The OGS–Northeastern Italy Seismic and Deformation Network: Current Status and Outlook

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Abstract

In this article, we describe the infrastructure developed and managed by the Italian National Institute of Oceanography and Applied Geophysics – OGS for the seismological and geodetic monitoring of northeastern Italy. The infrastructure was constituted in response to the M_L 6.4 Friuli destructive earthquake of 1976, with the main mandate of supporting civil protection emergency activities.

The OGS monitoring infrastructure is presently composed of a seismometric and a strong-motion network, complemented by a number of Global Navigation Satellite Systems stations, each delivering observational data in real time, which are collected and processed by the headquarters of the Center for Seismological Research of OGS in Udine. The OGS networks operate in close cooperation with Italian and international networks from neighboring countries, within the framework of the agreements for real-time data exchange, to obtain improved rapid earthquake location and magnitude estimations. Information regarding seismic events is released to the public through a dedicated web portal and, since 2013, through social media.

Aside from the standard monitoring activities (> 30,000 events have been recorded since 1976), the OGS has progressively increased the number of services to the public and to the Civil Protection of the Friuli Venezia Giulia and Veneto regions. The high availability of good quality data has resulted in the enhancement of scientific products, including advanced seismological studies of the area, spanning broadly from seismic source characterization to engineering seismology.

In the future, the OGS networks are expected to further contribute to the development of seismological research and monitoring infrastructures of the Central European region.

Introduction

In May 1976, a devastating earthquake of magnitude M_L 6.4 occurred in Friuli (northeastern Italy [NEI]), resulting in 976 deaths, 2000 injured, and 60,000 homeless (Zamberletti, 2018). At the time of the earthquake, only 33 seismological stations were operating within the whole of the Italian territory, and only the Trieste station of the World-Wide Standardized Seismograph Network (WWSSN) was located in the affected region, nearly 70 km from the epicenter (Rebez *et al.*, 2018; Slejko, 2018). The lack of information, combined with a dearth of mitigation planning for responding to such events, led to a clear and complete picture of the impact of the disaster being available only after a few days.

The event (star in Fig. 1) occurred in an area, Friuli Venezia Giulia (FVG), that, together with Veneto and Trentino-Alto Adige, includes the Italian part of the southeastern Alps to the north and the Friuli and Veneto Plains to the south to reach the buried margin of the northern Apennines in Emilia-Romagna. This area, here referred to as NEI, together with the neighboring regions of southern Austria and western Slovenia, is affected by moderate to strong seismicity (e.g., Sugan and

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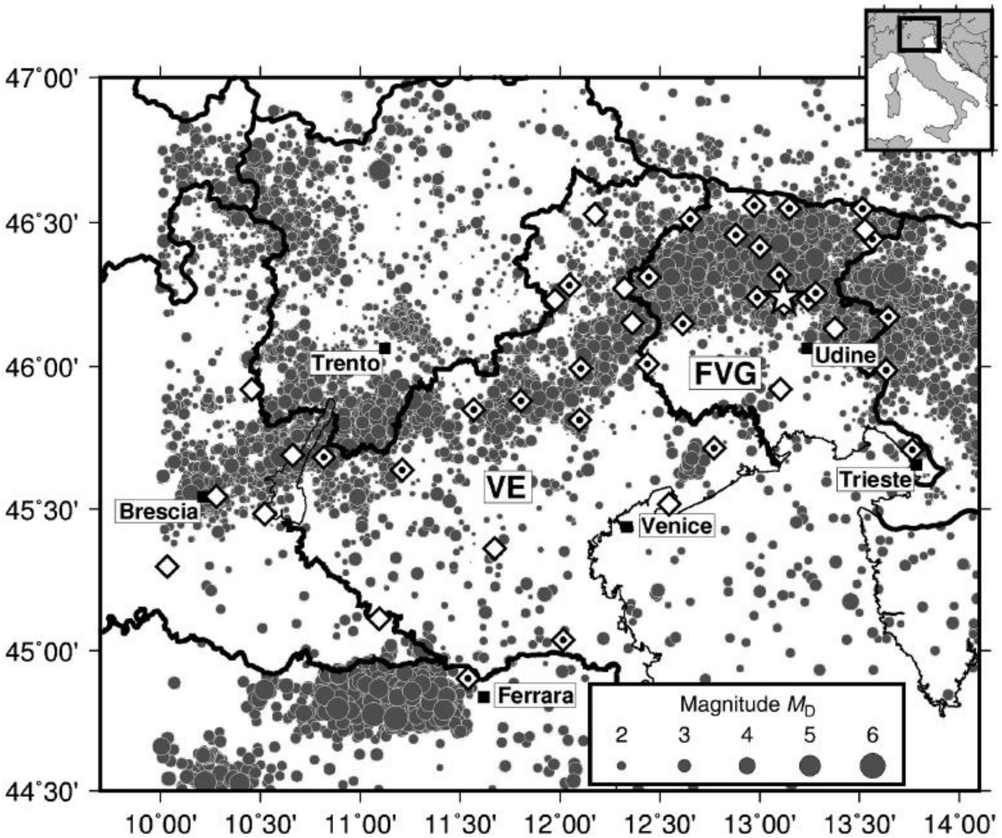


Figure 1. Seismometric stations managed by the National Institute of Oceanography and Applied Geophysics – OGS (dots highlight those also equipped with an accelerometer). Small gray circles in the background represent the epicenters of the earthquakes recorded between 1977 and 2019. The star indicates the epicenter of the 1976 Friuli earthquake. FVG and VE are Friuli Venezia Giulia and Veneto regions, respectively. The inset map shows position of the monitored area relative to Italy.

Peruzza, 2011; Bressan *et al.*, 2019) mainly located in the upper crust and directly related to the deformation along the western margin of the Adriatic indentation. The largest mainshocks ($M > 5.5$) instrumentally recorded in NEI are the 1976 M_w 6.4 Friuli earthquake (Rovida *et al.*, 2020), the 1998 M_s 5.7 Bovec earthquake (e.g., Bressan *et al.*, 2009), and the 2012 M_w 6.0 Emilia earthquake (Rovida *et al.*, 2020). In historical times (since A.D. 1000), about 30 earthquakes of magnitudes $5.5 \leq M \leq 6.5$ have occurred in this region (Rovida *et al.*, 2020).

The instrumental seismological observations in NEI started at the end of the nineteenth century, with the station of Trieste becoming first a reference station and then part of the WWSSN (station code TRI-117) (Finetti and Morelli, 1972; Priolo *et al.*, 2005, Sandron *et al.*, 2015). In 1931, the Trieste station was taken over by what is now the National Institute of Oceanography and Applied Geophysics – OGS (OGS in the following); currently, among other instruments, it still houses an original pair of Wood–Anderson seismometers (Lehner-Griffith TS-220) operating since 1971 (Sandron *et al.*, 2015). A seismological network over the rest of the region, however, has only been installed since 1977. The Italian law 828/1982 determined the extension of the seismic monitoring network and the creation of the Center for Seismological Research (CRS) in Udine as a part of the OGS. As a follow-up of this, in 1989, the Italian law 399/1989 assigned to the CRS the task of managing and developing the seismic network in NEI also for civil protection purposes. In this regard and as indicated by the previously mentioned law, the OGS and the Istituto Nazionale di Geofisica e Vulcanologia (INGV), whose function is also to coordinate regional and local seismic networks, have established cooperation through a formal agreement. The agreement, following which a joint permanent committee was established, aims to support national seismic monitoring for which the INGV is responsible.

