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On the crowdsourcing of macroseismic data to characterize geological settings

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ABSTRACT

Macroseismic data are obtained from observing the effects of an earthquake on people, buildings, and the natural environment. The crowdsourced macroseismic data are collected from a large number of people, often through online platforms or mobile applications. These data can be useful for characterizing geological features, depending on several factors, such as the quality of the data, the representativeness of the sample, and the methods used for data collection and analysis. As a case study, we consider the macroseismic data collected in Trieste (NE Italy) through online questionnaires completed by citizens after the 2020 Mw 6.4 earthquake in Petrinja (Croatia). The campaign was promoted through social media and in a short period of time more than 6000 questionnaires were completed by the citizens of Trieste. The analyzed macroseismic data show good agreement with the expected seismic response of the main soil types of the city. A comparison with a similar project we conducted in Trieste in 2012, following the 2012 Emilia May 20 and 29 earthquakes, shows that also in that case, although a much smaller number of questionnaires was collected, the main characteristics identified correspond well with the soil types of Trieste. Thus, our study proves the importance of collecting macroseismic data even in areas of low damage. Moreover, it shows how people's early engagement, computer skills, social networks, and smartphone popularity can influence the results of such data collection and opens new scenarios for a better understanding of earthquake risks and improved awareness and preparedness through citizen participation.

1. Introduction

Citizen participation in risk-related scientific activities can be very effective in increasing risk awareness and preparedness and is strongly recommended in the 2015–2030 Sendai Framework for Disaster Risk Reduction [1]. The crowdsourcing approach assumes that information collected from many citizens provides bottom-up evidence that improves knowledge and numerous studies have demonstrated that such approaches can support disaster management, disaster assessment, and emergency decision making (e.g., Refs. [2–4]. Although crowdsourcing is becoming increasingly popular in disaster contexts, the compatibility of disaster risk reduction and voluntary crowdsourcing has not been sufficiently explored [5,6]. Seismology is one of the research areas where citizen science projects are successfully used to share seismological information and collect useful data for seismic risk mitigation, and it has been proved that crowdsourcing reports can be used to quickly identify the impact of an earthquake [7].

Macroseismic questionnaires are used to collect information on the distribution of ground shaking and the effects of the earthquake on buildings, infrastructure, and people during earthquakes, supplemented by field surveys in the case of damaging earth-

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quakes. The use of online macroseismic questionnaires has gained popularity in recent years because of widespread Internet access and the ability to quickly collect and analyze data. Online questionnaires are less expensive than traditional paper questionnaires, can be distributed and completed more quickly, and reach a larger geographic audience in a short time, which can help improve the accuracy and completeness of earthquake data. Together with multilingual support, the widespread use of smartphones for macroseismic data collection enables the inclusion of as many people as possible from different languages and cultural contexts [8–10] and can improve disaster management in regions where expensive seismic instruments are not currently available.

Several organizations and initiatives have been established to promote the use of online macroseismicity questionnaires, including the U.S. Geological Survey's “Did You Feel It?” initiative [11–13], the European-Mediterranean Seismological Centre (EMSC) [14], and the “Hai sentito il terremoto (HSIT) ?" program of the Istituto Nazionale di Geofisica e Vulcanologia [15–17]. These programs provide a standardized framework for the acquisition and reporting of macroseismic data that can facilitate the comparison of earthquake impacts across regions and time periods.

Social media are fostering new opportunities to collect seismic data from large numbers of people and share information about earthquakes in real-time, including location, intensity, and damage [18]. With the ability to share multimedia content such as maps, photos, and videos, it is now possible to improve the quality and diversity of the data collected.

In addition, trained citizens can provide valuable information on perceived shaking and damage after an event and improve information on exposure data [19,20]. [21] have pioneered the use of appropriate training of civil protection volunteers to rapidly produce seismic impact maps that complement impact estimates obtained from recorded shaking data.

In this study, we describe our crowdsourcing experience with macroseismic data collected in Trieste (NE Italy), following the Mw 6.4 2020 Petrinja (Croatia) earthquake. The earthquake was clearly felt in Trieste, about 190 km from Petrinja in the WNW direction, and people spontaneously started posting on the social channels of our department, the Seismological Research Centre of the National Institute of Oceanography and Applied Geophysics (OGS), how they had felt the earthquake, where they were, and what they were doing. This is a common behaviour shortly after an earthquake, when people, to reduce their fear of losing information during a disaster, share posts on social media about the magnitude, feeling, and impact of the earthquake [22–25].

To address this voluntary offer of cooperation, we invited our fellow citizens via social networks to complete an online macroseismic questionnaire, which could also be managed via cell phone, with the aim to characterize the geological context of our city. Macroseismic data in urban areas have been already used in the past to identify zones of amplification (e.g., Refs. [26–33]. In this case, the novelty lies in media used to engage the public into our citizen science project.

In this paper, after describing the earthquake, the seismicity, and the geological environment of Trieste, we discuss the details of the questionnaire and the method used to analyze the collected data and assign the intensity. At the end, we create a macroseismic map comparable to the geological map of Trieste. For comparison, we also report on the similar attempt we made in 2012 after the Emilia earthquakes, when social media was not as widespread as it is today.

2. The 2020 M_w 6.4 Petrinja earthquake

On December 29, 2020, at 11:19 UTC (12:19 CET), an earthquake of magnitude M_W 6.4 occurred near the town of Petrinja, a settlement of about 25,000 people in central Croatia (Fig. 1); seven people died and about 15,000 people were temporarily displaced to safety ([34]; [35,36]. The earthquake occurred in a seismically active area in the boundary zone between the African and Eurasian tectonic plates, with underthrust of the Adria microplate under the Eurasian plate [37]. The main earthquake, which occurred at a depth of about 6 km, had two foreshocks the day before with magnitude M_W 5.2 at 05:28 and M_W 4.8 at 06:49 (UTC). Between December 28, 2020, and March 29, 2021, 9350 earthquakes were recorded with the strongest aftershock of M_W 4.8 ([38]). The main earthquake resulted in surface rupture and coseismic effects triggered by ground shaking, both permanent (e.g., landslides, sinkholes) and ephemeral, e.g., liquefaction phenomena [37]. In the epicentral area, the estimated peak ground acceleration (PGA) for bedrock ranged from 0.29 g to 0.44 g [34]. Damage was observed up to 60 km from the epicentre; the historic centers of neighbouring towns were significantly affected, as were numerous residential buildings consisting mainly of unreinforced masonry. The previous day's foreshocks in roughly the same area resulted in the abandonment of some damaged buildings, which likely helped reduce the number of victims of the main earthquake ([39]). The earthquake was strongly felt throughout Croatia, Slovenia, and most of Bosnia and Herzegovina, and was also reportedly felt in Austria, Slovakia, Hungary, Serbia, Montenegro, Italy, Germany, the Czech Republic, Romania, northern Macedonia, and Albania (Fig. 1).

