An Early Warning System for Seismic Events based on the Multi-Agent Model

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Abstract

When a disastrous earthquake is about to occur in a specific territory, there are a series of anomalies that alter the pre-existing natural balances. Seismic swarms, ground deformation, bright flashes, emissions of various gas types (radon, CO_2,..), changes in the composition and flow rate groundwater are just some physical-chemical perturbations induced by the growing stress condition borne by the crustal masses. Dilatancy theory and asperity model allow us to interpret the dynamic mechanisms to which the seismic precursors are due: the development of a network of cracks and the sliding of areas with less mechanical resistance are in agreement with seismic, mechanical and geochemical anomalies that occur before to high magnitude earthquakes. In areas with high seismic risk, constant monitoring of geophysical parameters is frequent, carried out using different types of sensors.

The MAS (Multi-Agent System) model is one of the most suitable choices for efficiently implementing a seismic alert system, based on the interpretation of experimental data obtained from the sensor network. Using this type of approach, a Seismic Early Warning (SEW) has been created that according to the data acquired by the sensors and through the activities carried out by agent clusters, define the risk of seismic events having magnitude at least six. The SEW system aims to interpret, in real-time, the variations of an adequate number of seismic precursors for specific threshold values, calculated statistically. The integrated and complementary analysis of them, using several specific Boolean expressions, assesses the contribution provided by each parameter for computing the level of risk, divided into soft, medium and hard. The model has been tested with data gathered in New Zealand, a nation with a high seismic and volcanic risk which offers free access to some seismic precursors.

Keywords

MAOP, MAS, multi-agent system, seismic precursors, earthquakes, geophysical parameters

1. Introduction

Software applications based on MAOP (Multi-Agent Oriented Programming) are widely used in various fields and have taken on an increasingly important role thanks to the use of artificial intelligence (AI) techniques [1, 2, 3]. The adoption of centralized methods presents intrinsic difficulties due to the growing complexity of the systems, the dimensions of which continue to increase: in this context, the architectural solutions proposed by the MAS (Multi-Agent System) offer different advantages and a good solution for the modelling of complex distributed

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systems [3, 4, 5]. One of the fundamental characteristics of the MAS paradigm is the interaction between agents, independent and autonomous software modules that perform specific propaedeutics activities for the development of one or more system functions. The innumerable properties that distinguish the agents (communication, persistence, reactivity, proactivity, etc.) make them potentially suitable for monitoring natural phenomena, especially those capable of producing catastrophic events.

The different activities required by a seismic early warning system, summarized in the acquisition, interpretation and formatting of geophysical data with the addition of real-time user assistance, make the MAS model one of the most appropriate systems for real-time monitoring of precursor parameters (seismic swarms, ground deformation, soil temperature, radon gas emission, etc.) aimed at predicting earthquakes potentially destructive.

Concerning the previous observations, a software system called SEW (Seismic Early Warning) has been developed, based on a dashboard that, in real-time, shows updates based on alert level (soft, medium and hard) that characterizes a specific area at high seismic risk. The system of agents, operating in the background, allows comparing the experimental data of seismic precursors with the corresponding threshold values, obtained statistically from seismic swarms which, in the past, have produced a destructive earthquake. Through simple Boolean expressions, it will then be possible to automatically establish a certain alarm level in the places surrounding the seismic source.

The remainder of this document is organized as follows. A literature survey is discussed in Sections II. Section III presents the seismic domain of the application and the methodologies used. Section IV defines the characteristics of the MAS and the collaborative interaction between agents. Section V illustrates the case study of New Zealand, a region with high seismic and volcanic risk in which a SEW prototype has been implemented and tested and the results of which are discussed in section VI. And in conclusion, the MAS approach advantages and all the new features presented were analyzed in Section VII.

2. Related Work

Many applications that combine artificial intelligence and MAS technologies, in various sectors, have been developed: some examples are represented by the new opportunities created respectively for traffic control at intersections[1], for monitoring and improving the cloud performance and security [2], or for alerting people about crowded destinations [6]. In the last years, a group of scientists presented a Multi-Agent System paradigm and discuss how it can be used to design intelligent and distributed systems [3]. Next, a decentralized approach of MAS has been developed using a distributed simulation kernel to solve partitioning, load balancing and interest management problems in an integrated, transparent and adaptive manner [4].

Different works have been produced on the implementation of multi-agent systems relating to coordination and rescue in the stages following the occurrence of a high-intensity seismic event. A multi-agent system for the evacuation of people in immediate post-emergency situations has been implemented for the city of Iaşi (Romania) [7]. A series of simulators using a MAS architecture, following the damage caused by the 1999 earthquakes in Turkey and Pakistan in 2005, have been developed: damage, victims and other auxiliary simulators [8]. A Disaster

Management System (DMS) developed with the multi-agent model has been proposed to adequately manage a multi-risk situation consisting of two or more disasters occur at the same time, such as, for example, the combination of earthquake and tsunami [9].

