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Earthquake-induced ground failures in Italy from a reviewed database

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Abstract. A database (Italian acronym CEDIT) of earthquake-induced ground failures in Italy is presented, and the related content is analysed. The catalogue collects data regarding landslides, liquefaction, ground cracks, surface faulting and ground changes triggered by earthquakes of Mercalli epicentral intensity 8 or greater that occurred in the last millennium in Italy. As of January 2013, the CEDIT database has been available online for public use (http://www.ceri.uniroma1.it/cn/gis.jsp) and is presently hosted by the website of the Research Centre for Geological Risks (CERI) of the Sapienza University of Rome.

Summary statistics of the database content indicate that 14 % of the Italian municipalities have experienced at least one earthquake-induced ground failure and that landslides are the most common ground effects (approximately 45 %), followed by ground cracks (32 %) and liquefaction (18 %). The relationships between ground effects and earthquake parameters such as seismic source energy (earthquake magnitude and epicentral intensity), local conditions (site intensity) and source-to-site distances are also analysed. The analysis indicates that liquefaction, surface faulting and ground changes are much more dependent on the earthquake source energy (i.e. magnitude) than landslides and ground cracks. In contrast, the latter effects are triggered at lower site intensities and greater epicentral distances than the other environmental effects.

1 Introduction

The recent strong earthquakes in Sumatra (2004, $M_\mathrm{w} = 9.1$), eastern Sichuan (China 2008, $M_\mathrm{w} = 7.9$) and Tōhoku (Japan 2011, $M_\mathrm{w} = 9.0$) have highlighted that earthquake-induced ground effects (e.g. tsunamis, landslides and liquefaction) can be responsible for major damage and losses, and represent a significant seismic-activity-related hazard (Bird and Bommer, 2004). Such effects can also affect localities tens or hundreds of kilometres distant from the earthquake epicentre, thus increasing the risk related to the earthquake shaking itself (Keefer, 1984; Rodriguez et al., 1999; Delgado et al., 2011; Jibson and Harp, 2012).

In this context, recording and analysing earthquake-induced ground failures is a relevant contribution to seismic risk mitigation for the purposes of understanding the triggering processes and for identifying areas that might be damaged by future seismic events.

Several studies have been conducted worldwide during the last few decades that report on ground failures triggered by earthquakes (Bommer and Rodriguez, 2002; Sepulveda et al., 2005; Porfido et al., 2007; Tosatti et al., 2008; Gorum et al., 2011; Tang et al., 2011; Alfaro et al., 2012; among many others) and that forecast, using predictive models, the distribution scenarios of earthquake-induced ground effects (Sassa et al., 1996; Jibson et al., 2000; Prestininzi and Romeo, 2000; Romeo, 2000; Jibson, 2007; Hsieh and Lee, 2011; among others). These studies provide inventory maps of the effects that have occurred or susceptibility maps of expected ground failures. Nevertheless, systematic inventories of historically documented earthquake-induced effects have rarely

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been produced until recently. A pioneering study in this field was that by Youd and Hoose (1978) who documented approximately 350 localities affected by ground failures (landslides, lateral spreads, ground settlement and surface cracks) in 46 earthquakes that occurred in Northern California between 1800 and 1970, the most documented one being the devastating 1906 San Francisco $M = 8.3$ earthquake. However, until now the majority of information regarding the ground failures triggered by earthquakes is usually not organised as individual catalogues, but included in conventional earthquake catalogues with the purpose to provide further constraints for the assignment of site intensity alone.

The Euro-Mediterranean Earthquake Catalogue (EMEC – Grünthal and Wahlström, 2012) represents the most updated version of the European inventory of earthquakes and related effects, although it does not include a consulting tool for earthquake-induced ground failures or other environmental effects. Similarly, the United States Geological Survey (USGS) composite catalogue PAGER-CAT (Allen et al., 2009), which contains reports of earthquake casualties and losses from the Preliminary Determination of Epicentres (PDE; NEIC, 1970; Sipkin et al., 2000), the Utsu catalogue of deadly earthquakes (Utsu, 2002) and the Emergency Events Database (EM-DAT) developed and maintained by the Centre for Research on the Epidemiology of Disasters at the University of Louvain, Belgium (Hoyois et al., 2007), do not include a direct listing of ground failures even if secondary effects, such as tsunamis, landslides, fires and liquefaction, are also reported in the earthquake record. An original feature of the latter catalogue is that when deaths are caused by these secondary effects, the related information is disaggregated with respect to recorded total deaths.

The current trend is to use the power of the internet to upgrade the existing global databases of environmental effects and to use the collected data to enrich the existing catalogues that were previously created using historical documents or reports. Currently, this modern upgrade process is being applied to several global databases (Petley et al. 2005; Kirschbaum et al., 2010) that are available online and are associated with public-access internet sites that provide map viewer systems linked to geo-databases. Examples include the National Aeronautics and Space Administration (NASA: http://gcmd.nasa.gov/), National Oceanic and Atmospheric Administration (NOAA: http://maps.ngdc.noaa.gov/viewers/) and American Geophysical Union (AGU: http://blogs.agu.org/blogs/) inventory projects, which are available at their respective web sites.

In addition to the many recent seismic events in Italy that have demonstrated the relevance of ground failures in total earthquake damage (e.g. 1976 Friuli $M_\mathrm{w} = 6.4$; 1980 Irpinia $M_\mathrm{w} = 6.9$; 1997 Umbria-Marche $M_\mathrm{w} = 6.0$; 2009 L'Aquila $M_\mathrm{w} = 6.2$), the last strong Italian earthquake, in May 2012 in Emilia ($M_\mathrm{w} = 6.0$), proved that earthquake-induced ground effects can pose a risk as severe as the earthquake shaking itself (Romeo, 2012).

Over the last decade, many Italian earthquake catalogues containing reported seismic effects (mainly structural and secondarily environmental) have been published online (e.g. CFTI – ING 1995; NT4.1 – Camassi and Stucchi, 1997; DBMI04 – Stucchi et al., 2007; CPTI04 – Gruppo di lavoro CPTI, 2004; ITC 2.0 – Tinti et al., 2007; CPTI11 – Rovida et al., 2011). Nevertheless, apart from the tsunamis that are listed in the specific ITC catalogue, other environmental effects cannot be directly found from consulting these catalogues. At the end of the 1990s, Delfino and Romeo (1997) published on the internet the first Italian Catalogue of Earthquake-Induced Ground Failures (the previous release of CEDIT), in which different typologies of ground effects were reported (i.e. landslides, ground cracks, surface faulting, liquefaction and ground changes) over a period of approximately one millennium, from 1000 to 1984. These effects were further divided into sub-categories, based on landform features or kinematic mechanisms, and information on the involved rocks was also reported. The database structure consisted of tables linked to each other to facilitate consulting and querying, but no visual representation tools were provided.

Presently, the Institute for Environmental Protection and Research (ISPRA) is conducting a project aimed at producing a general catalogue of Earthquake Environmental Effects (EEE: Guerrieri et al., 2009; http://www.eeecatalog.sinanet.apat.it/terremoti/index.php), in which ground effects are categorised into primary effects representing the surface expression of the seismogenic source (e.g. surface faulting, surface uplift and subsidence and any other surface evidence of co-seismic tectonic deformation) and secondary effects (phenomena generally induced by ground shaking), which are classified into the main categories of slope movements, ground settlements, ground cracks, hydrological anomalies, anomalous water waves (including tsunamis) and other effects such as tree shaking, dust clouds, thrown stones, and others. The EEE catalogue is aimed to support the Environmental Seismic Intensity scale (ESI; Michetti et al., 2004, 2007; http://www.isprambiente.gov.it/it/progetti/inqua-scale/environmental-seismic-intensity-scale-esi-2007), set up to integrate the European Macroseismic Scale (EMS; Grünthal, 1998; http://www.gfz-potsdam.de) that does not consider any environmental effect.

The present paper discusses the new release of the CEDIT catalogue, which revises and updates the previous release (Delfino and Romeo, 1997), and discusses some features of the database content, thus updating the previous study by Prestininzi and Romeo (2000).

2 Database content and structure

The new release of the CEDIT database introduces earthquakes and related ground failures that occurred after 1984, such as the following: Umbria-Marche 1997 ($M_{\mathrm{w}} = 6.0$); Pollino 1998 ($M_{\mathrm{w}} = 5.7$); Molise ($M_{\mathrm{w}} = 5.7$) and the southern Tyrrhenian Sea ($M_{\mathrm{w}} = 5.9$), both in 2002; L'Aquila 2009 ($M_{\mathrm{w}} = 6.2$); and Emilia 2012 ($M_{\mathrm{w}} = 5.9$). The previous release included all bibliographic sources available for historical earthquakes. However, new studies that have retrieved information about some historical earthquakes, published after the first release of the catalogue, made it necessary to revise the related data. Reference was made particularly to papers referring to specific earthquakes, such as those by Porfido et al. (2007) and Serva et al. (2007) that detail the ground effects that occurred in some earthquakes in historical (Sannio 1805) and recent times (Irpinia 1930 and 1980); studies referring to specific ground phenomena, such as the catalogue of liquefaction by Galli (2000); and studies referring to specific localities where earthquakes have produced some outstanding effect (Prestininzi, 1995; Mancini et al., 2001; Martino et al., 2004; Bozzano et al., 2004, 2008, 2011).

The CEDIT database reports approximately 2000 localities where ground failures were triggered by 166 earthquakes that occurred in the last millennium in Italy for which information about the occurrence of ground effects can be retrieved from historical documents. It is worth mentioning that only the name of the localities and a generic description of the type of ground failures can be reliably retrieved from the historical sources of information, especially when they refer to very old earthquakes. Therefore, a locality affected by several ground failures is counted only once, since in many cases there is no information about the number of triggered failures.

The ground effects collected in the database fall into five main categories: landslides, ground cracks, liquefaction, surface faulting and ground changes (these last ones including among others: subsidence, relevant morphological changes due to river damming, lake formation and so on). These categories are further divided into sub-categories, specifying the type of effect, such as, for example, the landslide kinematic type. The database underlying the new release of CEDIT is organised into data sheets that contain data about earthquakes and their associated ground failures (Fortunato et al., 2012). The relational database (Fig. 1) consists of five tables: "TERREMOTI" (the Italian translation of earthquakes), "LOCALITÀ" (localities), "FRASI" (sentences), "BIBLIO" (references), and "EFFETTI" (ground failures).

Data were collected from different seismic catalogues, as shown in Fig. 1, including the CPTI04 catalogue of earthquakes (Gruppo di lavoro CPTI, 2004), the DBMI04 macroseismic catalogue (Stucchi et al., 2007), the Catalogue of Italian Tsunamis (ITC 2.0; Tinti et al., 2007) and the Database of the Italian Seismogenic Sources (DISS 3.1.1; DISS WORKING GROUP, 2010). Localities where ground failures occurred were mapped according to the WGS84 coordinates system and are identified by an administrative code assigned by the Central Institute of Statistics (ISTAT; www.istat.it/en/).