After an initial estimate of nearly I_{max} = VIII-IX EMS (European Macroseismic Scale; [40]), the macroseismic intensity was later refined to I_{max} = VIII EMS ([41],). In Italy, the earthquake was felt in the north-eastern sector and along the Adriatic coast (Fig. 1). The HSIT portal collected 10,764 questionnaires on the Petrinja earthquake, 370 of which were from the city of Trieste. The intensity estimated in Trieste, based on the responses collected by HSIT, is I_{max} = IV EMS and I_{max} = IV MCS (Mercalli-Cancani Sieberg intensity scale, [42]).

3. Seismicity and geological setting in the Trieste area

Trieste is located in the Friuli-Venezia Giulia region (NE Italy), and is part of the External Dinarides system, which is characterized by overthrusts, reverse faults, and high-angle faults often with a transcurrent movement [43]. Some rare sub-vertical NE-SW oriented (anti-Dinaric trend) faults displace the previous faults in a strike-slip fashion (e.g., Refs. [44,45]. There is no relevant seismicity associated with offshore faults in the Gulf of Trieste or with inland faults. However, some active faults, such those in the Mt. Snežnik and the Gemona area (Fig. 1) caused significant shaking in the Trieste area [46]. The Italian macroseismic database [47,48] reports ten earthquakes with I > V for Trieste since 1500 (Fig. 2).

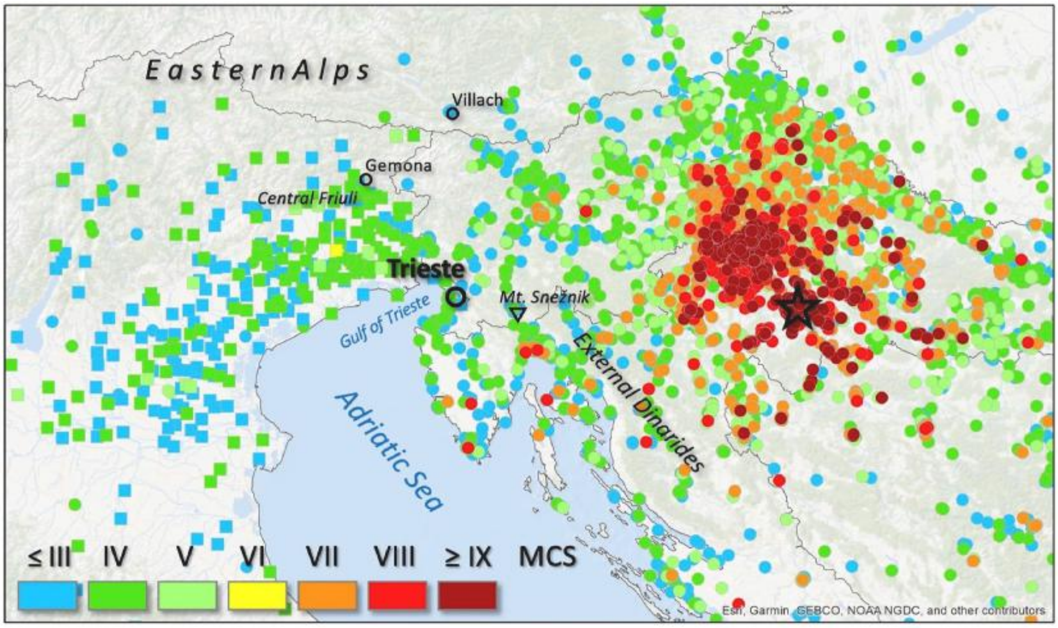

Fig. 1. Intensity map of the M_w 6.4 2020, 29 December Petrinja earthquake (star) obtained by the web-based macroseismic questionnaires. The intensity data are retrieved from the EMSC (circles) and the HSIT (squares) questionnaires.

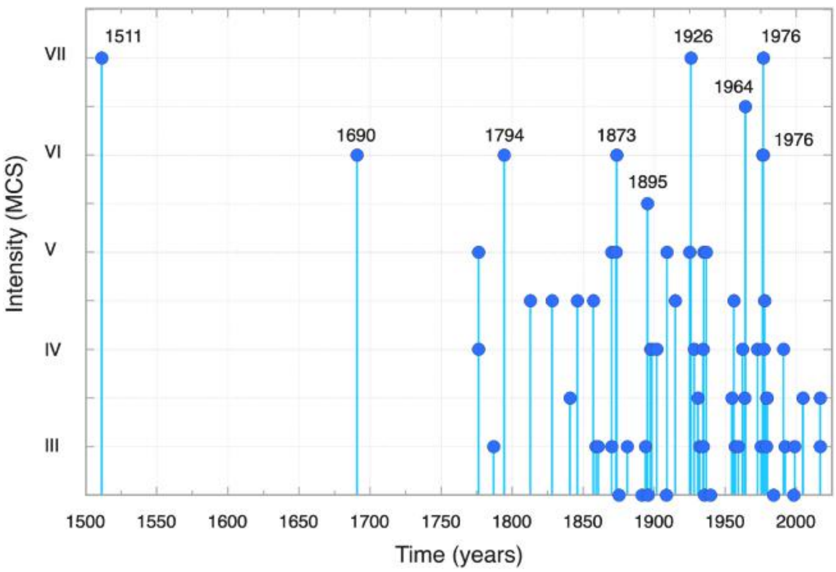

Fig. 2. Earthquakes felt in Trieste reported in the Italian macroseismic database DBMI15 v4.0 [47,48].

The most severe earthquake for the city was that of 1511 [49,50], which occurred on the border area between Italy and Slovenia, while the Friuli earthquake of May 6, 1976, was the most recent earthquake with an intensity I = VII (e.g. Refs. [51,52] and references therein). It is noteworthy that for a 1348 earthquake, considered the strongest in the Eastern Alps, no information on damage in Trieste has been found [53].

The Trieste area is characterized by calcareous carbonate formations (Cretaceous, upper to middle Eocene), flysch formations (an alternation of marl and sandstone, middle Eocene) and alluvial deposits dating from the Quaternary to the present [54–57]. [58] differentiated the area into three soil types (i.e., rock, stiff, and soft) according to the EC8 earthquake standard [59] and subsequent update guidelines (Fig. 3). Most of the city centre and the area facing the sea were built on a former saltern at the mouth of a river, characterized by thick, soft sediments (artificial fills, gravels, and sands). The entire northern part behind the city consists of a karst plateau of limestone, which is classified as bedrock. In contrast, part of the city and the slopes of the karst plateau consist of flysch soils, which can be classified as stiff soils.