Other systems for the management of the pre-post seismic phases have been developed by the authors in various ways: (i) through a Seismic and Volcanic Early Warning System in the Etna area based on specific threshold values for each geophysical precursor [10]; (ii) with an approach based on the coupling of multi-agent systems and intelligent systems (cellular automata) for simulation on rescue in the event of an earthquake disaster [11]; (iii) through simulations of various post-seismic evacuation scenarios for people using a multi-agent system [12]; (iv) integrating GIS with multi-agent seismic disaster simulations to investigate factors significantly affecting rescue efforts, and to clarify countermeasures for saving lives [13].

3. Approach

This section describes the model on which SEW is based and the methodologies used to implement the proposed system. The first activity concerns the extraction of useful information from the databases of seismic precursors (seismic swarms, soil deformations, ...) and their visualization in a SPA (Single Page Application), based on Angular. The next phase is the implementation of a multi-agent system defining the alert level of the seismic territory based on the result obtained from a set of Boolean expressions founded on the seismic precursors.

3.1. Methodology

Within each seismic zone, there are one or more seismogenic structures (faults) which, with their displacement, can produce the vibrations that generate the earthquake. Sequences of seismic events that, in some cases, may prelude to a major magnitude earthquake (mainshock) are called seismic swarms. Every single event (foreshock) belonging to the sequence often occurs a short time from the previous one.

Suppose we consider all the seismic swarms that in the past have given rise to mainshocks of medium-high magnitude (above 6) which, about to the characteristics of the territory concerned, can produce serious damage to people and things. We denote with S_1, S_2, S_3 three classes of seismic swarms which as a final result gave an earthquake of magnitude $\mathrm{M}_w \geq 6$ and with $(P_1, \bar{S}_1)$, $(P_2, \bar{S}_2)$, $(P_3, \bar{S}_3)$, the ordered pairs where P corresponds to the number of S elements and $\bar{S}$ to the arithmetic mean for each class S_1, S_2, S_3. The average of the averages for the three classes of seismic swarms that prelude to an earthquake of Magnitude M_w will be given by:

$$SS_{T_h} = \frac{1}{N} \sum_{i=1}^{3} P_i \bar{S}_i \tag{1}$$

$$N = P_1 + P_2 + P_3. \tag{2}$$

The SS_{T_h} value obtained corresponds to the most probable value for seismic swarms with $\bar{M}_w < 6$ for that specific seismogenic structure, and therefore a threshold value for the mainshock of magnitude $\mathrm{M}_w \geq 6$.

The same procedure is performed for geophysical precursors for which a consistent database of measurements is available. Consequently, three further threshold values (RC_{T_h}, GD_{T_h} and ST_{T_h}) will be obtained referring respectively to *Radon Concentration (RC)*, *Ground Deformation (GD)* and *Soil Temperature (ST)* for earthquakes with $\mathrm{M}_w \geq 6$. The four previously threshold values (T_h) will be associated with the respective standard deviations (σ) expressed by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{3}(\bar{S}_i - T_h)^2}{3}} \tag{3}$$

and the achievement of the threshold value (T_h) will occur when:

$$[\bar{M}_w \pm \sigma_w] \cap [SS_{Th} \pm \sigma_{th}] \neq \emptyset \tag{4}$$

where $\bar{M}_w$ represents the average magnitude of the current seismic swarm and σ_w the standard deviation associated with it. In real conditions in presence of an extensive seismic swarm (SS), the system will calculate the average magnitude value ($\bar{SS}$) of the seismic sequence in progress and the other three seismic precursors ($\bar{RC}$, $\bar{GD}$ and $\bar{ST}$). In the next step, it will compare the mean value of the four precursors with the respective threshold values.

The definition of the alarm level will be based on the evaluation of a series of Boolean expressions and conditional instructions, arranged in sequence, which allows defining the type of alarm based on the number of precursor parameters that have reached or exceeded the threshold value, going from *hard* (all variables are true) to *soft* (only two variables have exceeded the threshold value). Among the four Boolean variables, *SS* (*Seismic Swarm*) has a fundamental role in defining any alarm level:

if ($SS \wedge RC \wedge GD \wedge ST$) (5)
    return "hard";
if ($SS \wedge ((RC \wedge GD) \vee (RC \wedge ST) \vee (GD \wedge ST))$)
    return "medium";
if ($SS \wedge (RC \vee GD \vee ST)$)
    return "soft".

3.2. Theoretical Background of the SEW

Forecasting of high-magnitude seismic events has as its foundation some theories that, since the last century, have been proposed by various authors to explain the phenomena that determine earthquakes.

Dilatancy theory [14] foresees that before an earthquake the seismogenic area is subject to an increase in stress with an expansion of the crustal volume due to a substantial cracking of the rocks. Consequently, the rocks undergo a variation of their physical characteristics and from the external regions, the fluids are attracted by this extensive fracturing phenomenon. Both the gases and the liquids circulating within the crustal volume change their paths and upon contact with different rocks and/or fluids change their geochemical composition. The interpretation of the phenomena that prelude and follow an earthquake is the basis of what is proposed by Aki (1979) and Kanamori (1981) called respectively *barrier model* and *asperity model.*

In the *barrier model* [15, 16] it is assumed that, before the earthquake, the stress on the fault is uniform. The earthquake is produced by the sliding of the weakest area, while the most resistant area (*barrier*) is opposed to dislocation. In this way, there is an increase in barrier stress. Consequently, after the earthquake, the barrier may be affected by seismic (aftershock) or aseismic sliding episodes.

