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SISMIKO: INGV operational task force for rapid deployment of seismic network during earthquake emergencies

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1 Introduction

The National Institute of Geophysics and Volcanology (INGV, *Istituto Nazionale di Geofisica e Vulcanologia*), is an italian public research institute established in 1999. Since its inception, the mission of INGV included seismic surveillance and earthquake monitoring in Italy. INGV is part of the Civil Defence system (Margheriti et al., 2021). INGV has offices in different parts of Italy and operates the Italian National Seismic Network (Rete Sismica Nazionale—RSN; INGV Seismological Data Centre, 2006) and other networks at national scale (Michelini et al., 2017). INGV also operates a temporary seismic network infrastructure, a pool of instruments used to densify seismic networks for scientific experiments or in response to damaging earthquakes and to increase monitoring capabilities during seismic sequences.

SISMIKO is the operational task force of INGV whose core purpose is to rapidly deploy temporary seismic stations in response to moderate—large magnitude earthquakes or in areas where a seismic sequence is causing concerns and/or scientific interest (Moretti et al., 2016). By reducing the spatial distance between the seismic stations, temporary deployments can improve the RSN detection capability and the accuracy of the earthquake locations. SISMIKO was established in 2015 by Lucia Margheriti and Milena Moretti, so they became responsible for INGV emergency deployments of the temporary networks. SISMIKO involves INGV technicians and researchers from all over Italy, from Milano to Catania (see acknowledgments), grouped together by common interest technical and scientific issues. SISMIKO coordinates all INGV groups working on seismic emergencies (Figure 1).

The data acquired by the SISMIKO temporary networks, are made available to the scientific community, without any restrictions, via italian node of the European Integrated Data Archive portal (EIDA[1]; Danecek et al., 2021). Datasets are archived in near real-time in the "Standard for the Exchange of Earthquake Data (SEED)" format and have an associated Digital Object Identifier (DOI). The data are used for monitoring, surveillance and for scientific research.

Since its establishment, SISMIKO has installed seven temporary seismic networks, including the one used to monitor the 2016–2018 seismic sequence in central Italy (Moretti