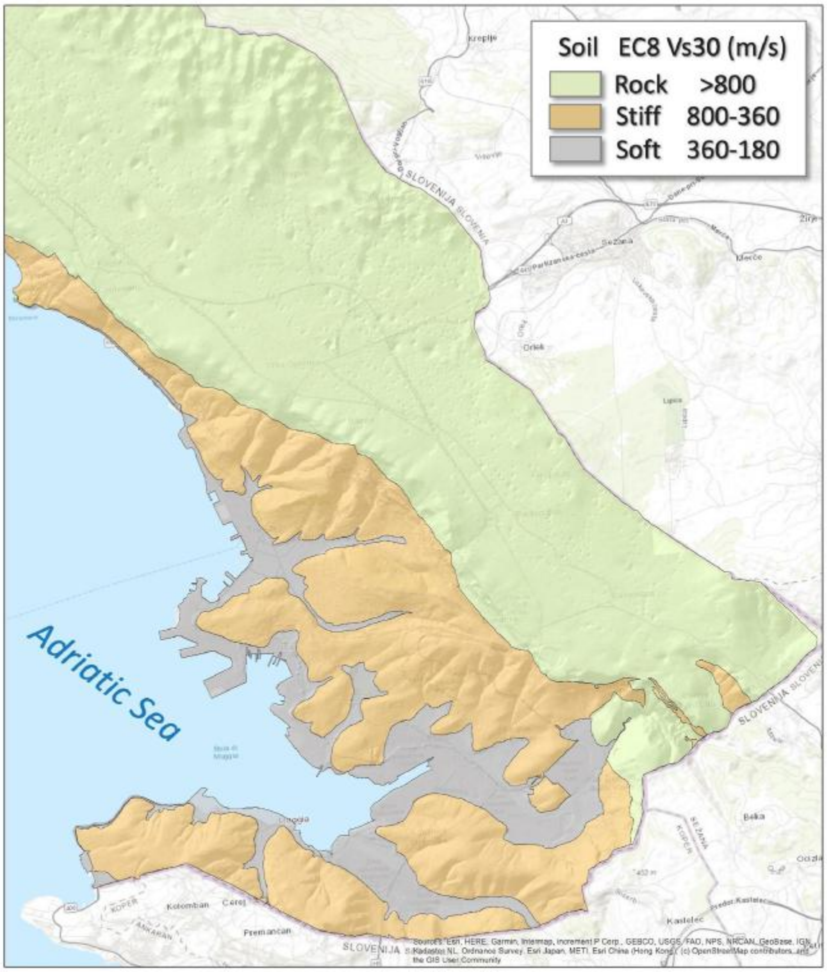

Fig. 3. Seismic soil classification of the study area [58]. In the legend are reported the relative values of Vs30 for each type of soil as classified in the EC8 [59].

Hazard maps for a return period of 475 years provide PGA values for Trieste ranging from 0.10 g [60] to 0.12–0.15 g [58] for rocky sites, depending on the different calculation approaches, and 0.17–0.20 g for soft soils [58]. Studies of site effects in the old town of Trieste have shown relevant amplification for frequencies around 2–4 Hz, consistent with the resonant frequency of soft sediment cover determined using a simple 1-D velocity model [61,62]. Such sediment cover could significantly amplify ground motions in the event of an earthquake.

4. Macroseismic data and intensity evaluation

The macroseismic effects of the 2020 Petrinja earthquake in the city of Trieste were analyzed using data collected with the online macroseismic questionnaire created with Google Form, which contains very similar questions to the HSIT questionnaire. The questionnaire, aimed at laypersons, is divided into three parts related to human impact, furniture, and damage observation, and consists of multiple-choice questions defined according to the macroseismicity scales (MCS and EMS). The form, initially published in Italian and later in English at the request of our followers, was promoted and disseminated through OGS social media, Facebook, and Twitter [63,64]. In addition, we personally invited colleagues and friends to also distribute the questionnaire via WhatsApp and invite their contacts to complete it. Fig. 4 summarizes the mode of data collection for this study. The use of personal social networks was very effective and resulted in the collection of 9453 responses, 6582 of which were from Trieste. In fact, although it was clearly stated that we were only collecting information for Trieste, many responses came from residents of nearby cities.

Before we started the analysis, a lot of editing work was needed to correct all the typos in the addresses so that they could be correctly converted into coordinates. It would have been more convenient to include a drop-down menu with the street addresses to be selected.

An initial overview of the questionnaire responses shows that most respondents (79%) felt the earthquake and described it as moderate (31%) to strong (38%) (Fig. 5a). The majority of those who felt it were sitting, lying down, or resting (96%), while 55% of those who did not feel it were in motion (Fig. 5b). Most were indoors, on the ground floor (23%) and between the first and fifth floors (66%), while only 5% of those who completed the questionnaire were outdoors (Fig. 5c). In this study, we will focus only on the ques-

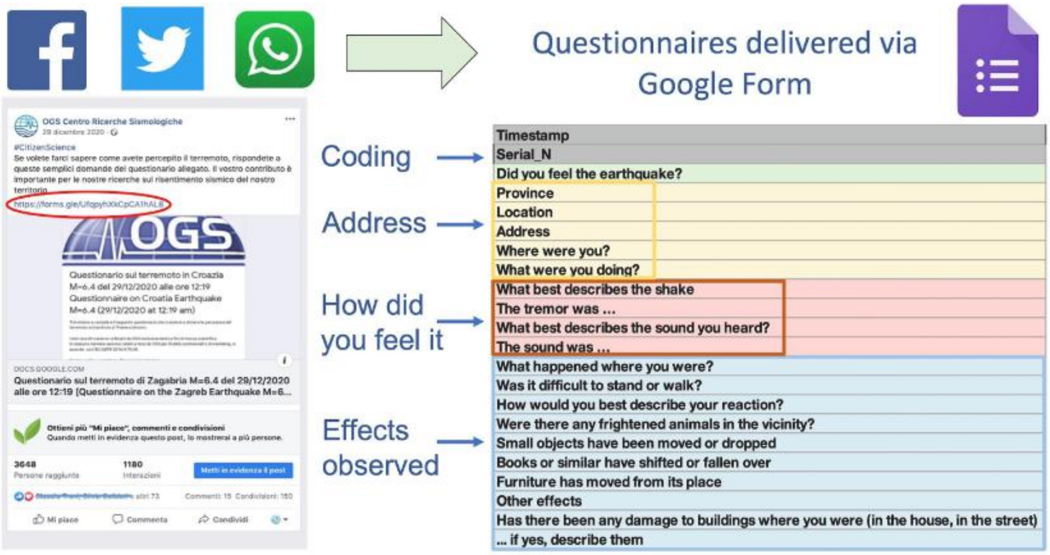

Fig. 4. Infographic representing the data collection procedure used for this study and the questionnaire main structure.

tionnaires filled out by people who were indoors, since very few of the people who were outdoors provided a complete address for which a unique coordinate assignment was possible.

The assessment of the macroseismic intensity of each questionnaire followed the method of [65]. Correspondence between the responses and the scores was established using a scoring matrix specifically developed for each intensity scale. Each row of the matrix represents a response, while the columns represent the corresponding macroseismic intensities. The score matrices consider all possible situations (asleep, at rest, in motion) and localizations (indoors at underground or ground level, indoors on the first to the tenth floor, outdoors) of the observer to account for all combinations of conditions described in the seismic scales.