The *asperity model* [15, 16] considers that the sliding that generates the earthquake concerns the most resistant area, i.e. the asperity. Before the mainshock, the stress on the fault is not uniform because aseismic sliding and preliminary shocks (*foreshock*) have reduced stress in the weakest areas of the fault, concentrating it on asperities. When stress reaches a critical value, the asperity yields giving rise to the earthquake.

The three models agree with the physico-chemical anomalies related to the extensive fracture affecting the seismogenic area (seismic precursors) and with the long sequences of earthquakes preceding (foreshock) and subsequent (aftershock) at the mainshock, providing a valid interpretative key.

4. Framework

The SEW dashboard consists of a series of software components (agents) capable of performing simple tasks, but unable to perform a complex task individually. Recall that each task can be decomposed into simpler parts, to be performed by individual agents or groups of them who cooperate. By planning their interaction through a multi-agent architecture, based on collaboration and the exchange of information, it is possible to achieve the common goal.

A more detailed analysis of the individual responsibilities attributed to each agent and the proposed architectures are described in the following sections.

4.1. Hardware and software architecture

A fundamental prerequisite for the implementation of SEW is the presence, in the seismic territory, of a capillary network of seismometers and GPS sensors, recently replaced by GNSS (*Global Navigation Satellite System*). By this acronym we mean a constellation of satellites that, by sending a signal from space, allow specific receivers to determine their geographical coordinates (longitude, latitude and altitude) on any point on the earth's surface: any ground deformation, before, simultaneously or after a seismic event, will be highlighted by deviations from the original positions.

The test of the system, carried out in the Experiments section, was based on the available datasets, i.e. *Seismic Swarms* and *Ground Deformation*. Additional precursor parameters, in seismic areas where they are available, could significantly improve the results obtainable from SEW: *concentration of Radon*, CO_2, *Arsenic* and *Iron*, *soil temperature* are some of the many precursors that give significant anomalies before a destructive earthquake. The sensors network, arranged optimally for the seismogenic structures, must guarantee monitoring of the precursor parameters with measurements carried out continuously through a Repeater-Gateway transmission system, as in the case of *ground deformation*, *earthquakes* and *soil temperature*. For other precursors (*Radon*, *Iron*, CO_2 and *Arsenic*) the data acquisition can take place directly with on-site sampling.

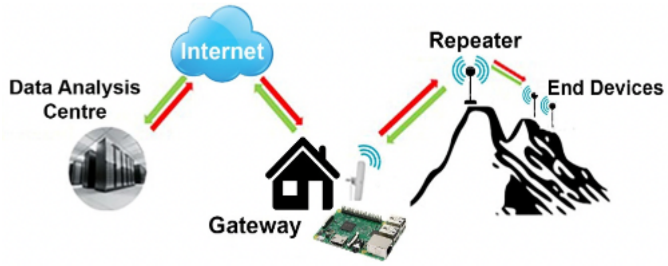

Figure 1: Repeater-Gateway transmission system [17]

Figure 1 shows the acquisition-transmission scheme of the wireless network, consisting of three main components: the gateway, the repeater, and the end devices [17]. GNSS receivers, seismometers and geochemical sensors acquire the experimental data and send them to a repeater which amplifies the signal strength to be transmitted to the gateway, equipped with an internet connection, which routes them to the respective servers of the data processing center. And from this moment on, software agents come into play, carrying out a series of sub-activities to achieve the final goal corresponding to the definition of the current alert level. The main features of the Multi-Agent System is based on some assumptions: (i) no agent can solve a problem on his own but must make use of the collaboration of the others to achieve the intended purpose; (ii) each agent differs from the others in the properties that distinguish it and the tasks it can perform; (iii) agents are divided and associated in a congregation, i.e. groupings of them that perform a series of semantically similar tasks.

With reference to the third point, we can consider that each group of agents acts in parallel and independently from the others, even if they share the same final objective. E.g., the cluster of agents SS (Seismic Swarm) acts in parallel with the clusters GD (Ground Deformation), RC (Radon Concentration) and ST (Soil Temperature): each group carries out similar activities to determine if there is an overlap between your current experimental data range and that of the corresponding threshold value, expressed by the relation (4). The interpretation of the data obtained from the n agent clusters and the definition of the alert level is the exclusive relevance of agent A. To verify that no malfunctions have occurred, a group of three demon agents (X_1, X_2 and X_3), periodically and alternately, checks whether the state of A is consistent, by sending it a message to which a response must follow. In case of no-confirmation, the role of the main agent will be assigned to one of the two "A substitutes" (A_1 or A_2) who will assume the same functions performed by A.

The detail of the interactions between the agents relating to different clusters is described in the following section.