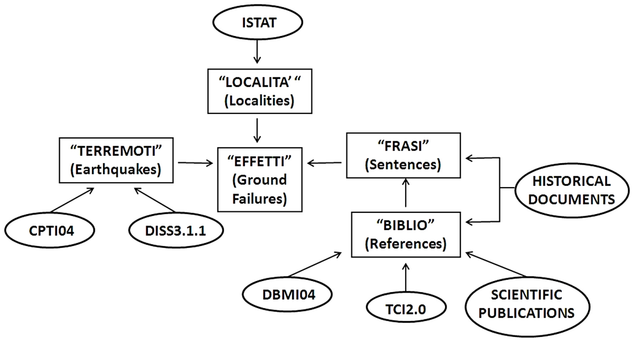

Fig. 1. Database structure of the CEDIT catalogue and links to the CPTI04 earthquake catalogue (Gruppo di lavoro CPTI, 2004), the DBMI04 macroseismic catalogue (Stucchi et al., 2007), the ITC 2.0 Italian tsunami catalogue (Tinti et al., 2007) and the DISS 3.1.1 seismic sources database (DISS Working Group, 2010).

The original descriptions gathered from the historical sources that describe the ground failures are preserved to allow for the retrieval of each effect. Moreover, to provide as much detailed information on each effect as possible, quotations from various authors about the same effect are also reported. For an improved understanding of the extent of seismically induced effects, the values of the dimensional parameters reported in the historical documents regarding distances, volumes and masses were converted into the decimal metric system, a process based on specific studies on the conversion between historical and modern measurement systems (Martini, 1883).

The CEDIT database is published online for public access at http://www.ceri.uniroma1.it/cn/gis.jsp and is hosted by the web server of the Research Centre for the Geological Risks (CERI) of the Sapienza University of Rome (Fortunato et al., 2012). The query system was developed by using the services of ArcGIS$^{\circledR}$-online and based on ESRI$^{\mathrm{TM}}$ cloud technology. The system provides a geo-database consulting and querying interface with graph or table outputs.

3 Descriptive statistics

The current version is an upgrade of the first release of the CEDIT database (Romeo and Delfino, 1997). Figure 2 shows a comparison between the two versions of the catalogue.

In the new release, the number of recorded landslides has increased compared with the first release due to the huge effort of the Italian scientific community in recent years to retrieve as much information and data as possible regarding landslides and other mass movements as part of an attempt to reduce the geologic hazards of the country. Similarly, another effect extensively investigated in recent years has been surface faulting, for which the number of records has been greatly increased in the new database. Although surface faulting is a primary effect of fault rupture, whereas ground

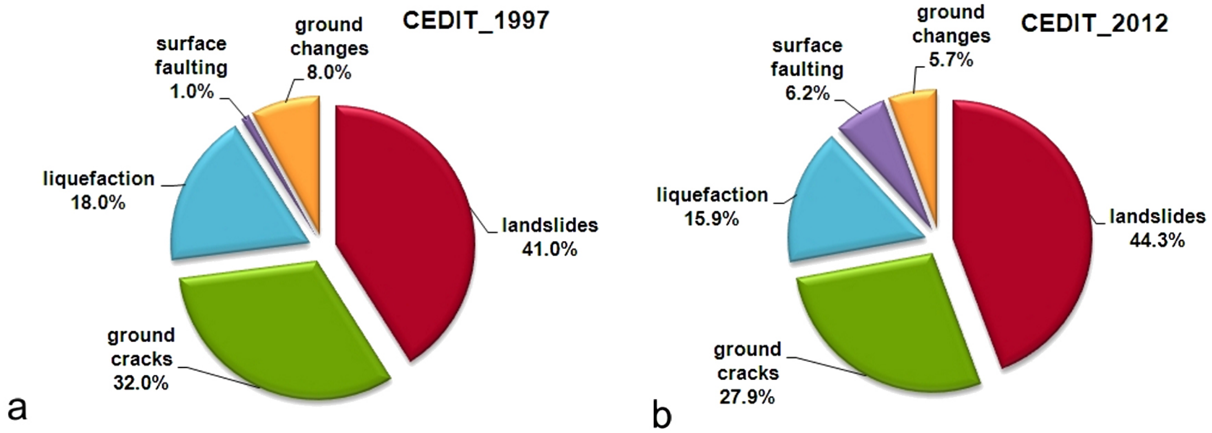

Fig. 2. Percentage of ground failures included **(a)** in the previous release of the CEDIT database (until 1984) and **(b)** in the current version of the CEDIT database (until 2012).

failures are secondary effects resulting from the ground response to the seismic shaking, in the current version of the database this effect has been retained due to its primary importance for the identification of active faults and the implications for seismic hazard (e.g. surface faulting is a primary cause of site rejection for many structures, especially in the case of critical facilities such as power plants and dams).

Among landslides, approximately 40 % can be ascribed to Keefer's (1984, 2002) type-1 category of landslides triggered by earthquakes (falls and disrupted slides), 22 % to type-2 (coherent slides), 6 % to type-3 (lateral spreads and flows) and a considerable number (approximately 32 %) are undefined. Type-3 landslides were distinguished from liquefaction-related effects based on the description given in the historical chronicles, which can be retrieved in the online version of the catalogue. For instance, in the case of slopes where the clear news of water ejected from the ground was not documented, the ground effect was interpreted as a landslide, otherwise as a liquefaction-related effect.

Figure 3 shows the time distribution of the earthquakes reported in the CEDIT database from which data about ground failures have been gathered.

Despite the general tendency of earthquakes towards clustering, the time distribution is clearly more continuous starting from the end of the 18th century as a consequence of the seismic crisis that affected the Calabria region in 1783. The crisis altered the way earthquakes and their effects were detected, as this event marked the first time in Italy (and perhaps in the world; Keefer, 2002) that a scientific mission was launched to detect and report earthquake damage and collateral hazards (Sarconi, 1784). This event also represented the first example of seismic technical provisions given by the local authorities for the reconstruction of the villages damaged by earthquake sequences (Postpischl, 1985a, b). Figure 4 shows the time distribution of the environmental effects reported in the CEDIT database.

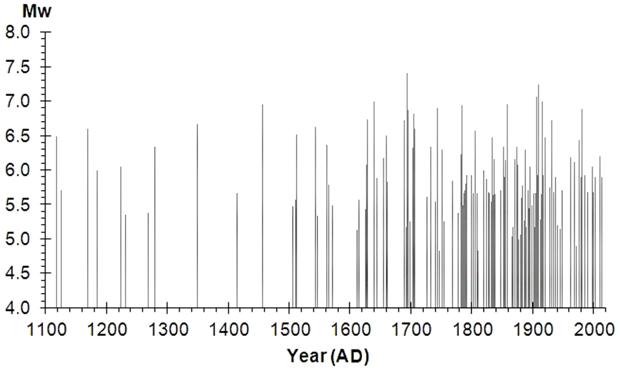

Fig. 3. Time distribution of earthquake magnitudes reported in the CEDIT database. A considerable increase of earthquakes from which information about localities affected by ground failures have been retrieved can be observed since the 19th century, after the Calabria, 1783 seismic sequence that marked the start up of scientific technical surveys after an earthquake occurrence.

Two major increases in the cumulative number of ground failures are apparent: the first increase relates to the already cited earthquake sequence that struck the Calabria region (Southern Italy) in 1783. This sequence involved at least three major earthquakes above magnitude 6.5 that triggered several ground failures, 145 of which are reported in the catalogue (Vivenzio, 1788; Minasi, 1785; De Lorenzo, 1877; Graziani et al., 2006). The second increase relates to the 1976 Friuli $M_\mathrm{w} = 6.4$ earthquake (northern Italy). This earthquake represents for Italy the starting point of the systematic development and detection of strong motion records, damage and environmental effects (Carraro et al., 1976). Moreover, since 1970s the availability of aerial surveys has allowed the detection of a number of effects more complete than in the past. Two other dates are worthy of mentioning: the first is the beginning of the last century which represents the starting of

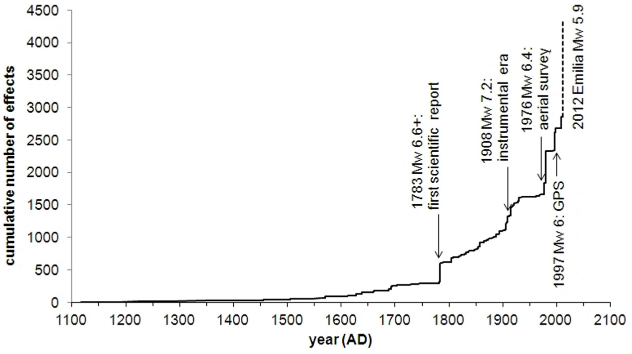

Fig. 4. Time distribution of the cumulative number of ground failures reported in the CEDIT database. Marked dates refer to turning points in the completeness and reliability of detected localities and effects, i.e., from older to younger: 1783 Calabrie $M_\mathrm{W} = 6.6+$ earthquakes, first scientific report; 1908 Messina Strait $M_\mathrm{W} = 7.2$ earthquake, beginning of the seismological instrumental era; 1976 Friuli $M_\mathrm{W} = 6.4$ earthquake, systematic aerial surveys; 1997 Umbria-Marche $M_\mathrm{W} = 6$ seismic sequence, starting point of GPS measurements; 2012 Emilia $M_\mathrm{W} = 5.9$ seismic sequence, most recent event.

the instrumental age from the seismological point of view. In fact, since the 1908 Stretto di Messina earthquake, the availability of instrumentally detected epicentres and magnitudes has allowed increasing the accuracy of earthquakes' parameters, whose sources of error were an unavoidable component in all the previous earthquakes. The second date is starting from the 1990s, when the diffusion of GPS measurements has virtually eliminated the error in the ground effects location. However, despite these key dates the catalogue is far from being complete, considering that most ground failures occur in scarcely populated areas, such as mountainous regions; even for the most recent events, the detection of such effects can be incomplete because the survey is often influenced by the induced risk (e.g. damage to buildings, lifelines and infrastructures), thus missing the detection of small or non-damaging ground effects.

As far the completeness of the earthquake magnitude records are concerned, in Fig. 5, the number of earthquakes reported in the CEDIT database is compared with the number of earthquakes listed in the CPTI earthquake catalogue.

The CPTI catalogue lists the earthquakes that occurred in Italy in the last millennium that are significant for seismic hazard assessments. The threshold of completeness of the CPTI catalogue is between $M_\mathrm{W} = 4.5$ and 5.0, after which there is a rapid decrease in the number of earthquakes per magnitude class that clearly follows an exponential decay pattern. The modal magnitude of the CEDIT database is between 5.5 and 6.0, which roughly corresponds to epicentral intensity 8 in the Mercalli scale, as further shown in Fig. 6. The decay of the number of earthquakes per magnitude class in the CEDIT database is less pronounced than in the CPTI catalogue because the larger magnitudes are associated with a higher likelihood of ground-failure triggering. Only approximately 15 % of the earthquakes above magnitude 5 of the CPTI catalogue are included in the CEDIT database, because most of the earthquakes listed in the CPTI occurred in historical times, when the attention mainly focused on building damage rather than on environmental damage. The list of earthquakes for which ground effects have been derived from the historical data sources are reported in Table 1, along with the number of affected localities and the inferred ground effects. For the earthquakes since 1900 (instrumental age), the focal depth, when available, is reported, too. Whereas hypocentral depth can play an important role in determining the ground response, almost all the earthquakes listed in Table 1 are reasonably crustal earthquakes (depth less than 30 km), according to the seismotectonic framework of Italy (Meletti et al., 2000). As an example of the possible influence of hypocentral depth, in the Emilia 2012 seismic sequence

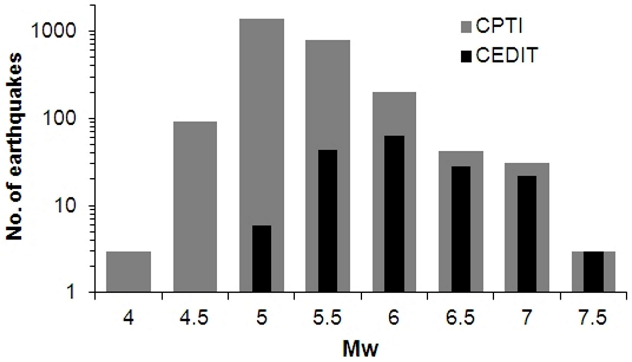

Fig. 5. Number of earthquakes per magnitude class reported in the CPTI earthquake catalogue for seismic hazard analyses and in the CEDIT database. In each graph of this paper showing on the x axis an interval scale, the interval itself is defined as the upper limit included and the lower limit excluded, i.e. $x_{i-1} < X \leq x_i$.

