, there are very few studies that address the question of needs in a broad sense, taking into account both a multiplicity of tools (each of which is specific to several key moments in the operational management of earthquakes) and a multiplicity of potential user types representing the key functions of a territory.

Given the challenges faced by the French West Indies in the event of a major earthquake, and in recognition of the key role played by Martinique in the civil protection system (see section 2), we decide to consider it as our case study. Based on an active consultation process with Martinique's stakeholders, our goal is to understand what the opportunities, challenges, and contingencies would be for deploying OE(A)F, EEW and/or RRE systems. In doing so, we aim to identify user-centered recommendations to build a desirable future in terms of seismic alerting for Martinique, and more broadly for the French West Indies and the Lesser-Antilles.

2. General overview of the French West Indies and Martinique case study

2.1. Exposure to seismic risk

Located in the eastern Caribbean, within the Lesser Antilles arc, the French West Indies are divided into three sectors, represented from south to north by the island of Martinique, the archipelago of Guadeloupe, and the "Northern Islands" comprising the islands of Saint-Barthélemy and Saint-Martin (the latter is divided into a French part, "Saint-Martin", and a Dutch part, "Sint-Marteen"). These islands are among the French territories that are most exposed to natural hazards, such as volcanic eruptions (e.g. the eruption of Montagne Pelée in Martinique in 1902 - Tanguy, 1994), cyclones (e.g. Lenny in 1979, Hugo in 1989, Irma in 2017 - Audouin, 2012; [54,55]) or frequent landslides and rockfalls [56]. As the Lesser Antilles mark the boundary between the North and South American plates through subduction under the Caribbean plate at an average rate of about 2 cm/year [57], the French West Indies are particularly exposed to seismic risk, with the highest level of hazard encountered in France. Although the rate of seismicity in the Lesser Antilles subduction zone is lower than in some other subduction zones, the study of historical seismicity (SISFRANCE-Antilles database from Lambert and Samarcq [58–60]) - documented only since the mid-17th century onwards - and contemporary seismicity [61–63] shows that destructive events occur regularly (Robson, 1964; Stein et al., 1982; Sykes & Ewing, 1965). It has also recently been shown that megathrust earthquakes can occur in this region [64].

The two most significant historical earthquakes in the region occurred only four years apart, first near the island of Martinique on January 11th, 1839 (maximum intensity VIII MSK and magnitude estimated between 7.5 and 8), then off the coast of the Guadeloupe archipelago on February 8th, 1843 (maximum intensity IX MSK and magnitude estimated between 8 and 8.5) [59,60]. Numerous other earthquakes causing damage in the French West Indies and neighboring islands are also documented: e.g., 1702, 1727, 1735, 1802, 1851, 1897, 1946, 1969, 2004, 2007 (SISFRANCE-Antilles database - Lambert, 2004). The last of these earthquakes, which occurred on November 7th, 2007, about 20 km north of Martinique, reached a magnitude of Mw 7.4: fortunately, the damage was relatively light (maximum intensity of VI-VII EMS-98 - [65]) as it occurred at a depth of about 150 km, within the intermediate subduction zone [66].

2.2. Organizing society to cope with natural disasters

The French West Indies, which are highly exposed to natural disasters, are characterized by (i) their great geographical remoteness from mainland France, which is more than 6700 km away on the other side of the Atlantic Ocean, (ii) a strong north-south elongation (400 km), and (iii) large territorial discontinuities between the islands (Fig. 2). As demonstrated by the 2017 hurricane sequence that devastated the northern territories of the Lesser Antilles and in particular the islands of Saint-Martin and Saint-Barthélemy ([55]; [67]), this particular configuration makes it extremely difficult to send reinforcements from mainland France in the event of a large-scale crisis. Moreover, this configuration makes some infrastructure systems (electricity and drinking water production plants, fuel stocks, etc.) even more critical, with a strong dependence on logistical hubs (ports, airports). In addition, despite major efforts to reduce vulnerability since the 2010s, the vulnerability of buildings to earthquakes remains relatively high in the West Indies.

In this context, the structuring of a robust civil protection organization, based on a strengthened regional level is essential. As in the rest of France, this organization is pyramidal in the West Indies, with: (i) a national level, responsible for interministerial political coordination and the dispatch of national reinforcements, and able to request the activation of the European Union Civil Protection Mechanism (UCPM) if necessary, (ii) a "zonal" level with headquarters (called “EMIZA”) located in Martinique, responsible in particular for the mobilization and coordination of zonal reinforcements (i.e. between the territories in the zone, namely: Martinique, Guadeloupe, Saint-Martin and Saint-Barthélémy) or national and/or international extra-zonal reinforcements, and (iii) a departmental level representing the French State in each territory, provided by the prefectures (one prefecture in Martinique, one prefecture in Guadeloupe covering the islands of Saint-Martin and Saint-Barthélémy, and one "delegated" prefecture in Saint-Martin) (Fig. 2). In addition to this civil protection structure set up by the French State, each territory has its own "ecosystem" of actors involved in risk and crisis management: local authorities, fire and rescue services (SIS), security forces, public or private managers of critical infrastructures, associations, etc.

Over the centuries, frequent destructive natural disasters have had a significant impact on the urban morphology of the French West Indies, with periods of post-disaster reconstruction marked by territorial reconfiguration and changes in construction methods [68]. However, it was not until the 1980s that natural hazard prevention became a public policy issue. Scolobig et al. [69] studied the technical and institutional characteristics of natural hazard governance in Guadeloupe, analyzing (i) governance, (ii) available technical capacities, and (iii) cooperation and communication among stakeholders. This study highlighted the strongly hazard-oriented historical Francophone approach to risk management [70] and the insufficient consideration given to vulnerability in risk assessment and decision-making tools (e.g. assessment of the intensity of the phenomenon but not of the expected impacts). It also highlighted a better level of cooperation and communication between stakeholders for high-intensity/low-frequency events, such as earthquakes and volcanic eruptions, than for more common risks such as marine floods and landslides. Although 10 years old, these lessons are still very relevant.

In terms of public policy for earthquake risk management, the French government launched a plan in 2007 to reduce the level of seismic risk in the French West Indies. Known as the “Plan Séisme Antilles”, this ambitious multi-billion euro plan is currently in its third phase (2007–2013; 2016–2020; 2021–2027). It consists mainly in reducing the vulnerability of structures through earthquake-resistant construction, reconstruction or retrofitting, particularly targeting crisis management infrastructures, schools, health facilities and social housing. The plan also has a significant “immaterial” component which includes actions to prepare for crisis management (in particular through the organization of crisis exercises), to improve scientific knowledge of seismic hazard, to train construction professionals, and to inform the population. Since the beginning of the plan, annual week-long awareness campaigns are organized in Martinique and Guadeloupe [71]. In addition, tsunami evacuation drills are held every year throughout the Caribbean basin, with the active participation of the local population and their local authorities [72]. Over the years, these public policy initiatives have increased community involvement, and have strengthened preparedness and response capacities to earthquakes and to their induced effects [71,73].

It is worth noting that despite a relatively high level of income in the French West Indies compared to other neighboring Caribbean islands [74], GDP per capita remains lower than in mainland France. Therefore, despite strong policies to reduce the vulnerability of

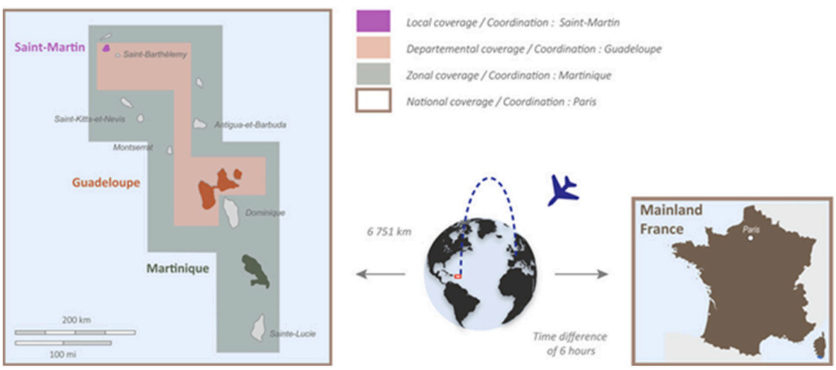

Fig. 2. Main levels of civil protection organization in the French West Indies (reproduced from [67]).

buildings to earthquakes, many private and public buildings still do not comply with seismic codes. In addition, insurance penetration is lower than in the rest of France (Calvet and Grislain-Letremy 2011).

2.3. Existing earthquake monitoring systems

As stressed by Scolobig et al. [69], "the available technical solutions and decision support tools influence the development of institutional frameworks and disaster policies". Therefore, in this section, we present an overview of the existing earthquake alert systems in French West Indies.

2.3.1. Seismic monitoring

In the French West Indies, seismicity is monitored by the Seismic and Volcano Observatories of Martinique (OVSM-IPGP) and Guadeloupe (OVSG-IPGP) ([75] a & b), based on their own seismological networks [76] and on the sharing of seismological data among regional partners in the Lesser Antilles (SRC of the University of the West Indies in Trinidad and Tobago, KNMI of the Netherlands, Montserrat Volcano Observatory, USGS, PRSN of the University of Mayaguez in Puerto Rico). Based on an automatic real-time analysis of these seismological records using their specific operational software system [77], earthquakes are automatically detected, localized and characterized (magnitude and depth estimates). This information is then rapidly (usually in less than half an hour) manually validated by an on-call seismologist before being disseminated in the form of a report providing an estimate of the macroseismic intensity level for each municipality, i.e. the "B-Cube" product [78].

2.3.2. OE(A)F capacities

To our knowledge, no specific study on the feasibility of an OE(A)F system has ever been carried out in the Lesser Antilles, or even in the Caribbean.

