An upgrade of the Italian catalogue of earthquake-induced ground failures CEDIT

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SUMMARY
An upgrade of the Italian catalogue (CEDIT) of ground failures triggered by earthquakes with epicentral intensity MMI-8 or greater occurred in the last millennium, is here presented. The ground effects include landslides, liquefaction, ground cracks, surface faulting and topographical changes. The first edition of the catalogue was released in 1997 and it included earthquakes up to 1980 A.D. The present release includes the following upgrades: the review of some relevant historical earthquakes (1805 Molise, 1905 Calabria, 1930 Southern Apennines, 1980 Irpinia); new data from recent earthquakes (1997 Umbria-Marche, 1998 Lauria, 2002 Molise and Palermo, 2009 L'Aquila); new parameters from the database of seismogenic sources (INGV-DISS3, 2010); references to the most recent lithological map of Italy by the National Environmental Institute (ISPRA); new location indexes from the National Institute of Statistics (ISTAT). Moreover, new statistical distribution of effects vs. geological and seismogenic features were derived as well as new relationships between earthquake magnitude and intensity vs. maximum expected distances for different ground failures.

Keywords: Earthquake-induced ground-failures, upgraded catalogue, Italy

1. INTRODUCTION

In the last decades an increasing number of studies regarding the ground failures triggered by earthquakes are being available. A key-date for regional catalogues of earthquake-induced landslides is represented by the pioneering study of Keefer (1984), who first collected information from 40 worldwide earthquakes and compiled a database of thousands of seismically-induced landslides that gave the start for a systematic collection of such data. Keefer's work has the merit to have categorized earthquake-induced landslides into three main types of movement (disrupted slides, coherent slides and flows) and to have provided maximum distances of the occurrence of landslides as a function of earthquake magnitude. Another relevant work at a worldwide scale is that by Rodriguez and Bommer (1999) who extended the Keefer's catalogue up to 1997 with an in-depth analysis of further 36 earthquakes. It generally confirmed the remarks of Keefer's study with some exception such as some outliers in the maximum distance versus magnitude correlation, outlining to be very careful when treating some special cases such as landslides involving quick clays. Several other studies detailed at a regional scale the two worldwide ones cited above, such as, among many others, those from Greece by Papadopoulos and Plessa (2000), New Zealand by Hancox et al. (1997 and 2002), Central America by Bommer and Rodriguez (2002). In Italy, the first attempt to collect information from ground failures triggered by earthquakes was made by Prestininzi and Romeo (2000), who collected data from about 1,800 ground failures reported in historical earthquakes occurred in Italy since 1,000 A.D. The catalogue, whose name is CEDIT (an Italian acronym for Catalogue of Ground Effects Triggered by Earthquakes), mainly recovered information from historical earthquake catalogues dating back at the beginning of the 20th century, integrated by scientific reports regarding the ground effects produced by the most recent earthquakes occurred until 1980. Nowadays, another catalogue specifically devoted to surface faulting is under development in Italy (ITHACA, Michetti et al. 2000) and continuously updated, whereas in the past a specific catalogue was realized for liquefaction phenomena (Galli,

2000) even if not yet supported and practically included in the new release of the CEDIT catalogue here presented.
Regional catalogues of ground failures triggered by earthquakes are specially devoted to the understanding of the mechanisms underlying the development of such phenomena during earthquakes in different seismotectonic environments, and to provide predictive thresholds of ground shaking and distances within which they may be triggered for the development of seismically-induced ground failure scenarios that are of primary importance in any emergency preparedness.

2. SUMMARY STATISTICS

The new release of the CEDIT catalogue includes 2568 earthquake-induced ground effects, about 45% more than the previous release, triggered by 158 earthquakes (5 more the previous ones) and occurred in 1688 sites (720 more than the previous ones) (Fig.1a). About half of the reported effects are landslides, followed by ground cracks (about one-quarter), liquefaction, surface faulting and topographic changes, in decreasing order. (Fig.1b).
A comparison between the two releases shows as landslides and surface faulting represent the most increased effects due to the updating of the historical earthquake dataset as well as to the upgrade from the most recent considered earthquakes. This is due to the fact that in the last century a special care was devoted to the recognize of potentially active and capable faults, as well as to some specific research projects finalized to realize specific landslide inventories. In terms of landslide mechanisms, disrupted and coherent slides (in the Keefer's meaning) represent, respectively, 38% and 23% of the total reported landslides, whereas flows and spreads are only 6% and about one-third of the total landslides have a not-well defined mechanism.

