



How Many Rainfall-Induced Landslides Are Detectable by a Regional Seismic Monitoring Network?

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Abstract

Mass wasting events occurring on the Earth's surface may induce seismic signals, which can be recorded also at tens of kilometers from the source area. The waveforms relevant to mass wasting differ from those caused by earthquakes, because they are usually characterized by a cigar shaped waveform, duration of several tens of seconds, and low frequencies (1–10 Hz). In literature, no studies have performed a systematic analysis on comprehensive catalogues of rainfall induced landslide records at regional scale. In this work, we analyze the seismic waveforms of 1058 landslides induced by rainfall in Italy, spanning the period between 2000 and 2014. Seismic data are gathered by several European research infrastructures and collected in the European Integrated Data Archive of the Observatories and Research Facilities for European Seismology. We present preliminary results obtained from this large effort, as well as some first statistical considerations on the rainfall-triggered landslides identified within seismic records. Such analyses may provide important insights for the development and calibration of automatic landslide identification algorithms, which might be then used to verify the validity of landslide forecasting procedures based on rainfall thresholds, as well as to enhance the catalogues completeness by exploiting quantitative measures and relying not only on chronicle information.

Keywords

Landslide • Rainfall • Seismic signal • Waveform • Italy

Introduction

Seismic techniques are increasingly adopted to detect signals induced by mass movements and to quantitatively evaluate geo-hydrological hazards at different spatial and temporal

scales. By analyzing landslide-induced seismicity, it is possible obtaining significant information on the source of the mass wasting, as well as on its dynamics. Site-specific monitoring systems of active channels (e.g., Coviello et al. 2015), large landslides (e.g., Helmstetter and Garambois 2010), or instable slopes (e.g., Amitrano et al. 2005) often

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integrate, among several monitoring devices, a ground vibration detector array.

Recent studies show that regional seismic networks may reveal ground vibrations caused by large mass wasting phenomena occurring at significant distance (e.g., Burtin et al. 2016; Coe et al. 2016; Hibert et al. 2015). When those signals are detected with broadband seismometers, the seismic inversion and the spectral analysis may allow the characterization of the phenomenon. A method was recently proposed for the near real-time detection, location, and characterization of landslides, by considering data acquired from regional seismic networks (Manconi et al. 2016).

In the literature, some examples of seismic signals relevant to landslide phenomena have been reported and discussed, mainly related to single events ranging from rock-falls, rockslides and rock avalanches, as well as debris- and earth flows (to cite a few: Weichert et al. 1994, in Canada; Berrocal et al. 1978, in Peru; La Rocca et al. 2004, in Italy; Uhrhammer 1996, in USA). However, few studies have focused on larger landslide datasets. Norris (1994) analyzed seismograms due to 14 rock falls and rock avalanches of moderate to large volumes ($104\text{--}107\text{ m}^3$) at Mount St. Helens, Mount Adams and Mount Rainier in the Cascade Range, North America. They found a consistent increase in seismogram amplitude with the volume of rock falls at Mount St. Helens and concluded stressing the importance of seismic networks for detecting large mass movements.

McSaveney (2002) reviewed several seismograms recorded during rock falls and rock avalanches occurred in 1991 and 1996 in Mount Cook National Park (New Zealand), from station at distances between 31 and 190 km. He defined an estimation of rock fall duration but did not provide any information about rock fall geometric properties or quantitative distribution of mass collapse over time.

Deparis et al. (2008) analyzed 10 rock-fall events recorded between 1992 and 2001 by the permanent seismological network Sismalp in the French Alps. They found a correlation between the signal duration at an epicentral distance of 30 km and the potential energy and the run out distance of the events. No clear relation between rock-fall parameters (fall height, run out distance, volume, potential energy) and seismic magnitudes was found. From the analysis of the seismic signals, they identified two distinct seismic sources: one corresponding to the initial rupture during the detachment and the other one generated by the rock impact on the slope.

Dammeier et al. (2011) assembled a dataset of 20 rockslides that occurred in the Swiss Alps (with volumes

between 1000 and $2,000,000\text{ m}^3$) and analyzed their corresponding seismograms. They observed that the main component of seismic energy is generally contained in frequencies below $\sim 3\text{--}4\text{ Hz}$, while higher-frequency signals may be caused by block impacts. Furthermore, they proposed for the employed seismic network a linear relationship for the detection limit of a rockslide as a function of volume.