The intensity distribution for each questionnaire was obtained by summing, for each intensity level, the scores of all answered items associated with that level. The mode of this distribution represents the intensity level that was most frequently identified by observer-reported effects [65]. When multiple local maxima occurred, the intensity was calculated as a weighted average of the local maxima. In the case of a non-felt response, a value of I– II was assigned. Following [65] we discarded questionnaires when there were fewer than three responses, when the calculated intensity differed by ± 3 units from the theoretical intensity determined by the intensity prediction equation (I_{IPE}), when there were more than three local maxima or when the local maxima were separated by more than one degree, and, of course, in the case of duplicate responses. In addition, questionnaires with missing addresses were not included in the final analysis. After the screening, 6240 questionnaires were scrutinized, of which 5901 were indoors (95%) and 339 were outdoors (5%); 342 were discarded. After georeferencing each questionnaire and assigning an intensity value, the intensity data were imported into the ArcGIS environment (ESRI®). The map of the received questionnaires (Fig. 6) shows good coverage of the city centre, while the outskirts of the Karst zone have a lower sample. This lower sample corresponds to a lower population density.

The I_{IPE} for Trieste was estimated as the mean of intensity values obtained using empirical relationships for moment magnitude (M_W) [66], PGA and maximum ground velocity (PGV) [67]. Although an accelerometer is installed in the sedimentary area of the city (CARC, see Ref. [62], the PGA was not available for the 2020 Petrinja earthquake. In this case, we used the PGV value recorded by the seismic station in Trieste (TRI, originally part of the WWSSN, now part of the MedNet and the Northeast Italy Network, see Ref. [68], located in the Karst area of the city. The calculated I_{IPE} = 4.0 (Table 1) is consistent with the macroseismic intensity calculated by HSIT.

5. Macroseismic intensity maps

To obtain a continuous smoothed intensity map for comparison with the geological map of Trieste (Fig. 3), we considered residual intensity data, like the study by [31]. The residual intensity data (Fig. 7a) were obtained by subtracting the I_{IPE} of Trieste from the intensity assigned to each questionnaire. It was not necessary to compensate for the attenuation effect with the distance from the epicentre since the extent of the municipality of Trieste is negligible compared to the epicentral distance.

An additional smoothed intensity map was created by a GIS procedure that calculated the moving average of the data within a circle with a radius of 500-m starting from the centroid of each hexagonal cell, and the average of the residual intensity was calculated for each cell (Fig. 7b). We used a 200 m hexagonal grid because it is more readable than a standard rectangular grid and improves the visual clarity of spatial distributions and homogeneity of cell neighbourhoods being the pattern symmetric with respect to distance [69]. For simplicity, we present here only the maps generated for MCS intensity, as MCS and EMS can generally be considered equivalent in the intensity range relevant to our case study [70].

The smoothed residual map (Fig. 7b) was overlaid and interpreted at the scale of the entire city, considering geological reconstructions (Fig. 8) to evaluate the variation of the macroseismic response. We obtained a good agreement between the values of the residu-

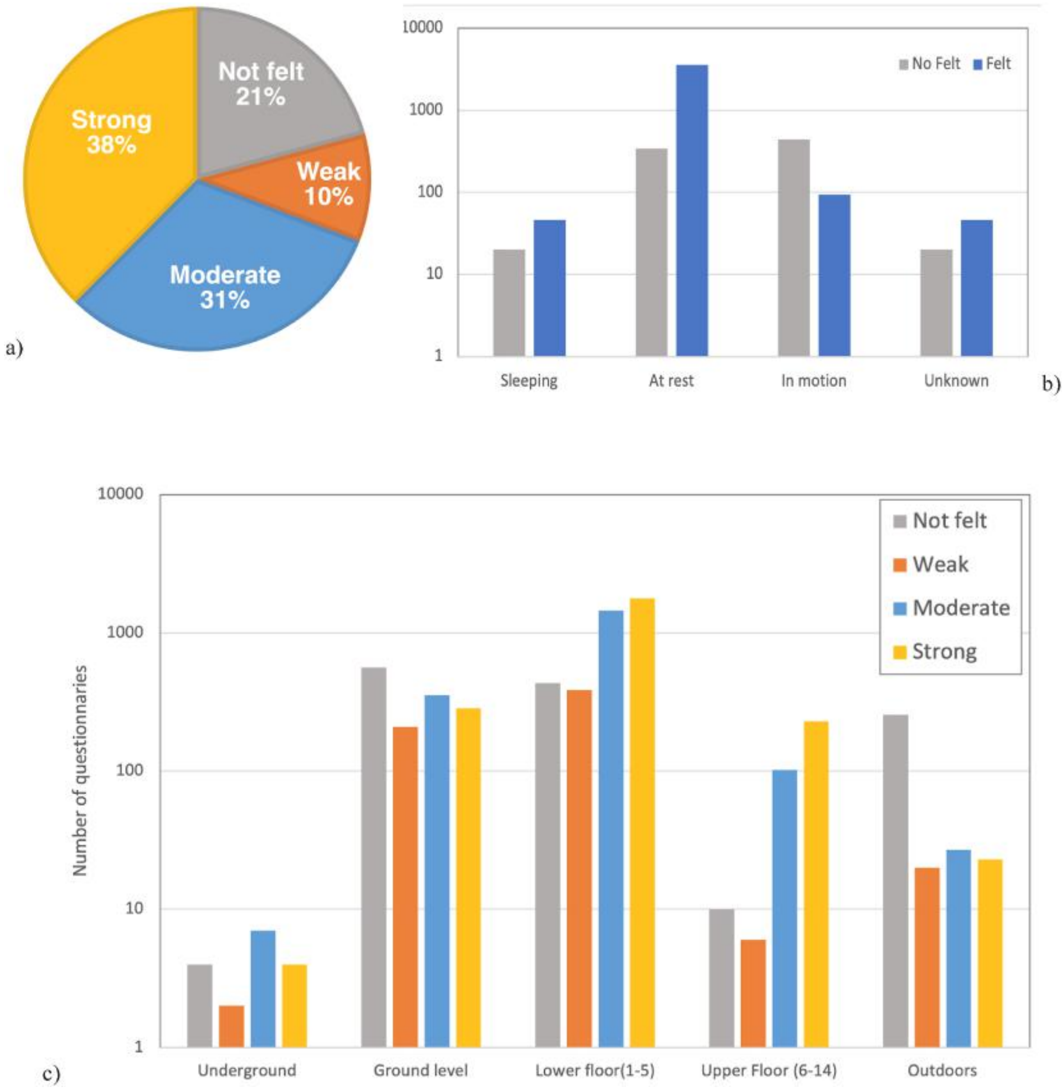

Fig. 5. Overview of raw data collected from the questionaries. a) how, b) what they were doing, and c) where the citizens from Trieste felt the earthquake.

als and the expected seismic response; in fact, in the rock class represented by limestones, the residuals are negative and show less earthquake felt shaking, in contrast to the urban area dominated by stiff soils represented by alluvial and artificial deposits, where the residuals are positive. Thus, the comparison between the results of the macroseismic survey derived from the online questionnaires and the lithoseismic classification provides evidence of areas of amplification.