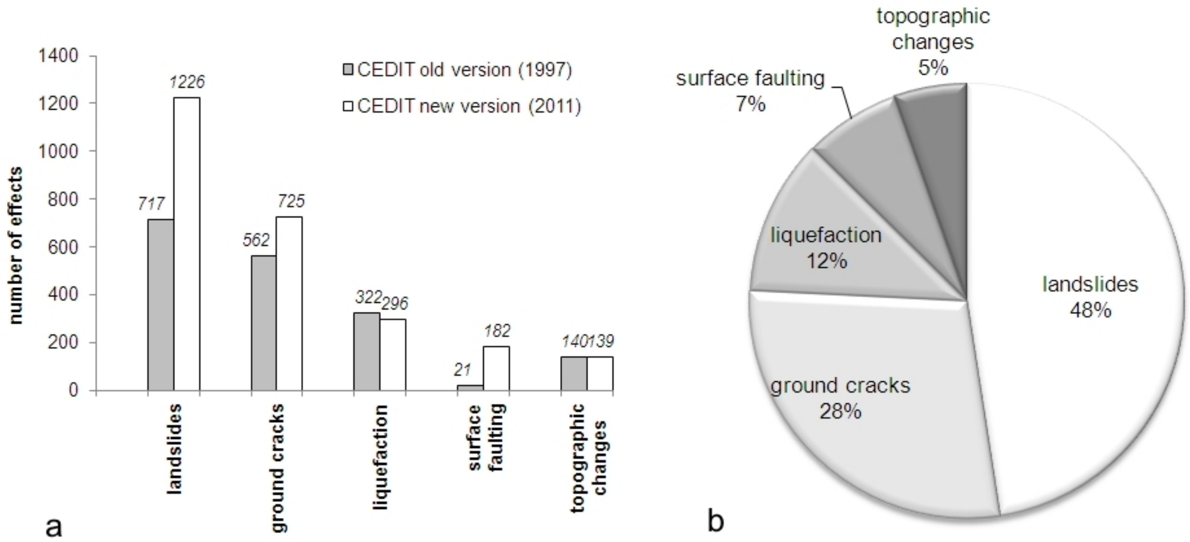

Figure 1. Number of effects (a) and relative frequency (b) reported in the CEDIT(2011) catalogue.

The spatial distribution of the earthquake-induced ground effects reported in the CEDIT catalogue (Fig. 2) mainly follows the elongation of the Apennine Chain, where most of the strongest seismicity is concentrated, with some secondary clusters such as those in Northeastern Italy and Eastern Sicily. No effect is documented in the Sardinia Island, which is practically aseismic, and only a small number of effects are documented all along the western Alps.
A detailed attribution of the landslides to the outcropping lithology as resulting from the Italian geological map at scale 1:500,000 by ISPRA (National Environmental Research Institute) was carried out. As it results, about 36% of the earthquake-induced landslides involve competent rocks (dolomite or limestone), a 30% weak rocks (marls, clays, sands and conglomerates), another 17% igneous and metamorphic rocks and the remaining 17% flysch deposits.
Since a reliable association of earthquake-induced ground effects with active faults is available only for the most recent events (practically since the 1980 Irpinia M6.9 earthquake), an inferable statistics

may be proposed only for selected earthquakes, skipped here for the sake of brevity.

Some interesting consideration can be asserted on the completeness of the CEDIT catalogue by analysing the chronological distribution of the documented earthquake-induced ground effects.