2.3.3. EEW capacities

Fifteen years ago, the French Geological Survey (BRGM) conducted a study specific to the French West Indies to assess the

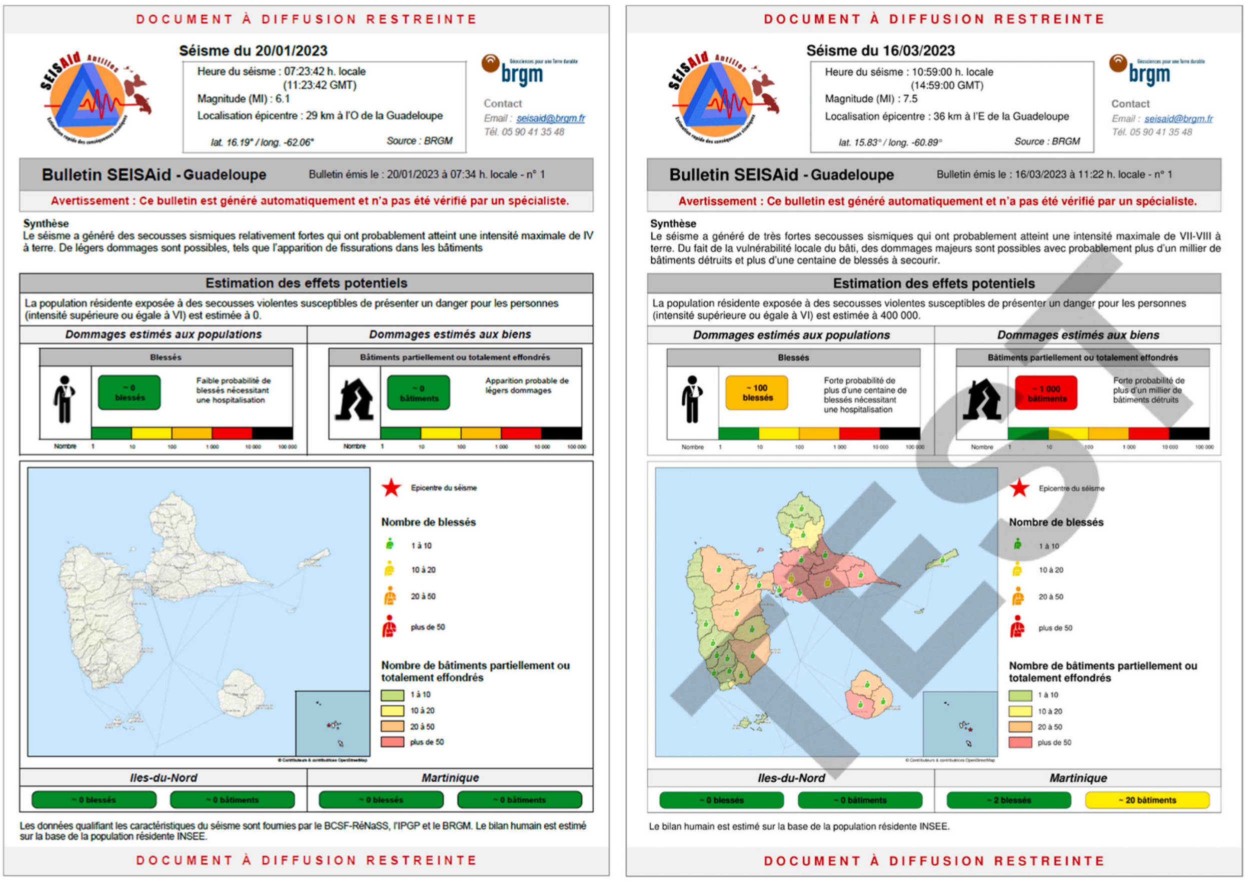

Fig. 3. SEISAid-Antilles reports generated for Guadeloupe as part of the testing phase after (i) the 5.0 magnitude earthquake of February 2nd, 2023 (left) and (ii) a fictive 7.5 magnitude earthquake scenario (right).

feasibility of an EEW system (Auclair and Bertil, 2009). Based on a comparison of theoretical warning times with an estimate of the extent of the affected areas, this study emphasized that such a tool would be inoperative in the most affected areas in the case of shallow earthquakes (due to the "blind zone" phenomenon), but potentially capable of providing early warnings some 10 s before the arrival of strong motions in the case of subduction-related earthquakes, whether very deep, such as the 2007 earthquake under Martinique, or of intermediate depth, such as the 1843 earthquake that devastated Guadeloupe.

A study by Zuccolo et al. (2016) was also conducted in the north (Antigua and Barbuda) and south (Barbados and Trinidad and Tobago) of the Caribbean, to assess the potential of an EEW system for a selection of critical infrastructures. This study also concludes that there is a theoretical potential for early warning of about 10 s for certain large earthquakes, but it does not address the question of the needs and capabilities of potential users to take advantage of these early warnings.

These studies are based on assumptions that take into account existing land-based seismological monitoring networks. However, in the Lesser Antilles - as in many parts of the world close to subduction zones, and even more so for island territories - the most destructive earthquakes occur mainly at sea. The potential for early warning would therefore be greatly enhanced if real-time underwater seismicity monitoring capabilities could be established.

2.3.4. RRE capacities

Since 2020, the BRGM has been developing an RRE system for the French West-Indies, called “SEISAid-Antilles”, which is capable of carrying out rapid loss assessments upon receipt of an earthquake notification [79]. Following the example of the USGS’s PAGER system [34,35], the results of these estimates are automatically fed into a report, the purpose of which is to highlight the potential operational impacts of these assessments in a way that is as easy as possible for recipients to understand. The goal is to provide the authorities with the relevant information they need to understand the scale of the earthquake and its likely consequences.

To ensure that the SEISAid-Antilles RRE system best meets the needs of the civil protection authorities in the French West Indies, a user committee was set up in 2020, composed of the General directorate for civil security and crisis management (DGSCGC), representing the national level, the inter-ministerial zonal staff of the French West-Indies (EMIZA), representing the zonal level, and the prefectures of Martinique and Guadeloupe and the delegated prefecture of Saint-Martin, representing the departmental level. Workshops held with these practitioners enabled the main functional specifications to be designed, upon which to build the SEISAid-Antilles tool [79]. In order for these reports to be used as decision support material, it was decided to include only two indicators of potential losses: (i) the number of partially or totally collapsed buildings, which gives a sectoral indication of priorities for "Urban Search & Rescue" (USAR) operations, and (ii) the number of injured people, which gives a sectoral indication of priorities for the resources to be mobilized for relief and hospitalization.

At the end of a test phase conducted under real conditions between July 2022 and April 2023 (see Fig. 3), the civil protection practitioners involved unanimously emphasized the usefulness of the SEISAid-Antilles system and their desire to have it rapidly available in operational mode [79]. However, this RRE system is specifically designed to provide decision support to civil protection authorities, without taking into account the needs of other actors who may have a role to play in the event of an earthquake.

In addition to this SEISAid-Antilles tool developed specifically for French West Indies by a national authoritative agency (BRGM as the French Geological Survey), it should be noted that these territories are also covered by other RRE systems having worldwide coverage. Although the USGS RRE system “PAGER” is known to some practitioners in Martinique, it seems to be little used, in particular because of its impact indicators, which are considered to be of little use for operational needs (cf. chapter 4).

Table 1
Involvement of Martinican stakeholders in the consultation process by area of activity: number of survey respondents, interviewees and workshop participants. In the case of multiple participants, the number of separate organizations represented is given in brackets. *Face to face interview/**Videoconference interview.

Sector	Survey	Interview	Workshop
Civil protection	4 (3)	3 (3)	3 (3)
- EMIZA	*1*	*1**	*1*
- Prefecture	*1*	*1**	*1*
- Rescue department	*2*	*1**	*1*
Drinking water/Wastewater	2 (2)	1*	2 (2)
Energy	7 (5)	1	2 (2)
- Electricity	*1*	-	-
- Oil and gas	*5 (3)*	*1***	*2 (2)*
- Biomass	*1*	-	-
Health sector	1	1**	2 (1)
Local authorities	6 (1)	–	1
Post-seismic damage assessment	1	–	1
Public safety	2 (2)	–	2 (2)
Risk prevention	1	–	3 (1)
Telecommunications	3 (3)	1**	1
Transports	2 (2)	–	–
- Airport	*1*	–	-
- Port	*1*	–	-
Total	**29 (21)**	**7**	**17 (14)**

3. Material and methods

In order to assess the perception of the potential contribution of the new OE(A)F/EEW/RRE tools for the Martinique territory, we adopted an active approach to consult Martinique practitioners involved in operational seismic risk management, in order to understand their specific issues, expectations and needs. It was decided to give priority to the first circle of practitioners directly involved in operational earthquake management, namely.

- Authorities responsible for coordinating crisis management;
- Civil protection and public safety forces;
- Risk prevention stakeholders;
- Operators of critical infrastructures;
- Health sector authorities;
- The main local authority covering the whole of Martinique.

Rather than adopting a strictly positivist approach, seeking generalizable lessons from the analysis of observable reality within society, we preferred to adopt an interpretivist stance, paying particular attention to contextual variables and factors [80]. Therefore, we decided to follow a three-step approach (Table 1).

1. Online survey, which aimed to gather the views of a wider panel of potential users in a structured way;
2. Interviews with specific stakeholders, to gain a better understanding of specific needs in terms of particular practices or constraints;

4. Organization of a workshop bringing together all stakeholders, to refine the diagnosis of the applicability of earthquake warning tools for each type of entity, and to draw up perspectives for Martinique as a whole

In particular, our study allowed us to collect a large amount of qualitative data, through responses to open-ended questions in the survey, as well as through individual interviews and the practitioners' workshop. The qualitative analysis of these data was carried out sequentially (first the responses to the questionnaire, then those to the interviews, and finally those from the workshop), with the aim of gradually deepening our understanding of practitioners' needs and practical contingencies.

Prior to our study, not all practitioners involved in seismic risk management were familiar with the OE(A)F/EEW/RRE tools, or had only an approximate perception of them. In order to address the potential contributions and limitations of these tools, the first step was to adjust their level of knowledge by sending them an awareness-raising brochure presenting each of the three approaches in a didactic way.