The seismic network underwent several substantial modifications in 1988 (when the network became digital), in 1994 (when a new system providing high-quality digital data was installed), and in the early 2000s (when the seismological monitoring was complemented with a network of Global Positioning System [GPS] stations). The development of the network and its description until 2011 are well documented by Priolo *et al.* (2005) and Bragato *et al.* (2011).

Since 2011, the network has been further developed, and it now consists of 43 broadband and short- and mean-period stations, 83 strong-motion stations (29 force balance accelerometers collocated with seismometers and 54 micro electro-mechanical systems [MEMS]–based accelerometers installed at selected buildings), and 19 Global Navigation Satellite Systems (GNSS) stations. The whole infrastructure is named the *Sistema di Monitoraggio terrestre dell'Italia Nord Orientale* (SMINO). Furthermore, new services that the CRS offers to both authorities and the public have been added to the standard network operational ones.

In this article, we first describe the current state of the seismological, strong-motion, and deformation networks. Then, we describe the services and products that the network is releasing. Finally, we illustrate the outlook and the future of seismological monitoring in this cross-border area, within the context of cooperation with Central European countries.

The NEI Seismic Network

The NEI seismic network consists of 43 seismological stations, with 24 broadband, 15 short-period, and four intermediate-period sensors. Figure 1 shows the distribution of the stations that are mainly installed in the mountainous and foothills areas and the seismicity recorded by the network since 1977. Two stations are co-owned by the INGV; one station is co-owned by the University of Trieste, whereas the station of Trieste is co-owned by the three institutions and included in the Mediterranean Very Broadband Seismographic Network (MedNet). The list of the stations, the coordinates, and other supplementary information of the NEI seismic network can be found online (see Data and Resources).

The short-period stations are mainly equipped with Lennartz Le3DLite sensors connected to Lennartz Mars88-MC, Sara SL06, or Quanterra Q330 digitizers. Three intermediate-period stations are equipped with Lennartz Le3D 5s seismometers and the INGV GAIA2 digitizer. A fourth one is equipped with Sara instrumentation: SS01 seismometer (natural period 10 s) and SL06 digitizer.

The broadband stations consist mainly of Trillium 40, Trillium 120, and Streckeisen STS-2 sensors, and Streckeisen STS-1 and Güralp CMG-3T units have also been installed in a few stations. Digitizers are mainly Quanterra Q330 and occasionally Güralp DM24 and the INGV GAIA2.

For all the stations, real-time data transmission is guaranteed by HiperLAN, GPRS, satellite link, and, in a few cases, ethernet communication. Seismograms are acquired by the CRS in Udine using the BRTT Antelope software system, which also carries out the automatic detection, location, and magnitude estimation of the recorded earthquakes. To ensure redundancy, the data acquisition and processing are duplicated to a secondary node installed at the Civil Protection of the Friuli Venezia Giulia Region (PCFVG) operational headquarters situated in Palmanova, ~15 km south of Udine. Furthermore, the connection between the headquarters of the CRS and the PCFVG is guaranteed by an HiperLAN radio link. This connection is used for the remote maintenance of the monitoring system in Palmanova and, in the occurrence of an earthquake, to transfer any information (earthquake parameters, estimations of the shaking and of the damage) that may be useful for supporting the civil protection activities.

In complement to scientific studies, the seismic network is dedicated to earthquake alert purposes. The locations of the earthquakes determined by the acquisition system are scrutinized by an automatic control system that assesses the quality and reliability of the derived data. Protocols have been defined for providing information regarding significant earthquakes to the PCFVG and the Civil Protection of the Veneto (PCV) region. All the earthquakes of magnitude $M_L \geq 2.2$ occurring within a radius of 40 km from the borders of each region are reported by email to the PCFVG or PCV. Larger earthquakes ($M_L \geq 2.8$) that may be felt by the population are notified to a broader audience, including regional authorities and rescue organizations. Messages are sent by email and short message service (SMS). The emails include an epicentral map and a classification of the municipalities according to three classes (A, B, and C, in which C is the most dangerous, possibly associated with heavy damage) depending on the estimated severity of the shaking and, through empirical relationships, of their effects. This classification, fully automatic and based on instrumental data, has been agreed with the PCFVG and the PCV authorities and intends to be a rough assessment to address the very early stage of the reaction to an earthquake.

The current configuration of the network and the distribution of all the recorded seismic events is shown in Figure 1. Over time, the network has changed in terms of station density or station functionality, which has affected the magnitude of completeness of the OGS catalog (Gentili *et al.*, 2011). In particular, starting since 2011, the number of the detected events increased (Fig. 2a) partly because of a change in the events detection procedure. The improved detection of the microseismicity was a result of the optimized setup of the BRTT Antelope automatic detection configuration (Moratto and Sandron, 2015).

From 2011 onward, the network records an average of ~1750 seismic events per year (Fig. 2a), even with negative magnitudes (Fig. 2b,c); 95% of the earthquakes have magnitudes $M_D < 3$ (Fig. 2b,c). The earthquakes are mainly located in the upper crust (Fig. 2d), with $M_D > 4$ events occurring all along the southeastern Alps. The most significant event since 2005 occurred at the southern boundary of the monitoring area during the 2012 Emilia seismic sequence (M_w 6.1) located in the external fold and thrust system of the northern Apennines belt.

Strong-Motion Network

To ensure in-scale measurements for strong earthquakes, most stations of the seismological network have also been equipped with strong-motion sensors (Fig. 3): 18 Kinemetrics Episensors FBA-ES-T, six Nanometrics Titan, four Sara SA10, and one Güralp CMG-5T. Furthermore, recently, new real-time strong-motion stations have been added (Fig. 3) in the framework of two projects (Progetto Edifici Sentinella, supported by the PCFVG and also involving the University of Udine and the University of Trieste, and the Interreg V-A Italy–Austria Armonia Project; see "Real-time acceleration network for monitoring sites and buildings in Italy and Austria", 2020). These new stations consist of 54 cost-effective, MEMS-based instruments Moho Suricat (the SentiNet-FVG network) installed across the region to improve the density of the ground-motion observations and to measure the level of shaking recorded at selected buildings (referred to as Sentinella buildings). In general, these accelerometers are installed in