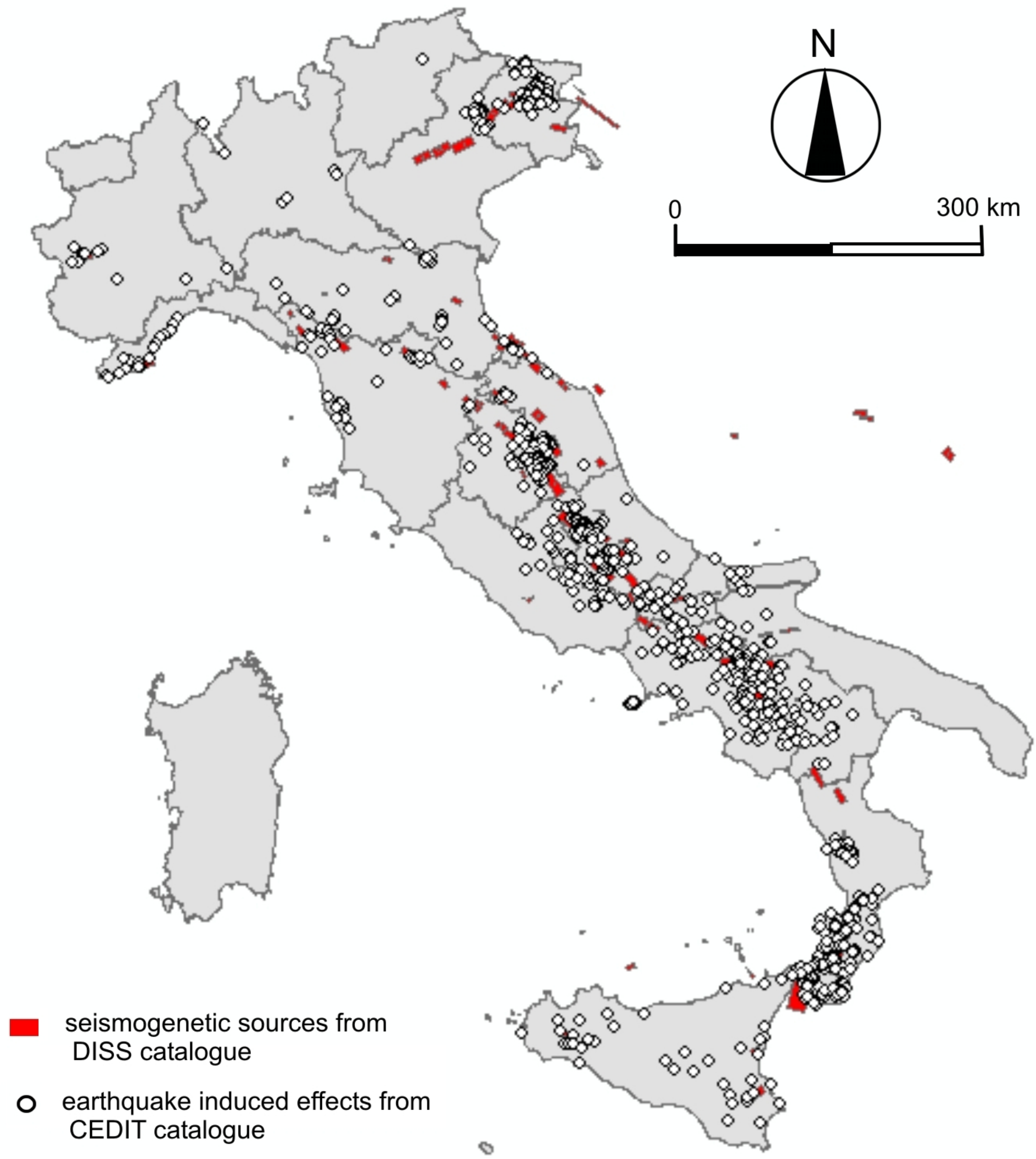

Figure 2. Geographical distribution of the sites affected by reported ground effects. Red polygons refer to the main seismogenic sources reported in the INGV-DISS database of active faults (http://diss.rm.ingv.it/).

The cumulative number of ground effects (Fig. 3) increases rapidly since about 1800 A.D., showing a typical stepwise trend related to the occurrence of large earthquakes; markedly, the difference between the 1693 Eastern Sicily earthquake (estimated M7.4) and the 1783 Calabria seismic sequence (at least three major events above M6.5) which occurred not far from each other and within not more than one century, is topically related to a switch in the systematic reporting of ground effects introduced by the scientific mission of Sarconi (1784), which represent the first, perhaps in the world, scientific inventory of earthquake-induced ground effects.