4.1. Online survey

Like Becker et al. (2020 [46] and Auclair et al. [41], we chose to collect information by conducting a questionnaire survey, following a deductive approach (Melnikovas, 2018). Indeed, survey data are particularly useful in a first step to quantifiably compare the views of a panel of participants. The main areas that inspired our questions were: the profile and experience of the respondent, the respondent's perception of his organization's exposure to seismic risk and level of preparedness, the perception of the value of an OE (A)F/EEW/RRE system and the constraints to its operational use. The survey consisted a total of 45 questions, 24 quantitative (closed questions) and 21 qualitative (open questions) - (Table 2).

The survey was conducted online using the Microsoft Forms tool from May to November 2023. In total, we received 29 responses from 21 different organizations representing public institutions (16 responses), private companies (12 responses), and one NGO. These respondents cover the major sectors of activity that are critical in the event of an earthquake (Table 1).

4.2. Interviews

In order to be able to deepen the results obtained through the online survey, it seemed necessary to gain a better understanding of the specific issues related to certain business sectors. Thus, taking into account the organizational constraints and the limited availability of key experts within the entities involved, we were able to conduct seven interviews with some of the respondents to the survey, selected to represent different areas of intervention, associated with strong "business" specificities. Six of these interviews were conducted in early December 2023, prior to the workshop (see section 3.3), and a seventh in February 2024.

Carried out face-to-face for three of them, and by videoconference for the others, these interviews did not aim to gather structured data that could be compared with one another, but rather to understand particularities. They were therefore conducted in the format of free discussions, with no predetermined framework of questions to be asked.

4.3. Workshop

To refine with practitioners the diagnosis of the applicability of the various earthquake warning tools to Martinique, a half-day workshop was organized on December 8th, 2023. This workshop, which was open to all the parties consulted in the survey, aimed in particular to identify possible sectoral (between entities operating in the same sector of activity) and intersectoral (between entities

Table 2
Presentation of the individual questions of the questionnaire, as well as the number of responses received for each of them.

Question		Possible answers	Nb. Answers
Profile and experience			
1	Entity	*Open question*	29
2	Type of entity	Public entity/Private company/Association/Other	29
3	Type of entity activity	Civil protection/Public safety/Health/Transport/Energy/ Telecommunications/Water and sanitation/Other	29
4	Your role within the entity	*Open question*	29
5	What experience do you have with seismic risk management?	*Open question*	22
6	Have you ever experienced an earthquake?	Yes/No	29
Exposure and to seismic risk and level of preparedness			
7	How do you perceive the level of seismic risk to which Martinique is exposed to?	Very low/Low/Moderate/Strong/Very strong	29
8	How do you assess the seismic risk for your entity and its activities? - Workers - Public/Users - Buildings - Production infrastructures - Distribution infrastructures - Engineering structures - Equipment/Machinery	Very low/Low/Moderate/Strong/Very strong	29
9	Are there other parts of your entity that are highly exposed to seismic risk? If so, which ones?	*Open question*	12
10	What are your entity's primary concerns regarding the effects of an earthquake?	Impact on the public and/or populations/Impact on employees/Impact on the organization's overall mission/Key functions or points of vulnerability/Interdependencies within your systems/Other	29
11	Specifically, what do you fear most in the event of an earthquake in relation to your entity's activities and missions?	*Open question*	29
12	What are your entity's primary goals in the event of an earthquake?	Ensuring public safety/Ensure employee safety/Protect property and equipment/Ensure business continuity & recovery/Protect company revenues and limit losses/Other	29
13	To what extent has your entity developed a culture of earthquake preparedness?	Rating from 1 (non-existent) to 5 (very strong)	29
14	Does your entity have earthquake response plans or procedures?	Yes/No/Other	29
15	Can you briefly describe them?	*Open question*	22
16	In light of your entity's activities, how do you feel about these statements? - The effects of earthquakes can only be reduced in the long term, through actions that take several years - The effects of earthquakes could be mitigated by increased safeguard actions, if they could be taken a few days before they occur - A few seconds' warning would be enough to minimize some effects of earthquakes - After the occurrence of an earthquake, it is important for us to act very quickly	Strongly disagree/Somewhat disagree/Somewhat agree/Strongly agree/No opinion	29
Perception of the value of an OEF system and constraints to its operational deployment			
17	Would it be useful for you to have reports qualifying the probability of a destructive earthquake occurring in the coming week*? ** Without presuming the scientific feasibility of such warnings*	Yes/No/No opinion	29
18	Could you be more specific?	*Open question*	2
19	How would you rate this usefulness?	Rating from 1 (Not very useful) to 5 (Very useful)	27
20	If you received these bulletins, would you consider taking any of the following actions within your organization? - Inform the public - Increase preventive measures - Relocate - pre-position equipment - Recall personnel - Put them on reinforced stand-by duty - Testing procedures - Verify proper operation of critical systems - Ensure business continuity	Possible/Not foreseeable/Not applicable/No opinion	27
21	For actions that you consider infeasible, can you explain why?	*Open question*	0
22	For the actions you consider feasible, can you state the expected benefits?	*Open question*	23
23	Can you think of other possible actions, and what are the expected benefits?	*Open question*	6
24	Evaluate the relevance of this information in terms of decision support for your organization: *"For the coming week, the probability that the city of ### will experience destructive seismic tremors … "*	Not relevant/Not very relevant/Moderately relevant/Very relevant/No opinion	27

(*continued on next page*)

Table 2 (*continued*)

Question		Possible answers	Nb. Answers
Profile and experience			
	- … is in line with normal - … is significantly higher than normal - … is one hundred times higher than normal)		
Perception of the value of an EEW system and constraints to its operational deployment			
25	Would it be useful for you to receive an alert a few seconds to a few tens of seconds before ground shaking? **Without presuming the scientific feasibility of such early warnings*	Yes/No/No opinion	29
26	Could you be more specific?	*Open question*	3
27	How would you rate this usefulness for your business, for an early warning arriving: −2 s before shaking −5 s before shaking −10 s before shaking −20 s before shaking	Not useful/Not very useful/Moderately useful/Very useful/No opinion	24
28	Upon receipt of these reports, would you consider the following actions at the level of your organization? - Automatic dissemination of the alert to the population – public - Manual dissemination of the alert to the population – public - Automatic dissemination of the alert to employees – agents - Manual dissemination of the alert to employees – agents - Automatic safety actions (close valves, open/close doors, back up computer) - Reflex actions to make systems safe (emergency stop button) - Individual "reflex" self-protection actions	Can be considered- 2s warning/Can be considered - 5s warning/Can be considered - 10s warning/Can be considered - 20s warning/Cannot be considered/Not applicable/No opinion	24
29	For the actions that you consider not to be feasible, can you state the reasons?	*Open question*	11
30	For the actions you consider that could be considered, can you state the expected benefits?	*Open question*	15
31	Can you think of other possible actions, and what are the expected benefits?	*Open question*	0
32	In your opinion, what would be the impact of a false alarm in terms of … ? - Loss of time - Loss of activity/operations - Loss of confidence in the system	Very low/Low/Moderate/Strong/Very strong/No opinion	24
33	Could you be more specific?	*Open question*	9
Perception of the value of an RRE system and constraints to its operational deployment			
34	After an earthquake, would it be useful for you to have a rapid assessment of the impact on the infrastructures of interest (hospitals, emergency centers, engineering structures, housing as a whole, etc.)*? ** Without presuming the scientific feasibility of such rapid assessments*	Yes/No/No opinion	29
35	Could you be more specific?	*Open question*	2
36	How would you rate the usefulness, for an estimate arriving … - Less than 30 min after the earthquake - Less than 1 h after the earthquake - Less than 12 h after the earthquake - Within the first 24 h after the earthquake	Not useful/Not very useful/Moderately useful/Very useful/No opinion	26
37	What information would be most useful for your entity to assess? - Shaking intensity - Level of damage to residential buildings - Level of damage to specific buildings – infrastructures - Functionality of roads - Potential number of victims (casualties, homeless, etc.) - Economic cost of material losses	Not useful/Not very useful/Moderately useful/Very useful/No opinion	26
38	Can you tell us how this information would be useful to you, and what other impact parameters you might have?	*Open question*	13
39	Would these reports cause you to take the following actions within your entity? **Assuming that these bulletins contain the information considered most useful in the previous questions, and depending on whether they are received 30* min*/1 h/12 h or 24 h after the earthquake* - Help in sizing the immediate operational response and requesting reinforcements - Help in prioritizing reconnaissance - Help in choosing itineraries and defining traffic plans	Can be considered – 30 min/Can be considered – 1h./Can be considered – 12h./Can be considered – 24h/Cannot be considered/Not applicable/No opinion	26

(*continued on next page*)

Table 2 (*continued*)

Question		Possible answers	Nb. Answers
Profile and experience			
	- Assess induced risks (landslides, tsunamis, liquefaction of mountain passes, etc.)		
40	For actions that you consider infeasible, can you explain why?	*Open question*	0
41	For actions you consider feasible, can you state the expected benefits?	*Open question*	1
42	Can you think of other possible actions, and what would be the expected benefits?	*Open question*	2
43	In your opinion, what would be the consequences of an incorrect assessment of the effects of the earthquake with regard to … ? - Disorganization of operational response - Loss of activity/operations - Loss of confidence in the system	Very low/Low/Moderate/Strong/Very strong/No opinion	26
44	Could you be more specific?	*Open question*	7
Additional comments			
45	Do you have any questions or comments?	*Open question*	1

operating in different sectors of activity) dimensions, and to draw up perspectives for Martinique as a whole. A total of 17 participants representing 14 different entities took part (Table 1).

5. Results

5.1. Findings from the online survey

Presentation of respondents and their perceptions of seismic risk.

From the answers to questions 4 to 6, it is clear that all the respondents have a high level of responsibility within their organization and extensive experience in the fields of risk and/or crisis management. In terms of specific seismic risk management, the level of experience is more variable, reflecting the fact that the return periods of significant earthquakes are relatively high in the French West Indies.

With regard to the perception of seismic risk, it is worth noting that almost all the respondents indicated that they had already felt an earthquake (only one respondent had never felt one), confirming that almost all of them are personally aware of the reality of this risk. In addition, the level of risk faced by the respondents' organizations is rated as high to very high overall, which is consistent with the fact that the seismic hazard faced by Martinique is rated as high to very high by a large majority of respondents (59 % and 28 %, respectively). However, this perception of risk varies according to the type of assets at risk, and appears to be somewhat less pronounced for materials and machinery (Fig. 4). Other specific assets that are highly exposed to seismic risk are also cited, such as the airport control tower, ships docked in port, radio communications infrastructure (cellular relay antennas, radio network, optical fiber), emergency operations, flood protection levees installed around certain industrial sites, and health care facilities.