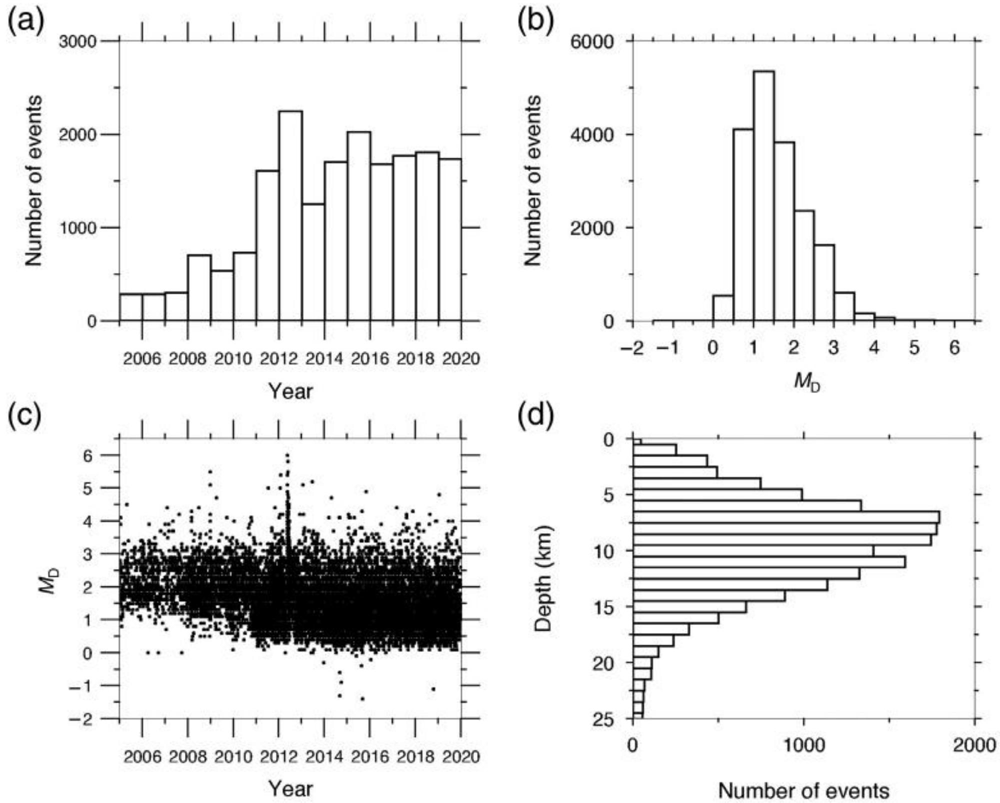


Figure 2. (a) Number of seismic events per year; (b) magnitude distribution (0.5 bin); (c) time–magnitude plot; and (d) depth distribution (1 km bin). The 2005–2019 seismic catalog used in the graphs is a combination of the catalog published by Peruzza *et al.* (2015) and the OGS bulletins available online (Friuli Venezia Giulia Seismometric Network Bulletin, 2019) for the periods 2005–2011 and 2012–2019, respectively.

the basement to reduce the building interaction and approximate free-field conditions. In a few cases, the building is equipped with two or more accelerometers at different levels to investigate the dynamic response of the structure. Although the standard strong-motion stations use the same data transmission system as the seismic network, the SentiNet-FVG network benefits from a dedicated VLAN connection provided by the INSIEL s.p.a. (the IT company of the Region FVG). The data collected by this network are used for civil protection goals, contributing to a better assessment of the shaking and the quasi-real-time impact of an event (Parolai *et al.*, 2020; Poggi *et al.*, 2021). The network is currently under further development with the installation of six new stations in the Veneto region, with the PCV support. This extension is based on triaxial MEMS accelerometers, Lunitek Sentinel-Geo, and GPRS for data transmission.

GNSS Network

The Friuli Regional Deformation Network (FReDNet; Zuliani *et al.* 2018) is the OGS geodetic network (Fig. 4), consisting of 19 continuously operating GNSS stations, capable of tracking GPS, Global Navigation Satellite System, Galileo, and Beidou satellite systems (detailed information provided at FReDNet website; see Data and Resources). The FReDNet equipment has been deployed in the FVG region (and partially in the Veneto region) to determine the distribution of crustal deformation, to relate it to the tectonic processes, to estimate the interseismic strain accumulation to better assess seismic hazards, and to monitor hazardous areas for emergency response management.

The system has been operating since 2002, when the first core of three stations was installed, with the help of the University of California at Berkeley. FReDNet, since 2009, has been improved with Real Time Kinematic (RTK) services to support high-precision real-time positioning. RTK enables the final user to reach the positioning with centimeter accuracy in every part of the FVG region during surveys. Different RTK modes are available, such as Multi Reference Station or Virtual Reference Station, and can be reached at no cost from the RTK server (GNCASTER Ntrip Caster, 2020). This technology can be of use in different contexts such geomatic fields (e.g., cadastral), real-time seismology (to assess coseismic displacements), real-time structure, and monitoring (e.g., landslides or infrastructures as buildings, bridges, and dams). A data exchange with Austrian (ÖBB Infrastruktur AG–Railway systems, EPOSA network) and Slovenian (the University of Ljubljana, Faculty of Civil and Geodetic Engineering, Geodetic Department; Harpha Sea, d.o.o., Koper) partners enables the service to also cover those parts of the region at the boundaries with these countries.

FReDNet, in the past 18 yr, has gained importance at three different levels:

1. local, because of the integration with the GNSS network of the Service Geographic Information System and Cartography of the FVG region;
2. national, because of the inclusion of four stations (ACOM, UDI1, TRIE, and ZOUF in Fig. 4) in the National Dynamic Network (RDN) of the Italian Military Geographical Institute; and