Hammer et al. (2013) proposed an automatic classification system, based on a stochastic classifier, for the recognition of different types of waveforms, even associated to very rare events. They applied the proposed tool to a data set of waveforms recorded on the Swiss Seismological Service (SED) network. The data set contains 159 earthquakes, 3 rock falls, 46 quarry blasts (an event detection was raised if at least 4 stations were triggered), and was pre-classified by the classification routine currently carried out at SED. Using data recorded from 2002 to 2010 at only one station for the calibration of the model, they detected and classified correctly 97 and 87% of the events, respectively.

De Santis et al. (2016) selected 18 well known mass movements occurred in the Italian Alps, characterized by volumes ranging between 25,000 and $34,000,000$ cubic meters and different failure dynamics, and 10 of those events showed a seismic waveform that can be attributed to the corresponding landslide. They analyzed waveforms recorded by seismic stations located, on average, 50 km away from the sources, focusing the study on the $1\text{--}30\text{ Hz}$ frequency band. The time and frequency domain analysis allowed identifying some common signal characteristics, including emergent onsets, slowly decaying tails and a triangular spectrogram shape.

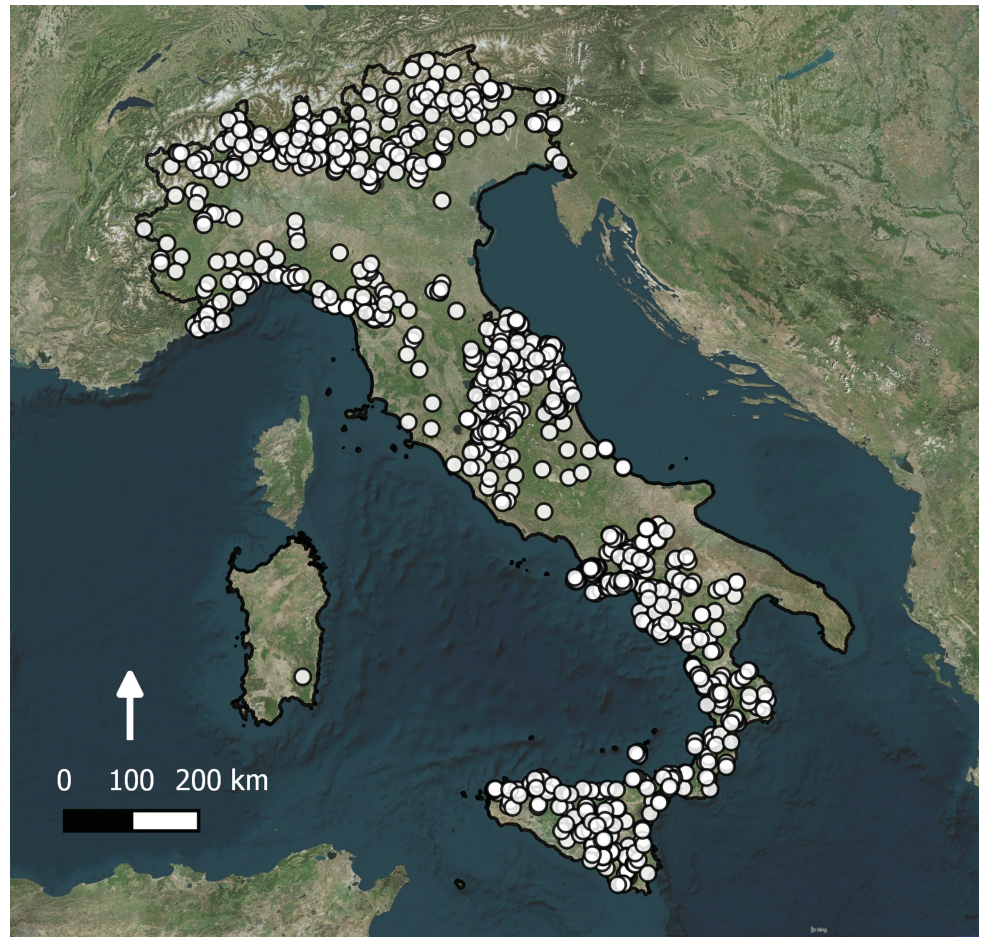
No studies have performed a systematic back analysis on large, comprehensive catalogues of rainfall induced landslide records at regional or national scale. Here we present preliminary results obtained from a deep investigation of a national catalogue of rainfall-induced landslides, as well as some statistical considerations on the rainfall-triggered landslides identified within seismic records.

Materials and Methods

Landslide Data

We analyzed the seismic waveforms of 1058 landslides induced by rainfall in Italy. Figure 1 shows the location of the landslides in the Italian peninsula. This is a subset of a larger catalogue of 2408 landslides collected by the Italian

Fig. 1 Map showing the distribution of the 1058 analyzed rainfall-induced landslides (*white dots*). Background image from Bing Aerial



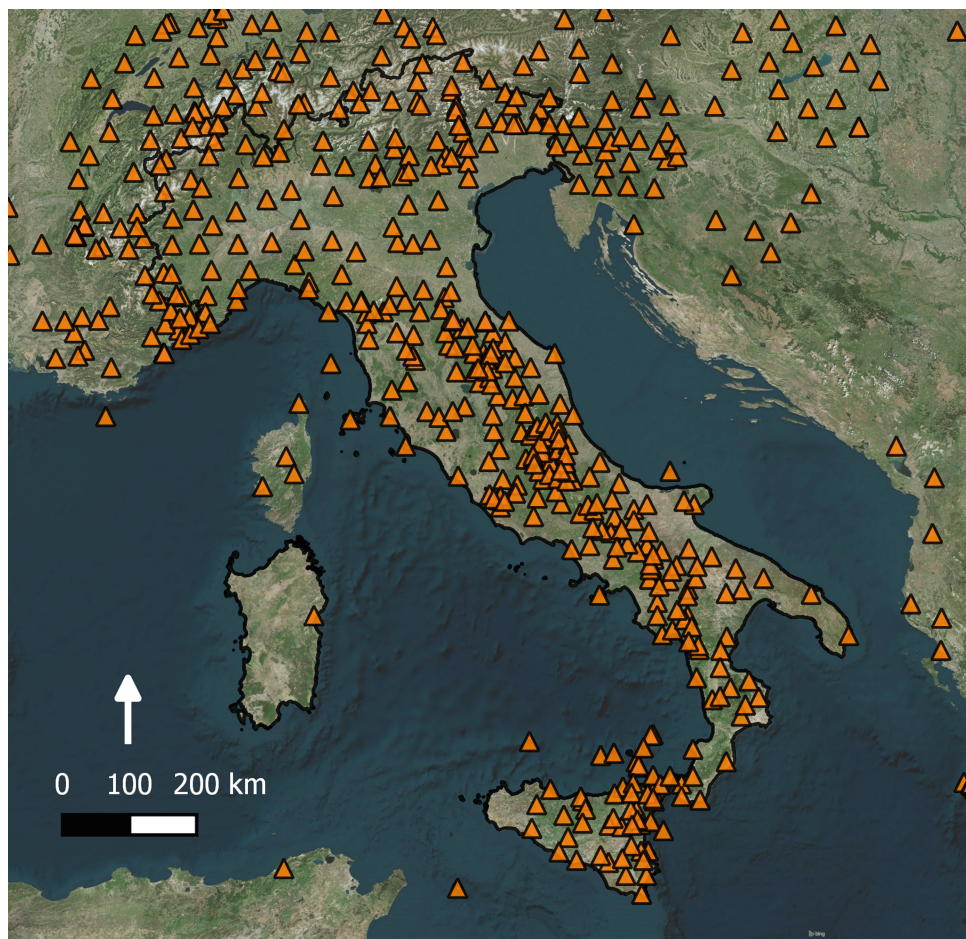
research institute for geo-hydrological protection during the period 2000–2014 (CNR-IRPI, cf. Brunetti et al. 2015). This catalogue was compiled by relying mainly on newspaper chronicle and on information gathered from reports made by local authorities. We have to underline that this catalogue is one of the largest available landslide catalogue worldwide. However, it is mainly populated by small-to-medium size events that affected populated areas or communication routes, as a consequence we cannot consider it as complete. For each record, the following information are reported: the type of landslide; the geographical location of the landslide (coordinates, site, municipality, province, and 3 classes of geographic accuracy); the temporal information on the landslide occurrence (day, month, year, time, date, and 3 classes of temporal accuracy); the rainfall conditions (rainfall duration and cumulated event rainfall) that have resulted in the landslide. In particular, the classes of temporal accuracy assigned to each landslide are (Gariano et al. 2012):

high, when the hour of occurrence of the failure was known; intermediate, when the period of the day (e.g., morning, midday, afternoon, evening, night) was known; low, when only the day of occurrence was known. We considered herein only 1058 rainfall-induced landslides with high temporal accuracy, for which exact date and time was known from chronicle information. Among these phenomena, there are 234 rock falls, 55 debris flows, 54 mud flows, and 715 unspecified shallow landslides. Most of the landslides (670, 63%) occurred between November and March.

Seismic Data

Seismic data are gathered by leveraging the European Integrated Data Archive (EIDA) of the Observatories and Research Facilities for European Seismology (ORFEUS). This platform collects data made available from the

Fig. 2 Map of the adopted seismic monitoring EIDA network (orange triangles). Background image from Bing Aerial



European research infrastructures (e.g., Istituto Nazionale di Geofisica e Vulcanologia, INGV, in Italy, Swiss Seismological Service, SED, in Switzerland). Figure 2 shows the location of the seismic stations available for our study area. We analyzed seismic signals recorded in an area up to 100 km^2 from each landslide location reported in the catalogue. On average, 28 seismic stations were located in this selected buffer, with a minimum (maximum) value of 18 (39) for each considered landslide event.

Results

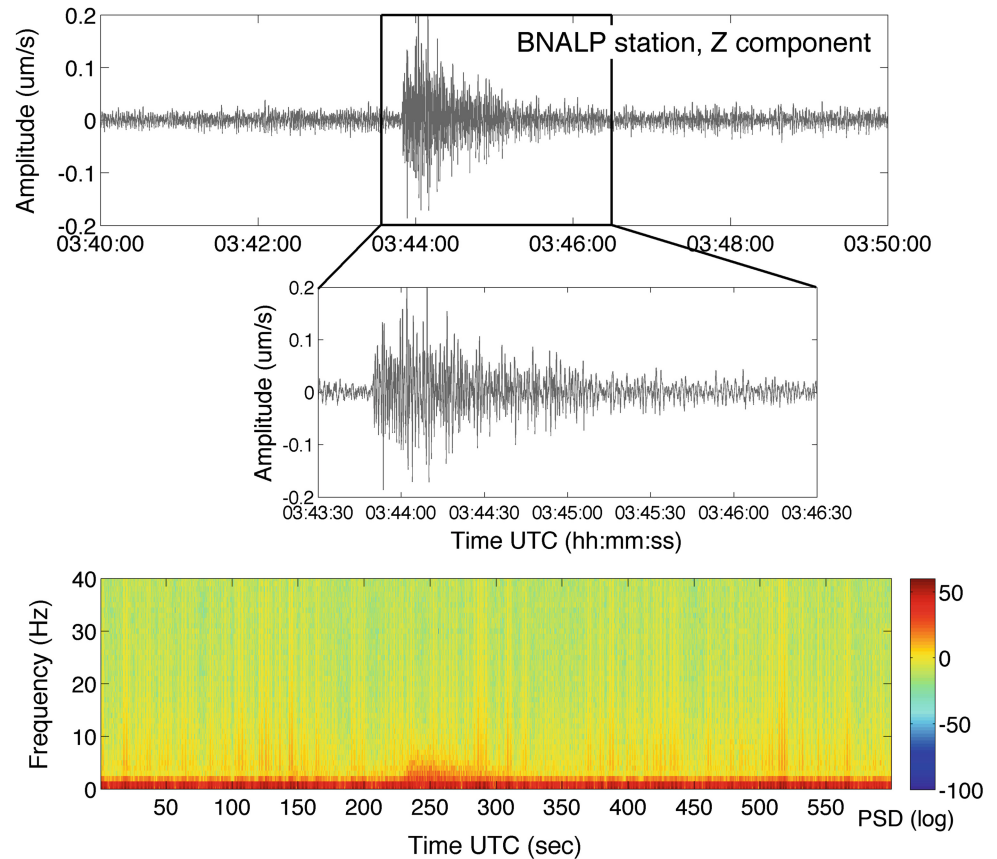
Detected Seismic Signal

We selected from the catalogue landslides events for which we had detailed temporal information. We focused on waveforms

related to mass wasting, which differ from those caused by earthquakes as they are usually characterized by a “cigar shape”, emerging onsets, duration of several tens of seconds, and low frequencies (1–10 Hz). An example of such a signal, most likely related to a landslide occurred in Lombardia region is reported in Fig. 3. Furthermore, an example of a signal related to a local earthquake, occurred in Calabria region, is reported in Fig. 4. Several differences can be noted both in the amplitude and in the frequency diagrams.