When asked about their primary organizational concerns in the event of an earthquake, respondents cited, equally, the impact on the overall mission of the organization they represent, and the impact on people (first the populations and the public they serve, then their employees). Issues related to key functions and interdependencies between systems are also mentioned several times. Table 3 details the specific areas of vigilance identified by respondents, grouped by business sector.

In line with respondents' concerns, the primary objectives in the event of an earthquake are business continuity and the protection

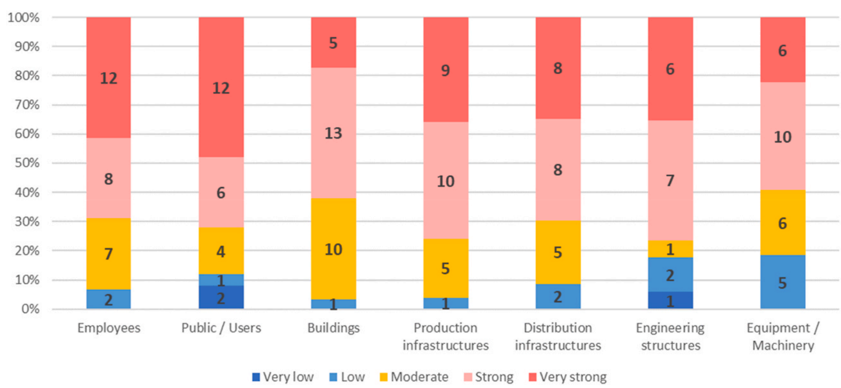

Fig. 4. Answers to question 8 – *"How do you assess the seismic risk for your entity and its activities?"*

Table 3
Answers to question 11 – Points most feared in the event of an earthquake according to respondents' business sector.

Local authorities
Disruption of public services
Structural and human impact on crisis management and recovery capabilities
Interruption of telecommunications and impracticability of roads
Physical and IT problems accessing buildings and tools used for crisis management
Post-seismic damage assessment
Interruption of telecommunications and impracticability of roads
Drinking water/Wastewater
Damage to drinking water production and storage facilities
Damage to public sanitation infrastructure
Energy
Loss of integrity of critical equipment
Loss of business continuity (production and distribution), particularly due to limited human resources
Environmental impact of damage to oil & gas tanks and equipment
Risk of fire outbreak
Health sector
Structural and human impacts on capacity to ensure continuity of patient care
Inability to cope with the influx of severely injured people as a result of the earthquake
Civil protection
Unavailability of teams (inaccessible sites, desire to ensure the safety of loved ones, etc.)
Incapacity to intervene due to damage to rescue centers and roads
Interruption of telecommunications
Public safety
Riots and pillages
Maintaining communication systems
Risk prevention
Impact on school populations
Telecommunications
Total loss of telecom resources
Lack of radio site interoperability
Transports
Inability to ensure continuity of port operations (unloading/loading of goods following damage to handling equipment, storage/evacuation of goods)
Destruction of landing runway and loss of air navigation systems

of people and property. Conversely, limiting financial losses seems to be of secondary importance.

To conclude on the profile of the respondents, while the vast majority of them indicate that their organization has earthquake response plans or procedures in place, overall they indicate that they have a medium to high level of earthquake preparedness culture, which demonstrates both a real awareness of this risk and an openness to improving existing procedures.

On the other hand, the initial spontaneous feedback - even before they were asked specific questions about OE(A)F/EEW/RRE tools - tends to indicate a great openness to the principle of RRE, and to a lesser extent to that of OE(A)F. Conversely, the EEW principle is less likely to meet respondents' expectations, given the extremely short lead times it offers (Fig. 5). As we will see later, this is not a definitive statement, but it provides an interesting indication of which tools respondents would tend to turn to more naturally, because they seem more suited to their needs, or simply more in line with their habits.

5.1.1. Perceived usefulness of OE(A)F

When asked, *"Would it be useful for you to have reports qualifying the probability of a destructive earthquake occurring in the coming week, like weather watch bulletins?"*, 26 of the 29 respondents answered in the affirmative, and only two in the negative (plus one person with no opinion), resulting in an average usefulness score of 4.6 out of 5. Respondents indicated that an OEF would be a useful anticipatory tool to limit certain effects of earthquakes and to better prepare for them. This feeling of usefulness is generally shared, regardless of the sectors from which respondents come.

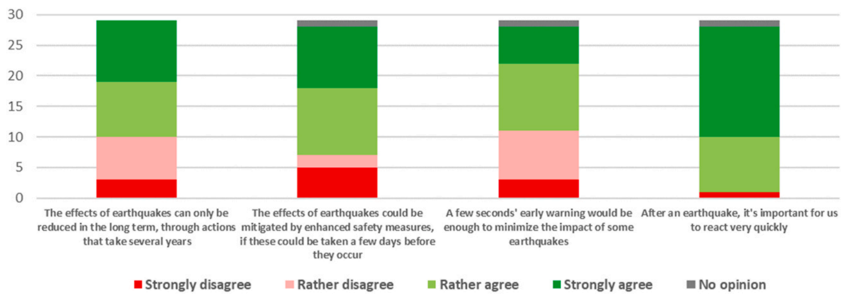

Fig. 5. Answers to question 16 – Respondents' perception of the phases during which action can be taken to minimize the impact of earthquakes.

Regarding the possible use of this operational forecast information, a large majority of the proposed actions were considered feasible upon receipt of the report, namely: Increasing preventive measures; Relocating/pre-positioning equipment; Recalling personnel/Reinforcing on-call duty; Testing procedures; Verifying the correct operation of critical systems; Securing business continuity. However, the prospect of being able to use this type of operational forecast information to inform the public seems to be less consensual.

When it comes to how operational forecast information should be communicated, respondents seem to be more receptive to highlighting significant and quantified changes in the probability of an earthquake occurring (Fig. 6).

5.1.2. Perceived usefulness of EEW

In response to the question *"Would it be useful for you to receive an alert a few seconds to a few tens of seconds before shakings occur?"*, 22 of the 29 respondents answered in the affirmative, 5 in the negative, and 2 were undecided. This feeling of usefulness is not only expressed by industrial players with a priori greater capacity to automate rapid safety actions. For example, while it is very strong among respondents from the energy and telecommunications sectors, it is also the case for the public authorities and civil protection sectors, and it is even unanimously shared by all respondents from local authorities. Furthermore, and not surprisingly, this perception of usefulness is strongly dependent on the time available between the receipt of the warning and the arrival of the seismic tremors, with very low perceived usefulness for warning times of only 2 s, becoming significant for warning times of at least 5 s, and very useful for times of around 10 s (Fig. 7). It is also interesting to note that, in some cases, even for extremely short warning times, several actions seem to be conceivable, despite the fact that they are only considered by a few respondents and that their effectiveness remains to be proven. This applies, for example, to automatic or reflex safety actions, or reflex self-protection actions (Fig. 8).

Conversely, reasons given for the inability to take advantage of very short early warnings include.

- Some safety measures take too long to be fully effective before the onset of shaking;
- Processes for disseminating warnings to individuals are too slow;
- Not all industrial sites are currently equipped with automatic remote control systems;
- Response times are too long to take appropriate action.

Finally, while the impact of false alarms is generally perceived to be moderate in terms of loss of business and time, the potential impact is greatest on confidence in the system itself (Fig. 9), especially in the case of repeated false alarms.

5.1.3. Perceived usefulness of RRE

To the question *"After an earthquake, would it be useful for you to have a rapid estimate of the damage on the infrastructures of interest?"*, 25 of the 29 respondents answered with the affirmative, three others - all from the industrial sector (from the energy, drinking water and telecommunications sectors) - answered with the negative, and one was undecided.

This usefulness seems to be highest 1 h after the earthquake and then decreases with time. Conversely, some respondents indicated that they were not interested in having rapid estimates of potential losses within the first half hour because they were not yet organized to process this type of information (Fig. 10). Indeed, while operational departments with continuously activated “hot” crisis cells appear to be able to take into account initial rapid response information arriving within half an hour, most organizations must first activate their “cold” cells, which can take some time. This optimum seems to be widely shared, insofar as the majority of people who indicated a very high level of usefulness of rapid response at other production times (i.e., at 30 min, 12 h and 24 h) retain the same level of usefulness for information arriving within the hour.

On the other hand, the impact parameters that are considered useful vary from respondent to respondent (Fig. 11). First of all, it is interesting to note the interest shown in estimating the shaking intensity. Although the operational importance of this more technical information is questionable, it is possible that its estimation could be perceived as less uncertain than that of potential damage. Intensity thus remains useful as contextual data that allows other impact indicators to be critically assessed.

The question of how quickly to estimate the practicability of roads seems to be an essential parameter common to all respondents, in order to assess the accessibility of different sites. Projections of the extent of damage to current buildings, as well as to specific buildings or infrastructures critical to a given organization, also emerged as a key concern. To a lesser extent, the estimation of potential human casualties is also highlighted as being of interest, particularly to civil protection services and local authorities, who are responsible for providing assistance and relief to disaster-affected populations.

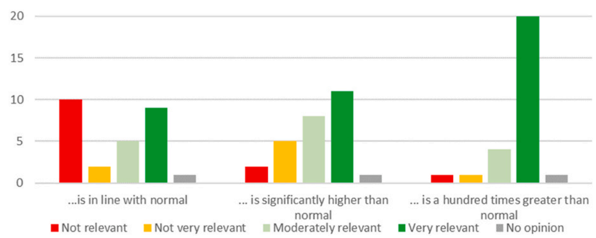

Fig. 6. Answers to question 24 – *“For the coming week, the probability that the city of ### will experience destructive seismic tremors …”*

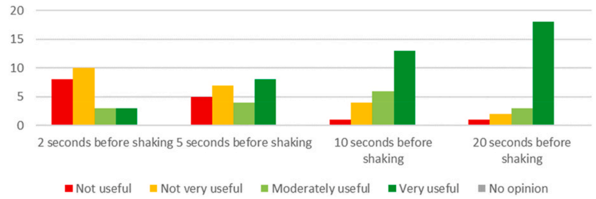

Fig. 7. Answers to question 27 – Perceived usefulness of early warnings in relation to the time available between their receipt and the arrival of shakings.

