Nat. Hazards Earth Syst. Sci. Discuss., 1, 2041–2078, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/2041/2013/
doi:10.5194/nhessd-1-2041-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

Earthquake-induced ground failures in Italy from a reviewed database

S. Martino[1], A. Prestininzi[1], and R. W. Romeo[2]

[1]"Sapienza" University of Rome, Department of Earth Sciences and Research Centre for Geological Risks (CERI), P.le A. Moro 5 00185, Roma, Italy
[2]Department of Earth Sciences, Life and Environment, University of Urbino, "Carlo Bo", Italy

Received: 30 March 2013 – Accepted: 1 May 2013 – Published: 17 May 2013

Correspondence to: S. Martino (salvatore.martino@uniroma1.it)

Published by Copernicus Publications on behalf of the European Geosciences Union.

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-level changes triggered by earthquakes of Mercalli 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 (URL: http://www.ceri.uniroma1.it/cn/index.do?id=230\&page=55) 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-level 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, $M_w = 9.1$), eastern Sichuan (China 2008, $M_w = 7.9$) and Tohoku (Japan 2011, $M_w = 9.0$) 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

NHESSD
1, 2041–2078, 2013

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 been produced until recently. These inventories are generally part of the existing earthquake catalogues and are included in the recording of the effects reported for the listed earthquakes, but they are not organised efficiently for direct consultation.

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), does not include a direct listing

NHESSD
1, 2041–2078, 2013

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 – URL: http://gcmd.nasa.gov/), National Oceanic and Atmospheric Administration (NOAA – URL: http://maps.ngdc.noaa.gov/viewers/) and American Geophysical Union (AGU – URL: 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 $M_w = 6.4$, 1980 Irpinia $M_w = 6.9$, 1997 Umbria–Marche $M_w = 6.0$, 2009 L'Aquila $M_w = 6.2$), the last strong Italian earthquake, in May 2012 in Emilia ($M_w = 6.0$), proved that earthquake-induced ground effects can pose a risk as severe as the earthquake shaking itself (Romeo, 2012).

Over the last decade, many 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; CTI2.0 – Tinti et al., 2007; CPTI11 – Rovida et al., 2011). Nevertheless, apart from the tsunamis that are listed in the specific CTI 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

NHESSD
1, 2041–2078, 2013

release of CEDIT), in which different typologies of ground effects were reported (i.e. landslides, ground cracks, surface faulting, liquefaction and ground-level changes) over a period of approximately one millennium, from 1000 AD 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; URL: 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 so on). The EEE catalogue is used for site intensity assessments with the Environmental Seismic Intensity scale (ESI: Michetti et al., 2004, 2007), a macroseismic scale that replaces conventional intensity scales (e.g. Mercalli's scales) when structural damage data are not available and whose application has been tested in some earthquakes (Serva et al., 2007; Silva et al., 2008).

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).

NHESSD
1, 2041–2078, 2013

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 ($M_w = 6.0$); Pollino 1998 ($M_w = 5.7$); Molise ($M_w = 5.7$) and the southern Tyrrhenian Sea ($M_w = 5.9$), both in 2002; and L'Aquila 2009 ($M_w = 6.2$). 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 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 sites where earthquakes have produced some outstanding effect (Prestininzi, 1995; Mancini et al., 2000; Martino et al., 2004; Bozzano et al., 2004, 2008, 2011).

The CEDIT database includes approximately 3000 ground failures triggered by 165 earthquakes at almost 2000 sites over a time period of approximately one millennium (from 1117 to 2009 AD). The most recent earthquake, Emilia 2012 ($M_w = 6.0$), which triggered many ground failures such as liquefaction, lateral spreads and ground cracks, is not yet included because the related phenomena are still being examined and analysed.

The ground effects collected in the database fall into five main categories: landslides, ground cracks, liquefaction, surface faulting and ground-level changes. 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 datasheets 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” (sites), “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 (CTI 2.0; Tinti et al., 2007) and the Database of the Italian Seismogenic Sources (DISS 3.1.1; DISS WORKING GROUP, 2010). Sites 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; URL: http://www.istat.it/it/).

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 the URL http://www.ceri.uniroma1.it/cn/index.do?id=230\&page=55 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®-online and based on ESRI™ cloud technology. The system provides a geodatabase consulting and querying interface with graph or table outputs.

NHESSD
1, 2041–2078, 2013

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 hydrogeological hazards of the country. Similarly, another effect extensively investigated in recent years has been surface faulting, whose number of records has been greatly increased in the new database.

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 consistent number (approximately 32 %) are undefined.

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 that a scientific mission was launched to detect and report earthquake damage and collateral hazards (Sarconi, 1794). This mission 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.

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

NHESSD
1, 2041–2078, 2013

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, 1778; Minasi, 1785; De Lorenzo, 1877; Graziani et al., 2006). The second increase relates to the 1976 Friuli $M_w = 6.4$ 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). However, the catalogue is far from being complete, considering that most ground failures occur in scarcely populated areas, such as mountainous regions, and even for the most recent events, the detection of such effects can be incomplete because the survey of ground failures is often affected by the induced risk (e.g. damage to buildings, lifelines and infrastructures).

A minor increase in the cumulative number of ground failures can also be observed at the beginning of the 20th century. At that time, there were at least three huge earthquakes, above magnitude 7, that struck southern (1905 and 1908) and central Italy (1915).

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 magnitude 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, and this value roughly corresponds to epicentral intensity 8 on the Mercalli scale, which was chosen as the threshold intensity for the compilation of the catalogue. 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. Overall, the percentage of earthquakes with documented ground failures is relatively small when compared

NHESSD
1, 2041–2078, 2013

with the number of earthquakes that have hit Italy (approximately 7 %) because most of the earthquakes listed in the CPTI occurred in historical times, when attention mainly focused on building damage.

In 1987, Zecchi published a distribution map of the geomorphologic effects induced by earthquakes that hit Italy before 1986 AD. Unfortunately, the work did not include any database or table of the affected localities, only a map available in a printed format. Nevertheless, the distribution of the earthquakes listed as the triggering events, in terms of epicentral intensity, is shown in Fig. 6.

The threshold intensity according to the CEDIT database is between the 6th and 7th degree of the MCS intensity scale (Sieberg, 1923), which corresponds to a moment magnitude (M_w) of 4.5–5, whereas according to the Zecchi map, the threshold intensity may be lowered to intensity 5–6, corresponding to an M_w of 4–4.5.

The spatial distribution of the earthquakes and ground failures reported 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 $M_w = 6.4$ earthquake, 1997 Umbria–Marche $M_w = 6.0$ earthquake, 2009 L'Aquila $M_w = 6.2$ earthquake, 1980 Irpinia $M_w = 6.9$ earthquake and the earthquakes above $M_w = 6.5$ that hit the Calabria region in 1783, 1905 and 1908.

The lithological features of ground failures are shown in Fig. 8, and they were attributed based on an official 1 : 250 000 Italian geological map (APAT, 2004, available on-line at http://www.isprambiente.gov.it/en/projects/the-geological-map-of-italy-1-250000-scale). This feature is the least reliable because most of the ground failures reported in the oldest earthquakes are only approximately located due to the poor information retrieved from historical chronicles.