For 144 landslides out of 1058 in our dataset (i.e., 14%), we identified a clear seismic signal (in at least 1 station) around the same time reported in the catalogue (Fig. 5). Among these landslides, there are: 39 rock falls, 11 debris flows, 11 mud flows, 4 earth flows, and 79 unspecified shallow landslides. We identified a seismic signal possibly related to the landslides in 99 stations, belonging to the following 7 networks: Swiss Seismological Network (CH),

Fig. 3 Example of a seismic signal likely induced by the landslide occurred at Taleggio (BG, Lombardia region) on October 24, 2006. Signal recorded at “BNALP” station, Switzerland (SED network). In the *top panel*, the raw signal; in the *zoom*, the 1–5 Hz filtered signal; in the *bottom panel*, the spectrogram



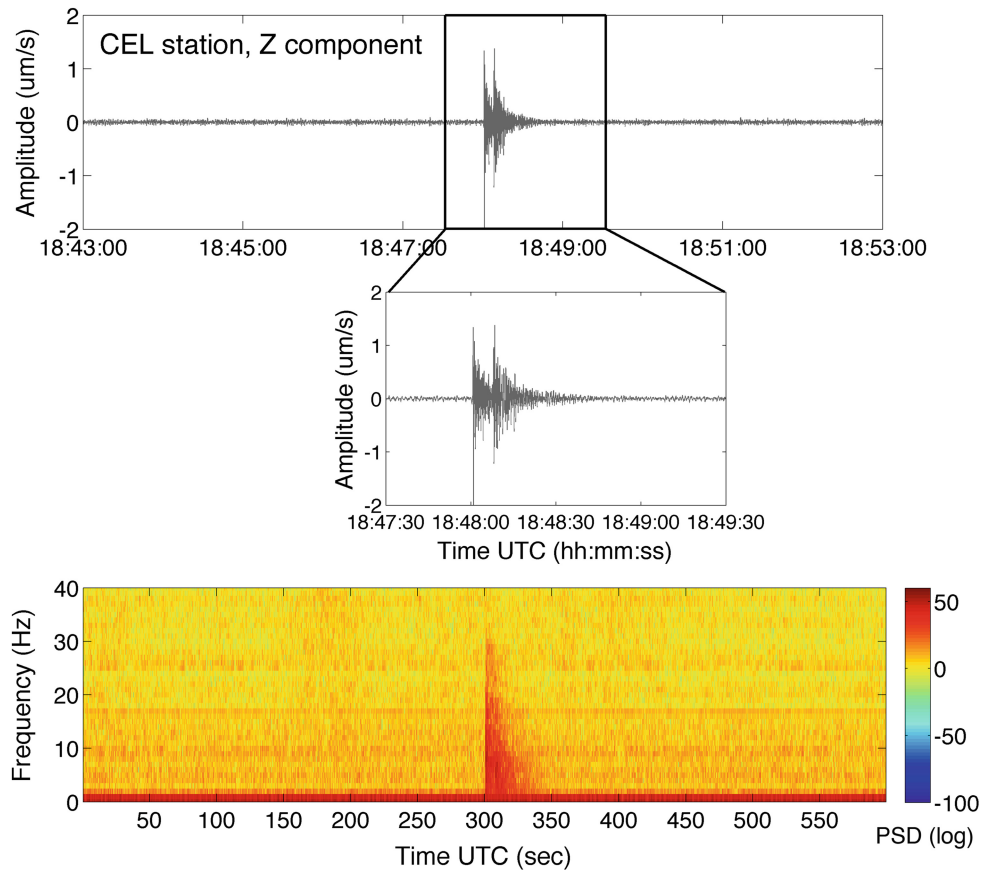
Switzerland; GEOFON Program (GE), GFZ Postam, Germany; IGG Seismic Network (GU), Genova, Italy; Italian Seismic Network (IV), Italy; MEDNET Project (MN), Roma, Italy; North-East Italy Broad Band Network (NI), Italy; Sudtiro network (SI), Italy. Table 1 reports the number of rainfall-induced landslides for which a seismic signal was recognized, in each of the 20 administrative Italian regions.

Then, to reduce uncertainty, we focused on signals detected by at least 3 stations. The identification of possible sources different from anthropic disturbances using signals recorded by only 1 station is tricky and can be misleading. We identified a signal in at least 3 station for 64 landslides (6% of the total dataset), classified as follows: 16 rock falls, 8 debris flows, 6 mud flows, and 34 unspecified shallow landslides. Among them, we identified: 20 local earthquakes (characterized by a waveform similar to that reported in

Fig. 4) and 2 teleseismic waveforms that produced the recorded signals coeval to the occurrence of a landslide reported in the catalogue (green dots in Fig. 5); 10 anomalous seismic signals characterized by irregular and impulsive waveforms in both time and frequency domain (blue dots in Fig. 5); 32 waveform characterized by a cigar shaped waveform, emerging onsets, duration of several tens of seconds, and low frequencies (1–10 Hz) (red dots in Fig. 5). These latter signals are likely related to the landslides reported in the catalogue.

To further validate the results, we tested on this dataset the methodology proposed by Manconi et al. (2016) for landslide/local earthquake classification in the Alpine region. They mapped the differences between earthquake and landslide waveforms into a peculiar difference between local magnitudes (M_L) and duration magnitudes (M_D). We have adopted here the relationships used by the Italian

Fig. 4 Same as Fig. 3 but for a seismic signal induced by a local earthquake occurred on August, 2, 2010 at Vibo Valentia (Calabria region)



Seismological Instrumental and Parametric Data-Base (ISIDe, <http://iside.rm.ingv.it>) for the Italian territory, in the form:

$$M_L = \log_{10}(A) + 1.110 \log_{10}(R) + 0.00189(R) + 3.591 \quad (1)$$

$$M_D = 2 \log_{10} \tau + 0.082(R) - 0.87, \quad (2)$$

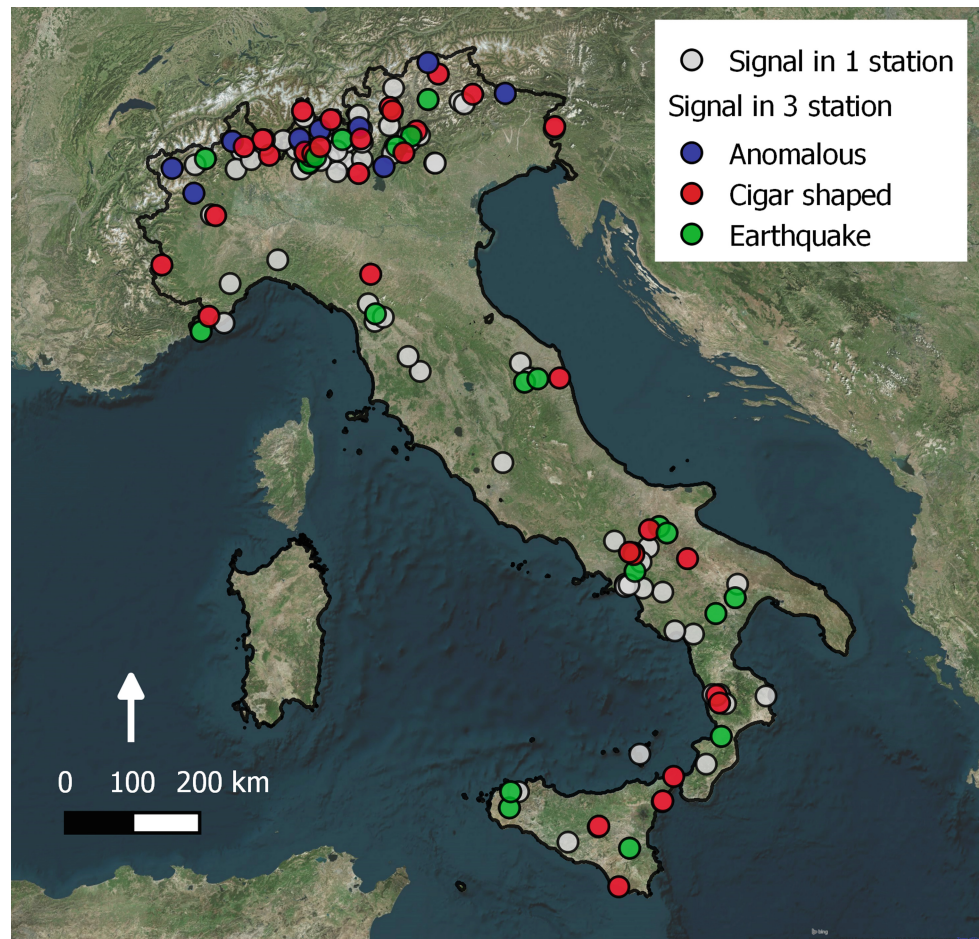
where A is half of the maximum recorded amplitude (in m), R is the distance between the hypocenter and the station (in km), and τ the signal duration. The calibration of M_L and M_D relationships for earthquake monitoring within a specific geographic area is based on the constraint that the two values provide very similar (possibly the same) estimate of earthquake magnitude. In the case of landslides, due to the relatively lower amplitude and longer duration of the generated signals, the ratio M_L/M_D is expected to be significantly less

than 1. This was found to be true for about half of the 32 signals mentioned above.

Discussion and Conclusions

The identification of small landslide events in seismic records is still a challenging task. Irregular network geometries and sensor heterogeneity have a significant impact on the detection of earth surface processes, as well as the typology of the investigated phenomenon. We know that not only giant landslides (e.g., see Ekström and Stark 2013) but also medium-size rock falls that directly impact on the bottom of the cliff, after a free-fall of hundreds of meters, can be detected at thousands of kilometers (e.g., the Aiguille Dru rockfall that occurred on June 30, 2005, see Dammeier et al. 2011). It is also well known that the intensity of ground vibrations produced

Fig. 5 Map showing the distribution of the 64 landslides for which the seismic signal was recognized in at least 3 stations. Among those, there are: 10 anomalous seismic signals (*blue dots*), 32 cigar shaped waveforms (*red dots*), and 22 earthquake signals (*green dots*). Moreover, 80 landslides for which the signal was identified in only one station are also reported (*light grey dots*). Background image from Bing Aerial



by debris flows diminishes with distance from the torrent bed following an inverse-square law due to geometric spreading of seismic waves; however, specific site conditions or flow characteristics may lead to different attenuation levels (Coviello et al. 2015; Burtin et al. 2016). For landslide events with a main fluid component, such as mud- and debris-flows, the dissipation of kinetic energy is predominant on the propagation as seismic energy. Therefore, for these phenomena the source-receiver distance plays a fundamental role as the signal damping is stronger than in case of falls and avalanches with comparable volumes (De Santis et al. 2016).

The results of our research show that also very small landslide events triggered by rainfall events can be recorded by broadband seismic stations. Our analysis may provide important insights for the development and calibration of automatic landslide identification algorithms, which might be then used (i) to verify the validity of landslide forecasting procedures based on rainfall thresholds, (ii) to enhance the catalogues completeness by exploiting quantitative measures and relying not only on chronicle information, and (iii) to provide additional quantitative details of the landslide events.

Table 1 Number of rainfall-induced landslides for which a seismic signal was recognized in at least one station, per region

Region	Number of landslides
Abruzzo	0 (0) [0]
Basilicata	5 (3) [1]
Calabria	8 (3) [2]
Campania	14 (4) [2]
Emilia-Romagna	1 (1) [1]
Friuli Venezia-Giulia	3 (2) [1]
Lazio	1 (0) [0]
Liguria	5 (2) [1]
Lombardia	47 (17) [9]
Marche	5 (3) [1]
Molise	0 (0) [0]
Piemonte	10 (6) [4]
Puglia	3 (3) [1]
Sardegna	0 (0) [0]
Sicilia	12 (7) [4]
Trentino-Alto Adige	16 (9) [5]
Toscana	6 (1) [0]
Umbria	0 (0) [0]
Valle d'Aosta	3 (2) [0]
Veneto	5 (1) [1]

Round brackets, landslides with a signal in at least 3 stations. In square brackets, landslides with a cigar shaped signal

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