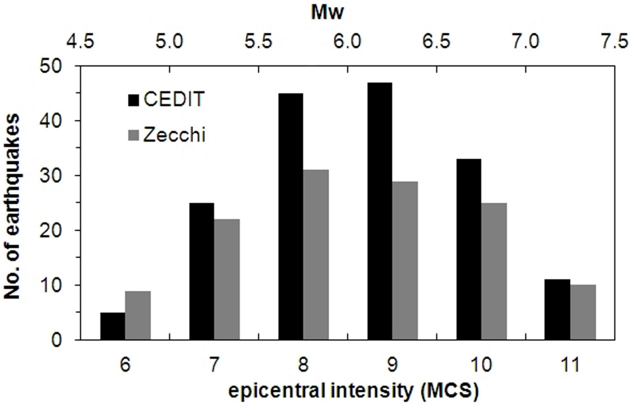

Fig. 6. Distribution of earthquakes per epicentral intensity that triggered ground failures in Italy as reported on the map by Zecchi (1987) and in the CEDIT database. The upper x axis shows an approximate conversion of epicentral intensity into moment magnitude (from Gruppo di Lavoro CPTI, 2004, with small adjustments).

Table 1. List of earthquake records in the CEDIT database with affected localities and triggered ground failures.

# eqk	ID CPTI04	Epicentral area	Date	Lat °	Long °	Io(MCS)	M_w (depth)	Sites	Land-slides	Ground cracks	Lique-faction	Surface faulting	Ground changes
1	30	Veronese	1117-01-03	45.330	11.200	9.5	6.49	2			1		1
2	33	Sannio-Molise	1125-10-11	41.600	15.000	8.0	5.71	1		1			
3	37	Sicilia orientale	1169-02-04	37.320	15.030	10.0	6.60	3	1	1	3		
4	40	Valle del Crati	1184-05-24	39.430	16.250	9.0	6.00	1	1				
5	47	Basso Bresciano	1222-12-25	45.480	10.680	8.5	6.05	5	4	2			
6	50	Cassino	1231-06-01	41.480	13.830	7.0	5.35	1	2	1			
7	55	Trevigiano	1268-11-04	45.730	12.080	7.5	5.37	1	1				
8	63	Camerino	1279-04-30	43.093	12.872	10.0	6.33	1	1				
9	94	Carnia	1348-01-25	46.254	12.883	9.5	6.66	2	1	2	1		
10	95	Lazio meridionale-Molise	1349-09-09	41.480	14.070	10.0	6.62	3	2	1			
11	135	Toscana occidentale	1414-08-07	43.271	11.120	7.5	5.66	1		1			
12	**153**	**Molise**	**1456-12-05**	**41.302**	**14.711**	**10.0**	**6.96**	**13**	**4**	**8**			**3**
13	202	Bologna	1505-01-03	44.480	11.250	7.0	5.47	2	1	1	2		
14	208	Calabria meridionale	1509-02-25	38.100	15.680	8.0	5.57	1	1	1			
15	210	Slovenia	1511-03-26	46.200	13.430	9.0	6.51	1	1				
16	238	Mugello	1542-06-13	44.000	11.380	9.0	5.91	1			1		
17	240	Siracusano	1542-12-10	37.220	14.950	10.0	6.62	1			2		
18	241	Borgo Val di Taro	1545-06-09	44.498	9.844	7.5	5.33	4	2	1	1		2
19	256	Vallo di Diano	1561-08-19	40.520	15.480	9.5	6.36	6	3	3	2		
20	259	Alpi marittime	1564-07-20	44.022	7.278	8.5	5.79	2	1	1			
21	262	Ferrara	1570-11-17	44.820	11.630	7.5	5.48	10	1	8	14		4
22	308	Scarperia	1611-09-08	44.020	11.370	7.0	5.13	1		1			
23	311	Naso	1613-08-25	38.120	14.780	8.0	5.57	1	1	2			
24	323	Argenta	1624-03-18	44.650	11.850	7.5	5.43	2		1	3		1
25	327	Girifalco	1626-04-04	38.820	16.420	9.0	6.08	2		2			
26	**330**	**Gargano**	**1627-07-30**	**41.730**	**15.350**	**10.0**	**6.73**	**15**	**5**	**8**	**10**		**2**
27	341	Calabria	1638-03-27	39.030	16.280	11.0	7.00	15	4	11	4	1	2
28	**343**	**Amatrice**	**1639-10-07**	**42.636**	**13.252**	**10.0**	**6.26**	**1**					**1**
29	349	Alpi marittime	1644-02-15	43.980	7.320	8.5	5.88	1	1				
30	358	Sorano-Marsica	1654-07-23	41.630	13.680	9.5	6.17	3	1	2			
31	361	Calabria centrale	1659-11-05	38.700	16.250	10.0	6.50	6	2	5			
32	365	Montecchio	1661-03-12	45.730	10.070	7.0	5.17	4	4	2			
33	366	Appennino Romagnolo	1661-03-22	44.020	11.900	9.0	5.83	6		5	1		
34	393	Romagna	1688-04-11	44.390	11.942	9.0	5.88	2	2	1			1
35	394	Sannio	1688-06-05	41.280	14.570	11.0	6.72	14	4	9	4		1
36	407	M. Valcalda	1692-05-00	46.350	12.800	7.0	5.17	1	1				
37	**410**	**Sicilia orientale**	**1693-01-11**	**37.130**	**15.020**	**11.0**	**7.41**	**20**	**7**	**11**	**16**		**4**
38	414	Irpinia-Basilicata	1694-09-08	40.880	15.350	10.5	6.87	12	5	9			
39	417	Bagnoregio	1695-06-11	42.612	12.110	8.5	5.77	1	1	1			
40	424	Vizzini	1698-04-12	37.312	14.878	7.0	5.25	1	1				
41	**430**	**Beneventano-Irpinia**	**1702-03-14**	**41.120**	**14.980**	**9.5**	**6.32**	**1**	**1**				
42	434	Appennino reatino	1703-01-14	42.680	13.120	11.0	6.81	5	2	3			
43	**435**	**Aquilano**	**1703-02-02**	**42.470**	**13.200**	**10.0**	**6.65**	**2**			**3**		
44	439	Villafranca	1703-12-28	44.780	7.505	7.5	5.37	1	1				
45	445	Maiella	1706-11-03	42.080	14.080	9.5	6.60	5	2	3			
46	484	Palermo	1726-09-01	38.120	13.350	8.0	5.61	2	1	1			
47	496	Foggiano	1731-03-20	41.270	15.750	9.0	6.34	1			3		
48	513	Naso	1739-05-10	38.100	14.750	8.0	5.54	4	2	3			1
49	520	Basso Ionio	1743-02-20	39.850	18.780	9.5	6.90	2		2			
50	526	Garfagnana	1746-07-23	44.088	10.444	6.0	4.83	2	3				
51	**535**	**Gualdo Tadino**	**1751-07-27**	**43.222**	**12.730**	**10.0**	**6.30**	**1**	**1**				
52	540	Valle del Chisone	1753-03-09	44.930	7.180	6.5	5.25	3	1	2	2		
53	575	Appennino Romagnolo	1768-10-19	43.930	11.870	9.0	5.84	1		1			
54	601	Radicofani	1777-10-05	42.880	11.756	7.5	5.37	1	1				
55	616	Faentino	1781-04-04	44.235	11.797	9.0	5.84	4		4	5		
56	618	Romagna	1781-06-03	43.594	12.506	9.5	6.23	5	5	4			
57	619	Cagliese	1781-07-17	44.280	11.950	8.0	5.53	1					1
58	626	Calabria	1783-02-05	38.300	15.970	11.0	6.91	98	58	47	70		32
59	**628**	**Calabria**	**1783-02-07**	**38.580**	**16.200**	**10.5**	**6.59**	**20**	**11**	**8**	**6**		**4**
60	629	Calabria	1783-03-01	38.770	16.300	9.0	5.92	1		1			
61	**630**	**Calabria centrale**	**1783-03-28**	**38.780**	**16.470**	**10.0**	**6.94**	**26**	**10**	**13**	**23**		**3**
62	637	Gerace	1784-10-14	38.293	16.210	7.0	5.09	1	1				
63	**643**	**Piediluco**	**1785-10-09**	**42.564**	**12.777**	**8.0**	**5.48**	**2**		**1**	**3**		
64	651	Riminese	1786-12-25	43.980	12.580	8.0	5.67	1	1	1	1		
65	661	Tolmezzo	1788-10-20	46.398	13.019	8.5	5.71	1		1			1
66	663	Val Tiberina	1789-09-30	43.505	12.208	8.5	5.80	1			2		1
67	667	Scopoli	1791-10-11	42.972	12.824	7.5	5.32	1		1			

Table 1. Continued.