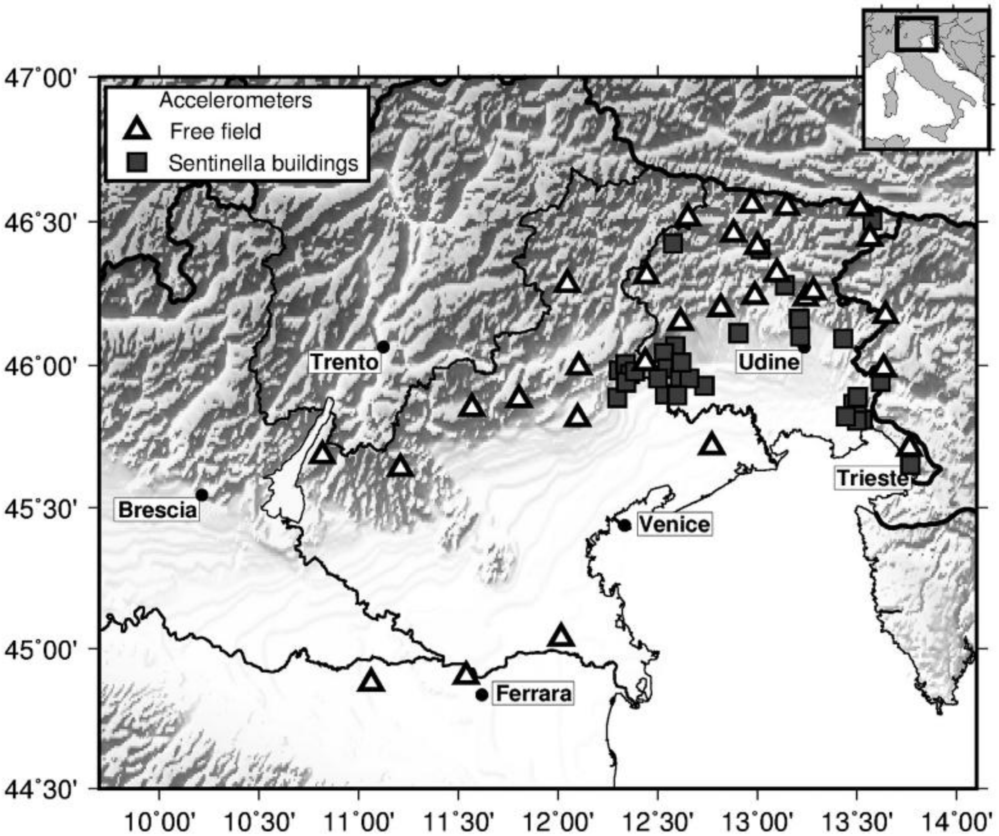


Figure 3. Strong-motion stations managed by OGS. Triangles indicate sensors collocated with the stations of the seismological network. Squares depict the position of the accelerometers in Sentinella buildings. The inset map shows position of the monitored area relative to Italy.

3. European, with the inclusion of the permanent station ZOUF of FReDNet as part of European Reference Framework Permanent Network (EPN).

The perspective for FReDNet is to develop and maintain an infrastructure for advanced services and products in the field of long-term and real-time precision positioning with GNSS technology. Products are intended to be exploitable by the public, scientific, and private sectors. The GNSS data collected for the past 18 yr represent a precious resource for researchers involved in the Friuli collision area's tectonic studies. Long-term displacement and velocity field time series can contribute in quantifying the seismic hazard and integrating seismological data to achieve a better understanding of the geodynamic evolution of the FVG region and adjacent areas (e.g., Rossi *et al.*, 2018) while also being able to reveal rapid transient deformations (e.g., Devoti *et al.*, 2015).

Products and Services

The seismic bulletin

Regular yearly seismic bulletins have been published since the establishment of the network in 1977, and they are available online (Friuli Venezia Giulia Seismometric Network Bulletin, 2019). Each bulletin includes manually picked phases from recordings of the OGS network and other stations managed by partner institutions in Italy, Austria, Croatia, Slovenia, and Switzerland (see Fig. 5 and Data and Resources), whose data streams are acquired in real time by the CRS based on agreements for data exchange. The contribution of the stations of the partner institutions is fundamental in achieving hypocentral solutions of acceptable quality near the boundaries of the monitoring area. In particular, thanks to the density of stations in the northwestern and eastern sector, in these areas it is possible to reach a detail comparable to that of the inner zone in FVG (azimuthal gap lower than 180° and statistical error on depth estimation of the order of 2 km). Hypocentral location solutions are calculated using the code HYPO71 (Lee and Lahr, 1975) configured with a set of parameters and a velocity model specifically calibrated for the region. For each earthquake, the bulletin reports the corresponding duration magnitude M_D, computed using the formulas of Rebez and Renner (1991), calibrated on the local magnitude M_L of the Wood–Anderson seismometer installed in Trieste. In the past, M_D was the only choice for weak earthquakes not recorded in Trieste or when the Wood–Anderson seismometer was not operational. With the advent of digital instrumentation, it was possible to simulate Wood–Anderson seismograms from the recordings of any network station and furnish a direct estimation of M_L with a calibration for the area of interest (Bragato and Tento, 2005). The bulletin is being revised to integrate the values of M_L for the current and the previous years. In association with this work, a new calibration scheme for M_L is also being developed to include the new stations installed since 2005, as well as the extended set of earthquake recordings now available.

The Real Time Seismology (RTS) service

We publish the seismicity located by our network on the website RTS (see Data and Resources) after a few minutes from an event's occurrence. Hypocentral location solutions are initially calculated by an automated system and then updated after revision by an operator. The website provides, in the fastest and most intuitive way, information about the location and magnitude of a recorded earthquake (Fig. 6). RTS (Saraò *et al.*, 2009) has been set up to display also other products of the real-time analyses carried out at the CRS (i.e., shake maps and moment tensors) and to visualize the daily seismograms of the OGS network. It also hosts the map with the network stations and, for each station, the type of instruments installed, some quick links to the webcams installed in selected sites housing our instruments and to the Friuli Venezia Giulia Seismometric Network Bulletin (2019). RTS will also be used for the free distribution of the digital seismograms of the recorded events. The website is designed to maintain a lightweight structure to withstand the high number of access requests in case of a seismic event. We count an average of 500 visualizations per day, mostly from NEI, which increase significantly in the case of earthquakes felt by the population; in the case of the 17 July 2020 M_L 4.3 Kobarid earthquake, there were 20,000 views of the homepage showing the map and the main information about the earthquake.

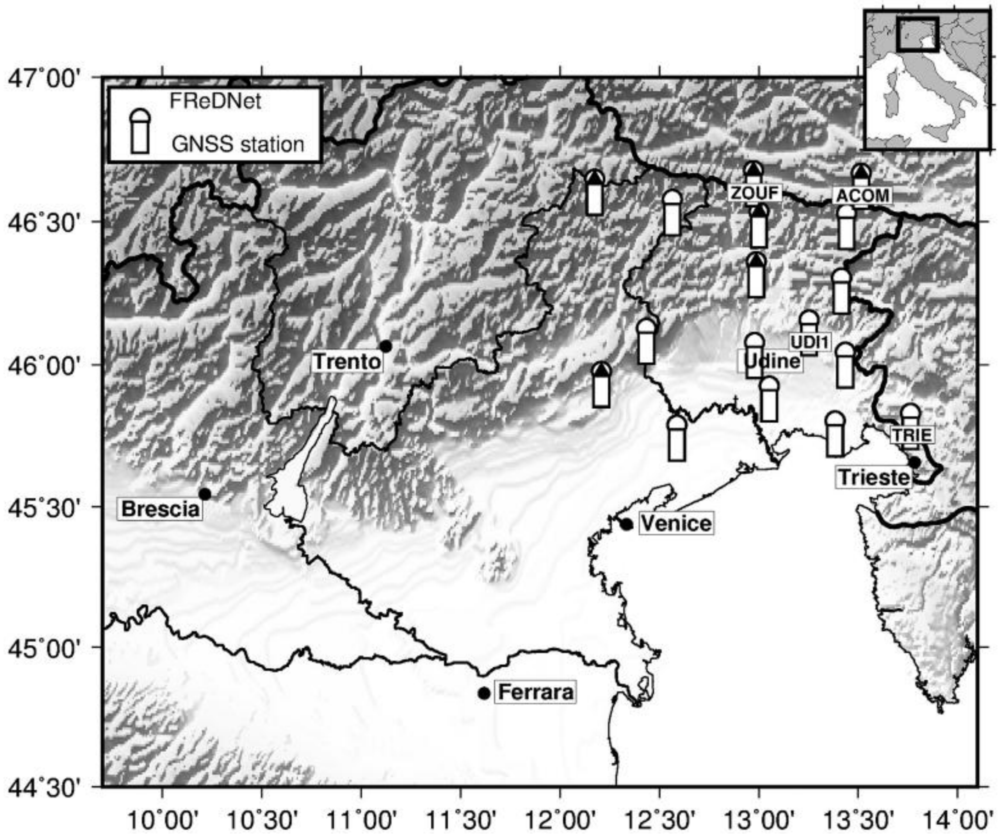


Figure 4. Global Navigation Satellite Systems (GNSS) stations managed by the OGS, making up the Friuli Regional Deformation Network (FReDNet) geodetic network (see Data and Resources). Black triangles indicate those that are collocated with the seismic stations. The GNSS stations ACOM, UDI1, TRIE, and ZOUF are included in the National Dynamic Network (RDN) of the Italian Military Geographical Institute. ZOUF is also part of European Reference Framework (EUREF) Permanent Network (EPN). The inset map shows position of the monitored area relative to Italy.