4.2. Collaborative interaction between agents

The description of the interactions in the SEW system is based on the assumptions the MAS implementation concerns earthquakes with a magnitude greater than six and each agent is characterized by its internal state, that is, by variables and data structures which, at a given instant, contain specific values. Agents are server-side back-end components queried by the

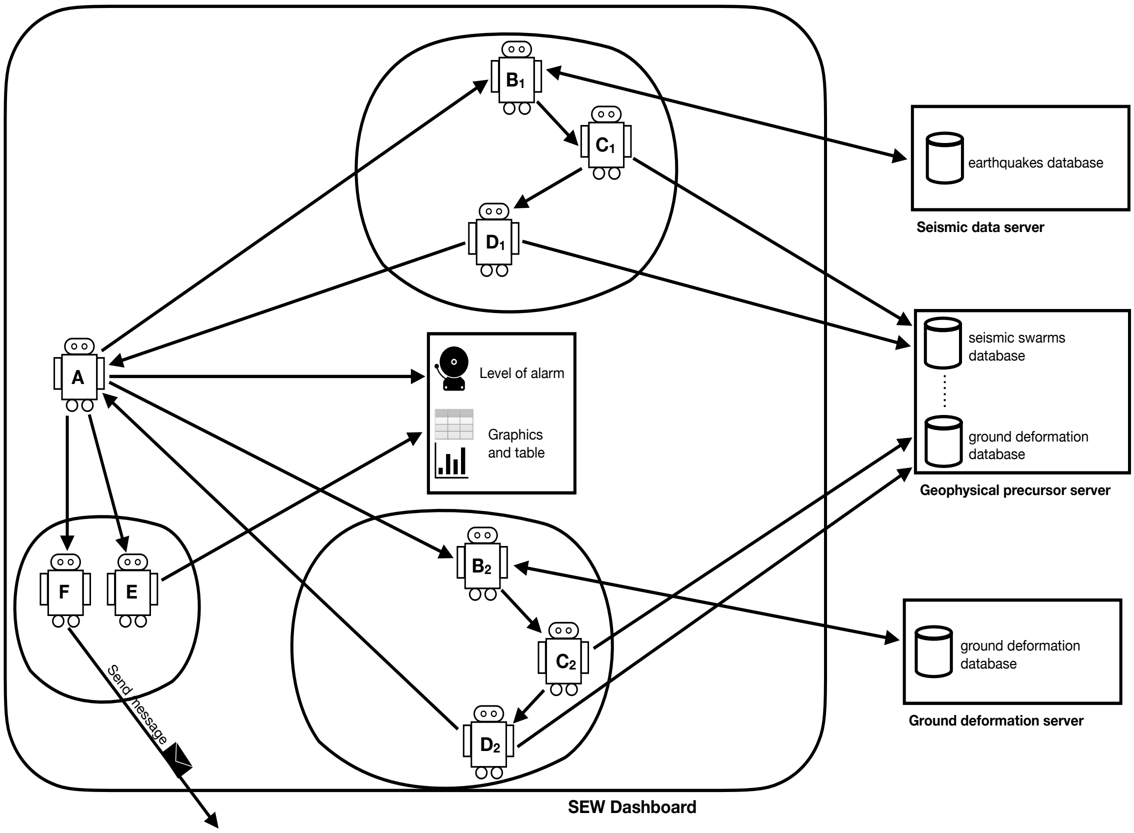

Figure 2: Agent interactions scheme

front-end. The system, still under development, uses Java Agent Development Framework (JADE), a network-oriented framework that guarantees very efficient communication. The example shown refers to the geophysical parameter "Seismic Swarm", but the actions and operations carried out can also be considered substantially equivalent for the other geophysical parameters.

Collaboration and exchange of information can be summarized with the following activities, distributed over a series of agents: (i) download of experimental data from the corresponding servers where they have been stored by the sensor network; (ii) filtering according to certain rules that establish whether they are suitable for registration or not; (iii) analysis of current data and comparison with statistically calculated threshold values; (iv) establish if the alarm level must be updated defining its criticality; (v) formatting and display of data to be presented to the user; (vi) notification of a warning to a select group of scientists on any existing critical problems.

Figure 2 highlights the different roles assumed by agents B_1, C_1, D_1, belonging to the same group of agents, while A belongs to a hierarchically higher level. Every 10 minutes agent A sends a notification to agent B_1 that queries the internal server for the latest updates on seismic events occurred in that source area. In case of a positive response, it sends a message to agent