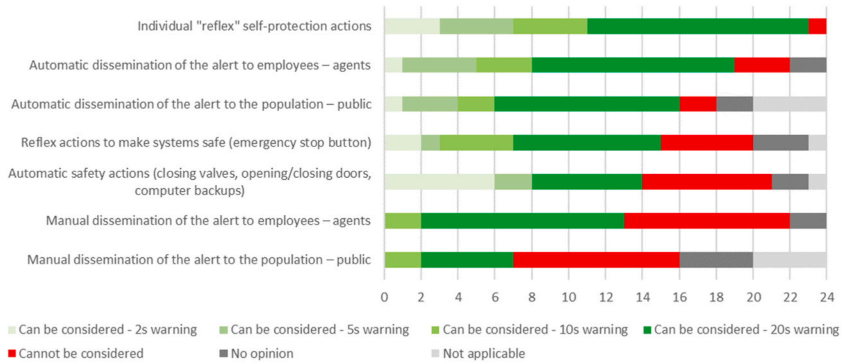

Fig. 8. Answers to question 28 – Possible actions upon receipt of early warnings, depending on the time available between their receipt and the onset of strong ground motions.

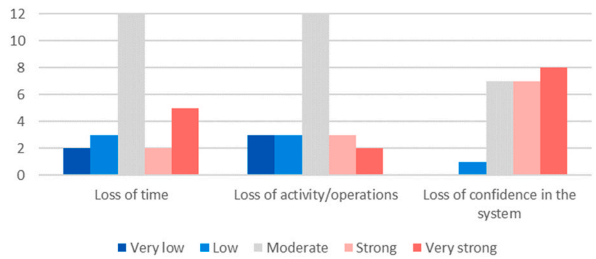

Fig. 9. Answers to question 32 – Respondents' perception of the impact of EEW false alarms.

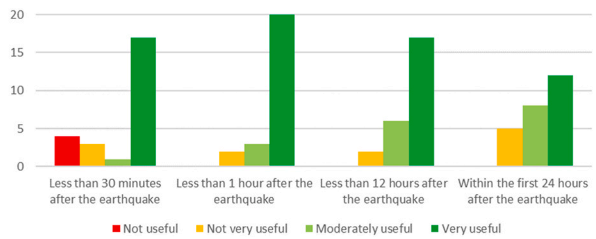

Fig. 10. Answers to question 36 – The benefits of rapid response in the different time periods following an earthquake.

With regard to the civil protection response, EMIZA points out that this type of estimate of the number of damaged buildings and victims is very useful not only for coordinating the USAR teams present in the area, but also for mobilizing national reinforcements. An initial description of the potential losses and damage helps to quickly express the need for reinforcements, taking into account the logistical constraints of deployment from mainland France. Similarly, the French association for earthquake engineering (AFPS) indicates that an estimate of the damage to current buildings would be very helpful in pre-dimensioning the number of inspectors needed to carry out damage assessments. Fig. 12 confirms the potential of rapid response as an aid to sizing the immediate operational response and requesting reinforcements.

In addition to the aforementioned issue of itinerary selection, respondents also expressed an interest in the rapid estimation of

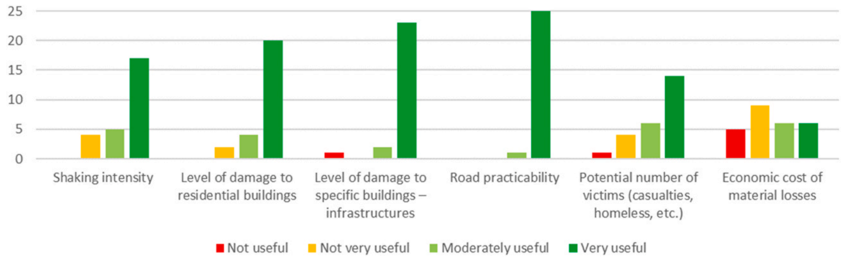

Fig. 11. Answers to question 37 – Usefulness of different impact indicators.

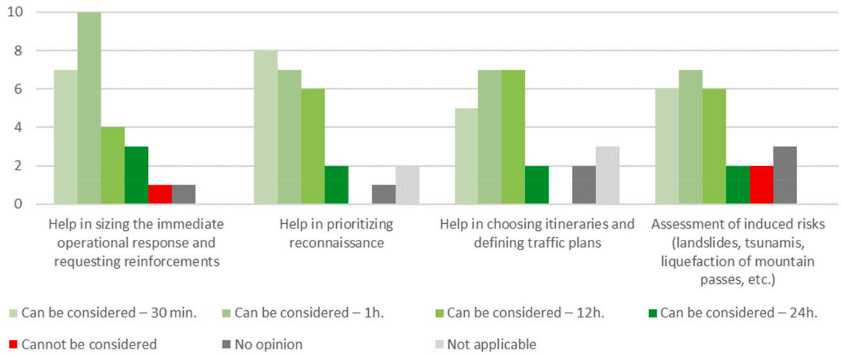

Fig. 12. Answers to question 39 – Actions envisaged upon receipt of rapid response reports.

indicators that would enable them to prioritize their investigations, as well as to obtain initial information on possible risks induced by shaking, such as landslides, soil liquefaction or tsunamis (Fig. 12).

In terms of the reliability of RRE systems, the most important consequences of incorrect impact estimates appear to be a potential loss of confidence in the tool. Such incorrect estimates can also have consequences in terms of loss of activity, if they are used to preventively shut down industrial facilities while checks are carried out, as well as in terms of disorganization of the operational response if they lead, for example, to prioritizing the dispatch of intervention teams to sites/sectors that in practice are not the most affected (Fig. 13). As underlined by one of the respondents, the main risk lies in the blind use of the tool, taking its estimated results as truth without critical analysis and comparison with other information received from the field.

5.2. Insights from interviews

5.2.1. Civil protection sector

In the aftermath of a destructive earthquake, the immediate priority is to rescue the victims, by taking care of the "visible" victims who are directly accessible, and by searching for and rescuing those who are trapped under the rubble. In France, these two missions fall under the responsability of the SIS: the first is part of the usual rescue capabilities of the SIS, while the second is a specific capability provided by specialized USAR teams within the SIS (e.g. reduced number of specialized personnel). These essential operations must be carried out as quickly as possible, as the chances of survival of victims decrease very rapidly with time, especially for those trapped under rubble [81,82].

However, it appears that the rapid mobilization capacity of the Martinique SIS (and probably of all SISs in France) is currently insufficient to cope with the effects of a major earthquake. In this context, the availability of OEF information could temporarily

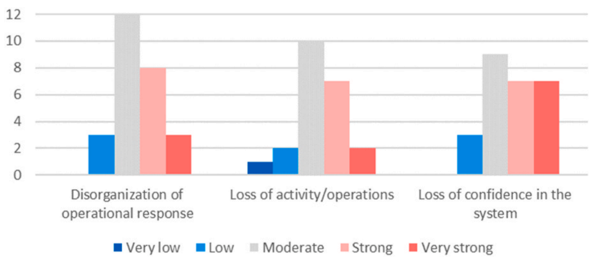

Fig. 13. Answers to question 43 – Consequences of incorrect rapid impact assessments.

reinforce this capacity by putting more personnel on duty during the periods of greatest risk. In addition, the head of EMIZA says he is very interested in the principle of OAF (operational forecast approach applied to aftershocks). Considered more reliable than OEF, OAF could be very useful for adapting the operational deployment of responders on the field, who are directly exposed to the consequences of aftershocks.

With respect to EEW, an often-cited example is the automatic opening of fire station garage doors to prevent them from warping, thus allowing emergency vehicles to exit freely [83]. Assuming that fire station buildings are earthquake-resistant and do not damage the vehicles inside, this type of measure seems to be of little use in the West-Indies, where, due to a favorable climate, fire station garage doors are practically always left open. However, it is conceivable to combine early warnings with a notification system that sends alerts to firefighters' pagers in order to activate reflex actions and speed up the mobilization of personnel. In this respect, it is interesting to note the thoughts of the director of the Martinique SIS, who stated that he was in favor of a fully automated rather than manual broadcast procedure, not so much for reasons of speed, but rather out of a concern to *"preserve the human element involved in rescuing people"*, since *"the pressure on the agent who would be responsible for relaying the early warning would be enormous, and any failure hard to bear"*. Still on the subject of early warning, the impact of false alarms on the Martinique SIS is considered to be very low. Discussions with the various levels of civil protection have also revealed a clear interest in having mobile EEW systems available to alert USAR teams in case of aftershocks [41].

Beyond emergency response, the civil protection stakeholders indicated that they would be interested in the possibility of disseminating early warnings to the population. In addition to the usual problems associated with the public dissemination of early warnings, such as raising public awareness, this would first raise the question of technical feasibility in terms of the means of dissemination available. Since 2022, France has had a national population alert tool (known as "FR-Alert") that allows mass alerts to be broadcast over a given area using "cell-broadcast" and "location-based SMS" technologies [84]. Although the delivery latencies of FR-Alert are little known, they are certainly significantly longer than the few seconds typically provided by EEW systems [85]. Furthermore, the system is currently designed to be activated manually by authorized authorities (prefectures) and cannot be activated automatically. While there are no technical difficulties in automating the public dissemination of alerts, this raises the question of the legal framework to be put in place and legal liability in case of false or missed alerts [86]. Recent studies, however, have demonstrated the feasibility of disseminating early seismic warnings in a timely and massive manner using smartphones [87].

While the OE(A)F and EEW systems arouse the interest of the interviewed civil protection practitioners from a prospective point of view, the RRE systems interest them for much more immediate operational uses. Thus, the three actors we met (SIS, prefecture and EMIZA) consider it essential to have an initial rapid assessment of the potential impact of an earthquake, identifying the most affected municipalities in order to (i) guide civil and military reconnaissance (by land, sea or air), (ii) anticipate the organization of rescue operations by prioritizing the allocation of resources, and (iii) anticipate and support any requests for reinforcements. The SIS director points out that *"it is a question of being able to regain control in the early stages after an earthquake, when you are not in control of what is happening"*. As far as the prefecture and the EMIZA are concerned, both indicate that the loss assessment provided by RRE systems can also be used to support the information they need to provide to their central administrations (national civil protection and government authorities).

In practice, EMIZA and the Prefecture are already recipients of the reports sent by the SEISAid-Antilles RRE system, and therefore they point out areas for improvement in relation to this tool, such as.

- For the most urbanized areas, there is a need to carry out assessments of potential losses at a finer scale than that of the municipality, e.g. at the level of the neighborhood. To this end, data distributed by the French Institute of Statistics (INSEE) can already be used to assess losses at a finer scale, but only in urban areas;
- In addition to the current assessment based on residential buildings, information may be provided on the potential impact of the earthquake on critical infrastructure systems, such as those housing operational resources (fire and rescue services, security forces barracks, etc.), vital functions (hospitals, airports, ports, command centers, etc.) or controlling mobility in the area (bridges, etc.);
- After the first report with decision support indicators focusing on the problem of victim rescue, there is a need to plan a second report with indicators related to damage assessment operations in the field and victim assistance (e.g. assessment of the number of buildings to be inspected and people to be rehoused by geographic sector);
- In addition to the direct effects of the earthquake, and as provided by the PAGER system, potential induced effects may be indicated, including, in order of priority: the possibility or not of a tsunami (i.e., coupling of RRE with tsunami early warning capabilities), identification of areas where landslides and rockfalls are likely to have affected roads, and identification of areas where liquefaction may have occurred, with particular attention to the impact on airport take-off and landing runways and to port embankments (lateral spreading).

An interesting learning point concerns the dissemination of RRE reports. The SIS, which does not currently receive the reports from SEISAid-Antilles, would like to receive them directly in order to be more efficient and to be able to use them without having to rely on their transmission by the prefectural services (possible loss of time or even non-transmission due to choice or omission). Conversely, the Prefecture of Martinique and EMIZA (which also reports to the Prefect of Martinique) wishes to retain control over the dissemination of rapid loss assessment information, leaving it up to the Prefect - as the sole coordinator of crisis management - to decide whether or not to disseminate this information via the liaison officers of the various services present in the departmental and zonal crisis centers.

Finally, whatever new earthquake information and warning tools may be put in place, the civil protection actors we interviewed stressed the need for a specific exploitation procedure to enable them to be used wisely and effectively.

5.2.2. Telecommunications sector

Telecommunications are an essential part of crisis management, especially via cell phones and the Internet. In the event of a destructive earthquake, these telecommunications resources are primarily threatened by the risk of failure of two types of infrastructure.

- Relay antennas: The risk of losing antennas depends first and foremost on the risk of collapse of the structures on which they are mounted: this risk is low for antennas fixed to towers and higher for those installed on buildings (depending on the physical vulnerability of these buildings). The second risk is the loss of the power supply needed to operate the antennas. Antennas that are considered strategic are usually backed up by dedicated generators that provide two to 3 h of autonomy. In addition, some antennas benefit from the backup power of the buildings on which they are installed.
- Buildings: The buildings that are most critical to maintaining telecommunications (e.g., the onshore arrival of Internet submarine cables) are designed to withstand very strong ground motions without damage. Also, potentially more vulnerable buildings play only a minor role in maintaining telecommunications after an earthquake.

A number of facilities critical to business continuity are remotely monitored and controlled, allowing operators to establish mutual aid procedures between the various territories of the French West-Indies. In addition, frequent IT backups enable the telecommunications system to be quickly restored if necessary.

On the basis of this brief description of the issues at stake, the prospect of an OE(A)F tool for the consulted operator suggests the possibility of.

- Pre-activating the crisis management system in response to an earthquake forecast issued by the authorities;
- Reviewing the status of relay antennas to assess whether any action is necessary and can be anticipated (e.g. software updates or fueling of backup generators, as is already done in the event of a hurricane warning);
- Anticipating the need for additional IT backups.

Although the operator clearly indicates a greater interest in operational forecasting for mainshocks (OEF), the principle also seems interesting to them during the aftershock period (OAF). On the other hand, given the very short lead times that can be expected, the principle of EEW is not of particular interest to the operator we met. At most, they consider that it might be possible to disseminate early warnings to staff in order to encourage reflex actions of self-protection. Similarly, as its critical infrastructure systems are monitored in real time, the operator has no specific expectations regarding RRE.

5.2.3. Water and wastewater sector

The operator we met manages the production and distribution of drinking water and the treatment of wastewater for a group of municipalities in Martinique. The infrastructure required to produce drinking water is based on a few production stations and dozens of reservoirs: all these installations are remotely monitored, with real-time visibility of volumes, flow rates, etc. On the other hand, the water distribution network is not yet remotely monitored. As for wastewater treatment, this is done by discharging treated water into the sea through infrastructure similar to that used for production (monitored infrastructure).

In the event of an earthquake, business continuity is ensured by (i) redundant computer servers and fortnightly backups, (ii) generators to provide power to high-priority sites (pumps, production and wastewater treatment sites), (iii) a 24/7 on-call system covering approximately twenty business functions required for wastewater treatment and drinking water production and distribution, and (iv) radio communication facilities for teams located at strategic sites.

In the event of an earthquake, the main criticalities identified by the operator concern, on one hand, the availability of spare parts in the event of breakage (availability of stocks, but in some cases the need to order them from mainland France) and, on the other hand, the chemicals needed to treat the water (chlorine degrades rapidly and cannot be transported by air). Because of these factors, the OE(A)F approach is not of particular interest to the operator interviewed.

On the other hand, they consider that an EEW system could be useful for remotely activating valves: however, this requires the early warning system to be "site-specific", i.e. capable of estimating the probability of exceeding intensity thresholds for incoming shaking at sites of interest.

After the occurrence of the shaking, the operator indicates that inspections would be carried out systematically on the main branches of the networks, so that no prioritization would be necessary (assuming the availability of teams and vehicles after the earthquake). Still, the operator considers that assistance in prioritizing surveys and interventions would be useful for other infrastructure components such as reservoirs: estimating the probability of failure of these structures - or even simply quantifying the intensity of the shaking at these sites - would seem to be very useful.

5.2.4. Energy distribution and hydrocarbon storage sector

The company we met owns gas and fuel depots in the French West Indies, as well as a number of service stations that distribute hydrocarbons and store small stocks of bottled gas.

According to the person we met, the OE(A)F principle is of real interest to ensure increased surveillance of hydrocarbon and gas tanks. For example, when work is carried out on these tanks, certain safety systems can be deactivated, temporarily increasing the vulnerability of the infrastructure: an operational forecast could make it possible to postpone such work. To a lesser extent, an increase in the probability of an earthquake could justify checking the condition of hydrocarbon distribution stations.

As for the case of EEW, it seems equally suited to the protection of distribution stations and storage sites. Given the heterogeneity of the stations, the first application could be to trigger the reflex action of moving away from them, for example by broadcasting an audible alert. In the case of storage sites, the reflex action on receipt of this alert could be for the staff to press the existing emergency stop buttons: it then takes about 30 s for the valves to close, thus limiting the volume of any gas and fuel leaks. However, our interviewee stresses that such actions would only be feasible in the case of a highly reliable system with very few early false alarms.

In the case of RRE, the fact that the company we met has a large number of sites means that the principle of a rapid impact assessment at the level of each service station is rather favorable, in order to provide management with an initial overview. Although this interest is obvious, its real operational added value is reduced by several factors: (i) the heterogeneity of service stations and their vulnerability make it difficult to assess the potential damage, (ii) the management of the situation to ensure business continuity is highly multifactorial, and - thanks to the wide territorial coverage - does not depend on the failure of a specific station, (iii) for fuel and gas depots, business cannot be resumed under any circumstances without an exhaustive assessment of the state of the installations.

5.2.5. Health sector

Martinique's healthcare system is based on three main pillars: (i) general medicine, (ii) hospitals and (iii) post-hospital care facilities, with hospital capacity and activity relatively comparable to those in mainland France. As demonstrated by the earthquake of November 29th, 2007, which caused significant damage to several hospital facilities in Martinique, this health system is vulnerable to seismic risk. Despite major efforts in recent years to reduce vulnerability and strengthen buildings, some facilities remain vulnerable.

In the event of a major earthquake, the two main challenges for the health system are (i) to ensure continuity of care, and (ii) to assist earthquake victims by increasing hospital care capacity. To deal with such situations, the Fort-de-France university hospital would play a central role in the care of serious pathologies, while other facilities would deal with lighter or stabilized pathologies. Many of these facilities are equipped with generators to provide them with electricity.

In terms of victim assistance, the increase in care capacity is based on procedures for (i) recalling personnel, with the possibility of requesting regional (Antilles/Guyana) and national reinforcements, (ii) deprogramming non-emergency interventions, and (iii) deploying forward medical posts in the field, or even field hospitals, in conjunction with the prefectural authorities and the SIS emergency services.

On this basis, our interlocutor - representing the regional health agency - considers the principle of OE(A)F very interesting in order to organize checks on strategic stocks (medicines, fuel for generators, food, etc.). On the other hand, it does not seem appropriate to use this type of information to reinforce the on-call staff, since the usual system is already in place to deal with all types of situations, including a system of regularization of emergency calls reinforced by general practitioners.

In the case of EEW, it could be used to alert medical staff in order to trigger reflex actions aimed at suspending sensitive technical procedures (surgery, laser, radiography), thus protecting patients. On a less specific level, an EEW could also be used to automatically control some equipment - mainly in hospitals - such as elevators. In addition, our interlocutor points out that an early warning, transmitted by an audible alarm, would be likely to limit panic effects such as those observed during the 2007 earthquake.

Finally, RRE tools such as SEISAid-Antilles are considered essential, particularly for anticipating capacity needs, anticipating the de-programming of non-emergency care, and supporting requests for reinforcements.