Debris and alluvial deposits, along with limestone, are the most represented lithological units. These units are also the most represented in liquefaction and landslides, respectively, which is expected, considering that most of the reported landslides are falls and topples that affect hard rock, particularly limestone, which widely outcrops in the Apennines chain. The inconsistency of some effects and the corresponding lithological units (e.g. liquefaction and lithological units different from debris and alluvia) can be explained by the already cited approximate location of the oldest effects and the fact that the geological map used to associate lithological units to ground failures was a countrywide map reporting only the geological substratum.

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 where a specific type of ground failure was reported.

In the database, landslides and ground cracks have been reported for at least 50 % of the earthquakes in each magnitude class. The percentage of earthquakes triggering all types of ground failure progressively increases as the earthquake magnitude increases in turn, reaching 100 % for all ground failures at the highest class ($M_w = 7.5$). Surface faulting alone is not reported for magnitudes greater than 7 because the records involve earthquakes that occurred prior to 1910 AD, when such an effect was still not well understood by the scientific community.

The relative abundance of ground failures per earthquake magnitude is shown in Fig. 10. The most represented types of ground failure in all magnitude classes are landslides and ground cracks (Fig. 10a). This finding is not surprising considering that the two effects are strictly related to each other, as ground cracks often represent the early status of mass movements and, vice versa, landslides are always linked to ground cracks. Moreover, landslides are the most reported ground failures triggered by earthquakes because they are the most threatening to humans, often causing damage, casualties and property loss. Nevertheless, liquefaction, surface faulting and ground-level changes increase much more than landslides and ground cracks with the increase

NHESSD
1, 2041–2078, 2013

of earthquake magnitude (Fig. 10b) because they are much more closely related to the earthquake source energy than other environmental effects.

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).

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 (Grunthal, 1998).

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-level 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). The definition of threshold intensity for surface faulting is quite misleading because such an environmental effect is improperly put into a database of ground failures or secondary effects due to seismic shaking, but it should be regarded as a primary effect due to fault rupture, as with tsunamis.

Figure 12 shows the probability of a ground-failure-type occurrence given an observed site intensity. Ground cracks display higher occurrence probabilities than landslides for the lowermost site intensities, whereas ground-level changes and liquefaction have practically the same occurrence probabilities over the entire site intensity range, with a lower occurrence probability compared with landslides and ground cracks. These

NHESSD
1, 2041–2078, 2013

probabilities prove that liquefaction and ground-level changes require a seismic shaking higher than that required to trigger ground cracks or landslides.

Source-to-site distance is the key parameter for characterising the susceptibility of an area to failures triggered by earthquakes. In fact, the distance from the earthquake source primarily drives the propagation of the seismic shaking in terms of amplitude, duration and frequency content. Thus, a relationship between the earthquake energy release and the distance at which ground failures can occur is straightforward.

Figure 13 shows the relative distribution of ground failures as a function of the epicentral distance. At the shortest distances (i.e. within 10 km), there is a substantial invariance in the distribution of ground failures, led by the constant energy release of the earthquake source in the near field. The modal distance for all ground failure types is between 10 and 20 km, which is consistent with the shortest distance from the fault rupture that would represent the best characterisation of the source-to-site distance. Starting from this distance, the local interaction between seismic waves and site conditions becomes more effective, although, the effectiveness progressively decreases as the epicentral distance increases.

The exceedance probabilities as a function of distance are poorly differentiated among the ground-failure types because of the exclusion from the relationship of the earthquake magnitude. What can be inferred is that at short distances (within 30 km), landslides and ground cracks have larger exceedance probabilities than liquefaction and ground-level changes (surface faulting is not displayed because the resulting relationship is statistically meaningless).

The maximum epicentral distances at which landslides and liquefaction have been reported as a function of the earthquake magnitude are compared in Fig. 14.

Ground cracks are not displayed because the distance distribution is not significantly different from that of landslides, whereas surface faulting and ground-level changes are not shown because of the rare instances that make their statistical distributions meaningless. Filled circles refer to statistical outliers, indicating that these data points significantly deviate from the assumption of a linear distribution. These data points also

NHESSD
1, 2041–2078, 2013

refer to earthquakes of small magnitudes that occurred in pre-instrumental times, when the reliability of the determination of earthquake severity was poor or the exact location of the ground failure uncertain.

The solid lines indicate the best estimate (regression fits) of the maximum epicentral distances at which landslides (red curve) and liquefaction (blue curve) occur. Data regarding landslides are more scattered than liquefaction, and the related fit has a wider dispersion, as apparent when looking at the scatter between the best estimate (solid line) and the upper bound (dashed line) of landslides compared to liquefaction.

5 Conclusions

This paper describes the new release of the CEDIT catalogue, a database of information on 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 the URL http://www.ceri.uniroma1.it/cn/index.do?id=230\&page=55.

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-level 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 may account for the seismic shaking responsible for the triggering of 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-level changes (7–8 MCS).

Magnitude-distance relationships, drawn for landslides and liquefaction, indicate that landslides may be triggered at greater distances than liquefaction, even if the scatter of the relationship for landslides makes the estimate of the expected maximum distance less reliable than for liquefaction given an earthquake magnitude.

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 sediment when the feature formed (e.g. relative density, degree of saturation, boundary stress conditions, and so on), and this the reason because 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 and 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 increasing recent availability of high-quality ground-motion records make it possible in some instances to tentatively approach this important target. Therefore, we anticipate that studies are in progress to analyse the relationships between ground effects and the triggering shaking levels for the most recent events included in the database (i.e. from the 1976 Friuli $M_w = 6.4$ earthquake) using multiple approaches for assessing the ground motion values at the affected sites, such as specifically derived attenuation relations to estimate the ground motion values and geostatistical analyses to extrapolate recorded ground-motion values to sites where ground failures have been detected.

Acknowledgements. The authors wish to thank C. Fortunato for her contributions on data cataloguing and A. Fantini, F. Nardoni and P. Sarandrea for mastering the online version of the CEDIT.

NHESSD
1, 2041–2078, 2013

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.

APAT: Carta Geologica d'Italia 1:250,000. Dipartimento Difesa del Suolo, available at: http://www.isprambiente.gov.it/images/progetti/progetto-1250-ita.jpg, last access: December 2012.

Bommer, J. J. and Rodrıguez, 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, available at: http://emidius.mi.ingv.it/NT/CONSNT.html (last access: December 2012), 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.

Costanzo, A., D'onofrio, A., and Silvestri, F.: Numerical simulations of the ground deformation recorded in the historical town of Gerace during seismic events in Calabria (1783), Proc.

4th International Conference on Earthquake Geotechnical Engineering, 25–28 June 2007, Paper No. 1613, 2007.
DBMI04: Database Macrosismico Italiano, INGV, available at: http://emidius.mi.ingv.it/DBMI04 (last access: December 2012), 2004.
D'Elia, B., Esu, F., Pellegrino, A., and Pescatore, T. S.: Some effects on natural slope stability induced by the 1980 Italian earthquake, Proc. XI International Conference on Soil Mechanics and Foundation Engineering, S. Francisco (12–16 August 1985), Balkema (Rotterdam), 4, 1943–1950, 1985.
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.
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.
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, available at: http://diss.rm.ingv.it/diss/ (last access: December 2012), 2010.
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.
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.: European Macroseismic Scale 1998, Cahiers du Centre Europèen de Gèodynamique et de Seismologie, Conseil de l'Europe, Conseil de l'Europe, 1998.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

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, available at: 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.
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.
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. Geophys., 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, Nat. 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.