1 https://eida.ingv.it/en/

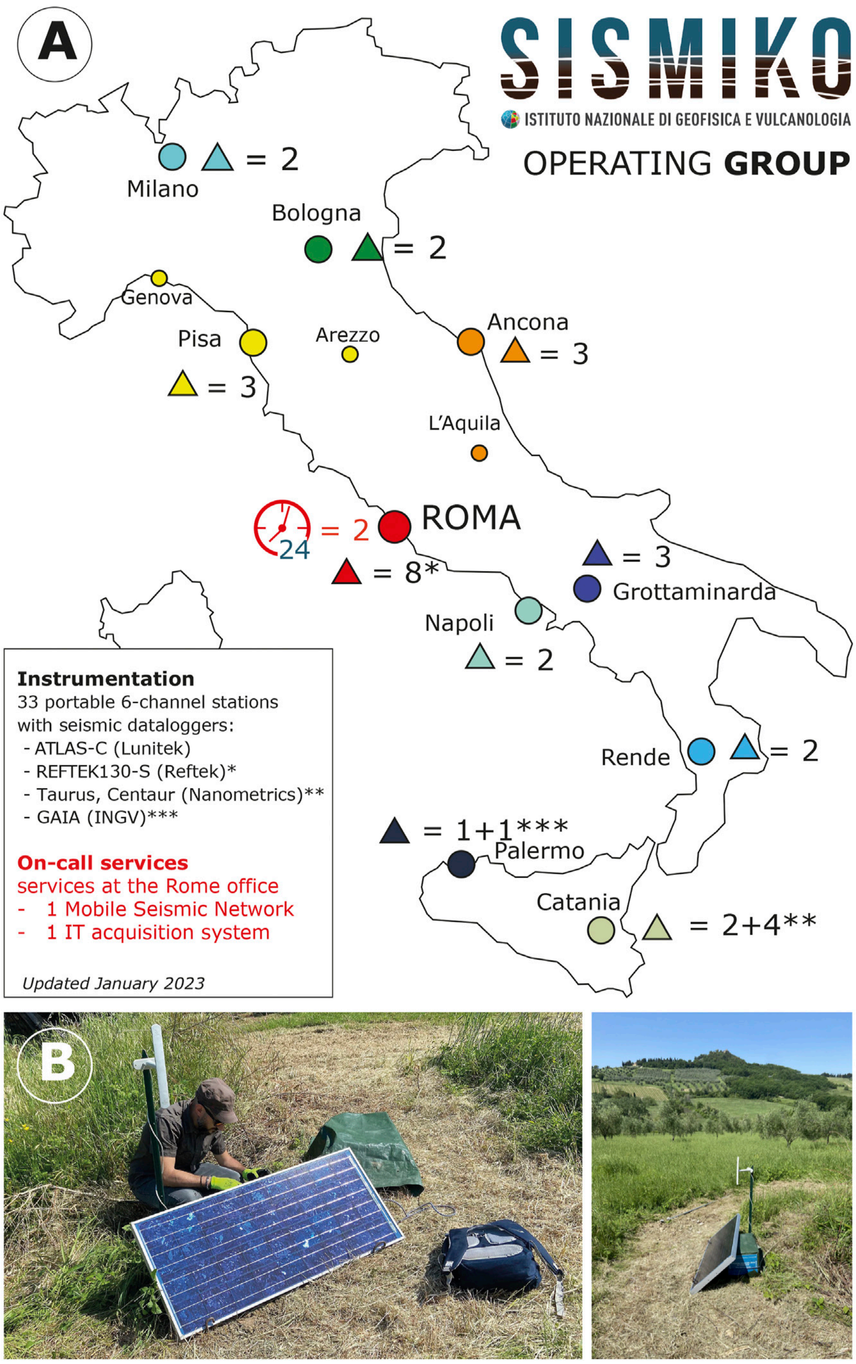

FIGURE 1
(A) Map of the 13 INGV offices involved in SISMIKO. Offices with few units of personnel are associated with larger ones (Genova and Arezzo are associated with Pisa office. L'Aquila is associated with Ancona). Currently SISMIKO has 33 stations from 4 different manufacturers but a standardized instrument pool is planned. **(B)** Photo of the T1618 station installed in Greve in Tavernelle, during a short-lived seismic swarm started in May 2022 in the small area of the Chianti region, about 15 km south of Florence (Piccinini et al., 2022; 2023). Behind the operator, the high-gain antenna support is visible for the transmission of data in real-time that flows into the INGV national monitoring system (photo by Damiano Biagini).

et al., 2016). The most recent activations of SISMIKO were in May and November 2022: Chianti-Fiorentino (Piccinini et al., 2022; 2023) and North Marche coast (D'Alema et al., 2022b), respectively.

The following section briefly describes the history of the INGV emergency mobile network.

1.1 The history of the INGV seismic mobile network

The deployment of temporary networks in response to seismic emergencies is one of the fundamental activities undertaken by

INGV to monitor seismicity and conduct research on earthquake physics and seismic risk.

In early 1990, before INGV was established, the former National Institute of Geophysics (ING, *Istituto Nazionale di Geofisica*) only included earthquake monitoring and research, and volcano surveillance was conducted by other agencies. At the time, an important step towards increasing ING earthquake detection capabilities was the development of a mobile seismic laboratory. This was set up on a truck, with the aim of acquiring seismic data via digital telemetry and process them in the truck (Supplementary Figure S1). This mobile laboratory represented an essential tool to monitor seismic sequences between 1990 and 2002: Potenza and then Siracusa in Sicily (1990); Colfiorito, Umbria-Marche (1997–1998); San Giuliano di Puglia, Molise (2002). The mobile laboratory was a smaller version of the ING's seismic surveillance room, able to receive via telemetry data from up to 10 temporary stations. Data from temporary deployments were acquired in real-time and analyzed by operator located in the mobile truck, that was placed in the earthquake epicentral area. The truck contained an analogue acquisition system and paper drums, alongside workstations to analyze the seismic waveforms.

In the past two decades, new technologies for data acquisition and transmission became available and the need to rapidly and accurately define seismogenic structures and the temporal evolution of the seismic sequence increased. This led to further development of the INGV emergency response model. Between 2006 and 2008, INGV designed and implemented the first real-time seismic data transmission systems for temporary stations. The system was capable of sending data to Rome main data centre, and in 2009 was used for the first time to monitor the L'Aquila seismic sequence from the central INGV monitoring room.

The experience gained during the L'Aquila (Margheriti et al., 2011) and Emilia (Moretti et al., 2012) seismic sequences, helped INGV to realize the need of defining a set of common rules and protocols to be used for rapid deployments. An operating protocol now establishes the timing of response and lays out what activities are to be carried out before, during and after a seismic emergency. This protocol also considers the data policy, including data archiving and distribution.