5.3. Crossed perspectives from the workshop

5.3.1. Perspectives about OE(A)F

Consistent with the findings of the survey (see section 4.1), concerns were expressed about the idea of informing the public about earthquake forecasts based on an OE(A)F tool, particularly because of the large uncertainties involved and the difficulty of providing clear instructions to accompany them. Moreover, as experience with weather warnings has shown, the general public easily loses confidence in the forecasts they receive, and quickly turns their attention away from them [88]. However, the issue of disseminating information to the general public is not only one of opportunity, but also of necessity. Assuming that such a system were ever to become available and operational, it would clearly be unacceptable for the authorities to keep information suggesting an increased likelihood of a destructive earthquake occurring in the near future to themselves. Required by a principle of transparency - and probably also by legal responsibility - this dissemination of information to the population could justify the temporary reinforcement of light preventive measures, such as school drills.

Beyond the elements already highlighted via the survey and interviews, it also emerges that, due to the presentation of feedback during the workshop on the implementation of OE(A)F in Italy [12,13] and New Zealand [16], participants tend to be more in favor of using the tool for forecasting aftershocks (OAF) rather than main shocks (OEF), the former being perceived as more reliable and easier to value in decision support. This is particularly true for civil protection practitioners and operators in the energy (hydrocarbons) and drinking water sectors.

5.3.2. Perspectives about EEW

Several of the industrialists present have already indicated that they have control systems for the automatic protection of certain equipment/processes (e.g. lightning protection systems) and that some of these could undoubtedly be triggered automatically upon receipt of an EEW.

As already noted in the survey, it is also very clear that the perception of the potential of EEW is very much linked to the length of time between the receipt of the warning and the arrival of the shaking. Although the prospect of delays of only a few seconds raises questions among the participants as to their real ability to take advantage of them, they are nevertheless interested in the principle and rather favorable to the idea of developing such a system for Martinique. In this context, it is worth noting that, due to the geographical configuration of the West Indies - and of the Lesser Antilles in general - with insular territories and a seismic hazard dominated by a subduction zone, an effective EEW system would necessarily (i) have to be shared by all territories, and (ii) be based on real-time underwater seismological monitoring capabilities. In the event that such a system is implemented, the SIS emphasizes the importance of working in "community", involving all the territorial stakeholders, as has been done for years in the Caribbean under the auspices of UNESCO for tsunami early warning [89].

5.3.3. *Perspectives about RRE*

In addition to the points already made in the survey and interviews, the importance of road trafficability in the post-seismic period is highlighted as critical by many practitioners. Whether to enable the deployment of intervention teams to critical facilities or to conduct inspections, it is essential to be able to quickly get an initial idea of the state of the road infrastructure, with a dual concern for (i) the resistance of engineering structures to shaking, and (ii) the effects of potential landslides. Through the combined use of observations and models ([90]; Cauzzi et al., 2018), RRE tools could provide useful information in this area for many users.

Furthermore, besides the road network, there is a need to estimate the expected impact on specific assets (emergency centers, hospitals, decision centers, etc.), in addition to more generic indicators such as those evaluated by SEISAid-Antilles at the municipal level. This may justify the use of specific seismological instruments at these sites of interest, firstly to reduce the uncertainty on the intensity of the ground shaking and, if necessary, to detect damage by analyzing records from sensors inside the structures.

Finally, EMIZA emphasizes a very important and widely shared point, namely that information from RRE systems should not be taken at face value, and that it should be in any case verified first by cross-checking with available information from the field. In this way, EMIZA envisages being able to prioritize inspections upon receipt of rapid response elements: depending on whether they confirm or invalidate the loss assessments in the recognized areas, the rapid response elements will be used differently.

6. Discussion

It is clear that the consulted stakeholders are very concerned about the impacts that earthquakes could have on the territory of Martinique, and that they overwhelmingly share the feeling that new methods of vigilance and alerting to earthquakes would allow them to gain in efficiency and ultimately reduce the impact of earthquakes.

The elements collected as part of the study remain a reflection of the individual perceptions of the people consulted and cannot therefore be considered conclusive of the positioning of their organizations. However, their joint analysis makes it possible to draw up the broad outlines of possible actions by sector of activity, for each of the three tools studied, namely OE(A)F, EEW and RRE (Fig. 14). This analysis of possible actions, which highlights the main trends, must not hide the fact that there may be differences of perception t

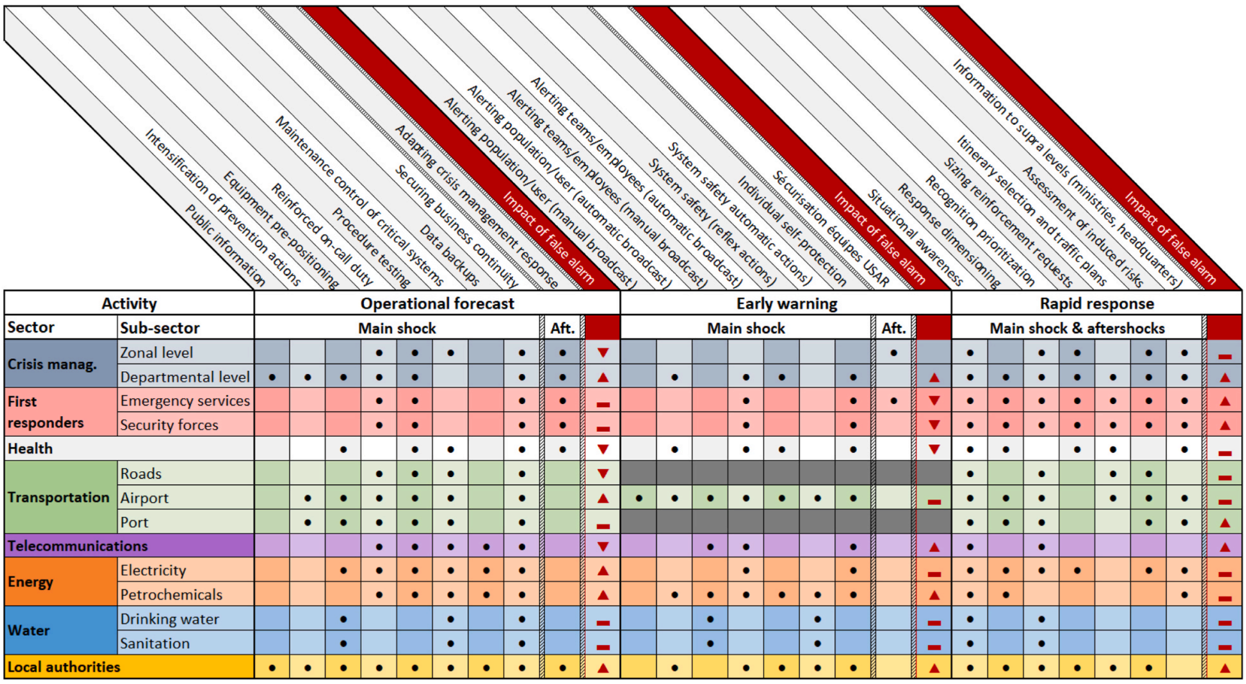

Fig. 14. Sectoral summary of the main types of actions envisaged by the Martinique stakeholders for the different types of earthquake warning tools. Actions envisaged specifically for use in aftershock sequences are indicated in the "Aft." columns. The impact of false alarms is indicated qualitatively: low impact (down arrow), moderate impact (dash), high impact (up arrow).

between actors from the same sector, or even from the same organization.

It is clear from this analysis that the type of tool for which an operational perspective is the most direct is that of RRE, which consists of estimating the impact of an earthquake a few tens of minutes to a few hours after it has occurred. In addition to contributing very directly to situational awareness [91] in a period characterized by high uncertainty on the extent of the situation, this type of tool can enable many entities – both public and private – to scale their operational response in advance or to prioritize their initial reconnaissance. Moreover, the cost of setting up and maintaining RRE systems remains relatively low, and such a tool already exists for the French West Indies (the SEISAid-Antilles tool – Auclair et al., 2024). This tool should therefore be operationalized in its current version dedicated to civil protection actors, while being improved to better meet the needs expressed in this study by practitioners from other sectors. In particular, it seems necessary to work on the development of capacities for assessing the impact on specific buildings and infrastructure, in addition to damage estimates for residential buildings: this orientation may require approaches using dedicated seismic instrumentation [92,93]. Another need shared by all the consulted practitioners is the integration of capabilities for estimating damage to road elements due to structural damage or the obstruction of roads, as well as the resulting functional impacts [90].

Secondly, it is the principle of OE(A)F, the use of which could be explored in Martinique and Lesser-Antilles in the next few years. Although the information that such systems can provide is considered to be very useful, in particular for reinforcing on-call systems, controlling critical systems or even securing business continuity, the reliability associated with such forecasts is strongly questioned by practitioners at this stage. It is therefore necessary to be able to test the algorithms established by the scientific community, such as the ETAS model, in order to truly assess their potential for application in the French West Indies and the Lesser Antilles, by deploying an experimental device such as those that constitute the Collaboratory for the Study of Earthquake Predictability (CSEP [94]). Furthermore, beyond the questions of feasibility and the direct costs of deploying such a system, the question of the costs of possible protective measures must also be considered. If, a priori, measures to inform the population would be inexpensive, this would not be the case for a decision to evacuate a municipality for one to several weeks on the basis of an OE(A)F tool [95]: in this respect, there are probably lessons to be learned from the evacuation issue related to volcanic risk, which is well known in the Lesser Antilles [96]. This highlights the need for careful cost-benefit studies to assess the contribution of one or another action in response to an operational forecast [9,97].