6. Comparison with the 2012 Emilia earthquakes

In 2012, we conducted a similar experiment to identify possible local amplification zones in Trieste using the macroseismic questionnaires related to the two main 2012 earthquakes in Emilia, about 200 km from Trieste (Fig. 9). The earthquakes occurred on May 20 at 2:03 UTC (4:03 CEST) with M_W 6.1 and on May 29 at 7:00 UTC (9:00 CEST) with M_W 6.0 and resulted in 7 fatalities, 50 injuries, and 5000 displaced persons. Most of the severe damage affected monumental buildings, industrial warehouses, farmhouses, barns, churches, towers, or bell towers. These types of buildings are particularly vulnerable to seismic ground shaking (e.g., Ref. [71]. Between May 20 and 29, the area of greatest damage shifted westward [72]. The intense seismic sequence lasted for weeks and counted more than 2000 events, six of which had $M_L > 5$ (e.g., Refs. [73,74[75]].

The maximum intensity value representing the cumulative damage in the area was I = VIII EMS. The 2012 May 20 and 29 earthquakes were felt in northern and central Italy (Fig. 10a and b) and as far away as Switzerland, Slovenia, Croatia, Austria, southeastern France, and southern Germany [72]. The slow decay of seismic wave amplitude with distance to NE is a well-known phenomenon due to the reflection and refraction of energy from deeper parts of the crust [76] [77]. The HSIT portal collected 12119 online questionnaires for the May 20 event and 7848 for the May 29 events. Trieste had an associated I EMS = III-IV (HSIT) calculated on 56 questionnaires for the May 20 event and 40 for the May 29 event.

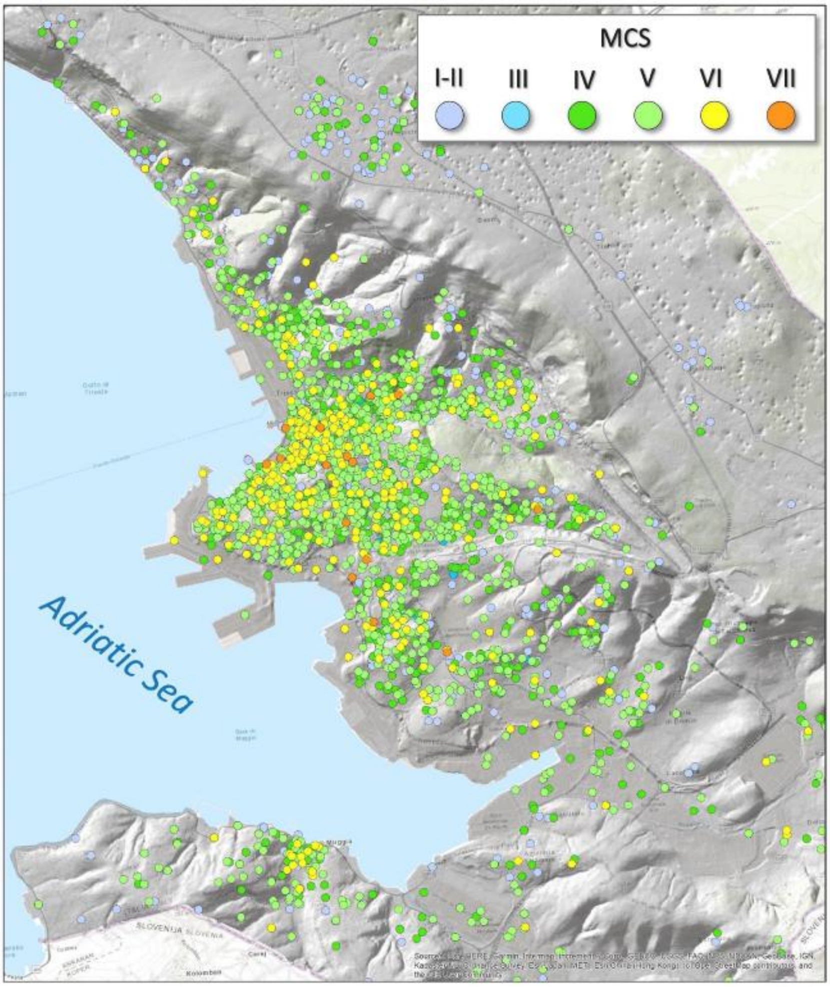

Fig. 6. Spatial distribution of macroseismic intensities (MCS) obtained from the 6240 questionnaires collected in Trieste.

Table 1
Parameters of the earthquakes investigated in this study. Each row indicates the date of the earthquake, the epicentral distance, M_W, PGA, PGV, and the theoretical intensity values (N.A. if the value was not available). I_{Mw} was calculated using the empirical relationship of [66]; I_{PGA} and I_{PGV} the relation by Ref. [67]; I_{IPE} is the average of I_{Mw}, I_{PGA} and I_{PGV}.

Date	*Epicentral distance (km)*	M_W	*PGA - CARC cm/s²*	*PGV - TRI cm/s*	I_{Mw}	I_{PGA}	I_{PGV}	I_{IPE}
2020-12-29	190	6.4	N.A.	0.51	4.2	N.A.	3.9	4.0
2012-05-29	215	6.0	4.4	0.09	3.4	3.2	2.7	3.1
2012-05-20	215	6.1	5.9	0.12	3.6	3.5	2.9	3.3

To investigate the macroseismic impacts in the city of Trieste, we collected data through an online macroseismic questionnaire advertised with a call in the local media and by email. 587 questionnaires were collected for the May 20 earthquake and 462 questionnaires for the May 29 earthquake. At that time, we did not consider our sample to be statistically significative. Now, in light of the Petrinja results. we decided to revisit those data. Therefore, following the procedure described in Section 4, we screened the questionnaires and assigned an intensity value to each questionnaire using the method described in Ref. [65].

The map of the collected questionnaires (Fig. 11a and b) shows sufficient coverage of the city centre while the outlying areas are under-sampled, especially for the second event. The theoretical intensities I_{IPE} are reported in Table 1.

Considering that the two events originated in the same area and have a very similar source mechanism, using the GIS procedure described in the previous section for the Petrinja case, we created a cumulative map of the macroseismic impact of the 2012 May 20 and 29 , events to improve the coverage and statistics of the collected data (Fig. 12). As in the case of the 2020 Petrinja earthquake, it can be noted that the part of the city facing the sea and founded on soft soils experienced an amplification of the earthquake impacts with respect to the Karst city area, placed on a rocky terrain.