Currently, SISMIKO has a well established procedure to integrate its temporary network deployments real-time to the seismic data acquisition system in the INGV Rome headquarters. The integration can now be achieved in a few hours, and SISMIKO is now a fundamental component of the INGV 24/7 seismic surveillance system and mission.

SISMIKO works throughout the year to continuously improve and refine the tools available to the operational group and review new technologies when they become available. This allow the group to improve its performance when responding to an emergency. Regular meetings are scheduled for technical-scientific discussions, alongside tests and periodic training of personnel to be able to manage an emergency, work with uncertainties, acquire new skills and build the SISMIKO team.

Recently, following the 09 November 2022 Mw 5.5 earthquake occurred off the north-eastern coast of the Marche region, Adriatic Sea, SISMIKO deployed 8 real-time stations that were sending data to INGV headquarters in less than 24 h, confirming the importance of continuous preparatory activity to obtain good performance results.

2 Methods

SISMIKO management system is finalized to collect seismological data; in the following we describe how the operational group is organized and how data acquisition, archiving and distribution is performed. Table 1 shows the data repository and DOIs, the collection periods, and information about all datasets acquired in the past 7 years of activity.

2.1 Staff, organization, deployment rules and equipment SISMIKO

SISMIKO governance is organized as a coordination group and a dedicated team.

The coordination group (SISMIKO committee) is made up of: two national coordinators, a contact person for each major office and experts with a diverse background to cover a range of strategic topics such as data acquisition, seismic surveillance in Rome headquarter and seismological research. The main responsibility of the SISMIKO committee is to prepare of all the activities that support the management of the emergency, such as: instrument pool the purchase, maintenance and upgrade; training of staff members; promotion and dissemination of the activities of the task force. Periodic meetings of technical-scientific staff are organized to allow SISMIKO to be always updated and promote the development of new tools to simplify the activities. The committee also engage with universities and research institutions to foster and maintain inter-agency relationships, and establish collaboration agreements when needed. Periodic meetings of technical-scientific staff, allow SISMIKO to be always updated and promote the development of new tools to simplify the activities.

The dedicated team is made up of researchers, technologists and technicians from all INGV offices. Membership is voluntary and updated annually. The team is constituted by personnel experienced in the management of temporary seismic networks: with expertise in station installation, data analysis, communication and engagement. Over the years, the working groups dedicated to specific issues have been formed. A group of technicians is focused on evaluating instrumentation maintenance and upgrades. Another group works on data acquisition, storage and distribution, data analysis and quality assessment. In the end, a group focus on information dissemination activities (reports, publications and web).

SISMIKO team is currently composed by more than one hundred people, 76% of which are male and 24% female. This same ratio is also reflected in the SISMIKO committee (see Supplementary Figure S2). De Lucia et al. (2021) did an analysis of gender diversity at INGV: as of 1 January 2019, INGV personnel was composed by 338 individuals identifying as female and 548 as male: This corresponds 38% female and 62% male employees, respectively. If we compare this ratio to the SISMIKO group, it appears that women are underrepresented, and well below the Institute's average. This can be explained considering that one of the primary objectives of SISMIKO concerns the installation and transmission of the stations, an activity that generally is done by technicians. De Lucia et al. (2021) indicates that only 25% of technicians are women. The SISMIKO group has only one female technician, out of the 44 technicians in the team.

TABLE 1 List of SISMIKO rapid deployments since 2015. Deployments with an * in the DOI column where collected before the dedicated network code policy was established, and have all been assigned the IV code. In the next future, we will assign the DOI and network code also at the 2016 emergency.