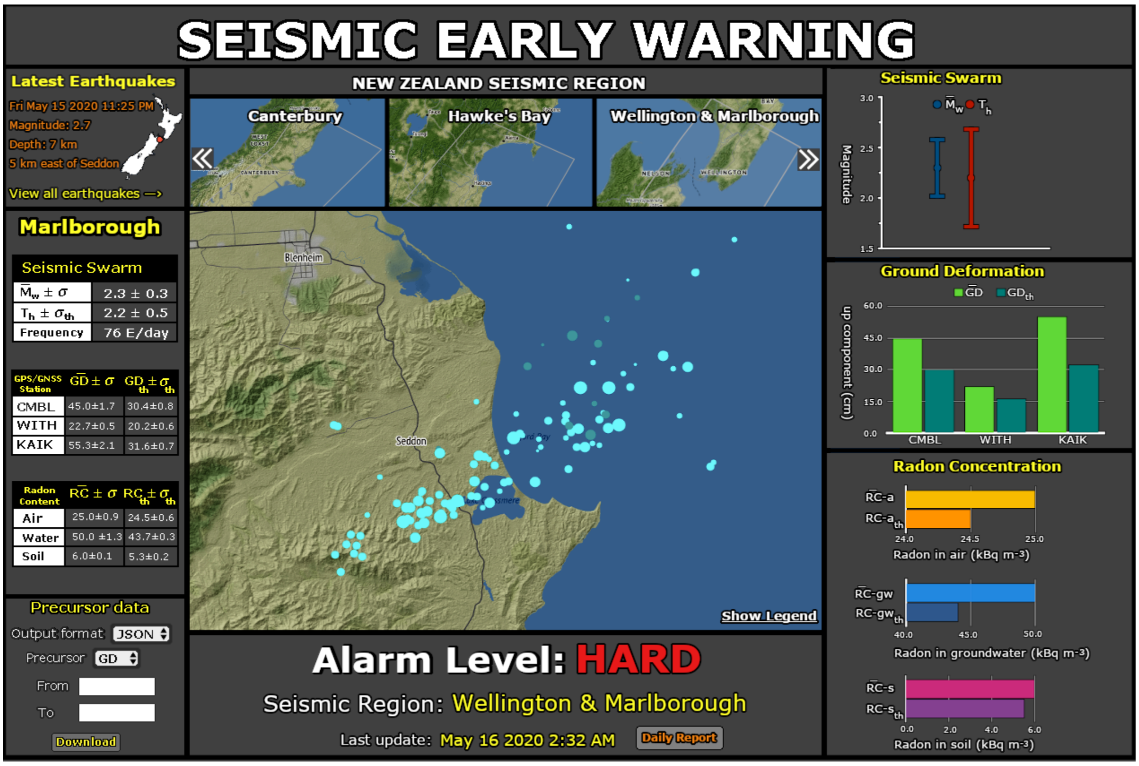

Figure 3: A mockup of the SEW dashboard

C_1 which includes the magnitude (M_w), the hypocenter (H_p) and the date/hour (D) in which the seismic event occurred. Received the message, the agent C_1 compares the data received with those of the previous earthquake, stored in its internal state: the earthquake will be entered in the seismic swarm database only if it has $M_w \geq 1$ and occurred within 24 hours from the previous one, otherwise it is discarded. If the earthquake is inserted in the current seismic sequence, C_1 sends a notification signal to agent D_1 which activates and checks the earthquake frequency (F_E) in its own state in the last seven days, with the specifications defined previously (hypocenter, magnitude). If the frequency is sufficiently high (e.g. $F_E \geq 5$ earthquakes/day), D_1 calculates the average magnitude and the associated σ for the current seismic sequence and compares it with the corresponding threshold value. In case it reaches or exceeds the threshold value, D_1 updates the value of $\bar{M}_w$ in the database and sends a message to agent A, whose evaluation will take into account the frequency of the seismic swarm in the last days.

Next, based on the result obtained from the Boolean expression (5), it will decide whether to activate an alarming level and of which type (soft, medium or hard), sending a notification to the E and F agents, "specialized" in user assistance. In particular, the E agent will update the table and the respective graphs (histograms, box-and-whisker diagrams, ...), while the F agent will send, via e-mail, a report to a small group of scientists. The document, created in an automated way, will report the experimental data that determined the activation of the specific alert level. At the end of the activity cycle, the clusters of agents listen for new notifications that can re-trigger the sequence of activities listed above. A mockup of the SEW interface, currently under development, is shown in Figure 3.

4.3. User assistance

Within the MAS, the purpose of Agents E and F is to assist users for the interpretation of experimental data and the notification of system status information documents. There are two degrees of access with level 2 users (scientists) who have more rights than level 1 (normal user). The main activities carried out by agent E can be summarized in: i) facilitating the interpretation of experimental data, showing them in real-time in the form of graphs and tables; ii) make them available in various formats, via download, for further research activities.

At the end of the activity cycle, carried out by the various clusters of agents, which aim at determining the alert level, A transmits the updates that have occurred: upon receipt of the notification, agent E is activated instantly by refreshing the SEW dashboard, which will show updated graphs and tables of each seismic precursor. For both user levels, there is a button pointing to the precursor databases which contains recent and historical experimental data. Through a multiple-choice menu, it is possible to select one of the following possible formats: JSON, CSV and KML. When the user clicks on the “download” button, reactively and according to the selected choice, Agent E will take care of data extraction, formatting according to the selected format and starting the download process.