The consistency of the collected macroseismic data was checked using the residuals computed for the three earthquakes in the common 500-m ray cells (Fig. 13). The three events share only 133 cells; for each common cell, we averaged the three smoothed

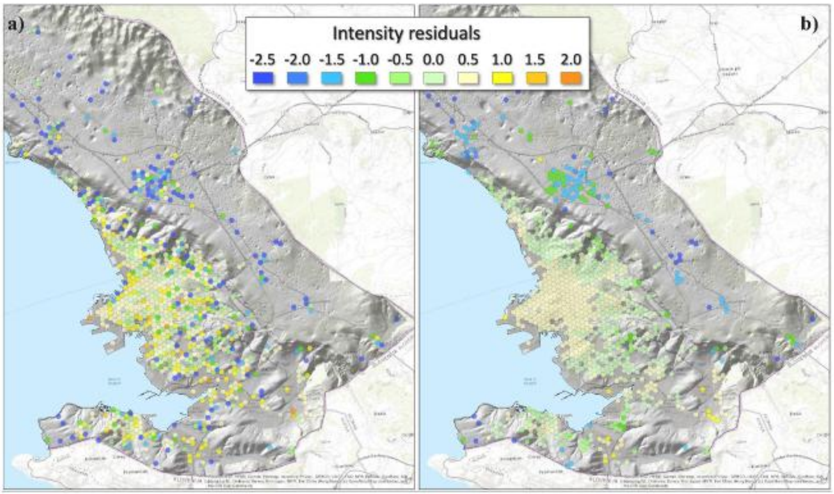

Fig. 7. a) Map of the macroseismic intensity residuals (MCS) in Trieste of the 2020 Petrinja earthquake; **b)** smoothed intensity residuals map.

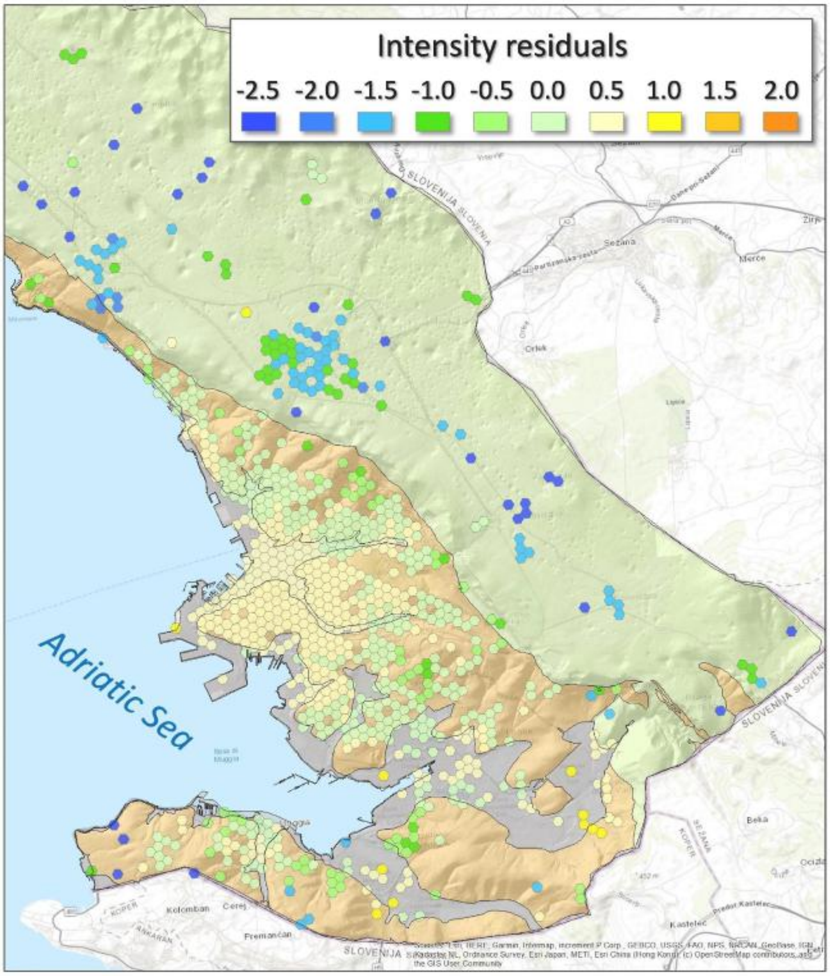

Fig. 8. Smoothed residual map overlaid with the seismic soil classification of the study area from Ref. [58]. Background colours are the same as in Fig. 3: light green for rock, light brown for stiff, and light grey for soft soils.

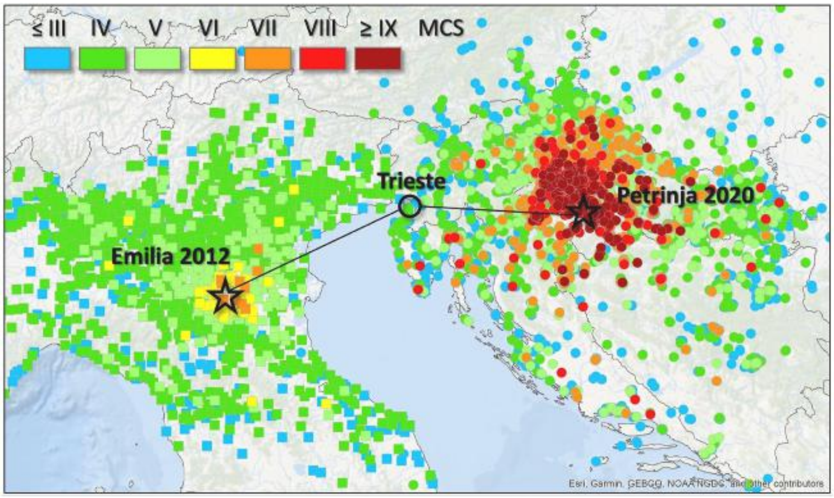

Fig. 9. Map showing the location of Trieste in relation to the 2020 Petrinja earthquake (215 km away) and the 2012 Emilia earthquake (190 km away). Intensity data are retrieved from the EMSC (circles) for the 2020 Petrinja earthquake and the HSIT (squares) questionnaires for the 2012 May 20 Emilia earthquake.

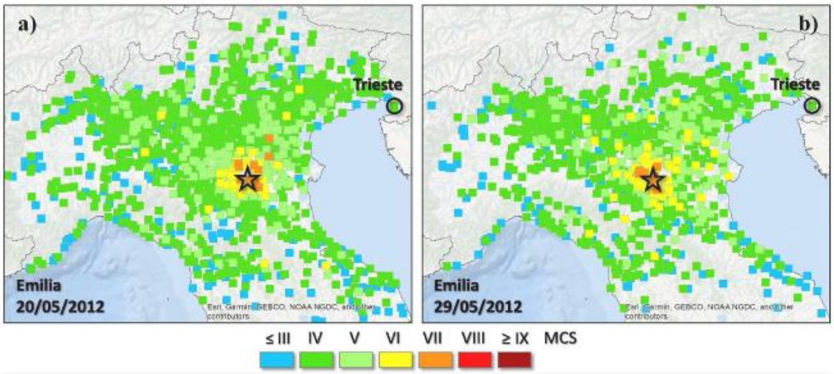

Fig. 10. Spatial distribution of macroseismic intensities (MCS) for **a)** 2012 May 20 Emilia (M_L 5.9) earthquake and **b)** for 2012 May 29 earthquake (M_L 5.8). The intensity data are from the HSIT (squares) questionnaires.

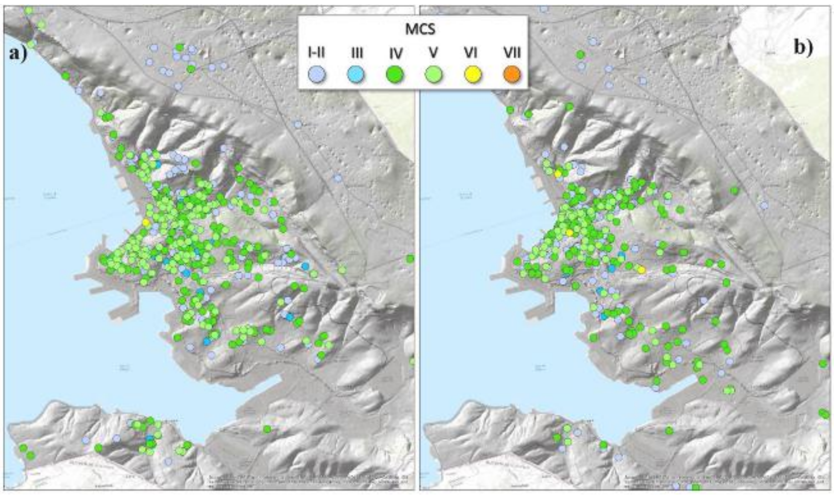

Fig. 11. Spatial distribution of macroseismic intensities (MCS) obtained from **a)** 587 questionnaires for the 2012 May 20 earthquake and **b)** 462 questionnaires for the 2012 May 29 earthquake collected in Trieste.

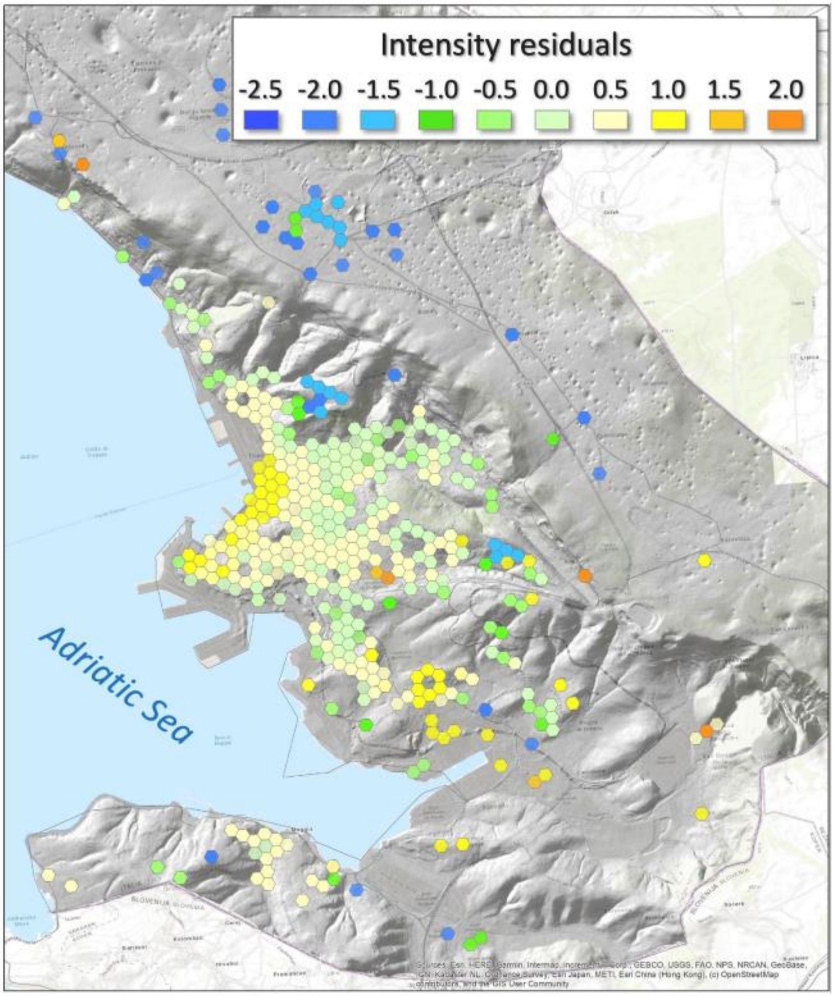

Fig. 12. - Map of the cumulative smoothed intensity residuals from the Trieste questionnaires obtained for the two Emilia events of 2012 May 20 and 29.

event residuals and the related uncertainties. The obtained values, grouped according to the seismic soil classification of Fig. 3, show good agreement with a mean value of the residuals of −1.85 for rocky sites, + 0.042 for stiff soils, and + 0.17 for soft soils (Fig. 13). The large uncertainty in some cases corresponds with a low number of questionaries in the cell.

7. Discussion

The macroseismic effects reported in the questionnaires match quite well with the expected seismic response of the main soil types of Trieste. Our investigation stemmed from idea to derive very local site effects from citizens' felt shaking. Although the number of questionnaires received for the 2020 Petrinja earthquake was large, the sample in the area was not dense enough and not evenly distributed to adequately capture specific effects that were not already expected based on the state of knowledge. In addition, we did not collect information on building typology because this information is not well known by most citizens. In fact, the building typology and type of constructive material in Trieste is a mixture of styles, from Classicism to Neoclassicism and Art Nouveau, with many examples of Gothic and Renaissance, Rationalism, Socialist Realism, and modern architectural styles [78]. Most older buildings, especially from the Middle Ages and the Renaissance, were constructed from local quarries, while brick and concrete were mainly used for residential buildings after the 19th century. As we found in the 2012 Emilia earthquake questionnaires, most respondents did not provide information on building materials or provided uncertain answers.

However, the results of the macroseismic impact analysis reported for the Petrinja earthquake could not be obtained for the 2012 Emilia earthquakes, because of the low citizen participation and the resulting in a small sample size in the urban area. The low participation in 2012 can be attributed to the lack of engagement in social media, which was less viral than today, but another important factor is undoubtedly the timing at which we acted in 2020 compared to 2012. After the 2012 May 20 earthquake, when we knew that many people in Trieste had felt the quake, it took us about three days to create the questionnaire, publish it on a page hosted on the OGS website, distribute the link by email to colleagues and friends, and publicize the initiative in the local media. Thus, data collection began a few days after the earthquake and slowly increased over eight days (Fig. 14a).

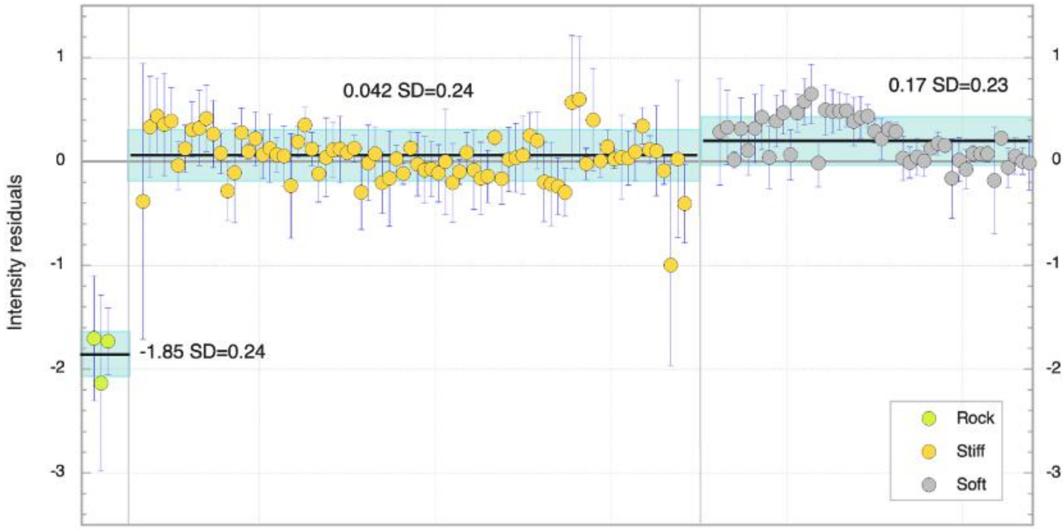

Fig. 13. - Intensity residuals for the 133 common cells of the 2012 May 20 and 29 Emilia, and 2020 December 29 Petrinja earthquakes. The cells are grouped following the reference soil (rock, stiff, and soft). The black lines indicate the average values for the three different soils. The pale blue shading represents the Standard Deviation (SD) of the average values.

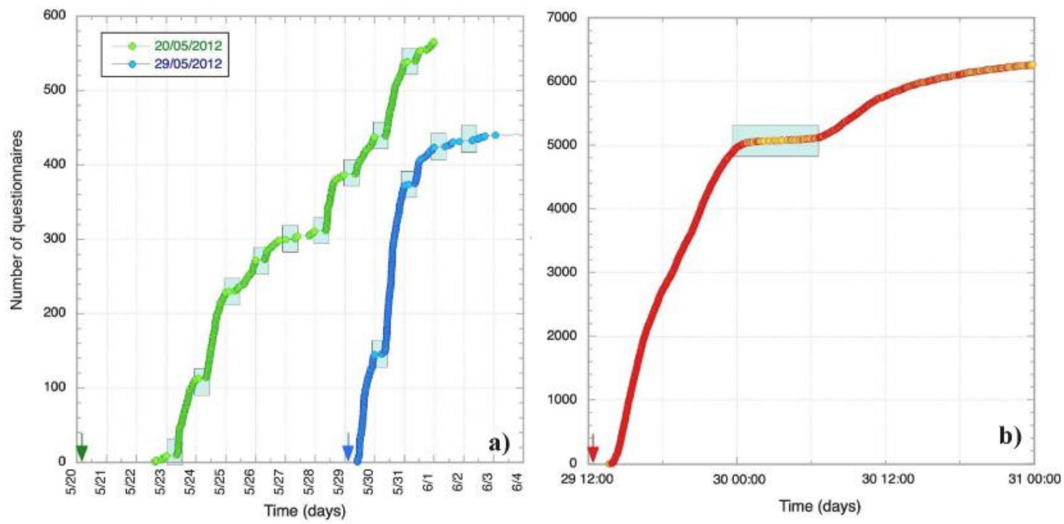

Fig. 14. Number of collected questionnaires vs time for **a)** the 2012 May 20 (green circles and line) and May 29 (blue circles and line) Emilia earthquakes and **b)** the 2020 29 December Petrinja earthquake. The arrows indicate the origin time of the events. The pale blue boxes indicate the night hours.

On May 29, the questionnaire was promptly resent, but the hoped-for higher participation did not materialize, probably because people were tired of repeating the same process twice in a short time. The time course of the responses is much steeper (Fig. 14a) than the May 20 curve, indicating a quick response from the population, but the number of questionnaires collected (462) was lower than that of May 20 (587), and the responses stopped over the next four days. Analysis of the responses also suggests that many confused the effects of one with those of the other. For the Petrinja earthquake of December 29, 2020, the questionnaire was distributed through social networks a few hours after the earthquake - because it was ready thanks to the December 28 M_W 5.2 foreshock that prompted us to prepare a questionnaire to be ready for the next occasion - and 5000 questionnaires were collected by midnight of the same day (Fig. 14b).

The experience gained during the three earthquakes shows that the timely engagement of people is of utmost importance. It is well known that during an earthquake, the efficiency of communication and active participation of the population is highest in the emotional phase after the catastrophic event. Once some time has passed, people no longer feel like talking or hearing about earthquake-related facts (e.g., Refs. [79–81].

We are aware of the limitations of this type of project, that lie in the online questionnaires themselves. The quality and accuracy of the data collected can be affected by factors such as the wording and structure of the questions, the extent to which respondents accurately remember and report on their experiences, response bias, incomplete responses, and the subjective nature of intensity estimates. Also, the absence of responses from inhabited areas where the earthquake was either not felt at all or only very weakly felt (e.g., the Karst area in our study), may bias the interpretation of the felt zone. The use of online questionnaires and social media may exclude certain populations that do not have access to the Internet, are not engaged with social media, or modern phone apps, or are simply not interested in such topics. Proactivity in earthquake reporting is influenced by many factors, particularly income, age, and education level [33,82,83,83]. Therefore, the sample of respondents may not be representative of the earthquake-affected population in terms of age, gender, education, and literacy. Consideration of all these aspects is paramount to ensure the reliability of results and interpretations.

However, our work is also an example of how to actively engage the public in earthquake issues and raise public awareness (e.g. [84], [85].Over the past two decades, earthquake risk communication in Europe has increasingly relied on social media to provide timely and actionable information in times of crisis and to engage citizens in the pre-crisis period, thereby increasing awareness and preparedness [81]. Engaging the people in reporting about felt earthquakes focuses their attention to earthquake related facts and the damage they cause or could cause and possibly to check or invest in seismic safety for their properties.

8. Conclusions

Seismic risk reduction is primarily achieved by raising public awareness. In this paper, we provide an example of how social media can be used to raise public awareness and involve people in seismic risk mitigation issues. Social media and smartphone apps have enhanced seismic risk communication and crowdsourcing of seismic data. This allows scientists to gather a wealth of information that can contribute to a better understanding of earthquakes and the underlying geological and geophysical processes. In this study, we analyzed the macroseismic effects of the December 29, 2020, Petrinia earthquake in Trieste to characterize its main geological features. The results of our study, which was possible thanks to the massive participation of citizens, confirm that crowdsourcing data if properly analyzed, can help improve knowledge about geology, for example, in areas where it is completely lacking, or complement existing information and address preliminary microzonation studies. Social media has greatly facilitated the dissemination of the initiative and the collection of data. A comparison with a similar project we led in 2012 shows how computer literacy, social networks, and the popularity of smartphones can influence the results and open new scenarios for a better understanding of seismic hazards and improving earthquake preparedness through citizen participation. Therefore, despite the limitations of such an approach, we believe that the lessons learned can provide useful guidance to further improve knowledge through the online acquisition of macroseismic data.

Authors contribution

A.S.: conceptualization, validation, data curation, data analysis, investigation, draft writing, supervision. A.T.: GIS data analysis, visualization. D.Sa.: data acquisition; investigation. D.Sl.: supervision. A.R.: conceptualization, data curation, visualization, funding resources, supervision. All authors contributed to the revision of the manuscript, read, and approved the submitted version.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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