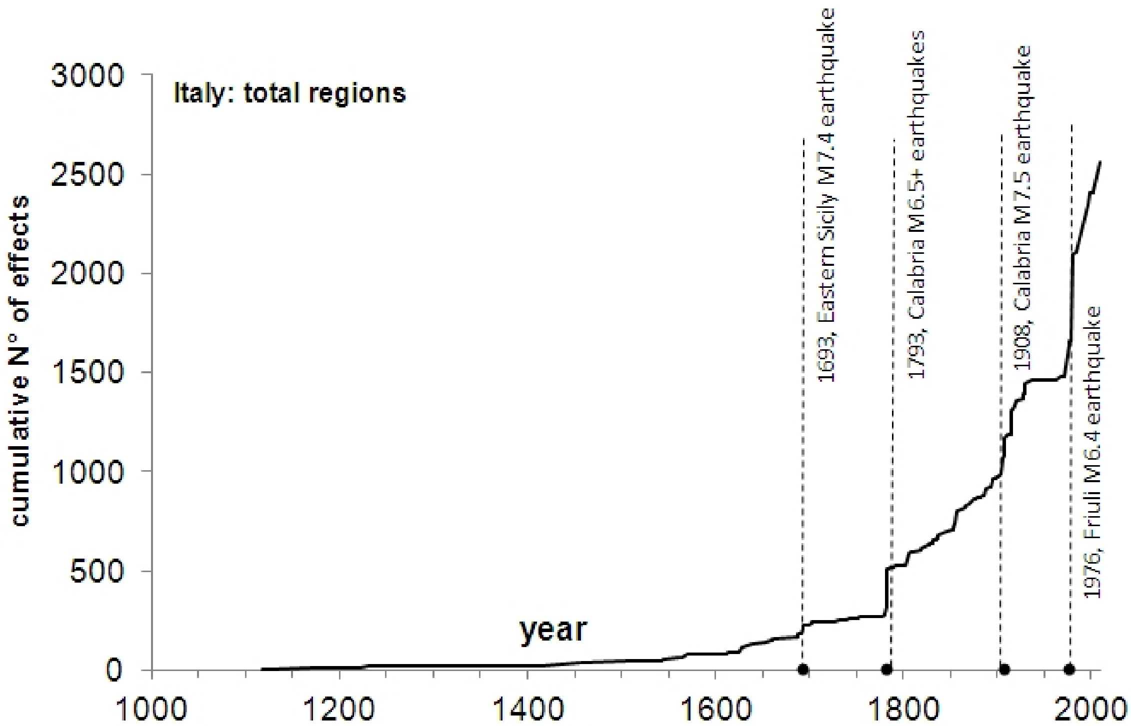

Figure 3. Time-distribution of the cumulative number of ground effects.

Another marked increase in the rate of earthquake-induced ground effects can be observed at the beginning of the 20th century (1905 Calabria M7.1 earthquake followed soon after by the 1908 Messina Strait M7.2 earthquake), due to the coming of the instrumental age but, above all, the increasing availability of scientific reports and well documented inventories of ground failures due to the awareness about the role played by ground effects in determining the earthquake damage like the response of the structures themselves.

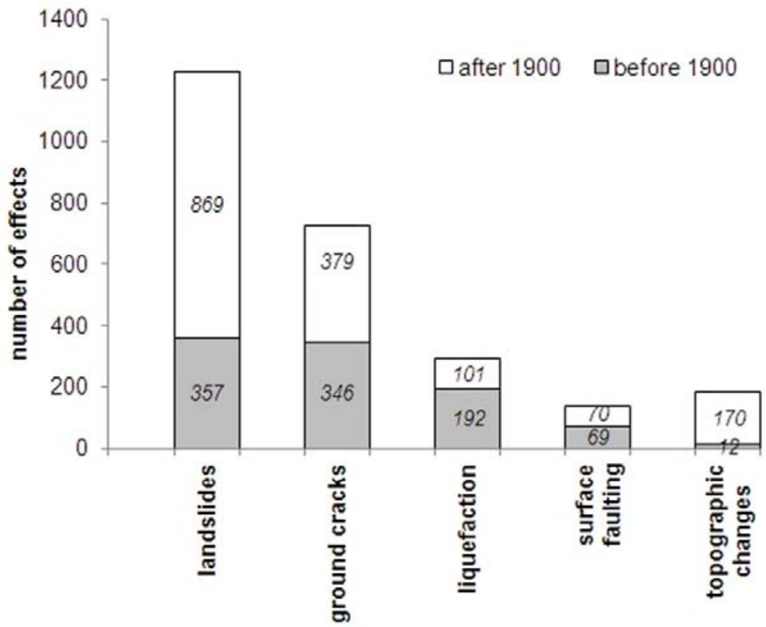

Figure 4. Earthquake-induced ground effects occurred before and after 1900 A.D.