At the same time, Agent F takes care of creating a report, in pdf, to be sent via e-mail to a small group of scientists whose e-mail addresses have been stored. The document will be sent only in the presence of a hard level alarm and will present several standard fields: (i) the geographical coordinates of the area in which the seismic swarm occurred and the hypocentral depth; (ii) the frequency of earthquakes in the last two days; (iii) the average values and the relative standard deviation of the seismic precursors; (iv) further technical information on the instrumentation used, the seismogenic structure affected by the seismic swarm, etc. The information reported in the document have been extracted from the databases and system variables in which they are stored and assembled in a specific template, used for the realization of the report. In the case of the other alarm levels, no notification will be sent to the scientists, however it will always be possible to access an updated report, once a day, directly from the dashboard whose access is limited to level 2 users only.

5. Case study: New Zealand, a land with high seismic and volcanic risk

New Zealand is a region characterized by a high seismic and volcanic risk due to the presence of a fair number of active volcanoes and the particular geodynamic location, in the collision zone between the Australian Plate and Pacific Plates. For this reason, the area is covered by a dense network of sensors, some of which have only recently been operating, which allow continuous monitoring of different seismic and volcanic precursors. The data are made available to users through the GeoNet project (Geological hazard information for New Zealand) at https://www.geonet.org.nz.

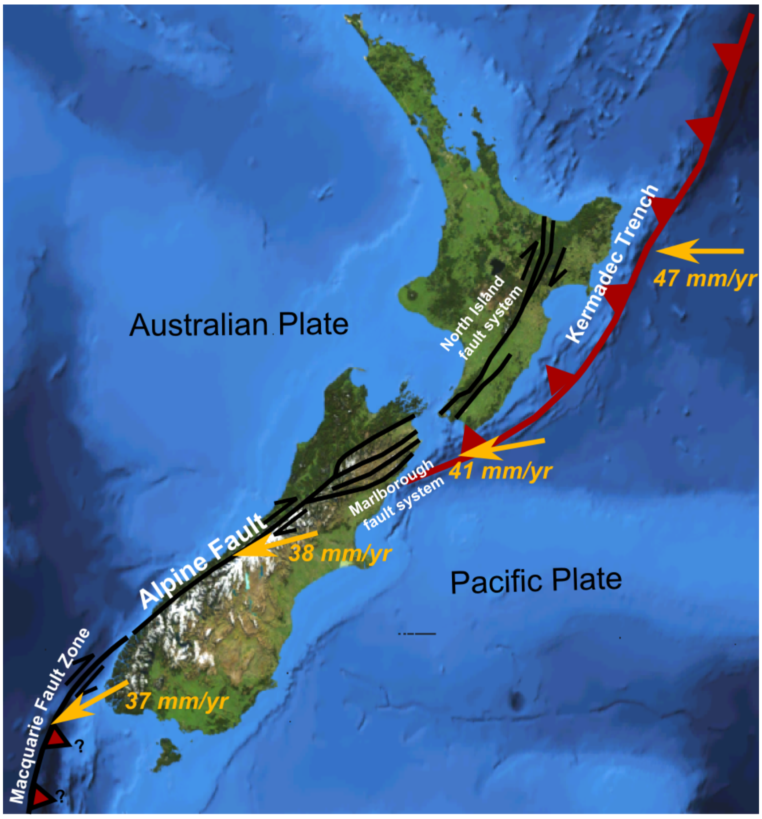

Figure 4: Scheme of the subduction area (Kermadec Trench) and the transform zone (Alpine fault) with the relative displacement speeds of the Pacific plate in collision with the Australian plate. *(Credit: Mikenorton via Creative Commons https://commons.wikimedia.org/w/index.php?curid=10735284)*

5.1. Seismotectonic overview

Within the GeoNet Quake Search section, New Zealand is divided into 10 seismic regions, from Auckland & Northland to Wellington & Marlborough. The intense tectonic and seismic activity is attributable to the presence of the Alpine fault, a large dextral transform structure, which crosses the southern part and marks the contact between the Pacific and the Australian plate. In the eastern off-shore area of the north island, the Pacific plate dips below the Australian plate: the phenomenon of subduction continues also at the Cook Strait and is the cause of deep earthquakes and the presence of active volcanism in the island of North. There are also a series of active secondary faults kinetically connected with the Alpine one, like Marlborough fault system, a set of four major faults which transfer displacement between Alpine fault and the Kermadec Trench (see Figure 4).

5.2. Experiments

The network of seismometers and GPS/GNSS sensors is well developed and represents a good way to test the seismic alert system. Each seismic region is covered by a fair number of

GPS/GNSS stations for the measurement of the ground deformation, even if for some stations the operativeness has occurred only in the last years and for others, the first registrations are from 1999. Of the three components that relate to displacement from the initial position (east, north, and up) only the up component was taken into consideration, relative to the vertical displacements of the ground. And this because the other two components, east and north, are mainly attributable to the displacement of the two plates.

The seismic data available on the "GeoNet Quake Search" page of the geonet.org.nz site were filtered by geographic coordinates, region and depth and downloaded in CSV format: the threshold value and the relative standard deviation were then calculated for two high magnitude seismic events. To download the data relating to the ground deformation, the GeoNet API was used, which allows the experimental data to be downloaded quickly, using special queries carried out in GET mode.