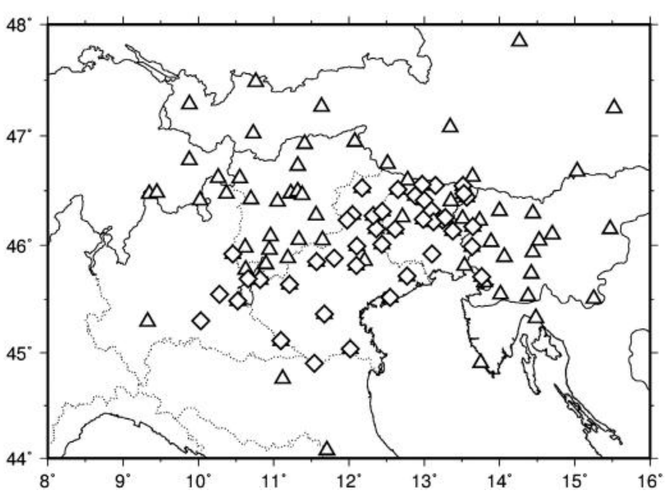


Figure 5. Integrated seismometric network used for the real-time monitoring and the bulletin production. OGS stations (diamonds) and the stations of the cooperating institutions (triangles) are plotted. Other details are provided in the Data and Resources.

The seismic moment tensor

Since 2009, the seismic moment tensor for the $M_L \geq 3.6$ earthquakes located in NEI and surroundings have been computed in near-real time using the TDMT_INV code (Dreger, 2003), tuned and validated for NEI (Saraò, 2007). The moment tensor solutions are then published on RTS (e.g., Saraò, 2016) after a thorough review by a seismologist to provide the best estimate of the focal mechanism and the moment magnitude. All the solutions have been recently revised and reported in the catalog of fault-plane solutions of the NEI (Saraò *et al.*, 2021).

Shake maps and rapid damage maps

For the earthquakes with $M_L \geq 2.5$ occurring in NEI, near real-time maps of ground shaking are produced using the software

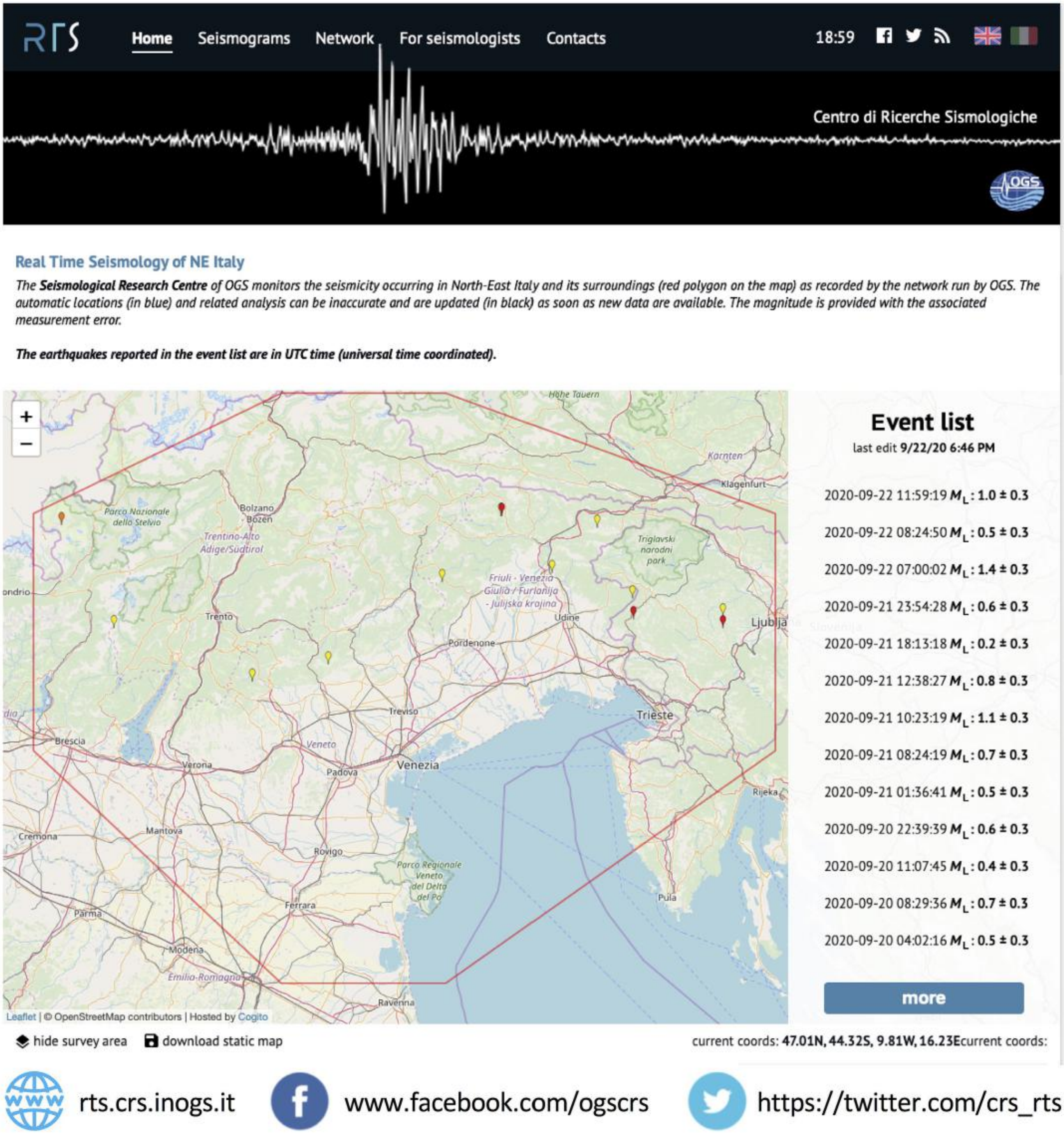


Figure 6. Home page of the website Real Time Seismology (RTS) of the Center for Seismological Research (CRS; see Data and Resources). The web addresses of the CRS social media accounts are reported at the bottom of the figure. The color version of this figure is available only in the electronic edition.