Anyway, it's only after the 1976 Friuli M6.4 earthquake that we can date the systematic collection of data and information regarding ground effects triggered by earthquakes; nevertheless, this doesn't automatically imply a completeness of the reported ground failures, because they still remain mainly linked to the interference with the exposed assets such as building structures, communication roads and lifelines, yet remaining undetected many phenomena occurred in uninhabited areas, as the experience of the most recent 2009 L'Aquila M6.2 earthquake taught us.

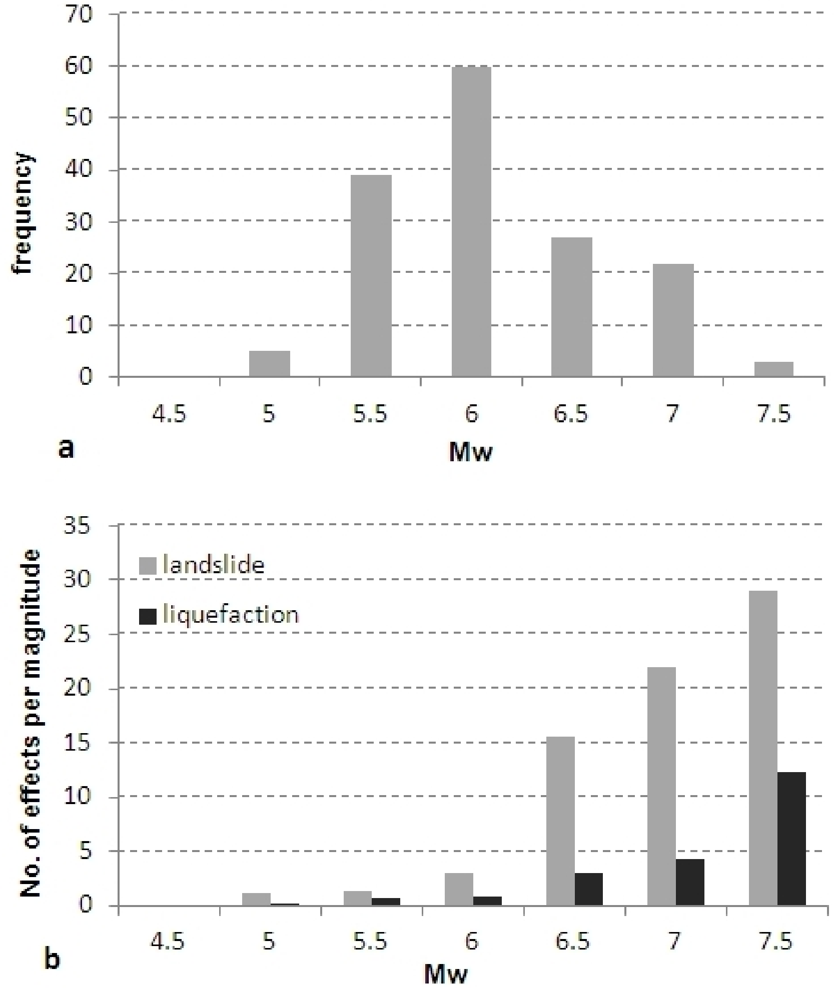

Figure 5. Frequency distribution of earthquakes that triggered ground failures (a) and the rate of ground failures per magnitude class (b).

Another way to infer the completeness of the earthquake catalogue come from the number of ground effects detected after the advent of the seismological instrumental age (since 1904 for the reported earthquakes) when compared with the previous ones (Fig. 4). As one can see more than 50% of data refer to the last century, despite the larger number of reported earthquakes prior the 20th century; this leads to an increase of more than 5 in the frequency of reported failures per seismic event after the beginning of the seismological instrumental age, which has therefore acted as a flywheel for the improvement of the information regarding all the effects due to earthquakes.

In Fig. 5a the frequency distribution of reported earthquakes that triggered ground failures is shown. Below magnitude 6, the most represented one, the number of earthquakes rapidly decreases for two main reasons: 1) the threshold epicentral intensity of MMI-8 corresponds to approximately M5.5; 2) lower magnitudes have a lower probability to trigger ground failures and are more likely to be affected by incompleteness.