NHESSD
1, 2041–2078, 2013

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. Hydrogeology, 37, 31–47, 2004.

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 pp., 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", n.114, 2A, Bologna, 1985a.

Postpischl, D.: Catalogo dei forti terremoti italiani dall'anno 1000 al 1980. CNR-PFG, Quaderni de "La Ricerca Scientifica", n.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, R. W.: 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, Italian 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, Milano, Bologna, available at: http://emidius.mi.ingv.it/CPTI (last access: December 2012), 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, 1794.
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, Quaternary 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.
Silva, P. G., Rodríguez Pascua, M. A., Pérez-López, R., Bardaji, T., Lario, J., Alfaro P., Martínez-Díaz, J. J., Reicherter, K., Giménez García, J., Giner, J., Azañón, J. M., Goy, J. L., and Zazo, C.: Catalogacion de los efectos geologicos y ambientales de los terremotos en Espana en la Escala ESI 2007 y su aplicacion a los estudions paleosismologicos, Geotemas, 6, 1063–1066, 2008.
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., available at: http://emidius.mi.ingv.it/DBMI04, 2007.

NHESSD
1, 2041–2078, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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, available at: http://roma2.rm.ingv.it/en/facilities/data_bases/27/catalogue_of_the_italian_tsunamis (last access: December 2012), 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, 1778.

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.

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

#eqk	Id-CPTI	Id-CEDIT	Date (YYYY-MM-DD)	epicenter Lat°	epicenter Long°	I_o (MCS)	M_w	Sites	Landslides	Ground-cracks	Liquefaction	Surface-faulting	Ground-changes
1	30	231	1117-01-03	45.330	11.200	9.5	6.49	2			1		1
2	33	1528	1125-10-11	41.600	15.000	8.0	5.71	1		1			
3	37	1946	1169-02-04	37.320	15.030	10.0	6.60	3	1	1	3		
4	40	1599	1184-05-24	39.430	16.250	9.0	6.00	1	1				
5	47	249	1222-12-25	45.480	10.680	8.5	6.05	5	4	2			
6	50	1237	1231-06-01	41.480	13.830	7.0	5.35	1	2	1			
7	55	197	1268-11-04	45.730	12.080	7.5	5.37	1	1				
8	63	1100	1279-04-30	43.093	12.872	10.0	6.33	1	1				
9	94	86	1348-01-25	46.254	12.883	9.5	6.66	2	1	2	1		
10	95	1238	1349-09-09	41.480	14.070	10.0	6.62	3	2	1			
11	135	646	1414-08-07	43.271	11.120	7.5	5.66	1		1			
12	153	1451	1456-12-05	41.302	14.711	10.0	6.96	13	4	8			3
13	202	762	1505-01-03	44.480	11.250	7.0	5.47	2	1	1	2		
14	208	1698	1509-02-25	38.100	15.680	8.0	5.57	1	1	1			
15	210	91	1511-03-26	46.200	13.430	9.0	6.51	1	1				
16	238	778	1542-06-13	44.000	11.380	9.0	5.91	1			1		
17	240	1950	1542-12-10	37.220	14.950	10.0	6.62	1			2		
18	241	543	1545-06-09	44.498	9.844	7.5	5.33	4	2	1	1		2
19	256	1548	1561-08-19	40.520	15.480	9.5	6.36	6	3	3	2		
20	259	468	1564-07-20	44.022	7.278	8.5	5.79	2	1	1			
21	262	868	1570-11-17	44.820	11.630	7.5	5.48	10	1	8	14		4
22	308	780	1611-09-08	44.020	11.370	7.0	5.13	1		1			
23	311	1837	1613-08-25	38.120	14.780	8.0	5.57	1	1	2			
24	323	870	1624-03-18	44.650	11.850	7.5	5.43	2		1	3		1
25	327	1643	1626-04-04	38.820	16.420	9.0	6.08	2		2			
26	330	1476	1627-07-30	41.730	15.350	10.0	6.73	15	5	8	10		2
27	341	1604	1638-03-27	39.030	16.280	11.0	7.00	15	4	11	4	1	2
28	343	1329	1639-10-07	42.636	13.252	10.0	6.26	1					1
29	349	471	1644-02-15	43.980	7.320	8.5	5.88	1	1				
30	358	1240	1654-07-23	41.630	13.680	9.5	6.17	3	1	2			
31	361	1651	1659-11-05	38.700	16.250	10.0	6.50	6	2	5			
32	365	286	1661-03-12	45.730	10.070	7.0	5.17	4	4	2			
33	366	801	1661-03-22	44.020	11.900	9.0	5.83	6		5	1		
34	393	834	1688-04-11	44.390	11.942	9.0	5.88	2	2	1			1
35	394	1454	1688-06-05	41.280	14.570	11.0	6.72	14	4	9	4		1
36	407	99	1692-05-00	46.350	12.800	7.0	5.17	1	1				
37	410	1951	1693-01-11	37.130	15.020	11.0	7.41	20	7	11	16		4
38	414	1549	1694-09-08	40.880	15.350	10.5	6.87	12	5	9			
39	417	903	1695-06-11	42.612	12.110	8.5	5.77	1	1	1			
40	424	1932	1698-04-12	37.312	14.878	7.0	5.25	1	1				
41	430	1531	1702-03-14	41.120	14.980	9.5	6.32	1	1				
42	434	1107	1703-01-14	42.680	13.120	11.0	6.81	5	2	3			
43	435	1332	1703-02-02	42.470	13.200	10.0	6.65	2			3		
44	439	419	1703-12-28	44.780	7.505	7.5	5.37	1	1				
45	445	1392	1706-11-03	42.080	14.080	9.5	6.60	5	2	3			
46	484	1903	1726-09-01	38.120	13.350	8.0	5.61	2	1	1			
47	496	1480	1731-03-20	41.270	15.750	9.0	6.34	1			3		
48	513	1841	1739-05-10	38.100	14.750	8.0	5.54	4	2	3			1
49	520	1965	1743-02-20	39.850	18.780	9.5	6.90	2		2			
50	526	546	1746-07-23	44.088	10.444	6.0	4.83	2	3				
51	535	1073	1751-07-27	43.222	12.730	10.0	6.30	1	1				
52	540	420	1753-03-09	44.930	7.180	6.5	5.25	3	1	2	2		
53	575	803	1768-10-19	43.930	11.870	9.0	5.84	1		1			
54	601	907	1777-10-05	42.880	11.756	7.5	5.37	1	1				
55	616	840	1781-04-04	44.235	11.797	9.0	5.84	4		4	5		
56	618	1075	1781-06-03	43.594	12.506	9.5	6.23	5	5	4			
57	619	841	1781-07-17	44.280	11.950	8.0	5.53	1					1

Table 1. Continued.