The SEW test was performed on the northern segment of the Marlborough fault system of the Wellington & Marlborough seismic region. The GPS/GNSS stations used for the calculation of the threshold values are those closest to the seismogenic structure analyzed, in which experimental data were available from 2004. Seismic events occurred on 2013-07-21 and 2016-11-14 were considered, respectively of $M_w = 6.5$ and $M_w = 6.2$. Only two mainshocks have been considered, although they are made up of more than 600 seismic events in total, because catastrophic earthquakes of high magnitude, over the last twenty years, are quite limited in number.

For the ground deformation, the registrations made up to four months before the mainshock was considered and the threshold values for each of the three stations were obtained using the data relating to the two seismic events of 2013 and 2016. In reality, by restricting the datasets to one month before the seismic event, the variation in the values obtained for the three stations is negligible and falls within the order of a tenth of a millimetre.

The *2013-08-16 earthquake* of $M_w = 6.5$ was used to test the correspondence between seismic swarms in progress and statistically calculated threshold values. A further test was performed on the *seismic swarm of May 2018* which as a final result did not give a mainshock.

6. Results

The data of the seismic swarms relating to earthquakes occurred on 2013-07-21 and 2016-11-14 are shown in Table 1: M_{ms} indicates the magnitude value of the mainshock. The threshold value obtained for the northern segment of the Marlborough fault system is of 2.2 ± 0.2. Table 2 shows the threshold values (T_h) and the respective standard deviations (σ), expressed in centimetres, relating to the 2013 and 2016 earthquakes for the three stations CMBL, WITH and KAIK. All stations are characterized by negative ground displacements which denote land subsidence before the mainshock.

The 2013-08-16 earthquake of $M_w = 6.5$, which occurred about a month later after the strong earthquake of July 2013, was used as a sequence to test the system. Figure 3 shows one of the seismic swarms, in the Marlborough fault system, which preceded the mainshock: you can see the alignment of the hypocenters along a preferential direction that corresponds to the direction of development of the fault system that generated it (see Marlborough fault system of Figure 4).

Table 1
Seismic swarms before the mainshock (Marlborough fault system)

Seismic swarms	M_{ms}	$\bar{M}$	N_{se}
2013-07-21	6.5	2.4	340
2016-11-14	6.2	2.0	290
Threshold value: 2.2			
Standard deviation: 0.2			
Total number of seismic events: 630			

Table 2
Ground deformation before the mainshock (Marlborough fault system)

GPS/GNSS Stations	$T_h(cm)$	$\sigma(cm)$	N_m
CMBL	-29	4.1	400
WITH	-4.6	0.8	400
KAIK	-17.2	0.4	400
Total number of measurements: 1200			

Table 3 reports the average magnitude value and the relative standard deviation of the seismic swarm before the mainshock which is in the range of 2.3 ± 0.4. The fields relating to the three ground deformation measuring stations show the values $\bar{GD} \pm \sigma_{gd}$. It can be seen that in all stations the intervals of the ground deformation in progress fall within the intervals of the threshold values $T_h \pm \sigma$. Hence, condition (4) is verified for both seismic precursors (SS and GD):

$$([\bar{M}_w \pm \sigma_w] \cap [SS_{Th} \pm \sigma_{th}] \neq \emptyset) \wedge ([\bar{GD} \pm \sigma_{gd}] \cap [GD_{Th} \pm \sigma_{th}] \neq \emptyset). \quad (6)$$

The evaluation of the Boolean expression for ground deformation corresponds to a logical AND between the three GNSS/GPS stations:

$$(CMBL) \wedge (WITH) \wedge (KAIK). \quad (7)$$

Figure 5 shows that in the three stations considered, before the event of August 2013, the ground deformation intervals intersects that of the respective threshold values and therefore, according to the final result, the evaluation of the GD parameter returns true. A similar result is also obtained for the seismic swarm parameter with an almost complete overlap between the confidence interval in progress and that relating to the threshold value. Table 3 also shows the results of the seismic swarm of May 2018 (about 115 foreshocks), indicated as two asterisks,

Table 3
Test 2013-08-16 earthquake* and seismic swarm** on May 2018

	Seismic Swarm	CMBL	WITH	KAIK
$\bar{GD}^*$	-	-24.6 $\pm$ 3.5	-4.9 $\pm$ 0.3	-16.8 $\pm$ 0.4
$\bar{GD}^{**}$	-	94.7 $\pm$ 0.5	9.4 $\pm$ 0.5	57.6 $\pm$ 0.5
$\bar{M_w}^*$	2.3 $\pm$ 0.4	-	-	-
$\bar{M_w}^{**}$	2.3 $\pm$ 0.7	-	-	-

which affected the same fault system. It can be observed that although the average value of the seismic swarm falls within the confidence interval of the respective threshold value, the expression (7) returns false because this does not happen for the ground deformation which has an inverse (positive) sign with respect to the corresponding (negative) threshold values.