In Fig.5b the number of effects per magnitude class is shown. Despite the number of earthquakes rapidly decreases above M6, conversely the number of effects per earthquake magnitude rapidly increases. Particularly, the number of reported landslides per magnitude class increases abruptly above M6, whereas the same rate may observed above M7 for liquefaction, because the latter requires a stronger shaking to be triggered than the former.

Exploding the category of landslides into the Keefer's (1984) seismic landslide categories (Fig. 6), it can be seen how the category of flows and spreads shows a rate increase for larger magnitudes than coherent and disrupted slides, respectively, thus requiring a stronger, longer and lower frequency-content of the seismic shaking to be triggered.

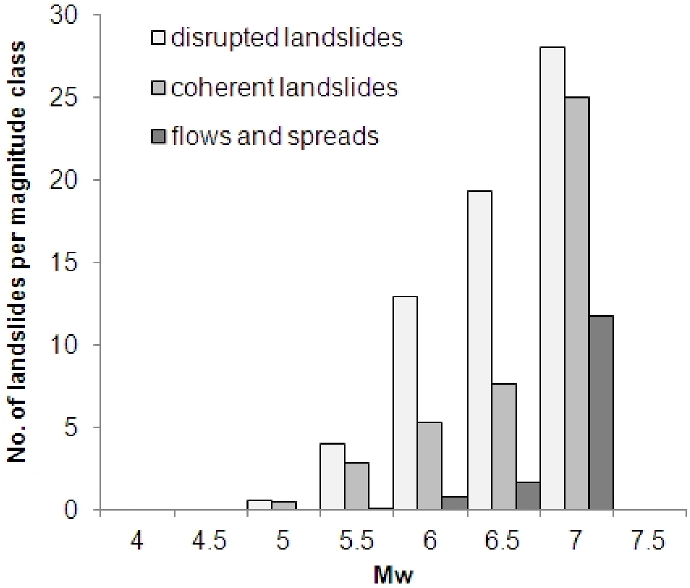

Figure 6. Number of landslides per magnitude class according to the Keefer's (1984) seismic landslide categories.

3. DISTANCE OF GROUND FAILURES FROM THE SEISMIC SOURCE

On the basis of the reviewed CEDIT catalogue an empirical distributions of epicentral distances versus magnitudes were derived and compared with those proposed by different authors (Keefer, 1984; Rodriguez et al. 1999), who provided "upper bound" curves representing the maximum distances at which earthquake induced landslides can be expected to occur for specific Mw values. In Fig. 7 the landslide distributions of the CEDIT catalogue are overlapped to the upper bounds provided by Keefer for his three seismic landslide categories (disrupted, coherent and flow landslides).

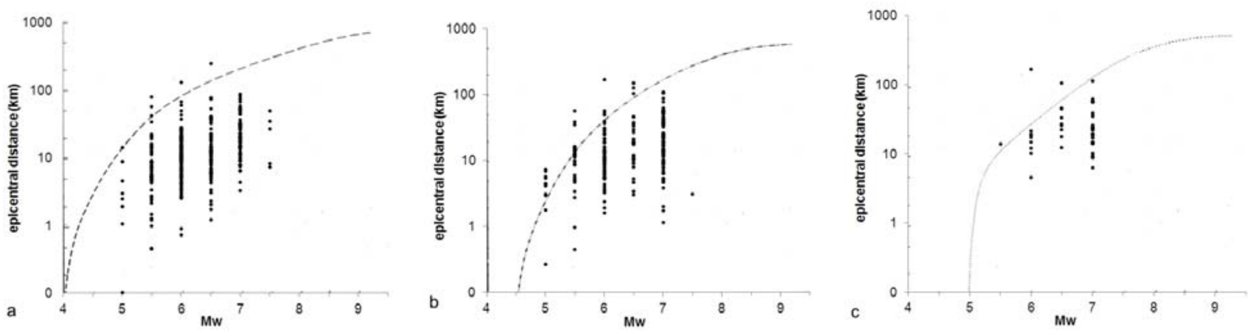

Figure 7. "Upper bound" curves representing the maximum distances at which earthquake-induced landslides can be expected (from Keefer, 1984) and data from the CEDIT catalogue referred to disrupted (a), coherent (b) and flow (c) landslides.

The graphs show how the data distribution from the CEDIT catalogue generally fit well the Keefer's relationships except for some outliers, an evidence pointed out already by Rodriguez at al. (1999), who stated as special cases such as, for instance, landslides in quick or very sensitive clays, may be underestimated by the Keefer's curves, which nevertheless preserve a general validity.