#eqk	Id-CPTI	Id-CEDIT	Date (YYYY-MM-DD)	epicenter Lat°	epicenter Long°	I_o (MCS)	M_w	Sites	Landslides	Ground-cracks	Liquefaction	Surface-faulting	Ground-changes
58	626	1655	1783-02-05	38.300	15.970	11.0	6.91	98	58	47	70		32
59	628	1656	1783-02-07	38.580	16.200	10.5	6.59	20	11	8	6		4
60	629	1657	1783-03-01	38.770	16.300	9.0	5.92	1		1			
61	630	1644	1783-03-28	38.780	16.470	10.0	6.94	26	10	13	23		3
62	637	1688	1784-10-14	38.293	16.210	7.0	5.09	1	1				
63	643	1115	1785-10-09	42.564	12.777	8.0	5.48	2		1	3		
64	651	1200	1786-12-25	43.980	12.580	8.0	5.67	1	1	1	1		
65	661	116	1788-10-20	46.398	13.019	8.5	5.71	1		1			1
66	663	1023	1789-09-30	43.505	12.208	8.5	5.80	1			2		1
67	667	1116	1791-10-11	42.972	12.824	7.5	5.32	1		1			
68	668	1662	1791-10-13	38.630	16.270	9.0	5.92	1		1			
69	687	1117	1799-07-28	43.147	13.123	9.0	5.93	2		1			1
70	694	289	1802-05-12	45.420	9.850	8.0	5.67	3		2	2		
71	700	1457	1805-07-26	41.500	14.470	10.0	6.57	42	32	19	6	4	2
72	710	423	1808-04-02	44.830	7.250	8.0	5.67	9	2	8			
73	714	257	1810-05-01	45.764	10.809	6.0	4.83	1		1			
74	736	1767	1818-02-20	37.600	15.130	9.0	6.00	9		7	6		
75	739	1882	1818-09-08	37.820	14.080	7.5	5.31	3	3	2			
76	752	1843	1823-03-05	38.000	14.100	8.5	5.87	9	3	7	2		2
77	759	1552	1826-02-01	40.520	15.730	8.0	5.68	2	2		2		
78	770	1427	1828-02-02	40.750	13.900	8.0	5.57	1	1				
79	776	523	1828-10-09	44.820	9.050	7.5	5.67	7	7				
80	790	474	1831-05-26	43.850	7.850	8.0	5.54	2	2	1			
81	795	1025	1832-01-13	42.967	12.659	8.5	5.80	5		3	5		
82	797	1632	1832-03-08	39.070	16.900	9.5	6.48	7	3	4	7		
83	798	617	1832-03-13	44.770	10.470	7.5	5.59	3		1	1		1
84	801	549	1834-02-14	44.449	9.859	8.5	5.64	1	1	1			1
85	808	1608	1835-10-12	39.330	16.300	9.0	5.91	2	3	1			
86	811	1595	1836-04-25	39.570	16.730	9.0	6.16	4	1	3	3		2
87	815	1554	1836-11-20	40.150	15.780	8.0	5.83	2	2	2			
88	819	552	1837-04-11	44.174	10.181	9.5	5.65	1	1	1			1
89	855	670	1846-08-14	43.531	10.500	8.5	5.71	11	3	5	14		
90	878	1535	1851-08-14	40.950	15.670	9.5	6.33	6	7	3			
91	886	126	1853-02-19	46.383	13.100	7.0	5.17	1	1				
92	887	1556	1853-04-09	40.820	15.220	9.0	5.90	3	2	2			
93	893	1610	1854-02-12	39.250	16.300	9.5	6.15	16	11	14	4		
94	899	376	1855-07-25	46.217	7.850	8.5	5.81	4	3		1		
95	912	1557	1857-12-16	40.350	15.850	10.5	6.96	35	32	21	2	1	2
96	945	1772	1865-07-19	37.700	15.150	9.0	5.03	15	5	13		6	
97	950	261	1866-08-11	45.727	10.783	7.0	5.17	1	1				
98	970	1612	1870-10-04	39.220	16.330	9.5	6.16	7	4	3	3		
99	985	184	1873-06-29	46.150	12.380	9.5	6.33	16	9	13	1		
100	1000	1207	1875-03-17	44.070	12.550	8.0	5.74	2		2	2		
101	1003	1508	1875-12-06	41.689	15.677	7.5	6.07	1			1		
102	1005	263	1876-04-29	45.750	10.780	7.0	4.99	1	1	1			
103	1043	1774	1879-06-17	37.680	15.150	9.0	5.06	6	4	2			
104	1066	1396	1881-09-10	42.230	14.280	8.0	5.59	1	1	1			1
105	1082	4003	1882-09-18	45.720	10.770	7.0	5.17	1	1				
106	1088	1434	1883-07-28	40.750	13.880	9.0	5.78	9	7	4			
107	1111	1537	1885-09-17	41.133	14.800	7.0	5.17	1		1			
108	1121	425	1886-09-05	45.036	7.306	6.5	5.27	1	1				
109	1128	479	1887-02-23	43.920	8.070	9.0	6.29	25	9	15	6		2
110	1136	1619	1887-12-03	39.570	16.220	8.0	5.52	3	3				
111	1154	134	1889-10-13	46.400	13.000	7.0	5.17	1		1			
112	1170	242	1891-06-07	45.570	11.170	8.5	5.71	7	5	2			
113	1186	399	1892-03-05	45.569	7.797	7.0	5.09	2	2				

NHESSD
1, 2041–2078, 2013

Table 1. Continued.