Finally, the concept of EEW is more delicate to approach. Although it can be potentially very useful for the territory of Martinique and more broadly for the Lesser-Antilles as a whole, the actual performance of such a system for the region also remains to be validated by experiments. However, the conditions to be met in order to be able to carry out these experiments are very restrictive and particularly expensive (much more than for the OE(A)F). In particular, due to the insular context of the territories of Lesser-Antilles, they require the deployment of permanent underwater seismological monitoring, such as the Japanese S-net observing network dedicated to early warning of earthquakes and tsunamis (Kanazawa et al., 2016; [98]). However, as Allen and Melgar [99] point out, the cost of such infrastructure is significantly higher than that of terrestrial networks. This should encourage multiple-use design, such as in Japan for example, where the combined installation of seismometers and pressure sensors also contributes to tsunami early warning and fundamental scientific research. Furthermore, a real-time underwater network would also help improve the potential performance of operational forecasting or rapid response tools. However, assuming that such an EEW system exists in the Lesser-Antilles, we would have to question the long-term sustainability of the maintenance effort of this system, as well as the automated systems capable of taking advantage of it. It would therefore be advisable to refine the investigation of opportunities outlined here, in particular by carrying out an in-depth cost-benefit analysis extended to all territories of the Lesser Antilles, before undertaking any experiments.

Furthermore, the collection of elements from several practitioners and the comparison of their points of view during a dedicated workshop have highlighted non-technical dimensions of an organizational, communicational, political and legal nature, which are often less visible and yet essential. For example, in the case of rapid response, there is a duality between, on one hand, different sectoral needs which tend to favor the dissemination of specific information for targeted decision support and, on the other hand, the issue of the sensitivity of these rapid loss assessments, which encourages top-level authorities to be the sole recipients in order to be able to control their dissemination. For instance, the system could send to the crisis management coordination a summary report with low geographical granularity and indicators linked only to the potential human and material toll, or, on the contrary, it could provide municipalities and emergency services with very high resolution maps showing, district by district, estimates of the number of homeless people to be sheltered and buildings to be inspected, for the former, and the number of victims to be rescued, for the latter. This duality is accompanied by the risk of distortion of information between organizations, which can result from the production of user-specific outputs and which could ultimately have the counterproductive effect of harming the emergence of a common operational picture. On another level, the issue of dissemination of alerts to the general public is also raised, in particular with regard to OE(A)F and EEW. Beyond the question of the benefits that the population may or may not obtain from such information, stakeholders from Martinique also raise the question of the risk associated with the non-public disclosure of information available to the authorities. This question has been widely debated at the legal level following the trial that followed the Aquila earthquake in 2009 [100,101], but relatively less from the perspective of social acceptability. Finally, regarding the legal framework, many questions have to be considered to identify who should be in charge of disseminating alerts, and who should be held responsible in case of false or missed alerts ([86]; [102]).

7. Conclusion and perspectives

The opportunity to implement local tools that allow practitioners to better anticipate the occurrence of earthquakes or to quickly characterize their effects is a complex question that must be considered on a case-by-case basis for each territory. The evaluation of this opportunity obviously supposes being able to estimate the scientific and technical feasibility of setting up and maintaining the systems, but even more to evaluate the real needs of the practitioners in the territory, and their capacities to implement actions capable of reducing losses in the event of an earthquake.

This is the question that this study aims to answer by initiating an in-depth consultation of stakeholders in the territory of Martinique (French West Indies in the Lesser Antilles), not limited to civil protection practitioners but, on the contrary, taking into account all the main sectors that play a major role in the operational management of seismic risk (coordination of crisis management, rescue and hospital services, securing the disaster area, production and distribution of energy and drinking water, assistance to the population, etc.).

To this end, the study is based on the analysis of the results obtained in three stages from a panel of practitioners through (i) an online survey, (ii) individual interviews, and (iii) a workshop bringing together all stakeholders. In total, about thirty participants took part in this consultation. Although relatively limited in number, this panel is particularly interesting because it is composed exclusively of experts and high-level managers with sufficient levels of knowledge and responsibility to have an informed opinion on the needs of their organizations in terms of earthquake warning. In addition, these stakeholders – who represent 21 different key-organizations and cover most of the vital functions of the territory of Martinique – have almost all already experienced an earthquake and have a very clear awareness of the actual level of seismic risk: this is very important because, as pointed out by Becker et al. [44], this "prior knowledge" increases people's ability to understand the scientific information presented to them, such as the notions of operational forecasting, early warning, and rapid response.

First, we have noted very positive and enthusiastic feedback from all stakeholders at the prospect of having new tools to manage seismic risk more effectively by better anticipating and/or responding to earthquakes. Well aware that the OE(A)F/EEW/RRE tools cannot in themselves improve seismic risk management, these practitioners were able both to identify both the actions they could take to fully benefit from these tools, as well as their limitations in use. While the tools studied can potentially benefit all actors in a given region, the example of Martinique shows that their appropriation is different and specific to each organization, depending on its own vulnerabilities, resources, processes, etc. However, for each of the three tools studied - OE(A)F, EEW and RRE - we were able to identify the main lines of action that could be envisaged for each sector of activity. These lessons can be considered at different levels.

- At the local level of Martinique, the results of this study clearly identify the priorities to be given in the coming years in terms of tool development: (i) to operationalize the existing SEISAid-Antilles RRE tool, to extend its functional scope and to make it accessible to more users, (ii) to test the technical feasibility of the OE(A)F principle, and (iii) to further analyze the opportunity of having an EEW system.
- At the regional level, the results must first be considered in relation to the French West Indies territories, which belong to the same country (i.e., France) and therefore share the same administrative and industrial structure, with common levels of civil security coordination, as well as crisis management and business continuity plans based on mutual synergies and reinforcements. The lessons learned from Martinique can thus be extended to the Guadeloupe archipelago, which has many similarities, and to a lesser extent to the islands of Saint-Martin and Saint-Barthélemy (which are further north and have significantly different exposed assets and seismo-tectonic contexts). Furthermore, given (i) the geographical extent of the geological structures involved and the models used for the OE(A)F approach, and (ii) the particularly costly seismological monitoring resources required to set up an EEW system, it is unreasonable to envisage the development of EEW and OE(A)F tools specifically for small territories such as Martinique. For this reason, it would be appropriate to extend the consultation process with practitioners carried out in this study to all the territories of the Lesser Antilles, from the perspective of pooling efforts to set up common tools.
- At the international level. Although carried out exclusively in Martinique, the interviews we conducted allowed us to highlight that the actions envisaged by practitioners were essentially driven by "business" contingencies (relief, energy, transport, etc.) that could be transposed to many other regions of the world. We therefore hypothesize that the sectoral summary of the main types of actions envisaged presented in Fig. 14 can be useful anywhere to initiate reflection on whether or not to develop OE(A)F/EEW/RRE tools. In a second phase, these generic actions should in any case be further developed through a consultation process that takes into account local specificities (natural, political, organizational, cultural, etc.).

It is also interesting to compare the main types of actions envisaged by practitioners with the continuum of temporalities covered by the OE(A)F (from a few months to a few days before the occurrence of an earthquake), EEW (a few seconds before the arrival of strong ground motions) and RRE (a few minutes to a few hours after the occurrence of an earthquake) tools (Fig. 1). This comparison reveals links - even continuities - between the tools and is consistent with the "dynamic earthquake risk framework" approach proposed by the Swiss Seismological Service (SED), which is working to standardize its OE(A)F/EEW/RRE products and workflows to promote synergies [103]. Thus, rather than considering each tool separately to assess its feasibility/potential usefulness, as is usually done, we believe it is relevant to promote the joint consideration of "multi" dimensions.

- Multi-tools (in our case OE(A)F, EEW and RRE);
- Multi-purposes: as the seismological monitoring and data analysis resources required to build and maintain these tools are very costly, multiple uses should be identified and encouraged (e.g. tsunami early warning, fundamental geoscience research activities, etc.);
- Multi-phenomena: potential induced risks (e.g. tsunamis, landslides, soil liquefaction) need to be taken into account, especially for EEW systems;

- Multi-users: each tool may be useful to many different users, and it is therefore necessary to identify all these potential users and their common and specific needs;
- Multi-territories: combining existing tools with a strong territorial rationale aims to pool expenditures and limit "side effects", especially for island regions such as the Lesser Antilles or cross-border regions sharing the same seismogenic sources [42]. While the modes of restitution and their use may vary greatly from one territory to another - particularly for organizational and legal reasons - the tools themselves (monitoring networks, data processing infrastructures and models, etc.) can usually be shared.

We also note that the information gathered from Martinique practitioners supports the recommendation of Auclair et al. [45] *"to bring down the barrier between, on one hand, the 'early stage' joining artificially and very closely early warnings with early actions, and, on the other hand, the 'rapid stage'"*. Thus, it seems appropriate to consider hybridizing the concepts of early warning and rapid response into a single *"Earthquake Early Response"* approach, taking advantage of the early assessment of the focal parameters of an earthquake (early warning principle) in order to improve the rapidity of RRE systems [45]. Even if the early safety actions thus initiated would not necessarily have all the time to take full effect before the arrival of the strongest shaking, it is reasonable to think that early warnings would enable, in some cases, to limit the risk of over-accident [49]. However, this point needs to be carefully analyzed for each system, insofar as certain industrial processes present an increased vulnerability during the safety phase, potentially making the "cure worse than the disease" (cf. example of civilian nuclear power - [43]). With this in mind, it would also be necessary to carry out updates to take into account new data as they become available: seismological data to refine earthquake parameters, instrumental measurements and macroseismic internet evidence to calibrate shaking intensity maps [104], feedback from first damage assessments conducted in the field to validate and recalibrate loss models [105], etc.

In conclusion, the joint analysis of OE(A)F/EEW/RRE tools carried out in this study argues for a better consideration of the needs and uses envisaged by practitioners through the use of user-centered approaches, considering the necessary "informational continuum" of decision support before, during and after the occurrence of earthquakes and their aftershocks. This is all the more important in the perspective of potentially complex seismic sequences, such as the one in central Italy in 2016–2017 [13], or in Canterbury (New Zealand) in 2010 [44], where several powerful earthquakes were followed by numerous aftershocks: in this type of seismic sequence, OE(A)F/EEW/RRE systems need to operate simultaneously and in concert, rather than sequentially.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL in order to improve the readability of the document in English. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Samuel Auclair: Writing – original draft, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Aude Nachbaur:** Project administration, Methodology. **Pierre Gehl:** Writing – review & editing. **Yoann Legendre:** Writing – review & editing. **Benoît Vittecoq:** Writing – review & editing, Funding acquisition.

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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Data availability

The authors do not have permission to share data.

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