Delgado et al. (2011) remarked that outliers respect to the Keefer's relationships can be further justified by different features among which the best documented ones are: effects due to local seismic response, cumulated strain effects due to seismic crisis (including multiple mainshocks), high saturation of the involved soils due to intense rainfall before the earthquake occurrence, among many others less relevant. We can further add to the list of the possible reasons for the outliers occurrence the erroneous location of the earthquake epicentre and/or that of the occurred landslide, as well as an erroneous estimate of the earthquake magnitude, all errors that may incur when the seismic events date back to the pre-instrumental age, when data parameterization and locations were essentially based on descriptive data sources and on macroseismic information.

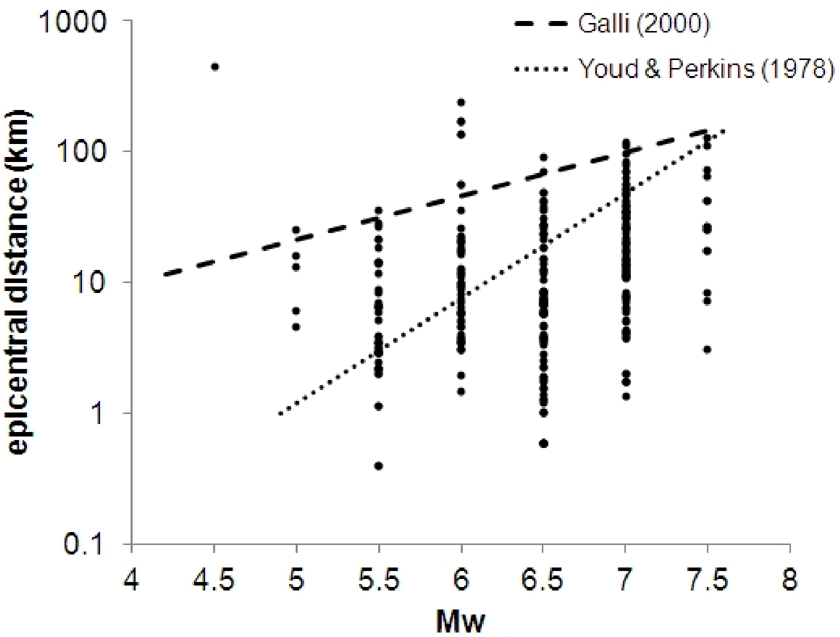

Figure 8. "Upper bound" curves representing the maximum distances at which liquefaction can be expected (by Youd & Perkins, 1978 and Galli, 2000) and liquefaction data from the CEDIT catalogue.

In the case of the CEDIT catalogue, two outlier events were investigated (Bozzano et al., 2008; Bozzano et al., 2011) and related to effects of local seismic response; they refer to the Cerda (06/09/2002) and the Salcito (31/10/2002) landslides which were triggered by the 6th September 2002 (Mw 5.89) Palermo earthquake and by the 31st October 2002 (Mw 5.78) Molise earthquake, respectively. In these cases, the reactivation of the two previously existing landslides has been related to a mechanism of self-excitation of the landslide mass due to the occurrence of a moderate far-field earthquake (about 50 km apart).

A distribution analysis of epicentral distances vs. earthquake magnitude was also performed for the liquefaction effects reported in the CEDIT catalogue (Fig.8). In this regard an "upper bound" curve was proposed by Galli (2000) from an Italian dataset, including 317 documented effects of liquefaction based on 61 earthquakes, with a magnitude varying within the range 4.2 - 7.5 and occurred in the time interval 1117 - 1990 A.D..

The resulting distribution shows that almost all the data of liquefaction events reported in the CEDIT catalogue are below the "upper bound" curve proposed by Galli (2000) while, on the contrary, a lot of them exceed the "upper bound" curve proposed by Youd and Perkins (1978), which is referred to liquefaction events occurred in California.