#eqk	Id-CPTI	Id-CEDIT	Date (YYYY-MM-DD)	epicenter Lat°	epicenter Long°	I_o (MCS)	M_w	Sites	Landslides	Ground-cracks	Liquefaction	Surface-faulting	Ground-changes
114	1207	1511	1893-08-10	41.720	16.080	8.0	5.44	2	2	2			
115	1212	1494	1894-03-25	41.867	15.323	7.0	5.17	1		1			
116	1215	1785	1894-08-08	37.650	15.120	9.5	5.23	5	3	4			
117	1216	1668	1894-11-16	38.280	15.870	8.5	6.05	24	10	17	3		5
118	1229	1034	1895-05-20	42.750	12.700	7.0	5.17	1		1			
119	1291	584	1898-03-04	44.503	10.314	6.5	5.07	2	1		1		
120	1299	1132	1898-06-27	42.415	12.905	7.5	5.48	1	1				
121	1304	1939	1898-11-02	37.216	14.495	5.5	4.63	1			1		
122	1340	426	1901-03-29	45.167	7.167	6.0	4.63	1			1		
123	1342	986	1901-04-24	42.100	12.736	7.5	5.15	1		1	1		
124	1353	270	1901-10-30	45.580	10.500	8.0	5.67	2	2	1			1
125	1356	555	1902-03-05	44.093	10.463	7.0	5.17	2	2		1		
126	1384	1303	1904-02-24	42.100	13.320	8.5	5.67	8		8			
127	1420	1672	1905-09-08	38.670	16.070	11.0	7.06	60	33	33	23		6
128	1463	1752	1907-10-23	38.130	16.020	8.5	5.93	12	12	6			
129	1495	1728	1908-12-28	38.150	15.680	11.0	7.24	58	47	25	5		9
130	1511	686	1909-08-25	43.150	11.403	7.5	5.40	1					1
131	1555	1800	1911-10-15	37.700	15.150	10.0	5.28	8	1	6		1	5
132	1581	1597	1913-06-28	39.530	16.230	8.0	5.65	3	1	2			
133	1596	1803	1914-05-08	37.670	15.130	9.0	5.30	14	3	10		5	5
134	1604	428	1914-10-26	45.072	7.337	7.0	5.36	1	1				
135	1608	1308	1915-01-13	42.013	13.530	11.0	6.99	66	41	38	12	3	9
136	1630	1212	1916-05-17	44.000	12.630	8.0	5.85	1		1			
137	1637	1213	1916-08-16	43.970	12.670	8.0	5.92	5		3	7		1
138	1650	1046	1917-04-26	43.465	12.125	9.0	5.80	4	1	3	3		
139	1651	990	1917-05-12	42.580	12.630	7.5	5.11	1	1				
140	1684	788	1919-06-29	43.950	11.480	9.0	6.18	7	3	5	4		
141	1687	918	1919-09-10	42.793	11.788	8.0	5.38	1			1		
142	1708	563	1920-09-07	44.180	10.280	9.5	6.48	23	25	6			1
143	1800	974	1927-12-26	41.700	12.700	7.0	5.02	1	2				
144	1805	147	1928-03-27	46.372	12.975	8.5	5.75	17	26	4			
145	1841	1543	1930-07-23	41.050	15.370	10.0	6.72	29	32	15		4	2
146	1847	1218	1930-10-30	43.659	13.331	9.0	5.94	2	1		1		
147	1886	1409	1933-09-26	42.050	14.180	8.5	5.68	2	2				
148	1921	192	1936-10-18	46.088	12.380	9.0	5.90	6	2	5			1
149	1950	573	1939-10-15	44.119	10.255	6.5	5.20	1	1				
150	1995	527	1945-06-29	44.830	9.130	7.5	5.15	1	1				
151	2007	1692	1947-05-11	38.650	16.520	8.0	5.71	1	1				
152	2175	1471	1962-08-21	41.130	14.970	9.0	6.19	2	1			1	1
153	2246	1925	1968-01-15	37.770	12.980	10.0	6.12	15	7	9	7		
154	2294	932	1971-02-06	42.442	11.846	7.5	4.90	2	2	1			1
155	2363	177	1976-05-06	46.241	13.119	9.5	6.43	103	84	17	46		14
156	2366	178	1976-09-15	46.250	13.120	8.5	5.92	9	5	5	5		2
157	2400	1186	1979-09-19	42.720	13.070	8.5	5.90	1	1				
158	2413	1587	1980-11-23	40.850	15.280	10.0	6.89	216	239	119	27	86	17
159	2441	9030	1984-05-07	41.666	14.057	8.0	5.93	6	4	2			
160	2478	9058	1990-12-13	37.266	15.121	7.0	5.68	1			2		
161	2515	5001	1997-09-26	43.019	12.879	8.5	6.05	203	194	82		3	4
162	2522	5002	1998-09-09	40.038	15.937	6.5	5.68	51	56	5		2	
163	2546	5003	2002-09-06	38.081	13.422	6.0	5.90	1	1	1			
164	2550	5004	2002-10-31	41.694	14.925	7.5	5.70	1	1	1	1		
165		5005	2009-04-06	42.334	13.334	9.0	6.20	168	95	5	5	65	1

NHESSD
1, 2041–2078, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◂◂ | ▸▸
◂ | ▸
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

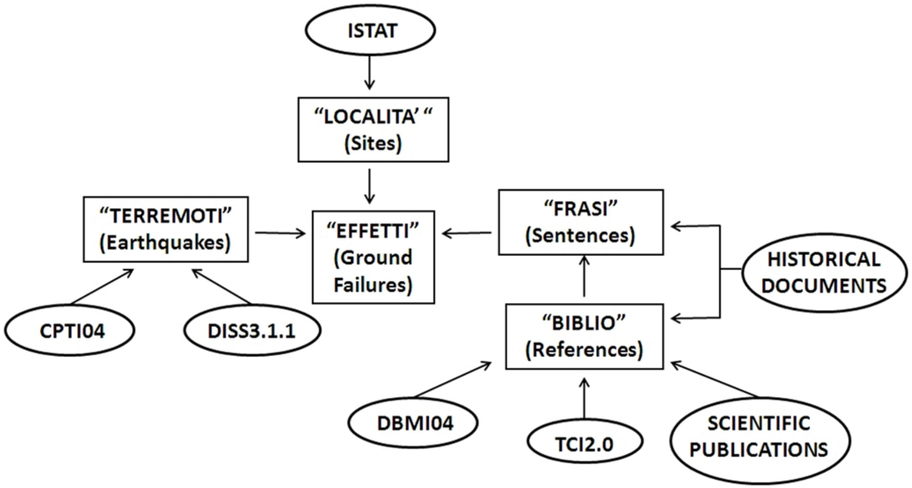

Fig. 1. Database structure of the CEDIT catalogue and links to the CPTI04 earthquake catalogue (Gruppo di lavoro CPTI, 2004), the DBMI04 macroseismic catalogue (Stucchi et al., 2007), the CTI 2.0 tsunami catalogue (Tinti et al., 2007) and the DISS 3.1.1 seismic sources database (DISS WORKING GROUP, 2010).

NHESSD
1, 2041–2078, 2013

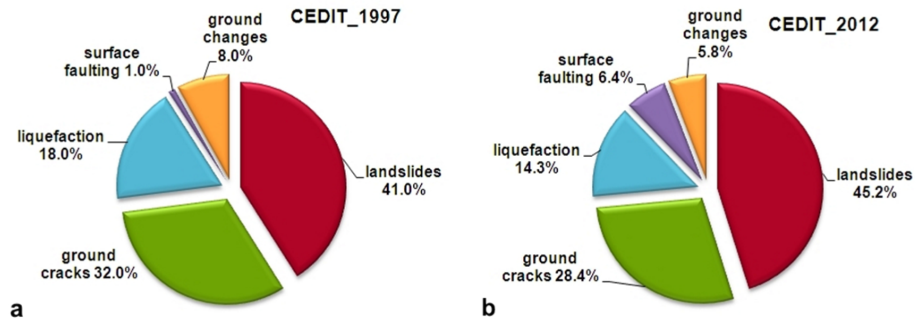

Fig. 2. Percentage of ground failures included **(a)** in the first version (approximately 1700 effects) and **(b)** in the current version (approximately 2900 effects) of the CEDIT database.