ShakeMap (Worden *et al.*, 2020). Four different maps are generated for peak ground velocity, peak ground acceleration, 5% critically damped response spectra (at 0.3, 1.0, and 3.0 s), and instrumental intensity (example in Fig. 7). The shake maps are then immediately sent to the PCFVG and PCV and uploaded onto the RTS website.

ShakeMap has been configured for Italy, as proposed by Michelini *et al.* (2020). Therefore, for seismic events $M_L \geq 4$, the ground-motion prediction equations (GMPEs) of Bindi *et al.* (2011) are used, whereas for smaller earthquakes, the regional GMPEs of Massa *et al.* (2008) are used. The shake maps are conditioned by the recordings acquired by the

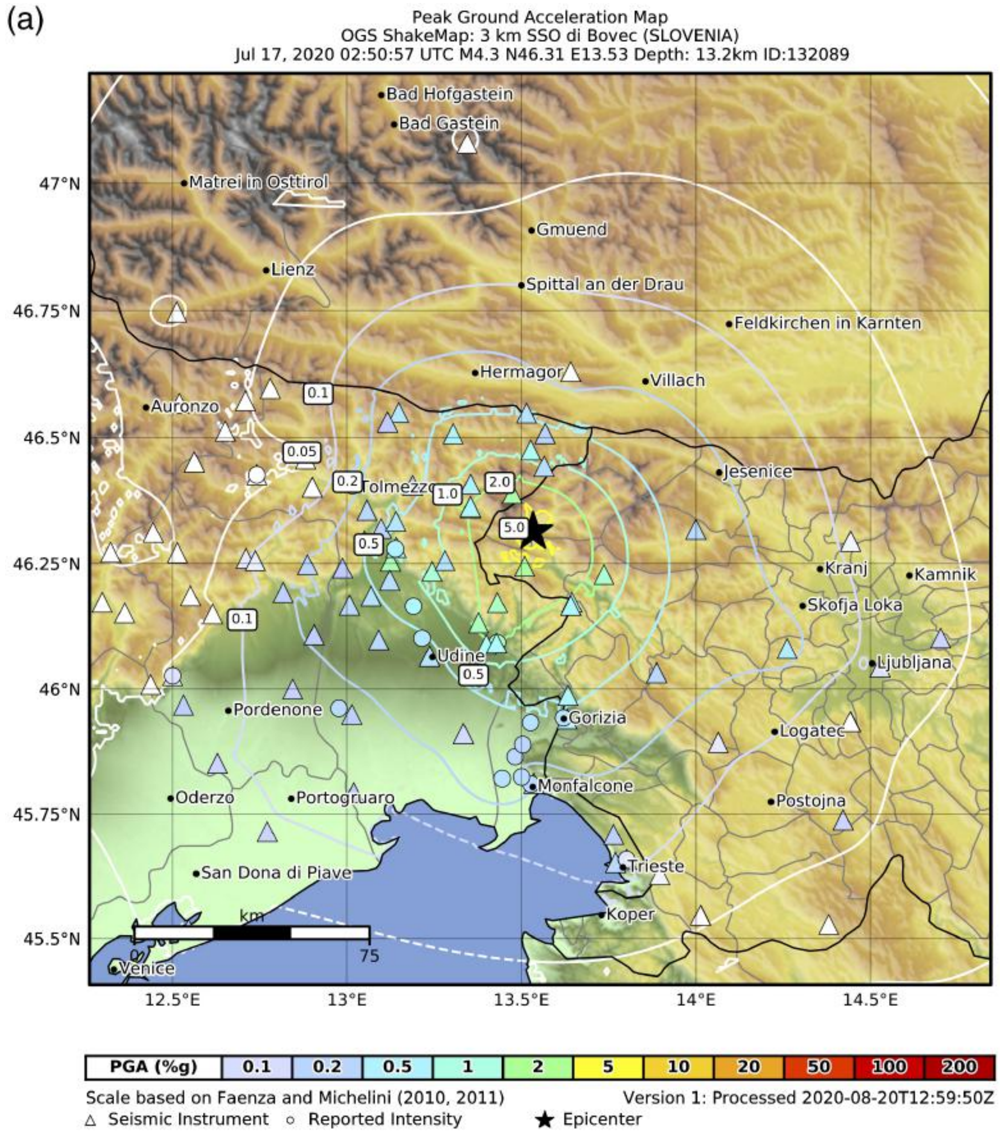


Figure 7. Example of a shake map for 17 July 2020 M_L 4.3 Kobarid earthquake. The star represents the epicenter, triangles show the cross-border stations, and circles represent the low-cost accelerometers that recorded the event. Ground-motion types presented are (a) peak ground acceleration (PGA in %*g*) and (b) instrumental intensity (PGV reported in the table is peak ground velocity in cm/s). The color version of this figure is available only in the electronic edition.

(Continued)

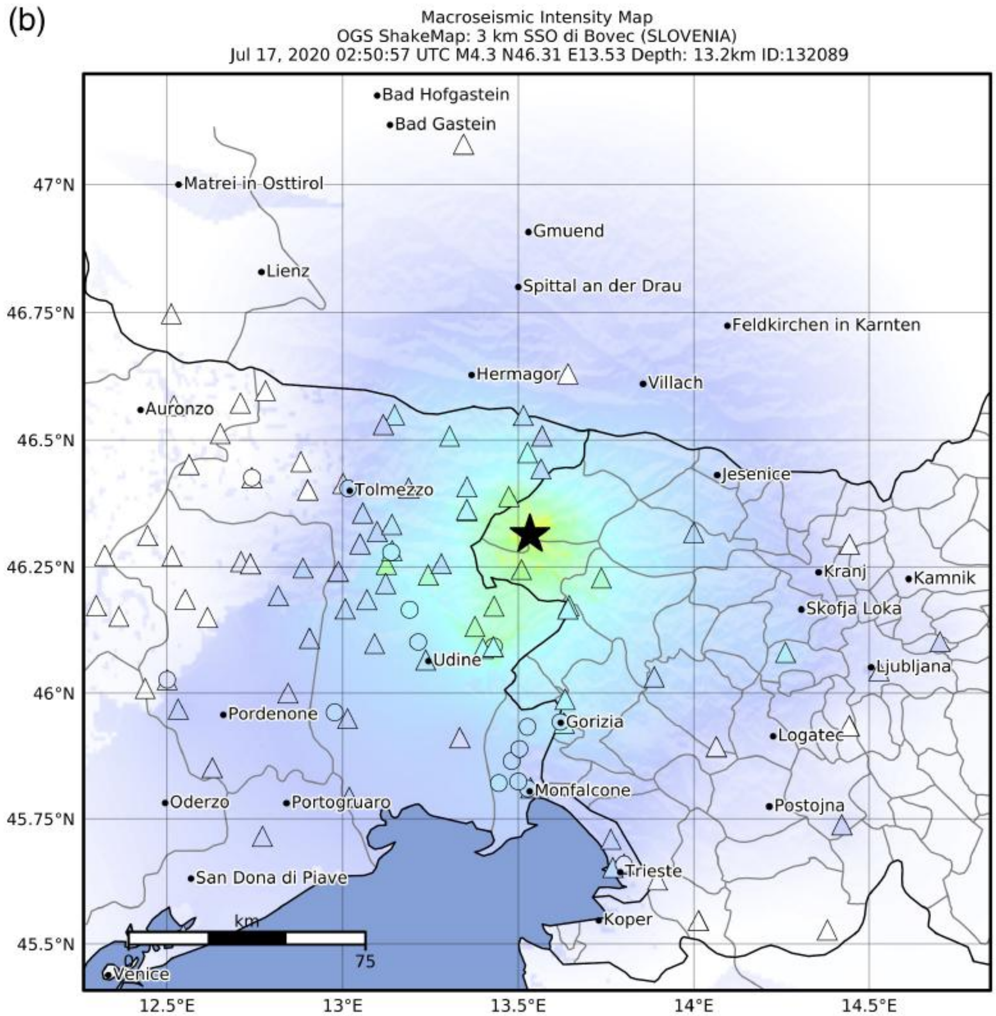
seismic and strong-motion networks managed by the OGS and by integrating data from other reporting agencies. The inclusion of data recorded by the Senti-Net-FVG network helps to reduce the uncertainties associated with the estimated shaking, especially in the near-source area (Moratto *et al.*, 2009).