# eqk	ID CPTI04	Epicentral area	Date	Lat °	Long °	Io(MCS)	M_w (depth)	Sites	Land-slides	Ground cracks	Lique-faction	Surface faulting	Ground changes
68	668	Calabria centrale	1791-10-13	38.630	16.270	9.0	5.92	1		1			
69	687	Camerino	1799-07-28	43.147	13.123	9.0	5.93	2		1			1
70	694	Valle dell'Oglio	1802-05-12	45.420	9.850	8.0	5.67	3		2	2		
71	700	Molise	1805-07-26	41.500	14.470	10.0	6.57	42	32	19	6	4	2
72	710	Valle del Pellice	1808-04-02	44.830	7.250	8.0	5.67	9	2	8			
73	714	Malcesine	1810-05-01	45.764	10.809	6.0	4.83	1		1			
74	736	Catanese	1818-02-20	37.600	15.130	9.0	6.00	9		7	6		
75	739	Madonie	1818-09-08	37.820	14.080	7.5	5.31	3	3	2			
76	752	Sicilia settentrionale	1823-03-05	38.000	14.100	8.5	5.87	9	3	7	2		2
77	759	Basilicata	1826-02-01	40.520	15.730	8.0	5.68	2	2		2		
78	770	Valle dello Staffora	1828-02-02	40.750	13.900	8.0	5.57	1	1				
79	776	Casamicciola Terme	1828-10-09	44.820	9.050	7.5	5.67	7	7				
80	790	Liguria occidentale	1831-05-26	43.850	7.850	8.0	5.54	2	2	1			
81	795	Reggiano	1832-01-13	42.967	12.659	8.5	5.80	5		3	5		
82	797	Foligno	1832-03-08	39.070	16.900	9.5	6.48	7	3	4	7		
83	798	Crotonese	1832-03-13	44.770	10.470	7.5	5.59	3		1	1		1
84	801	Alta Lunigiana	1834-02-14	44.449	9.859	8.5	5.64	1	1	1			1
85	808	Cosentino	1835-10-12	39.330	16.300	9.0	5.91	2	3	1			
86	811	Basilicata meridionale	1836-04-25	39.570	16.730	9.0	6.16	4	1	3	3		2
87	815	Calabria settentrionale	1836-11-20	40.150	15.780	8.0	5.83	2	2	2			
88	819	Alpi Apuane	1837-04-11	44.174	10.181	9.5	5.65	1	1	1			1
89	855	Orciano Pisano	1846-08-14	43.531	10.500	8.5	5.71	11	3	5	14		
90	878	Basilicata	1851-08-14	40.950	15.670	9.5	6.33	6	7	3			
91	886	Moggio Udinese	1853-02-19	46.383	13.100	7.0	5.17	1	1				
92	887	Irpinia	1853-04-09	40.820	15.220	9.0	5.90	3	2	2			
93	893	Cosentino	1854-02-12	39.250	16.300	9.5	6.15	16	11	14	4		
94	899	Vallese	1855-07-25	46.217	7.850	8.5	5.81	4	3		1		
95	912	Basilicata	1857-12-16	40.350	15.850	10.5	6.96	35	32	21	2	1	2
96	945	Area etnea	1865-07-19	37.700	15.150	9.0	5.03	15	5	13		6	
97	950	Monte Baldo	1866-08-11	45.727	10.783	7.0	5.17	1	1				
98	970	Cosentino	1870-10-04	39.220	16.330	9.5	6.16	7	4	3	3		
99	985	Bellunese	1873-06-29	46.150	12.380	9.5	6.33	16	9	13	1		
100	1000	Romagna sud-orientale	1875-03-17	44.070	12.550	8.0	5.74	2		2	2		
101	1003	San Marco in Lamis	1875-12-06	41.689	15.677	7.5	6.07	1			1		
102	1005	Monte Baldo	1876-04-29	45.750	10.780	7.0	4.99	1	1	1			
103	1043	Area etnea	1879-06-17	37.680	15.150	9.0	5.06	6	4	2			
104	1066	Abruzzo Meridionale	1881-09-10	42.230	14.280	8.0	5.59	1	1	1			1
105	1082	Monte Baldo	1882-09-18	45.720	10.770	7.0	5.17	1	1				
106	1088	Casamicciola Terme	1883-07-28	40.750	13.880	9.0	5.78	9	7	4			
107	1111	Benevento	1885-09-17	41.133	14.800	7.0	5.17	1		1			
108	1121	Val di Susa	1886-09-05	45.036	7.306	6.5	5.27	1	1				
109	1128	Liguria occidentale	1887-02-23	43.920	8.070	9.0	6.29	25	9	15	6		2
110	1136	Calabria settentrionale	1887-12-03	39.570	16.220	8.0	5.52	3	3				
111	1154	Tolmezzo	1889-10-13	46.400	13.000	7.0	5.17	1		1			
112	1170	Valle d'Illasi	1891-06-07	45.570	11.170	8.5	5.71	7	5	2			
113	1186	Pont Saint Martin	1892-03-05	45.569	7.797	7.0	5.09	2	2				
114	1207	Gargano	1893-08-10	41.720	16.080	8.0	5.44	2	2	2			
115	1212	Lesina	1894-03-25	41.867	15.323	7.0	5.17	1		1			
116	1215	Calabria meridionale	1894-08-08	37.650	15.120	9.5	5.23	5	3	4			
117	1216	Area etnea	1894-11-16	38.280	15.870	8.5	6.05	24	10	17	3		5
118	1229	Bajano	1895-05-20	42.750	12.700	7.0	5.17	1		1			
119	1291	Calestano	1898-03-04	44.503	10.314	6.5	5.07	2	1		1		
120	1299	Rieti	1898-06-27	42.415	12.905	7.5	5.48	1	1				
121	1304	Caltagirone	1898-11-02	37.216	14.495	5.5	4.63	1			1		
122	1340	Salò	1901-03-29	45.167	7.167	6.0	4.63	1			1		
123	1342	M. Lera	1901-04-24	42.100	12.736	7.5	5.15	1		1	1		
124	1353	Montelibretti	1901-10-30	45.580	10.500	8.0	5.67	2	2	1			1
125	1356	Garfagnana	1902-03-05	44.093	10.463	7.0	5.17	2	2		1		
126	1384	Marsica	1904-02-24	42.100	13.320	8.5	5.67	8		8			
127	1420	Calabria	1905-09-08	38.670	16.070	11.0	7.06	60	33	33	23		6
128	1463	Calabria meridionale	1907-10-23	38.130	16.020	8.5	5.93	12	12	6			
129	1495	Stretto di Messina	1908-12-28	38.150	15.680	11.0	7.24 (10)	58	47	25	5		9
120	1511	Murlo	1909-08-25	43.150	11.403	7.5	5.40	1					1
131	1555	Area etnea	1911-10-15	37.700	15.150	10.0	5.28	8	1	6		1	5
132	1581	Calabria settentrionale	1913-06-28	39.530	16.230	8.0	5.65	3	1	2			
133	1596	Tavernette	1914-05-08	37.670	15.130	9.0	5.30	14	3	10		5	5
134	1604	Area etnea	1914-10-26	45.072	7.337	7.0	5.36	1	1				
135	1608	Avezzano	1915-01-13	42.013	13.530	11.0	6.99	66	41	38	12	3	9

Table 1. Continued.

# eqk	ID CPTI04	Epicentral area	Date	Lat °	Long °	Io(MCS)	M_w (depth)	Sites	Land-slides	Ground-cracks	Lique-faction	Surface faulting	Ground-changes
136	1630	Alto Adriatico	1916-05-17	44.000	12.630	8.0	5.85	1		1			
137	**1637**	**Alto Adriatico**	**1916-08-16**	**43.970**	**12.670**	**8.0**	**5.92**	**5**		**3**	**7**		**1**
138	1650	Ternano	1917-04-26	43.465	12.125	9.0	5.80	4	1	3	3		
139	1651	Monterchi-Citerna	1917-05-12	42.580	12.630	7.5	5.11	1	1				
140	1684	Mugello	1919-06-29	43.950	11.480	9.0	6.18	7	3	5	4		
141	1687	Piancastagnaio	1919-09-10	42.793	11.788	8.0	5.38	1			1		
142	1708	Garfagnana	1920-09-07	44.180	10.280	9.5	6.48	23	25	6			1
143	1800	Colli Albani	1927-12-26	41.700	12.700	7.0	5.02	1	2				
144	1805	Carnia	1928-03-27	46.372	12.975	8.5	5.75	17	26	4			
145	1841	Senigallia	1930-07-23	41.050	15.370	10.0	6.72 (15)	29	32	15		4	2
146	1847	Irpinia	1930-10-30	43.659	13.331	9.0	5.94	2	1		1		
147	1886	Maiella	1933-09-26	42.050	14.180	8.5	5.68	2	2				
148	1921	Bosco Cansiglio	1936-10-18	46.088	12.380	9.0	5.90	6	2	5			1
149	1950	Garfagnana	1939-10-15	44.119	10.255	6.5	5.20	1	1				
150	1995	Valle dello Staffora	1945-06-29	44.830	9.130	7.5	5.15	1	1				
151	2007	Calabria centrale	1947-05-11	38.650	16.520	8.0	5.71	1	1				
152	2175	Irpinia	1962-08-21	41.130	14.970	9.0	6.19	2	1			1	1
153	**2246**	**Valle del Belice**	**1968-01-15**	**37.770**	**12.980**	**10.0**	**6.12**	**15**	**7**	**9**	**7**		
154	2294	Tuscania	1971-02-06	42.442	11.846	7.5	4.90	2	2	1			1
155	2363	Friuli	1976-05-06	46.241	13.119	9.5	6.43 (06)	103	84	17	46		14
156	2366	Friuli	1976-09-15	46.250	13.120	8.5	5.92 (11)	9	5	5	5		2
157	2400	Valnerina	1979-09-19	42.720	13.070	8.5	5.90 (06)	1	1				
158	2413	Irpinia-Basilicata	1980-11-23	40.850	15.280	10.0	6.89 (12)	216	239	119	27	86	17
159	2441	Appennino Abruzzese	1984-05-07	41.666	14.057	8.0	5.93 (20)	6	4	2			
160	2478	Sicilia sud-orientale	1990-12-13	37.266	15.121	7.0	5.68 (07)	1			2		
161	**2515**	**Umbria-Marche**	**1997-09-26**	**43.019**	**12.879**	**8.5**	**6.05 (10)**	**203**	**194**	**82**		**3**	**4**
162	2522	Appennino Calabro-Lucano	1998-09-09	40.038	15.937	6.5	5.68 (29)	51	56	5		2	
163	2546	Tirreno meridionale	2002-09-06	38.081	13.422	6.0	5.90 (27)	1	1	1			
164	**2550**	**Molise**	**2002-10-31**	**41.694**	**14.925**	**7.5**	**5.74 (25)**	**1**	**1**	**1**	**1**		
165	**NA**	**L'Aquila**	**2009-04-06**	**42.334**	**13.334**	**9.0**	**6.20 (08)**	**168**	**95**	**5**	**5**	**65**	**1**
166	**NA**	**Emilia**	**2012-05-20**	**44.889**	**11.228**	**7.5**	**5.90 (06)**	**1343**	**12**	**16**	**1514**		

Bold font: multiple events for which cumulative effects were likely.

the first mainshock (20 May) produced a greater number of ground effects than the second mainshock (29 May), although the two shocks had almost the same magnitude (5.9 vs. 5.8, respectively) and the same focal mechanism (reverse). One explanation could be the different focal depth, 6 km for the former and 10 km for the latter, although other differences, such as, amongst others, soil compaction after the first shock could have played a role in determining the lesser number of ground effects of the second shock.

In 1987, Zecchi published a distribution map of the geomorphologic effects induced by earthquakes that hit Italy before 1986. Unfortunately, the work did not include any database or table of the affected localities, but only a map available in a printed format. The distribution of earthquakes listed as triggering events is shown in Fig. 6 in terms of epicentral intensities, where, on the secondary x axis, an approximate correspondence with moment magnitude is shown, based on a correlation provided by the CPTI earthquake catalogue's authors (Gruppo di Lavoro CPTI, 2004) and therefore specifically calibrated for Italian earthquakes. The threshold epicentral intensity of ground failures occurrence is the 6th degree of the Mercalli scale for both catalogues, corresponding to a moment magnitude 4.5–5. In this epicentral intensity class the CEDIT database reports a lesser number of earthquakes than the catalogue by Zecchi. The difference can be explained considering that the catalogue by Zecchi reported for the 6th degree of epicentral intensity only earthquakes that occurred prior to the instrumental age or were located offshore, for which successive studies have reassessed the real occurrence of ground failures triggered by those earthquakes.

The spatial distribution of the earthquakes and affected localities listed in the CEDIT database is shown in Fig. 7. The highest concentration is along the Apennine chain, with some relevant clusters associated with the most well-documented and recent events such as, from north to south, the 1976 Friuli $M_\mathrm{w} = 6.4$ earthquake, 1997 Umbria-Marche $M_\mathrm{w} = 6.0$ earthquake, 2009 L'Aquila $M_\mathrm{w} = 6.2$ earthquake, 2012 Emilia $M_\mathrm{w} = 5.9$ earthquake, 1980 Irpinia $M_\mathrm{w} = 6.9$ earthquake and the earthquakes above $M_\mathrm{w} = 6.5$ that hit the Calabria region in 1783, 1905 and 1908.