NHESSD
1, 2041–2078, 2013

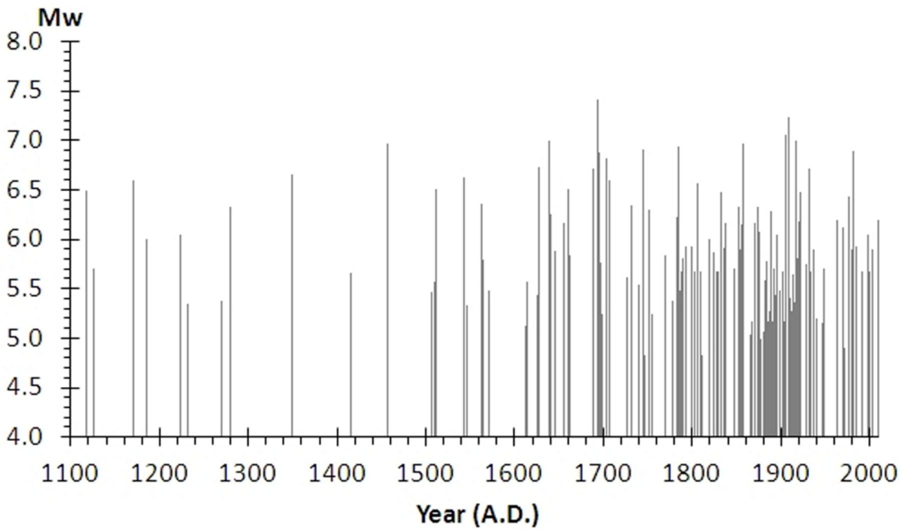

Fig. 3. Time distribution of earthquake magnitudes reported in the CEDIT database.

NHESSD
1, 2041–2078, 2013

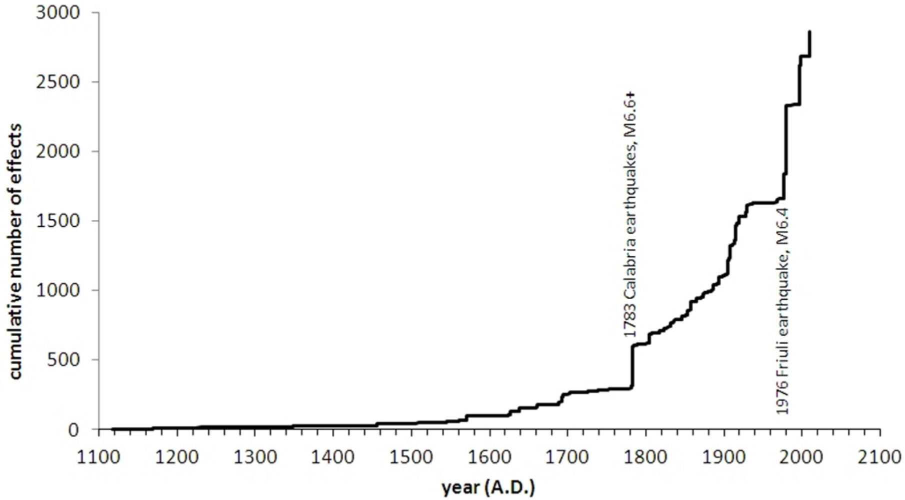

Fig. 4. Time distribution of ground failures reported in the CEDIT database.

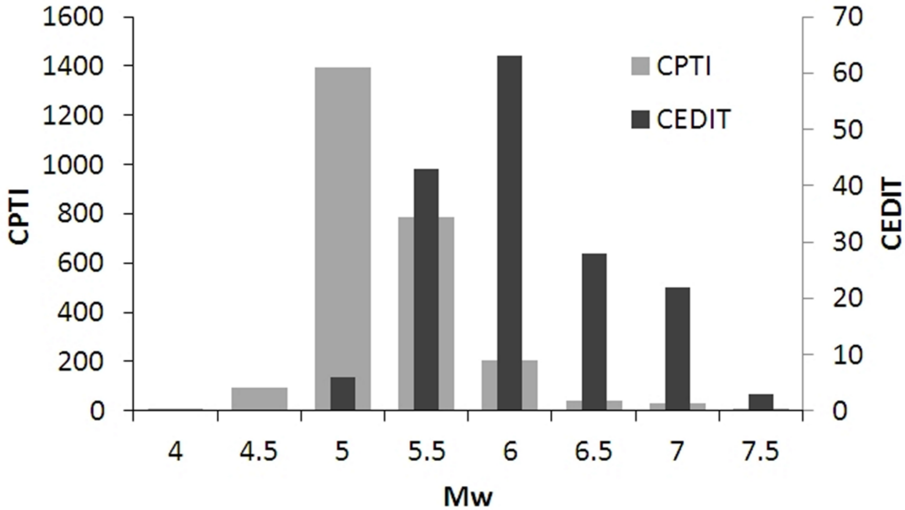

Fig. 5. Number of earthquakes per magnitude class reported in the CPTI earthquake catalogue and in the CEDIT database. (Note the different scale of the vertical axes).

NHESSD

1, 2041–2078, 2013

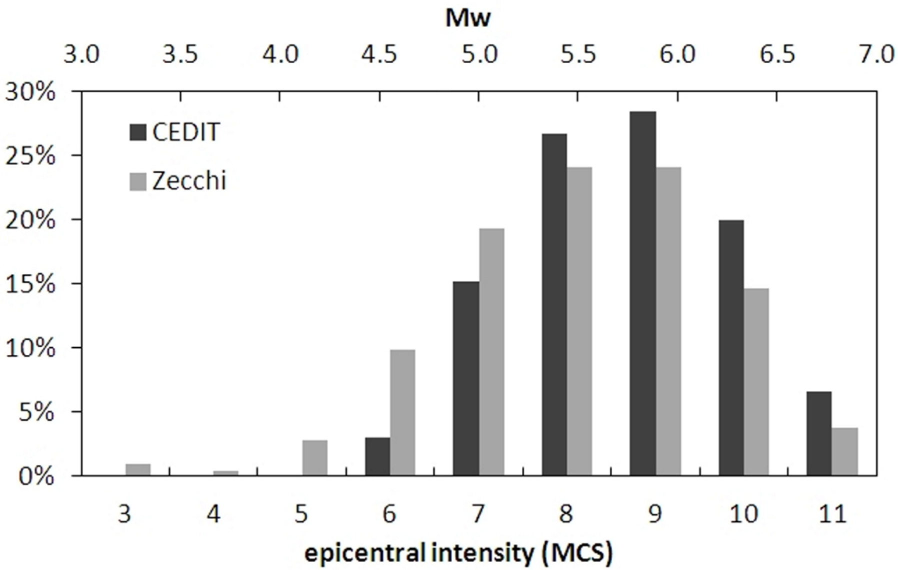

Fig. 6. Relative distribution of earthquakes that triggered ground failures in Italy as reported on the map created by Zecchi (1987) and in the CEDIT database. The upper x-axis shows an approximate conversion of epicentral intensity into moment magnitude.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