The shake maps are also used as input for the calculation of the expected damage to structures at the municipality level through an automatic procedure (Poggi *et al.*, 2021) based on the OpenQuake software engine (Pagani *et al.*, 2014). When a new shake map is available, a near-real-time calculation of the expected damage distribution is automatically started. The procedure relies on a static exposure database derived from the 2011 building census (Istituto Nazionale di Statistica [ISTAT], 2011) associated with a set of fragility curves, selected specifically for each building typology in the area (e.g., Project SYNER-G, 2009; Faravelli *et al.*, 2019). The corresponding impact assessment is provided through the estimated number of buildings expected to have sustained substantial damage (D4 or D5 of the European Macroseismic Scale, Grünthal, 1998). In addition, expected casualties are also derived based on empirical relationships developed for the Italian Risk Map (Dolce *et al.*, 2019). A detailed description of the approach is provided by Poggi *et al.* (2021).

The parameter (e.g., ground-motion intensity measure, damage level) to be calculated in real time and shown in the operative centers has been discussed and agreed upon with the PCFVG and PCV. For this reason, the visualization of the expected damage maps (Fig. 8) has been developed together with the end users, taking into account their opinion on graphical aspects that might facilitate the decision-making process during an emergency. This tool has also been used for training purposes within the periodic exercises led by the PCFVG. The OGS contributes to the training by providing all the support (e.g., event location, shake maps, expected damage maps). Such activities allow for systematic testing of emergency management, resource distribution, and decision-making process.

Social media

To ensure that in case of an earthquake, the information is reaching the broadest possible audience in real time and reducing potential technical problems caused by unexpectedly high



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.06	0.21	0.81	1.97	4.82	11.8	28.7	70.1	>171
PGV(cm/s)	<0.02	0.08	0.34	0.9	2.39	6.37	17	45.2	>120
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Faenza and Michelini (2010, 2011) Version 1: Processed 2020-08-20T12:59:50Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure 7. Continued

the most up-to-date information is distributed along with the alert post if this has been shared by the followers. For $M_L \geq 3.5$ events, the map showing the position of the epicenter is attached to the post. Each first day of the month, a map showing the seismicity of the previous month as identified by our center is posted. Social networks are also used to publish news about research or dissemination activities of the CRS members.

To date, more than 9000 people follow the CRS Facebook account. Often, the followers send public or private messages asking for clarification on earthquakes in general or to learn more about the seismic hazard of the area where they live. The followers of the social media accounts are mainly persons older than 25 yr, with the group most represented in the 35–54 yr range (similarly to the public engaged by RTS).

In the case of 17 July 2020 M_L 4.3 Kobarid earthquake, more than 165,000 people were reached by our alert post, which had been shared by more than 1200 people. Within 1 hr, 140 people voluntarily, posted a comment to let us know where and how they had felt the earthquake.

requests for access to RTS, in 2013, we opened our accounts on Facebook (OGS Centro Ricerche Sismologiche, 2013) and Twitter (CRS terremoti, 2013).

When an earthquake occurs, the information regarding the position and magnitude of the event, calculated automatically by the system, is transmitted from the computer center to the RTS website, and for earthquakes of $M_L \geq 1$, to the social accounts. The first information (alert post) is posted after 2 min and a possible update within 1 hr from the occurrence of the event; the revisions of the location (automatic or human) are published as a comment to the alert post so that

National and International Cooperation

Because the seismic events that can affect NEI might occur in the neighboring regions or countries, close cooperation was agreed upon with other Italian national networks and those of the neighboring countries to exchange data in real time to support alert operations. In particular, it is worth mentioning that the agreement of 2017 between OGS, Provincia Autonoma di Trento, Provincia Autonoma di Bolzano, Regione Autonoma Friuli Venezia Giulia, the University of Genova, and, in Austria, the Land Tirol Zentralanstalt für Meteorologie und Geodynamik. This agreement established

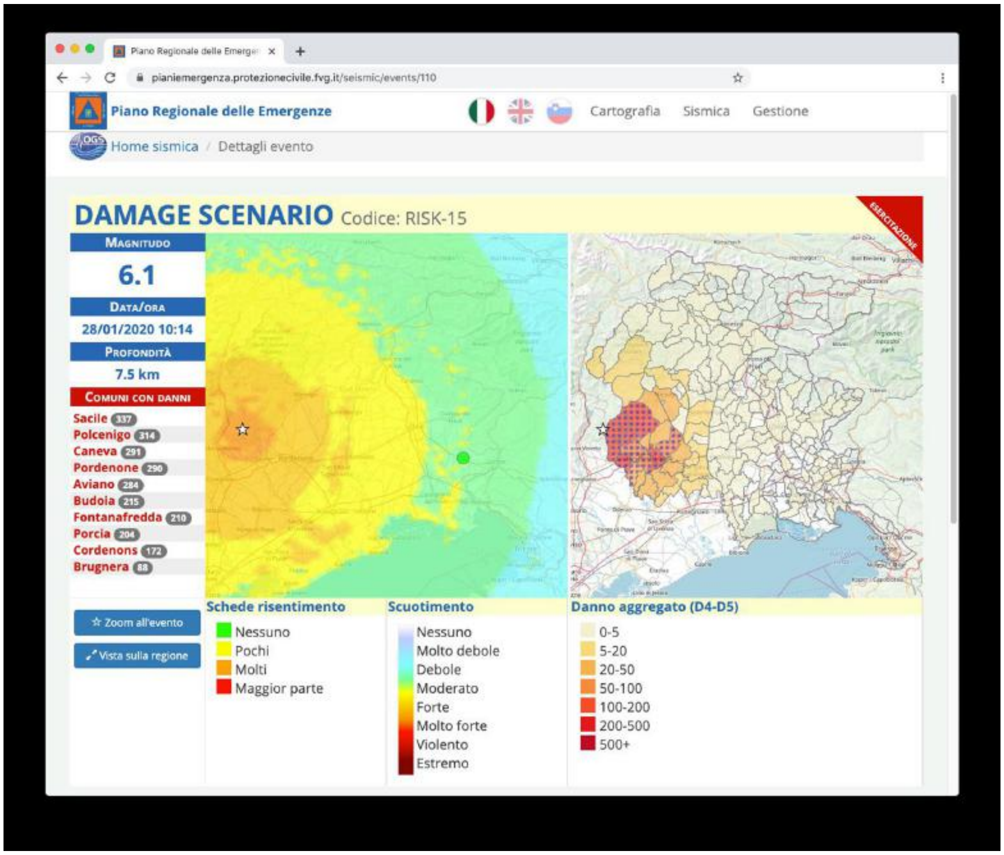


Figure 8. Example of a map of expected ground shaking (left) and damage (right) displayed on the Civil Protection interface. The damage scenario has been generated by OGS for training purposes. The color version of this figure is available only in the electronic edition.

close cooperation between the networks operating stations in northern Italy and across the Alps. Another agreement in 2012 with the INGV is defining the cooperation, already introduced by the Italian law 389/1989, whereas the establishment in 2014 of the CE3RN consortium de-facto created a virtual cross-border network for Central Europe (see Data and Resources), which aims at increasing and facilitating the cross-border cooperation for seismological data acquisition, exchange, and use for seismological and earthquake engineering and civil protection purposes. A list of the partners is provided on the CE3RN webpage (see Data and Resources).

Data from 20 stations of the OGS seismological network are provided to the European Integrated Data Archive (EIDA) with the network code OX. EIDA is a distributed federation of data centers for the archiving of seismic waveform data and metadata while supporting the European Plate Observing System (EPOS) infrastructure by the development and implementation of tools and services that provide access to seismological waveforms. The OX network, within this context, is included inside the Italian Joint Research Unit (JRU) EPOS-Italia. The CRS contributes to the Engineering Strong-Motion Database (Luzi *et al.*, 2016) and the INGV Strong Motion Data (Massa *et al.*, 2014) with the real-time transmission of the waveforms from 19 accelerometric stations.

Within the activity of the JRU EPOS-Italia, the OGS is currently working on testing the capability of sharing GNSS FReDNet data to the EPOS community through the Geodetic Linking Advanced Software System (GLASS), developed by the EPOS GNSS Thematic Core Service.

Conclusion: Outlook

Following technological developments, the OGS networks now grouped under the SMINO infrastructure have undergone several changes, and in particular, the services have been updated to take into account the emerging requirements of the end users. Notably, the close cooperation with the PCFVG and PCV has led to the improvement of the real-time services and to an increasing volume of higher quality data that will in turn provide the necessary input for scientific research. Recent works on source parameters (e.g., Bressan *et al.*, 2007; Moratto *et al.*, 2017), the analysis of the seismicity patterns (Bressan *et al.*, 2017; 2018; Peresan and Gentili, 2018, 2020; Benali *et al.*, 2020; Gentili and Di Giovambattista, 2020), seismicity detection, stress and strain patterns (Bressan *et al.*, 2009; Restivo *et al.*, 2016; Rossi *et al.*, 2016), crustal mechanical modeling (Magrin and Rossi, 2020), and real-time damage assessment and early warning systems (Pesaresi *et al.*, 2017; Parolai *et al.*, 2020; Poggi *et al.*, 2021) have taken advantage of the existence of such multiparametric infrastructure. Furthermore, it has triggered projects aiming at the development of the OGS Archive System of Instrumental Seismology (see Data and Resources), in which the waveforms recorded from 1994 to 2019 are stored jointly with information about the associated instrumentation and recording sites (Priolo *et al.*, 2015). The growing number of requests and increasing interest in data across this tectonically active and complex region (see The AlpArray Initiative, 2020), is stimulating the further development and improvement of the necessary infrastructure.

Because of the crucial position of the SMINO infrastructure and the natural research focus of the OGS toward Central Europe and the Balkan region, it is expected that an even stronger engagement will be carried out in the future in facilitating the development of seismological infrastructures and research. In this respect, we recall the 2019 Trieste Declaration on Science at the Central European Initiative (CEI Ministerial Conference on Science and Research, 2019), which expresses the will to "support the CEI-Executive Secretariat in promoting actions finalized to improve cross-border and transnational cooperation, starting from prevention and mitigation of natural disaster, based on existing initiatives as in the case of the seismic network of the OGS, aiming to create a real-time impact estimation system in case of earthquakes in Central, Eastern and South-Eastern Europe."

Data and Resources

Sistema di Monitoraggio terrestre dell'Italia Nord Orientale (SMINO) is composed of the Northeast Italy Seismic Network (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, 2016a), the Northeast Italy Broadband Network (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS and University of Trieste, 2002), and the Friuli Regional Deformation Network (FReDNet DC, 2016). SMINO shares data with the following networks: The Trentino Seismic Network (Geological Survey-Provincia Autonoma di Trento, 1981), the Collalto Seismic Network and the Cornegliano Laudense Seismic network (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale – OGS, 2012, 2016b), the Friuli Venezia Giulia Accelerometric Network (University of Trieste, 1993), the Italian Seismic Network (INGV Seismological Data Centre, 2006), the Italian Strong Motion Network (Presidency of Counsil of Ministers-Civil Protection Department, 1972), the Mediterranean Very Broadband Seismographic Network (MedNet Project Partner Institutions, 1990), the Province Südtirol Network, the Seismic Network of the Republic of Slovenia (Slovenian Environment Agency, 2001), the Austrian Seismic Network (ZAMG-Zentralanstalt für Meterologie und Geodynamik, 1987), the Switzerland Seismological Network (Swiss Seismological Service (SED) at ETH Zurich, 1983), and the Croatian Seismograph Network (University of Zagreb, 2001). ShakeMap 4.0 is released by the U.S. Geological Survey (USGS; https://usgs.github.io/shakemap/index.html). The maps have been generated by Generic Mapping Tools (GMT; Wessel *et al.*, 2019). The other relevant data are from the following sources: northeastern Italy seismic network (http://rts.crs.inogs.it/it/project/1_map.html), FReDNet (frednet.crs.inogs.it), Real Time Seismology (rts.crs.inogs.it), CE3RN (www.ce3rn.eu), and National Institute of Oceanography and Applied Geophysics – OGS Archive System of Instrumental Seismology (oasis.crs.inogs.it). All websites were last accessed in February 2021.

Declaration of Competing Interests

The authors acknowledge there are no conflicts of interest recorded.

Acknowledgments

The authors thank Editor-in-Chief A. Bent for handling the article in addition to P. Augliera and an anonymous reviewer for constructive suggestions that helped improve the article. *Sistema di Monitoraggio terrestre dell'Italia Nord Orientale* (SMINO) and the associated activities are financially supported by the Regione Autonoma Friuli Venezia Giulia and Regione Veneto. The ARMONIA-ITAT3016 project is financially supported by the European Regional Development Fund (ERDF), within the INTERREG V-A Italy–Austria 2014–2020 Cooperation Programme.

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