Emergency year	Earthquakes causative of the activation of SISMIKO Date aaaa-mm-dd/ Time UTC/Mw	Epicentral area	Number of stations installed	Duration IN (aaa-mm-dd) OUT (aaa-mm-dd)	Network code (FDSN)/ Station code	Link landing page	DOI Reference
2016	2016-01-16/18:55/4.3	Province of Campobasso, Italy	1	2016-01-19 2016-03-31	IV*/T11	https://eida.ingv.it/it/networks/network/IV	*
2016	2016-08-24/01:36/6.0 2016-10-26/17:10/5.9 2016-10-30/06:40/6.5 2017-01-18/10:14/5.5	Amatrice-Visso-Norcia, Central Italy	24	2016-08-24 2018-07-05	IV*/T12	https://eida.ingv.it/it/networks/network/IV	*
2017	2017-08-21/18:57/3.9	Island of Ischia, Italy	8	2017-08-26 2020-10-20	ZM/T13	https://eida.ingv.it/it/networks/network/ZM	Galluzzo et al. (2017)
2018	2018-08-16/18:19/5.1	Province of Campobasso, Italy	5	16/08/2018 26/10/2018	YD/T14	https://eida.ingv.it/it/networks/network/YD	Moretti et al. (2018)
2020	2020–09-09/04:56/3.5 2020-11-25/03:47/3.4	Salemi area, Province of Trapani, Italy	4	2020-09-22 2020-11-25	X3/T15	https://eida.ingv.it/it/networks/network/X3	Alparone et al. (2020)
2022	03-05-2022/15:50/3.7 03-05-2022/20:14/3.5	Chianti Fiorentino area, Province of Florence, Italy	5	2022-05-04 2022-09-07	ZH/T16	https://eida.ingv.it/it/networks/network/ZH	Piccinini et al. (2022)
2022-2023	09-11-2022/06:07/5.5	North Marche coast, Italy	8	2022-11-09 2023-03-07	Y1/T17	https://eida.ingv.it/it/networks/network/Y1	D'Alema et al. (2022b)

SISMIKO activation rules are defined in a dedicated protocol. The task force is activated when an earthquake of M≥ 5.0 hits the Italian territory. An operating procedure is used to allow the activation of the team. The coordinators are automatically notified via text messages containing the estimated earthquake parameters (hypocentral location and magnitude), within five minutes from the earthquake origin time. The SISMIKO committee is then activated and will meet within 3 h. To design the geometry of the temporary seismic network to be installed, the SISMIKO committee will take into account the mainshock characteristics, seismic sequence evolution and the status of the permanent seismic network in the epicentral area. The committee will then share this information with the INGV Directors, other research institutes and universities and the Civil Defence Department. This will allow the response work to occur in synergy between all involved parties. Once the temporary network design is completed, a team of INGV personnel will rapidly go to the field to install temporary stations in the epicentral area. Supplementary Figure S3 shows a deployment timing example from the 2016 Central Italy seismic sequence (Moretti et al., 2016). Thanks to the preparatory system in less than 24 h stations are integrated in the RSN, thus contributing to the improvement of the surveillance and seismic monitoring.

If deemed necessary, SISMIKO can install stations in response to earthquakes with magnitude less than 5.0 or during seismic sequences or swarms. This decision is taken by the SISMIKO committee in taking into account the seismic sequence characteristics, the affected area and other peculiar factors.

The SISMIKO instrument pool is distributed over 10 of the 13 INGV offices on the Italian territory. The pool is made up of 33 6-components stations (accelerometer and short period velocimeter), with high-gain data loggers and equipped with UMTS/LTE routers for real-time data transmission. SISMIKO aims at having a standard kit for its instrument pool (Figure 1A, legend) and at least 50 dedicated stations with e broad band velocimeter sensors. Currently, 75% percent of the SISMIKO instruments are standardized. This led to an improvement in the rapid deployments' performance, a more effective temporary network management and greater interoperability between the different INGV offices. We plan to have 100% of the pool made by standard kits by the end of 2023. In Figure 1B, shows a typical SISMIKO station.

2.2 Data acquisition, archiving and distribution

All the data acquired by SISMIKO are transmitted and collected in real-time in the Rome INGV office. Here, a dedicated acquisition system named "SISMIKA", has been developed (D'Alema et al., 2022a). SISMIKA is also used to make data readily available to the INGV seismic surveillance system in Rome and to the scientific community, the latter through the Italy node of the EIDA.

The SISMIKO LTE routers use DNS Service designed and built by INGV (Sorrentino et al., 2020). The data acquisition server uses the Seiscomp software, version 5.5.1 (Helmholtz-Center Potsdam - GFZ German Research Center for Geosciences and Gempa GmbH, 2008) with Linux Ubuntu 20.04 operating system.

All stations' parameters are preconfigured for the SISMIKA acquisition systems, with the exception location specific station coordinates. This guarantees an effective management of the instrument's response the activities and allows the immediate acquisition of SISMIKO data. In 2009, prior to the official SISMIKO launch, a standardized station naming was established. Station identifiers are composed by the letter "T" (for temporary), the two-digit number to indicated the emergency (consecutive numbers assigned since 2009) and two digit number to identify the station (each INGV office has dedicated numbers). For example, in 2022, during the last deployment (no. 17; SISMIKO working group, 2022) we installed stations T1711, T1714, T1718 (from the Rome office), T1741, T1742, T1743 (from Ancona office), T1756 and T1757 (from Bologna office).