7. Conclusions

An integrated, complementary and real-time analysis of a series of precursor parameters to establish of the alert level of a seismic risk territory, is the idea on which the SEW forecasting system is based. With the integrated analysis, we aim to simultaneously analyze the experimental data of the physico-chemical precursors for which an adequate network of sensors is available. Acting in a complementary way means considering the results obtained by each parameter not disjoint from the others but which contribute, in different ways, to the achievement of the final objective. The innovation of the proposed model lies precisely in these short and simple concepts and the final evaluation of Boolean expressions made up of representative variables of each precursor allows each of them to make their contribution. In this way, it is possible to assess whether the transformation that a seismic territory is undergoing is on average attributable to those that occurred in the past in the periods preceding earthquakes of equal magnitude ($M_w \geq 6$).

According to the *theory of dilatancy and asperity*, the transformations that a territory undergoes before a strong seismic event produce ground deformations which, by fracturing, generates foreshock and catalyzes fluids from the surrounding areas, making their geochemical properties vary. If we consider that the entity of the deformations depends on the mechanical characteristics of the rocks present in each seismogenic area, we can consider that before each "characteristic earthquake" [15], physico-chemical anomalies, on average similar to those that occurred in the past, can be generated.

The SEW system has been implemented using the MAS approach, hence ensuring modularity, efficiency and maintainability. The choice to use a multi-agent structure greatly facilitates the process of acquiring and processing experimental data carried out in parallel by the agent clusters, each of which deals with a specific precursor. Two further agents, specialized in user

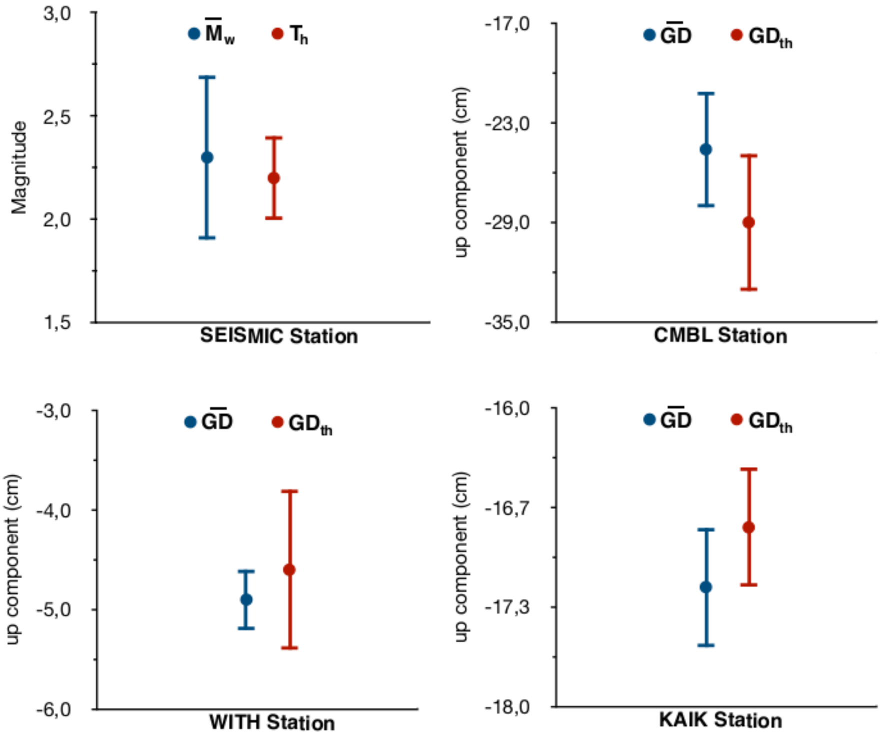

Figure 5: Comparison between the ranges of the data in progress and the threshold values for the ground deformation and the seismic swarms related to the August 2013 earthquake. Note that in all cases there is an overlap of the intervals.

assistance, take care of adequately formatting diagrams, tables and reports to be presented to users or sent to specific scientific groups to alert them of any critical states.

The results of the $M_w = 6.5$ earthquake test of 2013-08-16 on one of the seismic regions of New Zealand show an extensive overlap of the ranges $[\bar{M_w} \pm \sigma_w]$ and $[\bar{GD} \pm \sigma_{gd}]$ of both precursors with their respective confidence intervals of the threshold values and only small parts of the left interval are external to them. The ground deformation indicates that the areas surrounding the seismogenic structure undergo pronounced subsidence in the period before the seismic event. The choice of this datasets is due to the possibility of using both seismic swarms and ground deformations starting from 2004, a combination not possible for surface earthquakes in the other seismic regions of New Zealand.

On the contrary, the seismic swarm of May 2018, which affected the same area, shows that even if the seismic swarms in progress meet the threshold intervals, the deformation values in the three stations are largely outside the intervals $[GD_{Th} \pm \sigma_{th}]$: the absence of the mainshock is therefore in agreement with the result of the expression (7) which returns false. The results, therefore, confirm that a forecast based on a fair number of precursors can be a good solution for the implementation of a seismic alert system.

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