4. PROBABILITIES FOR EARTHQUAKE-INDUCED GROUND EFFECTS

Site intensity (Mercalli scales) is a measure of the local earthquake shaking, depending on both the earthquake severity (epicentral intensity and magnitude, as well) and the source-to-site distance. In Fig. 9a the distribution of landslides and liquefaction as a function of reported site intensities is shown, along with the probability that a ground failure may be triggered below threshold intensities. For

instance, given an intensity MMI-7, there is about a 10% probability that liquefaction may be triggered for site intensities equal to or lower than the threshold one, opposite to about a 30% probability for landslides, which are therefore more prone to be triggered for a lower shaking than liquefaction.
Figure 9b shows how likely a landslide (disregarding the type) may be triggered above a threshold distance given an earthquake within a magnitude class. As an example, up to magnitude 5.5 there is a 10% probability that a landslide may be triggered for epicentral distances greater than about 30km, but at the same probability level the distance threshold increases to about 40 km for earthquake magnitudes up to 6.5 and to about 70 km for earthquake magnitudes up to 7.5.
Figure 9b extends the predictability of distances to which landslides may be triggered by an earthquake magnitude associating to each of them an occurrence probability level or reliability.

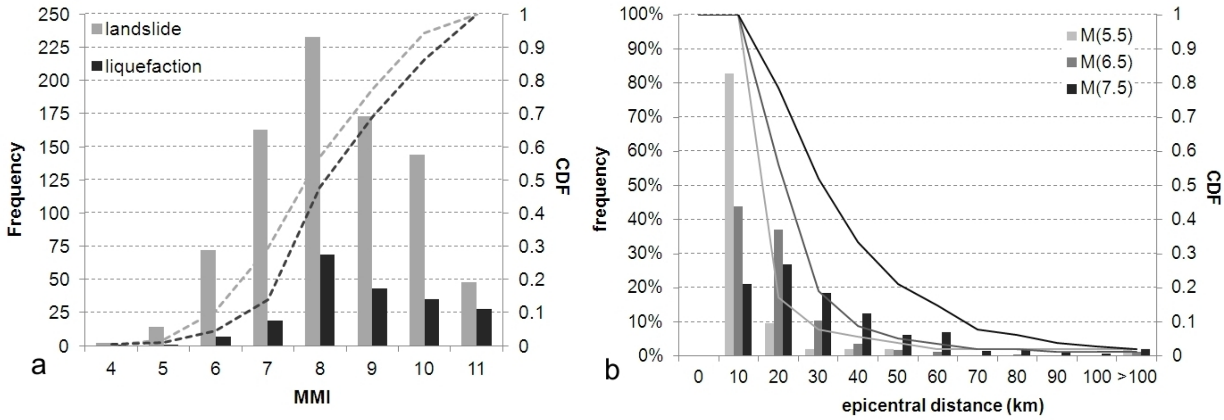

Figure 9. Probability of occurrence of earthquake-induced landslides and liquefaction as a function of MMI (a) and probability of occurrence of earthquake-induced landslides as a function of epicentral distance (b).

5. CONCLUSIONS

The upgrading of the Italian Catalogue of Earthquake-Induced Ground Effects (CEDIT) confirmed that a considerable part of effects induced by earthquakes in Italy consists on landslides; these events are mainly distributed along the Apennine Chain, where most of the recognised seismogenic sources are located. A completeness analysis of the catalogue showed that it is much more reliable only after the 1976 (data of occurrence of the Friuli M6.4 earthquake in Northeastern Italy) even if since the beginning of the 20th century a much more constant rate of the cumulative number of documented effects can be observed, a key-date corresponding to the beginning of the instrumental age of the earthquake monitoring and to the advent of the modern and systematic reporting of earthquake effects. All the earthquake induced events collected so far, made it possible to compare these data with the proposed “upper bound” curves representing the maximum distances at which earthquake-induced landslides can be expected to occur for specific magnitude values; the comparison demonstrated a good fit except for some outlier events some of which related to specific site effects due to local seismic response.
Based on the distribution of landslides and liquefaction, as a function of reported site intensities derived from the CEDIT catalogue, the probability that a ground failure may be triggered below a threshold intensity was evaluated for both landslide and liquefaction effects; results demonstrate that there is about a 10-20% higher probability of a landslide occurrence than a liquefaction occurrence for any given site intensity value. Moreover, the probability that a landslide may be triggered above a given distance from the earthquake source, has been found to not increase linearly with the earthquake magnitude; namely, for one magnitude increase, a given distance has a much more probability to be exceeded when jumping from M6.5 to M7.5 than when jumping from M5.5 to M6.5, thus considerably extending the maximum affected area by landslides as the earthquake magnitude increase.

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