Starting from 2017 each temporary network has its own required network code, registered at the International Federation of Digital Seismograph Networks (FDSN). For each emergency, the dataset acquired by the SISMIKO temporary networks has been associated with a unique DOI. The DOI is assigned accordingly to a set of rules defined by the INGV data management office (https://data.ingv.it/en/) and the SISMIKO group. Dataset users are requested to use these DOIs when using the data.

Since 2015, SISMIKO deployed seven emergency networks to respond to significant earthquakes or seismic sequences (Table 1). SISMIKO data policy, established since its beginning, define that all data are available to the scientific community. This is accomplished by archiving the data in quasi real-time in the EIDA italian node (Danecek et al., 2012) in SEED format.

Data is also used for monitoring and surveillance. The seismic surveillance service of INGV is the first user of this data: a real-time acquisition system that uses a seedlink server feeds in parallel the Earthworm automatic location system and the EIDA archive. The latter is also used for by Time domain moment tensor analysis (Scognamiglio et a al., 2006) and for off line research.

The improvement in earthquake detection and location accuracy obtained installing a real-time temporary dense seismic network is very significant. Knowing the number, the magnitude and the spatio-temporal distribution of small aftershocks can be useful for decision makers to assess the current situation during seismic crises (Dolce and Di Bucci, 2014).

In Table 1 provides information about the datasets acquired through SISMIKO, including the year of emergency occurrence, mainshocks' origin time, impacted regions, number of stations installed, the duration of the deployment, the FDSN network code and dataset landing page and its DOI.

3 Concluding remarks on the contribution to the research of mobile seismic networks during seismic emergencies

The rapid deployment of temporary seismic stations soon after the occurrence of a moderate—large earthquake is an essential factor in understanding seismic activity. Data collected in the first hours following a mainshock are crucial for reconstructing and characterizing the fault system in detail and to constrain the spatial distribution of the seismicity (Improta et al., 2019).

Seismic waves recorded at a dense seismic network are an extraordinary tool for monitoring and studying the earthquake physics and a powerful key to investigate the interior of the Earth. The off-line analysis of the recorded seismograms allows the imaging of the fault system geometry and kinematics, and provides invaluable data for scientific studies related to seismic hazard, and tectonics.

The earthquake hypocenter location accuracy is strongly dependent on the geometry of the network, the distance between the seismic stations and the type of seismic sensor. The RSN in Italy guarantees good locations for events of $M_L > 2.0$. The temporary seismic networks are deployed to improve the detection performance and accuracy of the permanent monitoring systems.

In Supplementary Figure S4 we show how the deployment of temporary stations improve the accuracy of the locations and how the possibility of processing offline continuous recordings of dense networks improve the number of seismic events detected and located (Margheriti et al., 2011). This huge amount of data and the accuracy on hypocenter determinations allow us to image the exact geometry of the fault system (hypocenters are shown in cross sections) giving important clues on the damage zones around the main faults (Valoroso et al., 2013; Michele et al., 2020). In these studies, in fact, the availability of continuous waveforms allowed us to define the fault system very sharply.

Moreover, knowing the number, size, and timing of aftershocks during a seismic emergency and defining the clustering seismic events can help in foreseeing the characteristics of future seismic sequences in the same tectonic or volcanic environment (IAVCEI Subcommittee for Crises protocol 1999).

The improved azimuthal coverage near the causative fault aid seismic source studies (determination of focal mechanisms), including the possibility of identifying rupture directivity, and calculating stress drops.

Recording continuous data from a dense network facilitates new discoveries, such as observations of non-volcanic tremors associated with slow earthquakes that play an important role in the generation of large earthquakes (Obara and Kato, 2016).

We expect that SISMIKO data will be useful for seismic hazard studies detailing near field variability in strong ground motions (i.e., Cochran et al., 2020). We are confident that these data are useful to the international seismological community, and will enhance the understanding of earthquake sequences and contribute to the basic understanding of earthquake physics. We believe that the philosophy and rules of SISMIKO working group, based on cooperation between offices and on open data access policy for the data have been influenced by the fact that the initial main coordinators were women.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MM wrote the manuscript; coordinated the data collection; she has been the national coordinator of SISMIKO in the years 2015–2023. LM wrote the manuscript and coordinated the SISMIKO working group in the years 2015–2019. ED wrote the manuscript and has coordinated the SISMIKO working group since 2019. DP reviewed the manuscript and started coordinating the SISMIKO working group on 17 March 2023. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2023.1146579/full#supplementary-material

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