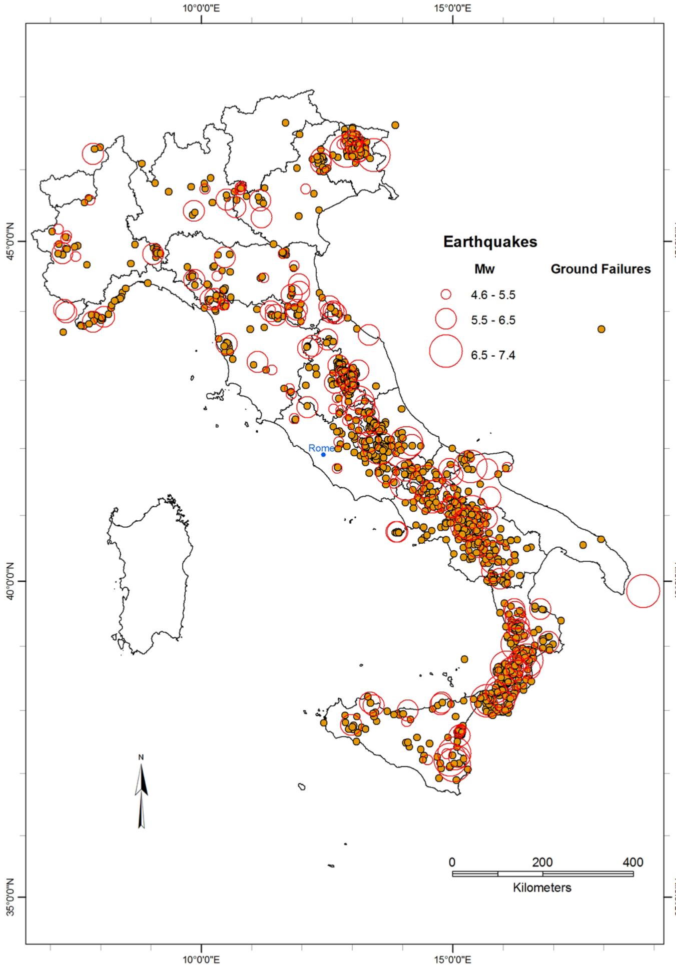

Fig. 7. Spatial distribution of earthquakes and related triggered ground failures reported in the CEDIT database.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

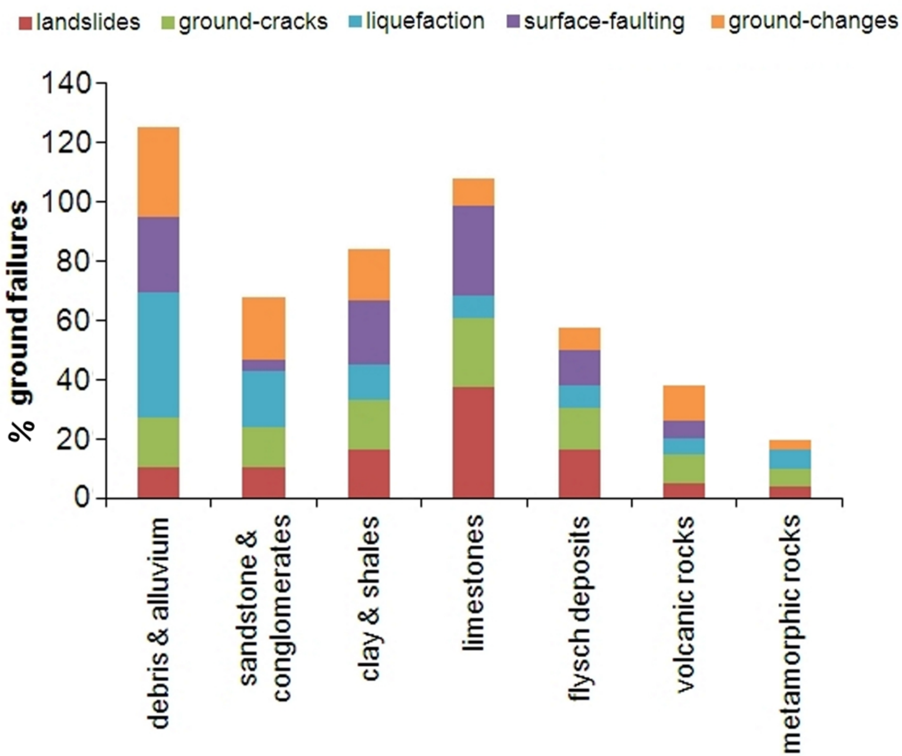

Fig. 8. Percentage of ground failures per lithological unit.

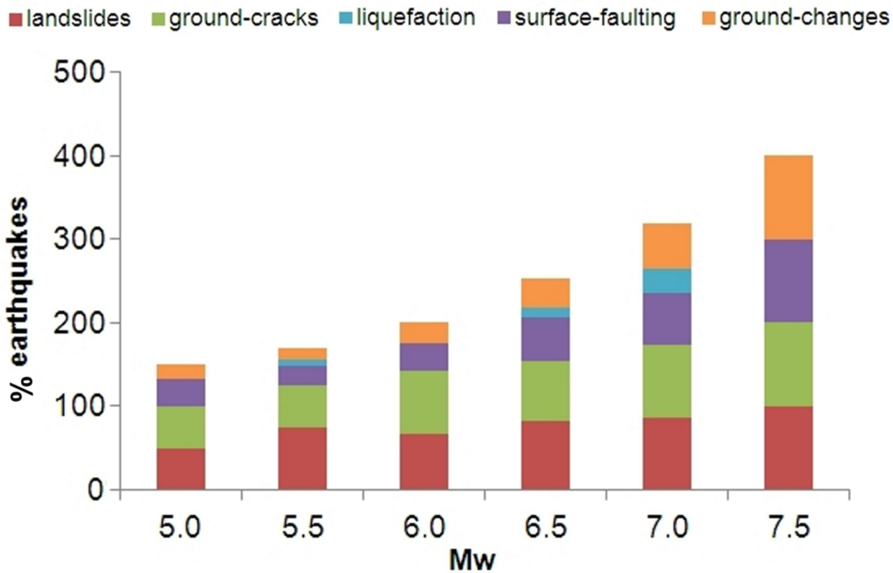

Fig. 9. Percentage of earthquakes in each magnitude class reporting different types of ground failure.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

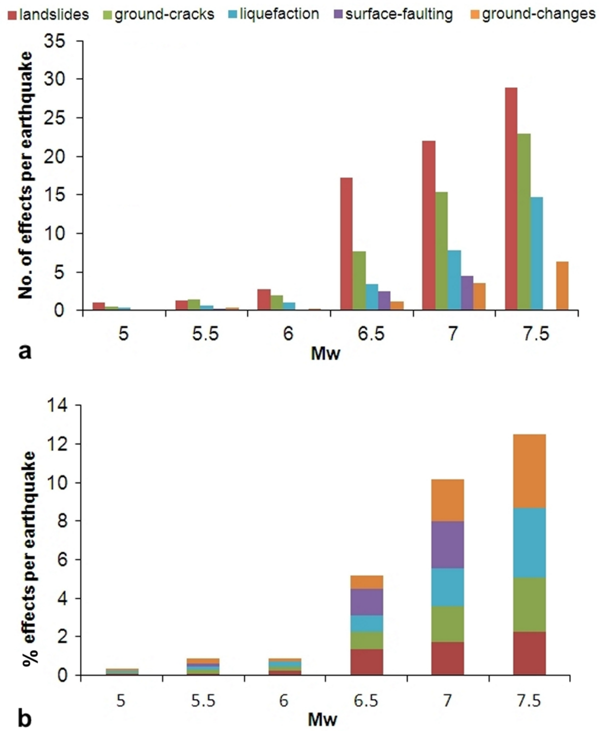

Fig. 10. Absolute **(a)** and relative **(b)** frequency of ground failures per earthquake magnitude class.