The lithological features of localities affected by ground failures are shown in Fig. 8, based on the official Italian Geologic Map at scale 1 : 100 000 (ISPRA, available online at http://sgi.isprambiente.it/geoportal/catalog/content/project/litologica.page). Due to the map scale resolution, only localities reported in the most recent earthquakes (since 1908) for which a reliable location is available (error within 1 km) are graphed. While the relative abundance of liquefaction in the class of alluvia and debris is obvious, landslides

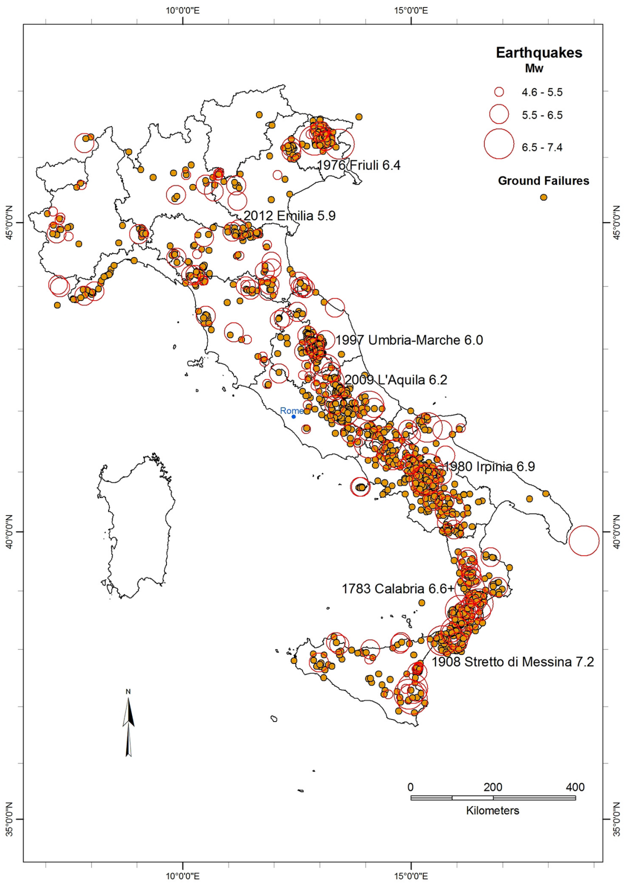

Fig. 7. Spatial distribution of earthquakes and localities affected by ground effects reported in the CEDIT database. Earthquakes that contributed most to the inventoried ground failures are marked on the map with the corresponding M_{W}.

are most concentrated in limestone, due to the wide outcropping of calcareous rocks in the Apennines which represent the orogenic area with the highest seismicity in the Italian peninsula. This supports the idea that most of the undefined landslides of the CEDIT database can be ascribed to falls and disrupted slides (Keefer's type-1category).

It is worth noting that some irresolution still exists in the attribution of lithology to the ground effects (e.g. liquefaction effects reported in weak or hard rocks) due to the combined effect of the map scale resolution and of the basic information contained in the geological map that mainly refer to the substratum, rather than to the overlying quaternary deposits in which most of the ground failures usually occur.

4 Relationships between ground failures and seismic parameters

Earthquakes may trigger different types of ground failure depending on the released seismic energy, source-to-site distance and local conditions. As far as the source energy is concerned, Fig. 9 shows the relative distribution of earthquakes per magnitude class for which a specific type of ground failure was reported. Landslides and ground cracks are reported in not less than 50 % of earthquakes in each magnitude class, percentages that progressively increase up to 100 % for earthquakes above magnitude 7. The same trend can be observed for liquefaction and ground changes with a relative minimum at magnitude interval 5–5.5, due to the considerable increase in the number of earthquakes in this magnitude class relative to the previous class ($M_{\mathrm{W}} = 4.5$–5). The absence of earthquakes above magnitude 7 documenting the surface-faulting effect is because they occurred in times when the scientific community did not yet acknowledge such effects, whose systematic study and recognition started only with the most recent earthquakes, as also witnessed by Fig. 2.

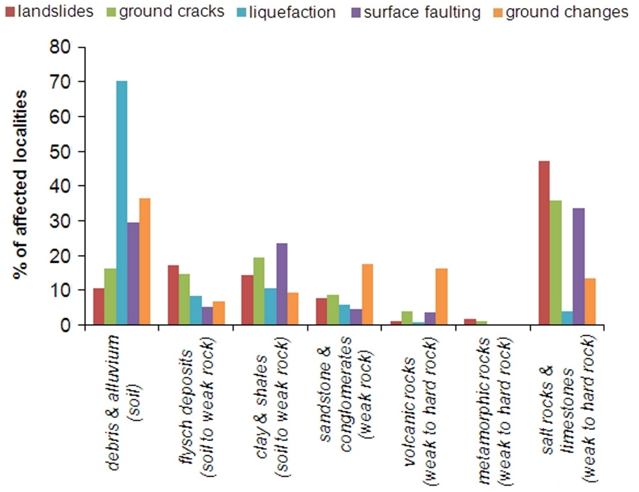

Fig. 8. Percentage of localities affected by ground failures in each lithological unit (ISPRA, 2004) for seismic events occurring since the 1908 Messina Strait earthquake. The lithotechnical attributes of each lithology are provided in brackets.

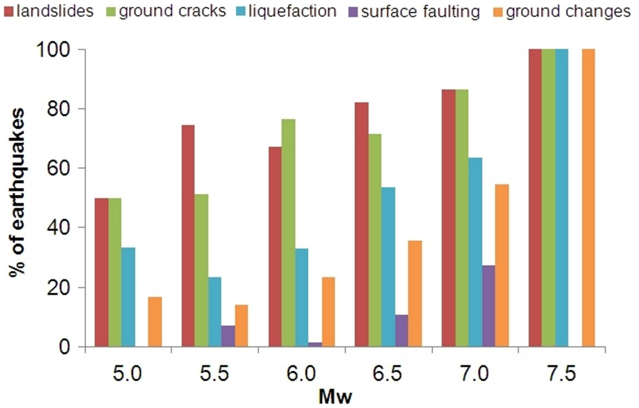

Fig. 9. Percentage of earthquakes in each magnitude class for which a specific type of ground failure was reported.

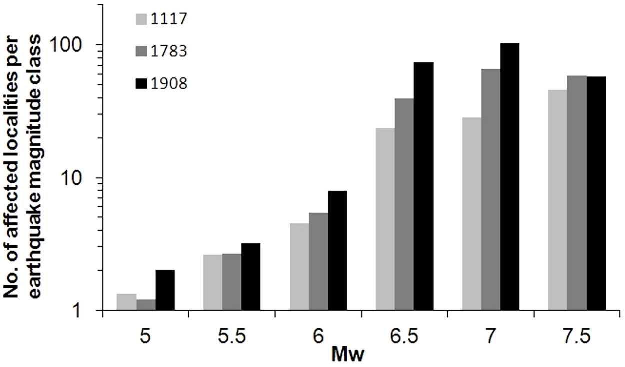

Fig. 10. Average number of localities affected by ground failures for each magnitude class and different time intervals related to the completeness of available information according to the time graph shown in Fig. 4.

The average number of affected localities for earthquakes in each magnitude class is shown in Fig. 10. Data have been disaggregated into time intervals referring to the key dates of increase in the completeness of documented information. The number of localities affected by ground effects continuously increases with the earthquake magnitude, with the shortest period (since 1908) being more complete than the other intervals. Only the last magnitude class ($M_\mathrm{w} = 7$–7.5) shows a lesser number of affected localities per earthquake magnitude since they all occurred before the availability of aerial surveys (the second half of 20th century) after that a more complete detection of ground failures is assured, even in the less populated areas.

Site intensity is a ground motion parameter that can be used to estimate the shaking level of a site on the basis of the effects (i.e. damage) locally produced by the earthquake. Site intensity is the only parameter that can be used to represent the local seismic shaking in historical earthquakes before the instrumental age. Nevertheless, site intensity is an integral parameter because it includes information about the shaking level (seismic demand) and the site response (seismic capacity). Distributions of surface faulting as a function of site intensity and distance are quite meaningless, as surface faulting is a primary effect being related only to the seismic source energy release. Therefore, surface faulting has been discarded from every correlation with site intensity and distance.

Figure 11 shows the number of earthquakes in which each ground-failure category was reported at a particular minimum intensity (Keefer, 1984). As far as the intensity scale is concerned, most of the site intensities described in the Italian earthquake catalogues use the Mercalli–Cancani–Sieberg scale (Sieberg, 1923), which strictly conforms, at least up to the 10th degree (Musson et al., 2010), to the Modified Mercalli intensity scale (Richter, 1958) and, ultimately, to the European Macroseismic Scale (Grünthal, 1998).

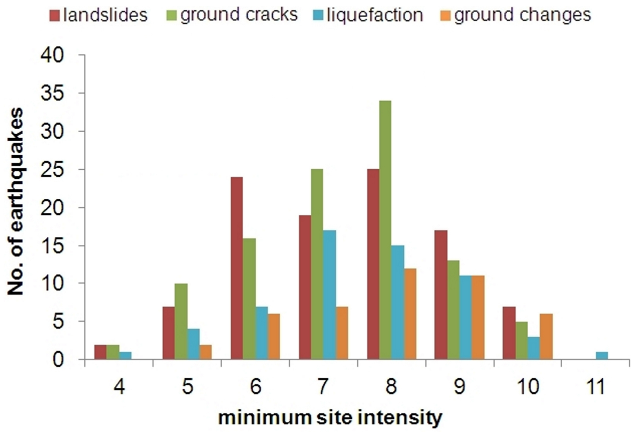

Fig. 11. Minimum site intensity at which ground failures occurred in the earthquakes listed in the CEDIT database.

Ground cracks are associated with the lowermost threshold intensity (4–5 on the MCS scale), followed by landslides with a threshold intensity between 5 and 6, whereas the other ground failures display higher threshold intensities, such as 6–7 for liquefaction and 7–8 for ground changes. Threshold intensity is assumed to be a sudden increase in the number of earthquakes per minimum site intensity (a relative maximum in the first derivative).

Site intensity is assessed on the basis of the damage degree to buildings (EMS scale) or the ground effects (ESI scale) and on their relative abundance. Indeed, a weak motion can produce ground effects only in the soils that are already close to their failure state when the earthquake occurs, as opposed to a strong motion that can produce ground effects even in the soils that are quite stable in static conditions. Figure 12 shows the likelihood of a ground effect being observed given a site intensity that represents a relative measure of ground shaking. The absolute frequencies (shown as histograms) for each type of ground failure have been used to derive a probability curve according to the Weibull distribution, which is aimed to simulate the reaching of failure states. Looking, for instance, at ground cracks, it can be seen that the frequency distribution is apparently bimodal, given the relative maxima at site intensities 8 and 10. This makes all inferential statistics meaningless, whereas modelling these frequencies with a probability distribution makes feasible the comparison concerning the relative likelihood that each ground failure can be triggered at a given site intensity. Thus, at the lowermost site intensities ground cracks are more likely to be triggered than landslides, whereas liquefaction approaches landslides at the highest site intensities. The probability trends can be interpreted as measures of the progressive increase of the seismic shaking required to trigger ground failures: ground cracks initiate at the lowest seismic level intensities, and after they evolve at the stage of mass movements (landslides); as the seismic level increases again, pore water

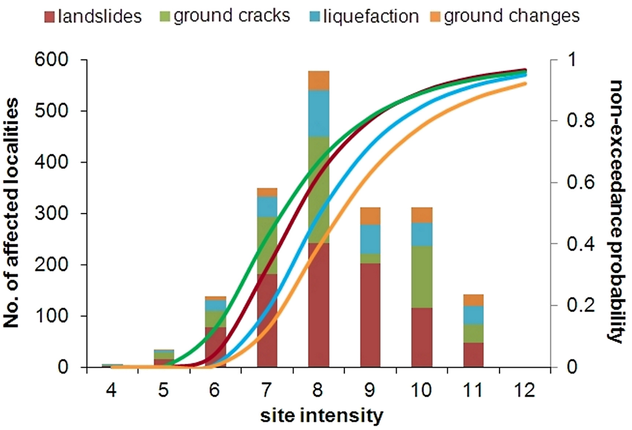

Fig. 12. Frequency distribution and non-exceedance probability (Weibull distribution) of site intensity for localities affected by ground effects.

overpressures generate and can progressively evolve into liquefaction, cyclic mobility and flow failures that at the ultimate stage can produce ground-level changes such as subsidence over wide areas.

Source-to-site distance is a key parameter for characterising the susceptibility of the ground to fail under the seismic shaking. In fact, distance modulates the seismic shaking by attenuating the amplitude and altering the duration and fundamental period of vibration, and all these factors influence the ground response. Thus, a relationship between the earthquake energy release and the distance at which ground failures can occur is straightforward.

Figure 13a shows the distribution of the maximum epicentral distance of landslides with the earthquake magnitude for the whole time span covered by the database (1117–2012). There is a great data scatter that makes any best-fit statistically meaningless; the most scattered data belong to earthquakes that occurred prior the instrumental age or even before the Calabria earthquakes of 1783. In fact, in his paper from 2002, Keefer reported that before 1783 "…historical accounts of the occurrence of landslides in earthquakes are typically so incomplete and vague that conclusions based on these accounts are of limited usefulness". According to this notice, Figure 13b shows the distribution limited to the time span 1783–2012. The reduction of the time span brings an evident improvement of the goodness of fit due to the greater accuracy of the observations. Taking also into account the greater precision gained after the advent of the instrumental age (Fig. 13c), the goodness of fit improves again: all the data, including error bars, are encompassed into one standard error of best fit, except for one rockfall that occurred during the 1928 Carnia (Northern Italy) $M_W = 5.8$ earthquake that indeed also lies outside Keefer's (1984) upper bound for falls and disrupted slides.

Figure 14 shows the magnitude–distance distribution for liquefaction. This effect shows a different pattern from landslides. In fact, in this case the goodness of fit does not improve with the reduction of the time span, and the time interval 1908–2012 has too few data to be displayed. In fact, liquefaction of the Emilia 2012 earthquake lies above the best-fit line in the graph 1783–2012, whereas it is well captured by the best-fit line in the graph 1117–1783. Moreover, some outliers (shown as open circles) were discarded from the analysis, as they were documented in literature to be exceptional in terms of epicentral distance or as they were described with vague attributes in the available historical sources. This choice allowed also for the relationships to be non-flat or

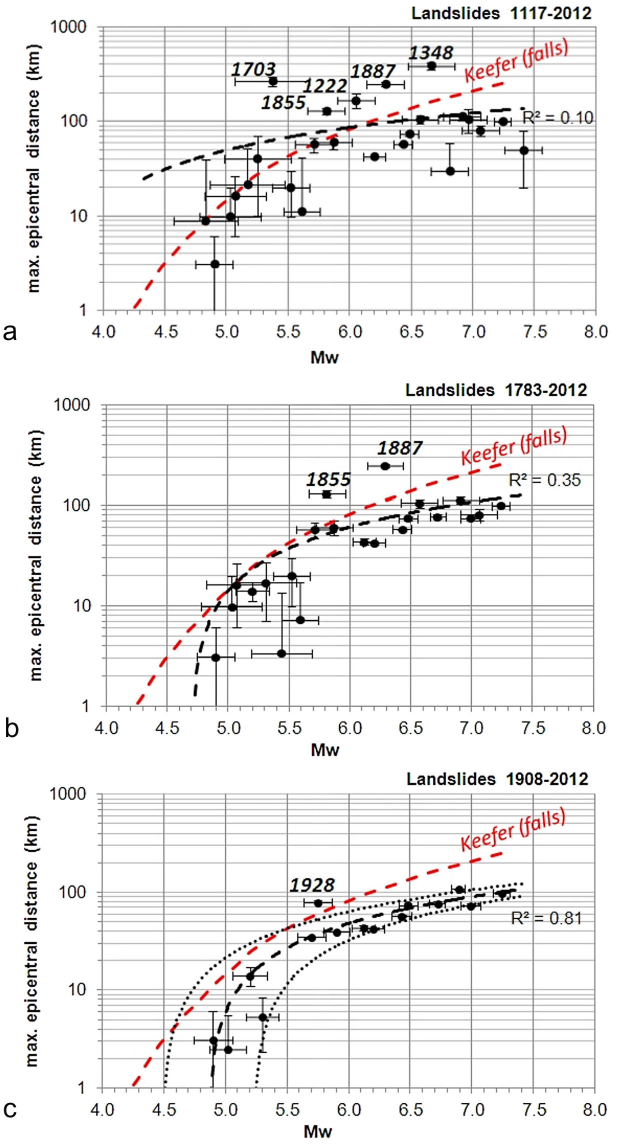

Fig. 13. Magnitude–distance relationships for landslides in different time periods (**a**: 1117–2012; **b**: 1783–2012; **c**: 1908–2012) compared to Keefer's (1984) upper bound for falls and disrupted slides (red dashed line). Black dotted lines in **(c)** refer to one standard error straddles the best-fit line (black dashed line).

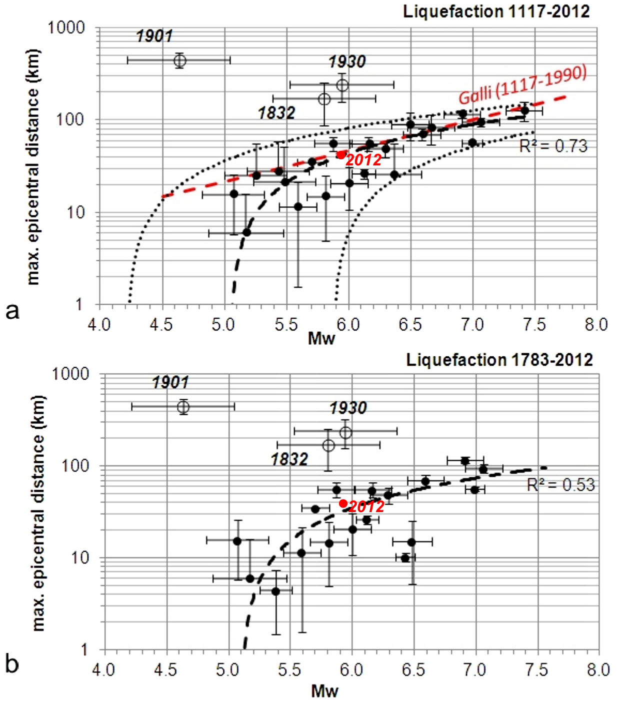

Fig. 14. Magnitude–distance relationships for liquefaction in different time periods (**a**: 1117–2012; **b**: 1783–2012). In **(a)** the comparison with the upper bound curve by Galli (2000), derived from Italian earthquakes that occurred in the period 1117–1990 is shown (red dashed line). Black dotted lines in **(a)** refer to two standard errors across the best-fit line (black dashed line). The red full circle corresponds to the liquefaction effects of the 2012 Emilia earthquake. Few outliers (black open circles) have resulted to be statistically meaningless and therefore they were discarded from the regression analysis.

even negative. Data distribution is more scattered than in the case of landslides and requires two standard errors to be encompassed (Fig. 15a). The comparison with the upper bound for liquefaction obtained by Galli (2000) for Italian earthquakes that occurred during 1117–1990 shows that it is not conservative for a significant M_{w}-range (5.9 to 7). The main inference is that liquefaction needs more accurate investigations during earthquakes in order to be properly addressed and parameterised so that some conclusive relationships can be drawn.

5 Discussion

The CEDIT database represents a collection of information of the ground failures triggered by the most important earthquakes that hit in Italy in the last millennium. As for every collection of historical data, two main problems arise that need a thorough discussion in order to highlight advantages and shortcomings of such a kind of repository: data completeness and accuracy.

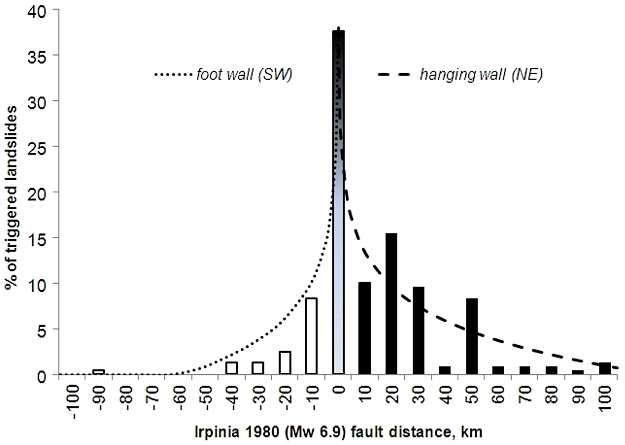

Fig. 15. Relative distribution of landslides as a function of the fault distance on the hanging wall and the foot wall of the 1980 Irpinia $M_{\mathrm{w}} = 6.9$ earthquake main causative fault (normal faulting NE dipping).

Data incompleteness is an unavoidable problem when referring to historical or even pre-historical events. Nevertheless, even for current events data completeness can be problematic, due to the scale of the survey and the size of the detectable effects (Harp et al., 2011). As an example, this is the case for the different liquefaction inventories compiled after the recent Emilia 2012 earthquake in northern Italy and reported by Emergeo Working Group (2013), Di Manna et al. (2012) and the Liquefaction Working Group of the Emilia–Romagna Regional Government (http://ambiente.regione.emilia-romagna.it/geologia/temi/sismica/liquefazione-gruppo-di-lavoro). The effect of incompleteness is particularly meaningful when dealing with the computation of the frequency of occurrence, as it is the case for the computation of seismicity rates in earthquake hazard analysis, but, where this is not the case, it is more important to be confident that the most important cases for which some documentation is available have been captured. In fact, the detection of extreme events such as large-distance effects from the earthquake sources, can provide the rationale for the development of scenarios at regional scale, even if a formal assessment of the ground failure hazard is prevented by the data incompleteness. Moreover, the availability of even a few instances of ground failures in previous earthquakes are useful for a perspective assessment of the environmental response to earthquakes, as is the case of the Emilia 2012 earthquake that showed a similar pattern of ground failures as reported and documented by the CEDIT catalogue for a previous earthquake that occurred in the same area in 1570.

As far as the accuracy of the earthquake and ground effect parameters determination is concerned, uncertainty affects to a varying extent all the parameters, characterising both the triggering events and the triggered effects and encompassing errors from the epicentral coordinates and magnitude of the causative earthquakes, to the site coordinates of the induced ground effects.

Epicentral errors as large as hundreds of kilometres were reported by Postpischl (1985a, b) for the PFG (Italian Geodynamics Project) earthquake catalogue compiled on the basis of previous historical catalogues (Bonito 1691, Baratta 1901, Cavasino 1931–1935, Iaccarino 1968–1971, Carrozzo 1973, Peronaci 1973, ENEL 1979). In 1990s the Italian seismological community launched a program to provide a reliable earthquake catalogue for the seismic hazard map of Italy, resulting in the NT4.1 earthquake catalogue (1997) and the following CPTI series of earthquake catalogues (1999, 2004 and 2011: http://emidius.mi.ingv.it/CPTI/). Starting from the former CPTI99 catalogue, historical epicentres were determined using the Boxer method by Gasperini et al. (1999). Nevertheless, a formal error for macroseismic determination of epicentral coordinates cannot be computed, as it depends, from time to time, on the number of felt points and on their azimuth and spatial distribution. The uncertainty associated with the algorithm used for the epicentral location provides only a measure of the reliability of the estimate: for instance, a large value may only implicitly indicate the existence of anomalous intensity points (as in the case of offshore epicentres) or incompleteness of data distribution, for instance sparsely populated areas (see Gasperini et al., 1999: Appendix 1). The same effects apply to the uncertainty in the magnitude assessment of historical (pre-instrumental) earthquakes, since the severity of the earthquake is dependent on the mesoseismal area that, in turn, is dependent on the felt points (which affects the epicentral location, too). A crude estimate of the relationship between error and magnitude value, as derived from the CPTI catalogue, shows how error tends to be inversely proportional to the magnitude value and also progressively decreases with time toward the present, due to the increase of macroseismic information.

The uncertainty in the distance computation of the ground effect from the earthquake source is in turn a joint function of the error in the epicentral location and the error in the ground effect location. Since the former is difficult to quantify, only the latter can be reasonably assessed considering the timing and the toponym of localities where ground effects are reported in historical chronicles. According to the administrative hierarchy of Italian territories, the CEDIT database assigns an error to each ground effect location based on the spatial extent of the place name according to the following ranking scheme, from closer to farther:

1. Site (GPS measurement): no error or negligible.

2. Village (area extent of square kilometres): average error 1 km.

3. Town (area extent of tens of square kilometres): average error 3 km.

4. City (area extent of hundreds of square kilometres): average error 10 km.

5. Province (area extent of thousands of square kilometres, comparable to US county or England shire): average error 30 km.

The older the effect, the higher the error: for instance, site error is assigned only to ground effects detected since the 1990s, when systematic detection of ground effects through GPS measurements became the practice.

In this direction, the greater availability of good quality data for the most recent earthquakes, makes it possible to infer more accurate information on the spatial distribution of ground effects. For instance, landslides triggered by the 1980 Irpinia earthquake (Fig. 15) were more widespread on the hanging wall of the causative fault (normal faulting NE dipping) than on the footwall, as a result of the activation of another fault antithetic to the main one (Westaway and Jackson, 1984; Bernard and Zollo, 1989).

This is only an example of the potential of the CEDIT-DB to investigate more in depth the relationships between triggering events and induced effects. Additional and more accurate relationships can be inferred from the spatial distribution of ground effects and ground motion parameters deriving from the seismic records.

6 Conclusions

This paper describes the new release of the CEDIT catalogue, a database of information regarding localities affected by ground failures triggered by the strongest earthquakes that have occurred in Italy over the last millennium. The database is an update of the former version released at the end of the 1990s, and extends the investigated time period and includes some specific studies on past earthquakes with improved descriptions of their ground effects. The database has been available online since January 2013 at http://www.ceri.uniroma1.it/cn/gis.jsp.

The distribution of earthquake magnitudes indicates that a threshold value of approximately 4.5 is likely to be the minimum magnitude required to trigger ground failures.

The rate of increase of ground failures with the increase in seismic energy release (i.e. with earthquake magnitude) clearly indicates that the ground effects requiring stronger energy contents, such as liquefaction, ground changes and surface faulting, increase much more with the earthquake magnitude than landslides and ground cracks, which can also be triggered by seismic events of lower energy.

Local site intensity is used to account for the seismic shaking responsible for the triggering of many of the ground failures, as most of the reported effects occurred in historical earthquakes prior to the advent of monitoring systems. The threshold intensity progressively increases from landslides and ground cracks (5–6 MCS) to liquefaction (6–7 MCS) and ground changes (7–8 MCS).

Magnitude–distance relationships for landslides are more reliably drawn than for liquefaction, whose effects appear to be more scattered. Such relationships, when compared with similar ones from literature, are shown to be more or less conservative depending on the time span considered. For instance, the accuracy of the most recent data on landslides leads to more reliable relationships that can be usefully applied for seismic landslide scenarios over large areas. At the same time, the completeness of the inventories for the most recent events contribute to reducing the scatter of the inferred relationships, and so increasing their precision.

One shortcoming when using ground failures as a proxy for the seismic shaking or, conversely, for magnitude–distance relationships, is that they depend on the properties of the lithologies when the feature formed (e.g. relative density, degree of saturation, boundary stress conditions, joint orientation, and many others), and for this reason the data are widely scattered and the resulting relationships are affected by high uncertainty.

Until now, there has been a lack of databases containing data on ground failures caused by earthquakes and a comprehensive analysis of the relationships between ground effects as well as ground motion. The main reason for this lack is the scarcity of ground-motion records and the mismatch between the location of sites affected by ground failures and recording stations. Nevertheless, the recent increase of availability of high-quality ground-motion records make it possible in some instances to tentatively approach this important target. In Italy, for instance, the good coverage of strong motion recording stations, available since the 1976 Friuli $M_\mathrm{w} = 6.4$ earthquake, would make it possible to investigate the relationships between ground shaking and the triggered ground effects, deriving the ground motion at localities affected by ground failures either developing earthquake-specific ground motion attenuation relationships or using interpolation techniques available in many computer programs of geostatistics.

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References

Alfaro, P., Delgado, J., García-Tortosa, F. J., Giner, J. J., Lenti, L., López-Casado, C., Martino, S., and Scarascia Mugnozza, G.: The role of near-field interaction between seismic waves and slope on the triggering of a rockslide at Lorca (SE Spain), Nat. Hazards Earth Syst. Sci., 12, 3631–3643, doi:10.5194/nhess-12-3631-2012, 2012.

Allen, T. I., Marano, K., Earle, P. S., and Wald, D. J.: PAGER-CAT: A composite earthquake catalog for calibrating global fatality models, Seism. Res. Lett., 80, 50–56, 2009.

Bernard, P. and Zollo, A.: The Irpinia (Italy) 1980 earthquake: Detailed analysis of a complex normal faulting, J. Geophys. Res.-Sol. Ea., 94, 1631–1647, 1989.

Bird, J. F. and Bommer, J. J.: Earthquake losses due to ground failure, Eng. Geol., 75, 147–179, 2004.

Bommer, J. J. and Rodríguez, C. E.: Earthquake-induced landslides in Central America, Eng. Geol., 63 , 189– 220, 2002.

Bozzano, F., Martino, S., Naso, G., Prestininzi, A., Romeo, R. W., and Scarascia Mugnozza, G.: The large Salcito landslide triggered by the 31st October 2002, Molise earthquake, Earthq. Spectra, 20, 1–11, 2004.

Bozzano, F., Lenti, L., Martino, S., Paciello, A., and Scarascia Mugnozza, G.: Self-excitation process due to local seismic amplification responsible for the reactivation of the Salcito landslide (Italy) on 31 October 2002, J. Geophys. Res., 113, B10312, doi:10.1029/2007JB005309, 2008.

Bozzano, F., Lenti, L., Martino, S., Paciello, A., and Scarascia Mugnozza, G.: Evidences of landslide earthquake triggering due to self-excitation process, Int. J. Earth Sci., 100, 861–879, doi:10.1007/s00531-010-0514-5, 2011.

Camassi, R. and Stucchi, M.: Gruppo Nazionale per la Difesa dai Terremoti NT4.1, un catalogo parametrico di terremoti di area italiana al di sopra della soglia del danno. A parametric catalogue of damaging earthquakes in the Italian area. versione NT4.1.1 luglio 1997, http://emidius.mi.ingv.it/NT/CONSNT.html, 1997.

Carraro, F., Cavallin, A., Frascari, F., Gasperi, G., Gelmini, R., Govi, M., Manfredini, U., Martinis, B., Panizza, M., Petrucci, F., Stefanini, S., and Zanferrari, A.: The Friuli earthquake of May 6, 1976 geology, Bollettino di Geofisica Teorica ed Applicata, 19, 755–808, 1976.

DBMI04: Database Macrosismico Italiano, INGV http://emidius.mi.ingv.it/DBMI04, 2004.

De Lorenzo, A. M.: Scilla inondata dal mare nella notte dopo il 5 febbraio 1783. In Memorie da servire alla storia sacra e civile di Reggio e delle Calabrie, Cronache e Documenti rari, 4 (4–7), Reggio Emilia (IT), 317–376, 1877.

Delfino, L. and Romeo, R. W.: C.E.D.I.T., Catalogo nazionale degli Effetti Deformativi del suolo Indotti da forti Terremoti, RAPPORTO TECNICO SSN/RT/97/04, 1997.

Delgado, J., Garrido, J., López-Casado, C., Martino, S., and Peláez, J. A.: On far field occurrence of seismically induced landslides, Eng. Geol., 123, 204–213, doi:10.1016/j.enggeo.2011.08.002, 2011.

Di Manna, P., Guerrieri, L., Piccardi, L., Vittori E., Castaldini, D., Bersulsconi, A., Bonadeo, L., Comerci, V., Ferrario, F., Gambillara, R., Livio, F., Lucarini, M., and Michetti A. M.: Ground effects induced by the 2012 seismic sequence in Emilia: implications for seismic hazard assessment in the Po Plain, Ann. Geophys., 55, 697–703, 2012, http://www.ann-geophys.net/55/697/2012/.

DISS Working Group: Database of Individual Seismogenic Sources (DISS), Version 3.1.1: A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas, http://diss.rm.ingv.it/diss/, 2010.

Emergeo Working Group: Liquefaction phenomena associated with the Emilia earthquake sequence of May–June 2012 (Northern Italy), Nat. Hazards Earth Syst. Sci., 13, 935–947, doi:10.5194/nhess-13-935-2013, 2013.

Fortunato, C., Martino, S., Prestininzi, A., and Romeo, R. W.: New release of the Italian catalogue of earthquake-induced ground failures (CEDIT), Italian J. Eng. Geol. Environ., 2, 63–74, 2012.

Galli, P.: New empirical relationships between magnitude and distance for liquefaction, Tectonophysics, 32, 169–187, 2000.

Gasperini, P., Bernardini, F., Valensise, G., and Boschi, E.: Defining seismogeneic sources from historical earthquakes felt reports, B. Seismol. Soc. Am., 89, 94–110, 1999.

Gorum, T., Fan, X., van Westen, C. J., Huang, R. Q., Xu, Q., Tang, C., and Wang, G.: Distribution pattern of earthquake-induced landslides triggered by the 12 May 2008 Wenchuan earthquake, Geomorphology, 133, 152–167, 2008.

Graziani, L., Maramai, A., and Tinti, S.: A revision of the 1783–1784 Calabrian (southern Italy) tsunamis, Nat. Hazards Earth Syst. Sci., 6, 1053–1060, doi:10.5194/nhess-6-1053-2006, 2006.

Grünthal, G. (Ed.): European Macroseismic Scale 1998, Conseil de l'Europe, Cahiers du Centre Europèen de Gèodynamique et de Seismologie, vol. 15, 101 pp., 1998.

Grünthal, G. and Wahlström, R.: The European-Mediterranean Earthquake Catalogue (EMEC) for the last millennium, J. Seismol., 16, 535–570, 2012.

Gruppo di Lavoro CPTI: Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04), INGV, Bologna, http://emidius.mi.ingv.it/CPTI04/, 2004.

Guerrieri, L., Porfido, S., Esposito, E., Blumetti, A. M., Michetti, A. M., and Vittori, E.: Cataloguing Earthquake Environmental Effects: a tool for the comparison of recent historical and paleoearthquakes, Proc. 1st INQUA-IGCP-567 International Workshop on Earthquake Archaeology and paleoseismology, Baelo Claudia, Spain, 2009.

Harp, E. L., Keefer, D. K., Sato, H. P., and Yagi, H.: Landslide inventories: The essential part of seismic landslide hazard analyses, Eng. Geol., 122, 9–21, 2011.

Hoyois, P., Below, R., Scheuren, J. M., and Guha-Sapir, D.: Annual disaster statistical review: numbers and trends 2006, Centre for Research on the Epidemiology of Disasters, School of Public Health, Catholic University of Louvain, 54 pp., 2007.

Hsieh, S. U. and Lee, C. T. : Empirical estimation of the Newmark displacement from the Arias intensity and critical acceleration, Eng. Geol., 122, 34–42, 2011.

I.N.G.: Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980, edited by: Boschi E., Ferrari G., Gasperini P., Guidoboni E., Smriglio, G., and Valensise, G., ING-SGA, Bologna, 970 pp., 1995.

ISPRA: Carta Litotecnica d'Italia 1:100,000. Dipartimento Difesa del Suolo, available available at: http://sgi.isprambiente.it/geoportal/catalog/content/project/litologica.page, 2004.

Jibson, R. W.: Regression models for estimating coseismic landslide displacement, Eng. Geol., 91, 209–218, 2007.

Jibson, R. W. and Harp, E. L.: Extraordinary Distance Limits of Landslides Triggered by the 2011 Mineral, Virginia, Earthquake, BSSA, 102, 2368–2377, doi:10.1785/0120120055, 2012.

Jibson, R. W., Harp, E. L., and Michael, J.,M.: A method for producing digital probabilistic seismic landslide hazard maps: an example from the Los Angeles, California area, US Geological Survey Open-File Report, 98–113, 1998.

Keefer, D. K.: Landslides caused by earthquakes, Geol. Soc. Am. Bull., 95, 406–421, 1984.

Keefer, D. K.: Investigating landslides caused by earthquakes – A historical Review, Surv. Geohys., 23, 473–510, 2002.

Kirschbaum, D. B., Adler, R., Hong, Y., Hill, S., and Lerner-Lam, A.: A global landslide catalog for hazard applications: method, results, and limitations, Natural Hazards, 52, 561–575, 2010.

Mancini, B., Martino, S., Prestininzi, A., Rischia, I., and Romeo, W. R.: Studio delle condizioni di stabilità dei versanti a seguito di forti terremoti: applicazione ad un'area tipica dell'Appennino Centrale, Mem. Soc. Geol. It., 56, 83–98, 2001.

Martini, A.: Manuale di metrologia, Ed. Loescher, Torino, 1883.

Martino, S., Prestininzi, A., and Scarascia Mugnozza, G.: Geological-evolutionary model of a gravity-induced slope deformation in the carbonate Central Apennines (Italy), Q. J. Eng. Geol. Hydrogeol., 37, 31–47, 2004.

Meletti, C., Patacca, E., and Scandone, P.: Construction of a seismotectonic model: the case of Italy, Pure Appl. Geophys., 157, 11–35, 2000.

Michetti, A. M, Esposito, E., Gurpinar, A., Mohammadioun, B., Mohammadioun, J., Porfido, S., Rogozhin, E., Serva, L., Tatevossian, R., Vittori, E., Audemard, F., Comerci, V., Marco, S., Mccalpin, J., and Morner, N. A.: The INQUA Scale. An innovative approach for assessing earthquake intensities based on seismically-induced ground effects in natural environment. Memorie descrittive della Carta Geologica d'Italia, 67, 2004.

Michetti, A. M., Esposito, E., Guerrieri, L., Porfido, S., Serva, L., Tatevossian, R. Vittori, E. Audemard, F., Azuma, T., Clague, J., Comerci, V., Gürpinar, A., Mc Calpin, J., Mohammadioun, B., Mörner, N. A., Ota, Y., and Roghozin, E: Environmental Seismic Intensity scale – ESI 2007 La scala di Intensità Sismica basata sugli effetti ambientali – ESI 2007, Memorie descrittive della carta geologica D'Italia, LXXIV, APAT, 2007.

Minasi, A.: "Continuazione ed appendice sopra i tremuoti descritti nella relazione colla data di Scilla de 30 settembre 1783, con altro che accadde in progresso, Messina", 1785.

Musson, R. M. W., Grünthal, G., and Stucchi, M.: The comparison of macroseismic intensity scales, J. Seismol., 14, 413–428, 2010.

Petley, D.N., Dunning, S.A. and Rosser N.J.: The analysis of global landslide risk through the creation of a database of worldwide landslide fatalities, in: Landslide risk management, edited by: Hungr, O., Fell, R., Counture, R., and Ebergardt, E., Balkema, Amsterdam, 367–374, 2005.

Porfido, S., Esposito, E., Guerrieri, L., Vittori, E., Tranfaglia, G., and Pece, R.: Seismically induced ground effects of the 1805, 1930 and 1980 earthquakes in the Southern Apennines, Italy, Boll. Soc. Geol. It., 126, 333–346, 2007.

Postpischl, D.: Atlas of isoseismal Maps of italian Earthquakes, CNR-PFG, Quaderni de "La Ricerca Scientifica", 114, 2A, Bologna, 1985a.

Postpischl, D.: Catalogo dei forti terremoti italiani dall'anno 1000 al 1980, CNR-PFG, Quaderni de "La Ricerca Scientifica", 114, 2B, Bologna, 1985b.

Prestininzi, A.: Il ruolo degli eventi naturali sulla evoluzione urbana del centro abitato di Caulonia-Castelvetere (Reggio Calabria), Geologia Applicata ed Idrogeologia, 30-1, 393–405, 1995.

Prestininzi, A. and Romeo, R.: Earthquake-induced ground failures in Italy, Eng. Geol., 58, 387–397, 2000.

Richter, C. F.: Elementary seismology, Freeman, San Francisco, 1958.

Rodriguez, C. E., Bommer, J. J., and Chandler, R. J.: Earthquake-induced landslides: 1980–1997, Soil Dynam. Earthq. Eng., 18, 325–346, 1999.

Romeo, W. R.: Seismically induced landslide displacements: a predictive model, Eng. Geol., 58, 337–351, 2000.

Romeo R. W.: Emilia (Italy) M 5.9 earthquake on 20 May 2012: an unusual pattern of liquefaction, Ital. J. Eng. Geol. Environ., 2, 63–74, 2012.

Rovida, A., Camassi, R., Gasperini, P., and Stucchi, M.: CPTI11, the 2011 version of the Parametric Catalogue of Italian Earthquakes, edited by: Rovida, A., Camassi, R., Gasperini, P., and Stucchi, M., Milano, Bologna, http://emidius.mi.ingv.it/CPTI, 2011.

Sarconi, M.: Historia dé fenomeni del tremuoto avvenuto nella Calabria e nel Valdemone nell'anno 1783, Posti in luce alla Reale Accademia delle Scienze e delle Belle Lettere di Napoli, 1784.

Sepulveda, S. A., Murphy, W., Jibson, R. W., and Petley, D. N.: Seismically induced rock slope failures resulting from topographic amplification of strong ground motions: The case of Pacoima Canyon, California", Eng. Geol., 80, 336– 348, 2005.

Serva, L., Esposito, E., Guerrieri, L., Porfido, S., Vittori, E., and Comerci, V.: Environmental effects from five historical earthquakes in southern Apennines (Italy) and macroseismic intensity assessment: Contribution to INQUA EEE Scale Project, Quatern. Int., 173–174, 30–44, 2007.

Sieberg, A.: Geologische, physikalische und angewandte Erdbebenkunde, G. Fischer, Jena, 1923.

Sipkin, S. A., Person, W. J., and Presgrave, B. W.: Earthquake bulletins and catalogs at the USGS National Earthquake Information Center, IRIS Newsletter, 2000, 2–4, 2000.

Stucchi, M., Camassi, R., Rovida, A., Locati, M., Ercolani, E., Meletti, C., Migliavacca, P., Bernardini, F., and Azzaro, R.: DBMI04, il database delle osservazioni macrosismiche dei terremoti italiani utilizzate per la compilazione del catalogo parametrico CPTI04, Quaderni di Geofisica, 49, 38 pp., http://emidius.mi.ingv.it/DBMI04, 2007.

Tang, C., Zhu, J., Qi, X., and Ding, J.: Landslides induced by the Wenchuan earthquake and the subsequent strong rainfall event: A case study in the Beichuan area of China, Eng. Geol., 122, 22–33, doi:10.1016/j.enggeo.2011.03.013, 2011.

Tinti, S., Maramai, A., and Graziani, L.: The Italian Tsunami Catalogue (ITC), Version 2.0, avaiilable at: http://roma2.rm.ingv.it/en/facilities/data_bases/27/catalogue_of_the_italian_tsunamis, 2007.

Tosatti, G., Castaldini, D., Barbieri, M., D'Amato Avanzi, G., Giannecchini, R., Mandrone, G., Pellegrini, M., Perego, S., Puccinelli, A., Romeo, R. W., and Tellini, C.: Additional Causes of Seismically-Related Landslides in the Northern Apennines, Italy, Revista de geomorfologie, 10, 5–21, 2008.

Utsu, T.: A list of deadly earthquakes in the World: 1500-2000, in: International handbook of earthquake engineering and seismology, edited by: Lee, W. K., Kanamori, H., Jennings, P. C., and Kisslinger, C., Amsterdam, Academic Press, 691–717, 2002.

Vivenzio, G.: "Historia de' Tremuoti avvenuti nella Provincia della Calabria ulteriore e nella Città di Messina nell'anno 1783 e di quanto nella Calabria fu fatto per lo suo risorgimento fino al 1787 preceduta da una Teoria", Istoria Gen. De' Tremuoti, Vol. 1–2 Stamperia reale, Napoli, 1788.

Westaway, R. and Jackson, J. A.: Surface faulting in the southern Italian Campania-Basilicata earthquake of 23 Nov. 1980, Nature, 312, 436–438, 1984.

Youd, T. L. and Hoose, S. N.: Historic Ground Failures in Northern California Associated with Earthquakes: US Geological Survey Professional Paper 993, 177 pp. + 5 plates, 1978.

Zecchi, R.: Carta della distribuzione degli effetti geomorfologici indotti dai terremoti che hanno interessato l'Italia dall'anno 0 al 1986, Mem. Soc. Geol. It., 37, 823–826, 1987.