NHESSD

1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

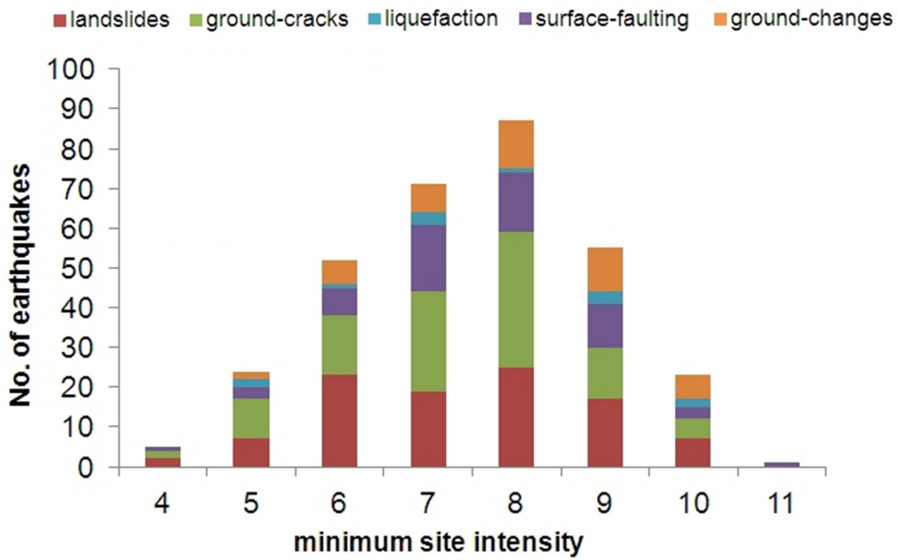

Fig. 11. Minimum site intensity at which ground failures occurred in earthquakes listed in the CEDIT database.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

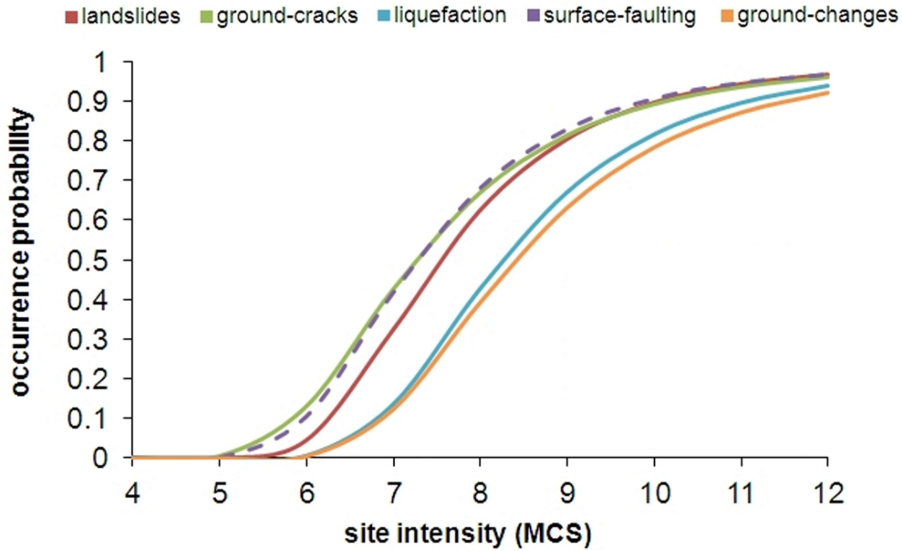

Fig. 12. Occurrence probability of ground-failure types as a function of the local site intensity.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

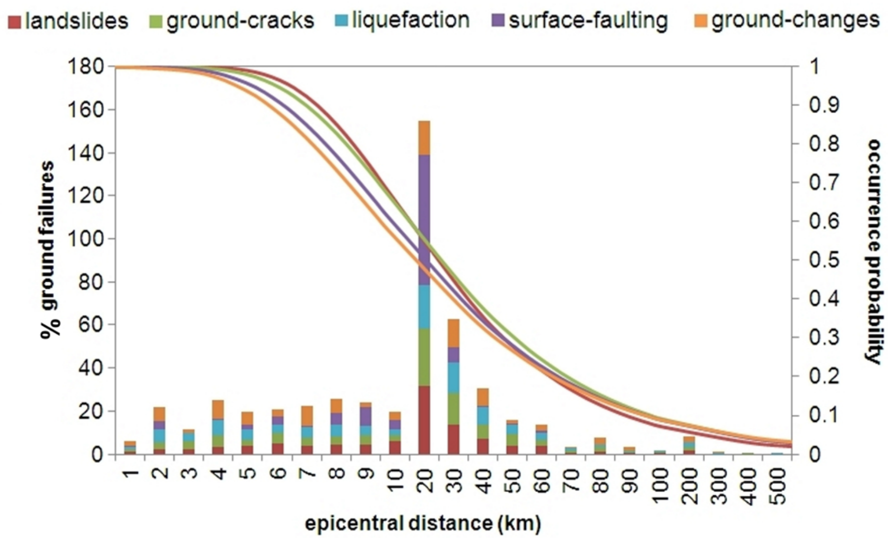

Fig. 13. Relative distribution and occurrence probability of ground failures as a function of the epicentral distance.

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

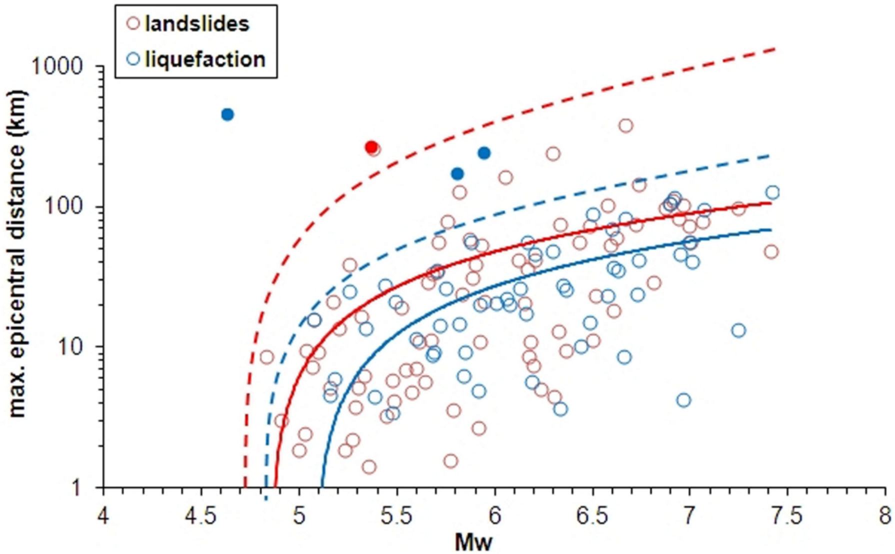

Fig. 14. Maximum epicentral distances as a function of the earthquake magnitude at which landslides and liquefaction have been detected (filled circles mark outliers; solid lines best estimate; dashed lines upper bound).

NHESSD
1, 2041–2078, 2013

Earthquake-induced ground failures in Italy

S. Martino et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion