DOI: 10.4408/IJEGE.2017-01.O-04

EARTHQUAKE-INDUCED LANDSLIDES IN ITALY: FROM THE DISTRIBUTION OF EFFECTS TO THE HAZARD MAPPING

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EXTENDED ABSTRACT

Nel panorama dei rischi naturali, le frane sismoindotte sono il risultato di un "effetto domino" poiché rappresentano effetti innescati da eventi (i terremoti) rispetto ad esse indipendenti. In tal senso, la loro probabilità di accadimento è più bassa rispetto a quella del terremoto che le innesca. Allo stesso tempo, la concatenazione di terremoto e frana può determinare effetti di danneggiamento ben più significativi di quelli associati ai singoli eventi (terremoto o frana), innalzando di conseguenza il livello di rischio ad essi associato. L'Italia può trarre vantaggio da una banca-dati storica tra le più complete al mondo per ciò che attiene gli effetti sismoindotti, le cui informazioni sono state sistematizzate e rese consultabili dal 2012 nel Catalogo degli Effetti Deformativi Indotti da forti Terremoti (CEDIT), presso il portale del CERI (http://www.ceri.uniroma1.it/cn/gis.jsp). L'ultimo aggiornamento del CEDIT è del 2017 ed è stato effettuato a seguito della sequenza sismica che ha colpito l'Appennino Centrale, iniziando il 24/08/2016 con il terremoto di Amatrice di Mw 6.0, culminando il 30/10/2016 con il terremoto di Norcia di Mw 6.5 ed includendo il terremoto di Capitignano del 18/01/2017 di Mw 5.5. La distribuzione areale degli effetti sismoindotti da questa sequenza sismica è in ottimo accordo con le curve di massima distanza attesa in funzione della magnitudo derivate dal CEDIT, cosa che dimostra l'affidabilità del catalogo italiano nel fornire indicazioni previsionali sugli areali potenzialmente interessati da effetti sismoindotti. I dati inventariati nel CEDIT mostrano che circa il 56% degli effetti sismoindotti censiti sul territorio Italiano è riferibile a frane. L'esigenza di restituire distribuzioni di effetti di frane sismoindotte su vasta area territoriale, ed in una prospettiva di mitigazione del rischio naturale ad esse associato, si confronta oggi con le richieste dei prodotti di Microzonazione Sismica di livello 3, le cui linee guida, per ciò che attiene le instabilità sismoindotte (tra le quali le frane), sono di recente pubblicazione da parte del Dipartimento di Protezione Civile Nazionale. A tale proposito, un processo virtuoso dovrebbe consistere nell'utilizzo dei dati storici provenienti dal Passato per validare studi di scenario ottenibili nel Presente al fine di costruire, in una prospettiva per il Futuro, strumenti di gestione e mitigazione del rischio naturale associato agli effetti sismoindotti.

In tal senso, il CERI, in collaborazione con ENEA e Dipartimento di Scienze della Vita e dell'Ambiente dell'Università di Urbino "Carlo Bo", sta conducendo, anche nelle aree terremotate nel 2016 della Regione Lazio, la sperimentazione di un approccio finalizzato alla ricostruzione di scenari probabilistici di franosità sismoindotta alla scala di territori comunali, mediante l'applicazione del metodo PARSIFAL (*Probabilistic Approach to pRovide Scenarios of earthquake Induced slope FAiLures*), proposto da Esposito *et alii* (2016). Il PARSIFAL si articola in tre moduli di analisi: a) analisi morfologica, volta ad individuare unità territoriali predisposte a franosità sismoindotta, di prima generazione (comprendenti scorrimenti superficiali in terra, scorrimenti planari, scorrimenti di cunei e ribaltamenti in roccia) o per riattivazione di frane esistenti (con specifico riferimento a frane rotazionali/traslative); b) analisi di stabilità statiche, per accertare la suscettività nei confronti delle azioni sismiche (accelerazioni di soglia), pseudodinamiche per calcolare la probabilità di superamento di spostamenti critici al collasso, pseudostatiche per valutare i margini di sicurezza in condizioni sismiche di movimenti sotto soglia apprezzabile di spostamento o di stabilità di corpi rigidi alla pura rotazione (es. ribaltamenti); c) cartografia, finalizzata ad una restituzione integrata dei risultati di analisi mediante carte di scenario (eventualmente anche per prefissati valori di probabilità di eccedenza in un tempo di riferimento: carte di pericolosità).

Il PARSIFAL ha le seguenti peculiarità:1) è predisposto a valutare la pericolosità da frane di prima generazione e seconda generazione (ovvero riattivazioni di frane pre-esistenti, censibili già prima di un evento sismico); 2) effettua analisi differenziate per meccanismo di frana; 3) restituisce una cartografia di sintesi con indicazioni sulla probabilità di eccedenza rispetto a soglie di spostamento cosismico in caso di loro superamento, ovvero sui margini di sicurezza in condizioni sismiche per spostamenti non apprezzabili o cinematismi puramente rotativi (ribaltamenti); 4) consente un'analisi probabilistica ponderata e combinata, per singola unità cartografica, degli effetti attesi in termini di meccanismo di frana e intensità dello stesso, tenendo anche in considerazione diversi scenari in termini di condizioni di saturazione dei versanti.

ABSTRACT

Earthquake-induced landslides should be viewed, in the perspective of natural risk, like "domino effects" since they represent hazardous phenomena induced by independent triggering events. In this sense, the probability of an earthquake-induced landslide occurrence is lower with respect to that related to the earthquake itself. However, at the same time, the induced damage become much more intense thus increasing the related risk. Italy takes advantage from one of the most ancient and complete historical databases of earthquake-induced ground effects that was collected recently in the CEDIT (Italian Catalogue of Earthquake-inDuced ground failures in ITaly) catalogue (an open access database available at the http://www.ceri.uniroma1.it/cn/gis.jsp website). The last updating of the catalogue was performed on 2017 after the seismic sequence in the Central Apennines that started with the 24/08/2016 Mw 6.0 Amatrice earthquake, culminated with the 30/10/2016 Mw 6.5 Norcia earthquake and included the 18/01/2017 Mw 5.5 Capitignano earthquake. The maximun expected distances for the earthquake-induced effects of this seismic sequence are in very good agreement with the CEDIT-derived curves of maximum distance vs. magnitude, so demonstrating the reliability of the Italian inventory to constrain areas potentially involved in earthquake-induced effects. The inventoried data prove that almost 56% of the earthquake-induced ground effects are due to landslides. The space-time distribution of earthquake-induced landslides in the Italian territory solicited new solutions for mapping the related hazard at a Municipality scale to depict scenarios of earthquake-induced ground effect also in the frame of seismic micro-zonation studies. In this way, a virtuous scientific path can be followed starting from evidences of the Past, collecting them for constrain studies in the Present and applying technical methodologies to the establishment of a prevention strategy for the Future ranging from land-use management to natural risk mitigation.

Keywords: *earthquake-induced landslides, natural hazard, catalogue, mapping*

INTRODUCTION

Earthquake-induced landslides are generally responsible for severe damage and losses as proved by the last seven years records, which demonstrate that more than 50% of the total losses due to landslides in the World are due to co-seismic slope failures (Petley, 2012). Moreover, as reported by Bird & Bommer (2004) the greatest damages caused by earthquakes are often related to landslide events. Several historical earthquake-induced landslides demonstrated the severity of such events as they often involved areas which have been intensely damaged by the seismic shaking. This was the case, among others, of the Las Colinas landslide, triggered by the January 13 2001 Mw 7.6 El Salvador earthquake, which caused about 585 losses (Evans & Bent, 2004). Earthquake-induced landslides can also trigger co-related phenomena, by a sort of "domino-effect", like river damming and tsunamis as recently reported by Collins & Jibson (2015) for the 25 April 2015 Nepal earthquake.

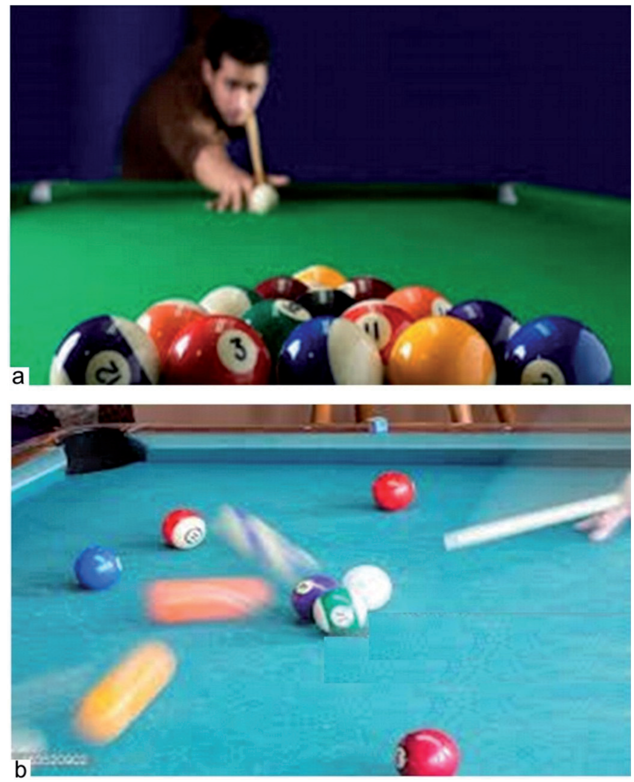

Fig. 1 - Risk perspective for multi-hazard. a) a single hazardous event can threat many exposed subjects (human and/or natural); b) a single a hazardous event can trigger several phenomena by a "domino effect", i.e. a concatenated sequence of effects

Earthquake-induced landslides are also responsible for diffuses and intense environmental changes which often require high resilience by socio-economical systems to recover the status quo ante land-use conditions or to modify them by readjustment or renovation strategies.

The recently published database of earthquake-induced ground effects in Italy (CEDIT by Martino *et alii*, 2014 - http://www.ceri.uniroma1.it/cn/gis.jsp_CEDIT/), whose main peculiarity is to be based on several historical documents over a period of approximately one millennium from 1000 AD to present, demonstrates that landslides represent the most documented type of ground failures, corresponding to almost 56% of the inventoried effects, which include ground-cracks, liquefactions and superficial faulting.

Earthquake-induced landslides should be distinguished in "first time slope failures" and "reactivated landslides" as they have a very different meaning in terms of risk mitigation strategies.

Indeed, an already existing phenomenon can be recognized and inventoried by technical maps, while a not yet occurred slope failure cannot be identified easily without performing specific susceptibility and slope stability analyses.

On this basis, two opposite solutions could be combined for advancing risk mitigation strategies: i) inventorying occurred earthquake-induced landslides, ii) providing a comprehensive hazard mapping also for first-time earthquake-triggered slope failures. This combined strategy takes advantage from past memories to output the severity of occurred "domino effect" scenarios and drive toward future events according to a prevision approach for risk management, which favors time-delayed and out-of-emergency solutions.

EARTHQUAKE-INDUCED LANDSLIDES IN A RISK PERSPECTIVE

All natural phenomena can be considered in a risk perspective. As far as landslides are regarded, they can occur as a result of time-dependent evolution of deformational processes involving slopes, but can also be triggered by external actions like rainfalls or earthquakes. In a risk perspective, this second possibility represents a "domino effect" causing a multi-hazard occurrence due to the sequential happening of one another induced effects (Fig. 1). The probability of such a domino effect is lower with respect to that related to a single event but, at the same time, the damage caused becomes much more intense thus increasing the related risk.

In this regard, while the earthquake hazard is related to the return time that can be linked to the physics of the seismogenetic source (i.e. active fault), the probability of landslide trigger when an earthquake occurs depends on several factors, which significantly vary the susceptibility to slope failure (Fig. 2). These factors include both the physical properties of the ground motion generated by the earthquake (energy, frequency content, maximum acceleration) and the local setting of the slope (geometry, layering, mechanical properties of rocks and soils). Moreover, earthquake-induced slope failures are favoured by already existing landslide masses since their re-activation can be caused by "self-excitation" processes due to the amplification of the seismic ground motion within the landslide debris which generally overlays a stiffer bedrock (Martino, 2015 and references therein).

Such effects can also affect localities at tens or hundreds of kilometres from the earthquake epicentre, thus increasing the risk related to the earthquake shaking itself (Keefer, 1984; Rodriguez *et alii*, 1999; Delgado *et alii*, 2011; Jibson & Harp, 2012).

Earthquake-induced landslides can also trigger co-related phenomena contributing to the domino effect among which are river damming and tsunamis. An extraordinary example of such a multi-hazard is reported in some historical chronicles (Fig. 3) that testify the catastrophic scenario due to the earthquake-induced Scilla rock avalanche, triggered by the 6th February 1783

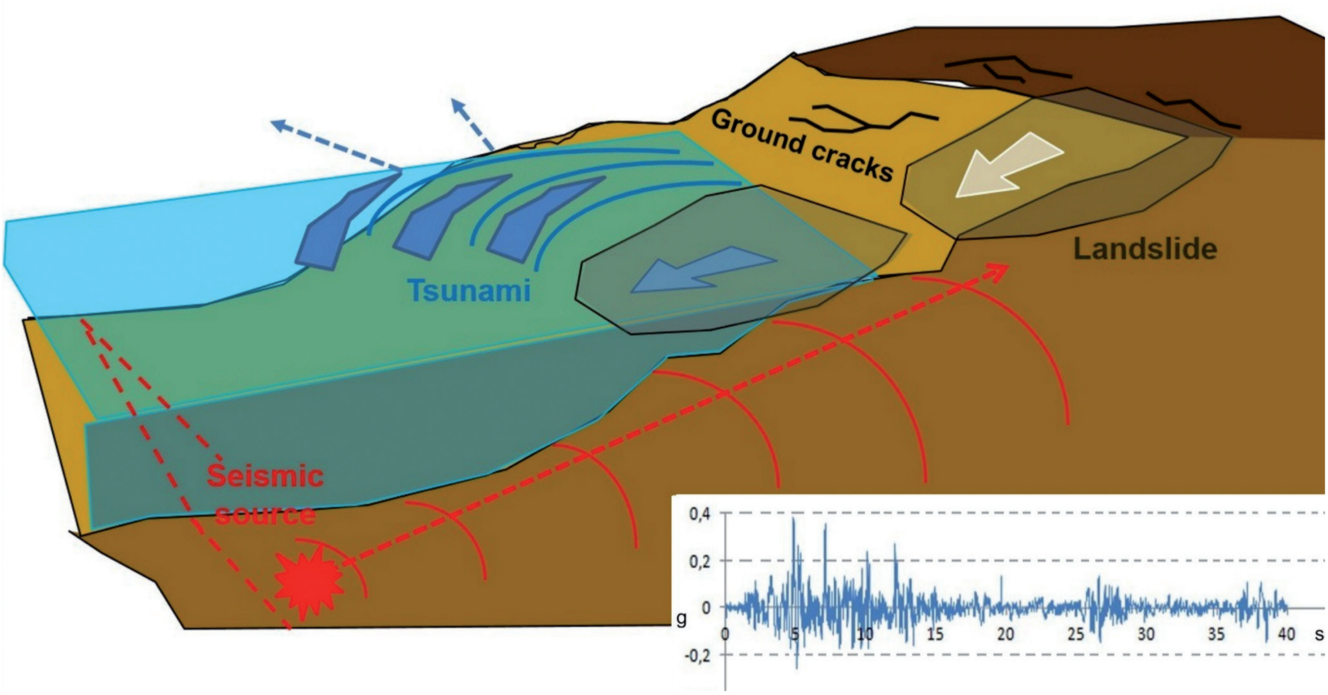

Fig. 2 - Earthquake-induced landslides can be regarded as part of a "domino effect" since they are triggered by an action external respect to the slope. However, they can also cause other effects, such as tsunamis

earthquake in Southern Italy (Bozzano *et alii*, 2011), which killed almost 1500 people as it produced a 16 m height tsunami wave along the coastline where people found refuge after the main shock that had occurred one day before (Mazzanti & Bozzano, 2011). The Scilla landslide is actually the most severe earthquake-induced landslide event testified in Italy due to the number of casualties caused.

FROM PAST TO PRESENT: A NEW CATALOGUE OF EARTHQUAKE-INDUCED LANDSLIDES

Historical sources

The relevance of historical data for studying earthquake-induced landslides was demonstrated by several studies conducted during the last few decades that use predictive models, based on empirical co-relations derived from database collected worldwide (Keefer, 1984; Rodriguez *et alii*, 1999), to arrive at the expected distribution of effects. Nevertheless, systematic inventories of historically documented earthquake-induced effects, including landslides, have rarely been produced until recently. A pioneering study in this field was that by Youd & Hoose (1978) who documented approximately 350 localities affected by ground failures (landslides, lateral spreads, ground settlement and surface cracks) in 46 earthquakes occurred in Northern California between 1800 and 1970 AD, the most documented one being the devastating 1906 San Francisco M8.3 earthquake.

The Euro-Mediterranean Earthquake Catalogue (EMEC - Grünthal & Wahlström, 2012) represents the most updated version of the European inventory of earthquakes and related effects, even though it does not include a consulting tool for earthquake-induced ground failures or other environmental effects. The United States Geological Survey (USGS) composite catalogue PAGER-CAT (Allen *et alii*, 2009), which contains reports of earthquake casualties and losses from the Preliminary Determination of Epicentres (PDE: Sipkin *et alii*, 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 alii*, 2007) are similar. The PAGER-CAT catalogue likewise inventories documented domino effects including earthquake-induced landslides, tsunamis, fires and liquefactions. Over the last decade, many Italian earthquake catalogues containing reported seismic effects

Fig. 3 - a) "Carta corografica della Calabria Ulteriore" edited by Padre Eliseo della Concezione in 1784 showing the ground effects induced by the 1783 Terremoto delle Calabrie earthquake. Examples of landslides induced by the 1783 Calabria earthquake: the Oppido di Mamertino landslide (b) and the Mt. Pacì (Scilla) landslide (c)

(mainly structural and secondarily environmental) have been published online (e.g., CFTI – ING 1995; NT4.1 - Camassi & Stucchi, 1997; DBMI04 - Stucchi *et alii*, 2007; CPTI04 - Gruppo di lavoro CPTI, 2004; ITC 2.0 – Tinti *et alii*, 2007; CPTI11 – Rovida *et alii*, 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 & Romeo (1997) published on 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 AD to 1984. 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 alii*, 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 others).

To upgrade the already collected databases (i.e. consisting in the inventoried historical data which are reported in chronicles and documents), including the most recently occurred events, the current trend is to use the power of the internet through blog communities or on-line repositories which can be upgraded in real time after earthquake occurrence thereby allowing a very fast process of detection, inventorying and mapping (Petley *et alii*, 2005; Kirschbaum *et alii*, 2010).

FROM DATABASES TO CATALOGUES OF EARTHQUAKE-INDUCED LANDSLIDES IN ITALY

The incredible quantity of information on earthquakes and induced ground effects that are available from historical sources for the Italian territory has been used in the last decades for realising different databases by several Authors, including the CPTI04 catalogue of earthquakes (Gruppo di Lavoro CPTI, 2004), the DBMI04 macroseismic catalogue (Stucchi *et alii*, 2007), the Catalogue of Italian Tsunamis (ITC 2.0; Tinti *et alii*, 2007) and the Database of the Italian Seismogenic Sources (DISS

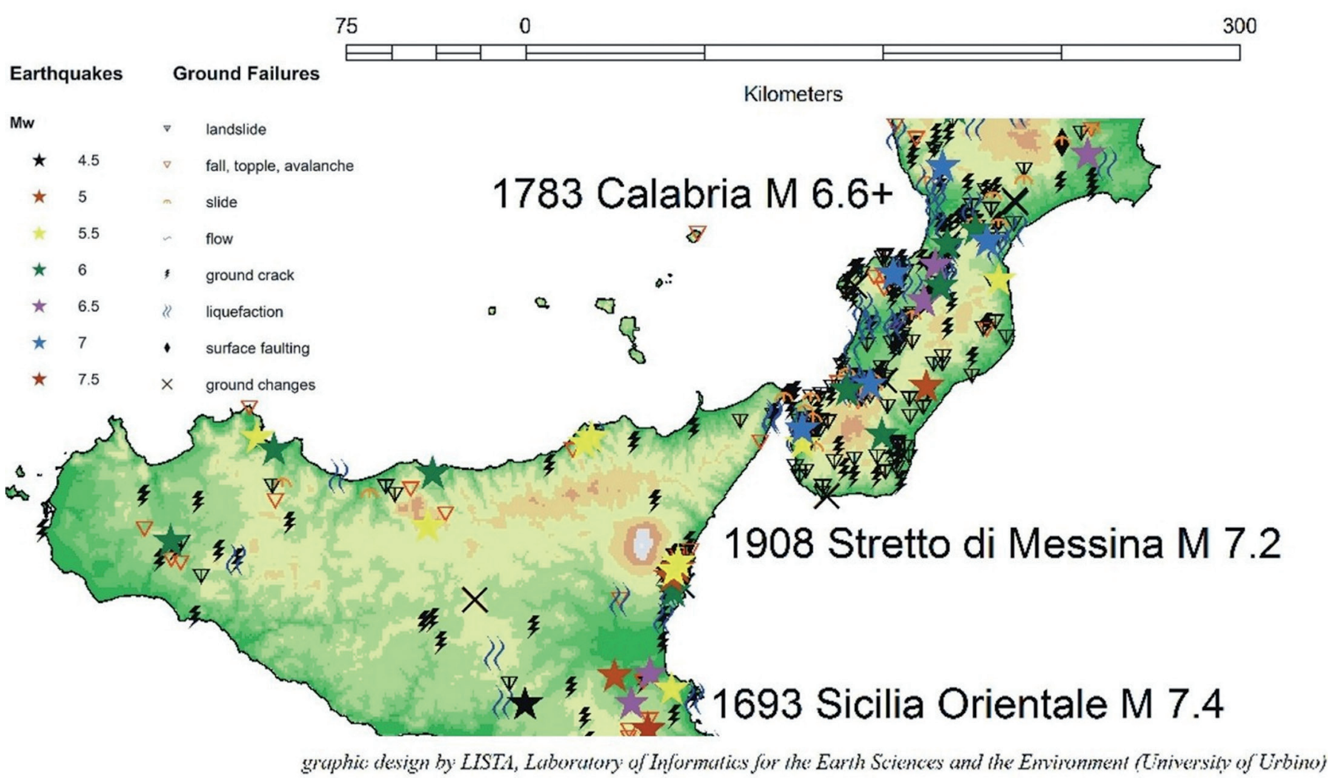

*Fig. 4 - Excerpt of the CEDIT map (*Fortunato *et alii, 2012) showing the inventoried earthquake-induced ground effects and the related earthquake epicentres for southern Italy*

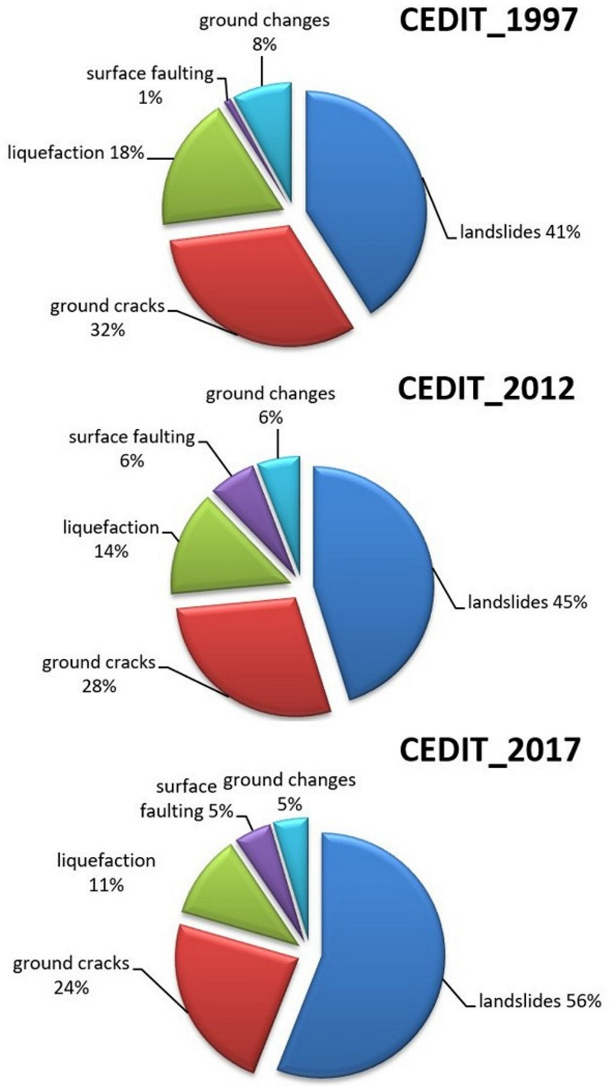

Fig. 5 - Percentage distributions of earthquake-induced effects inventoried in the three last updated versions of the CEDIT catalogue (1997, 2012, 2017)

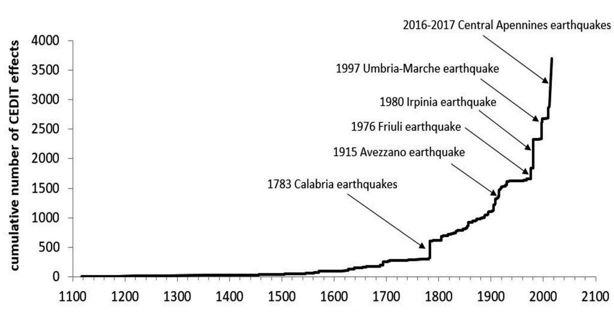

Fig. 6 - Time distribution of the cumulative number of ground failures reported in the CEDIT database updated to 2017. Marked dates refer to turning points in the completeness and reliability of the catalogue

3.1.1; DISS Working Group, 2010).

The original idea of the CEDIT, specifically devoted to earthquake-induced ground effects, was by Delfino & Romeo (1997). The catalogue considered the distribution map of the geomorphologic effects induced by earthquakes published by Zecchi (1987) that did not include any database for recovering the original collection of data. CEDIT represented the basis for the first statistical analysis of earthquake-induced landslides in Italy performed by Prestininzi & Romeo (2000).

The last release of CEDIT is published online for public access at the URL 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 alii*, 2012). The query system was developed by using the services of ArcGIS®-online and based on ESRI™ cloud technology. The system provides a geo-database consulting and querying interface with graph or table outputs. The CEDIT database (Martino *et alii*, 2014) reports approximately 2000 localities where ground failures were triggered by 169 earthquakes that occurred in the last millennium in Italy for which information about the occurrence of ground effects can be retrieved from historical documents (Fig. 4). The ground effects collected in the CEDIT database fall into five main categories: landslides, ground-cracks, liquefaction, surface-faulting and ground-changes (the last ones including among others: subsidence, relevant morphological changes due to river damming, lake formation and so on).

The CEDIT updating performed over time changed the percentage distribution of typologies of earthquake-induced effects in Italy even if their priority rating is preserved (Fig. 5). After last seismic sequence occurred in Central Apennine on 2016-2017 from August to January, the highest percentage among the categories of the inventoried earthquake-induced effects corresponds to landslide (56%), followed by ground crack (24%) and liquefaction (11%). It's worth noticing that the ground crack category could also include in past evidence of landslide, which were not correctly recognised and reported in the historical documents.

The time-distribution of the earthquakes reported in the CEDIT database (Fig. 6), from which data about ground failures have been gathered, shows that it is quite continuous starting from the end of the 18th century as a consequence of the seismic crisis that affected the Calabria region in 1783 (namely "Terremoto delle Calabrie" earthquake). This seismic crisis modified the way in which earthquakes and their effects were detected, as this event marked the first time in Italy (and perhaps in the world: Keefer, 2002) a scientific mission was planned to detect and report earthquake damage and collateral effects (Sarconi, 1784). Three major increases in the cumulative number of ground failures are apparent: the first 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 alii*, 2006). The earthquake-induced landslide inventoried in the CEDIT for the 1783 seismic crisis are 58 and represent 28% of the induced ground effects (Fig. 7a).

The second increase relates to the 1980 Irpinia Mw 6.89 earthquake (northern Italy) that represents the starting point of the systematic development and detection of strong motion records, damage and environmental effects in Italy (Carraro *et alii*, 1976). For this seismic event, the inventoried landslides are 239 representing 49% of the earthquake-induced effects (Fig. 7b).

The third increase relates to the last seismic sequence

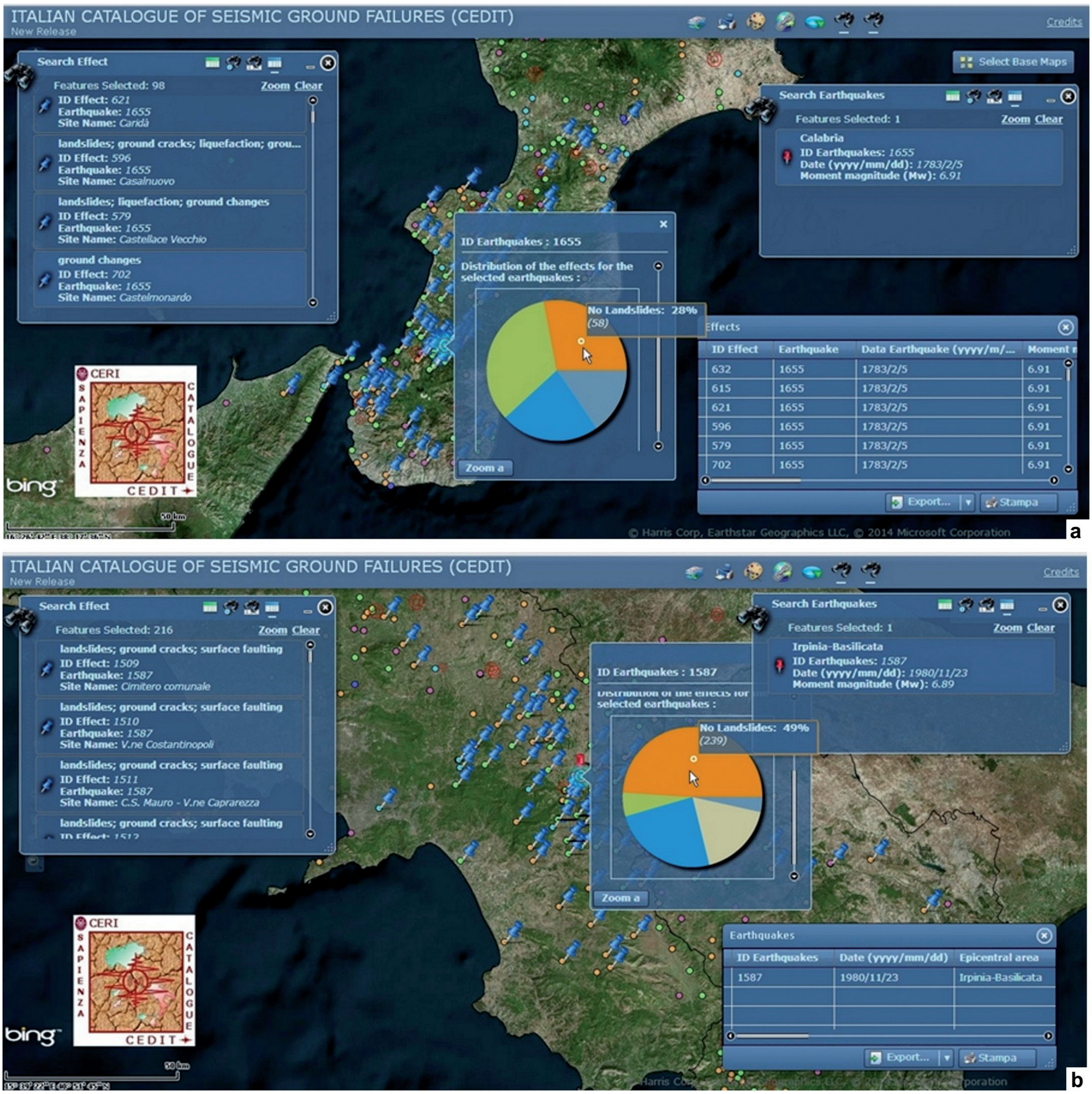

Fig. 7 - Screen shots from the CEDIT web-GIS available on the http://www.ceri.uniroma1.it/cn/gis.jsp web-site showing the distribution of the ground effects induced by the 1783 Calabria earthquake (a) and by 1980 Irpinia earthquake (b) with the related pie graphs reporting the percentages of inventoried ground effects (including landslides)

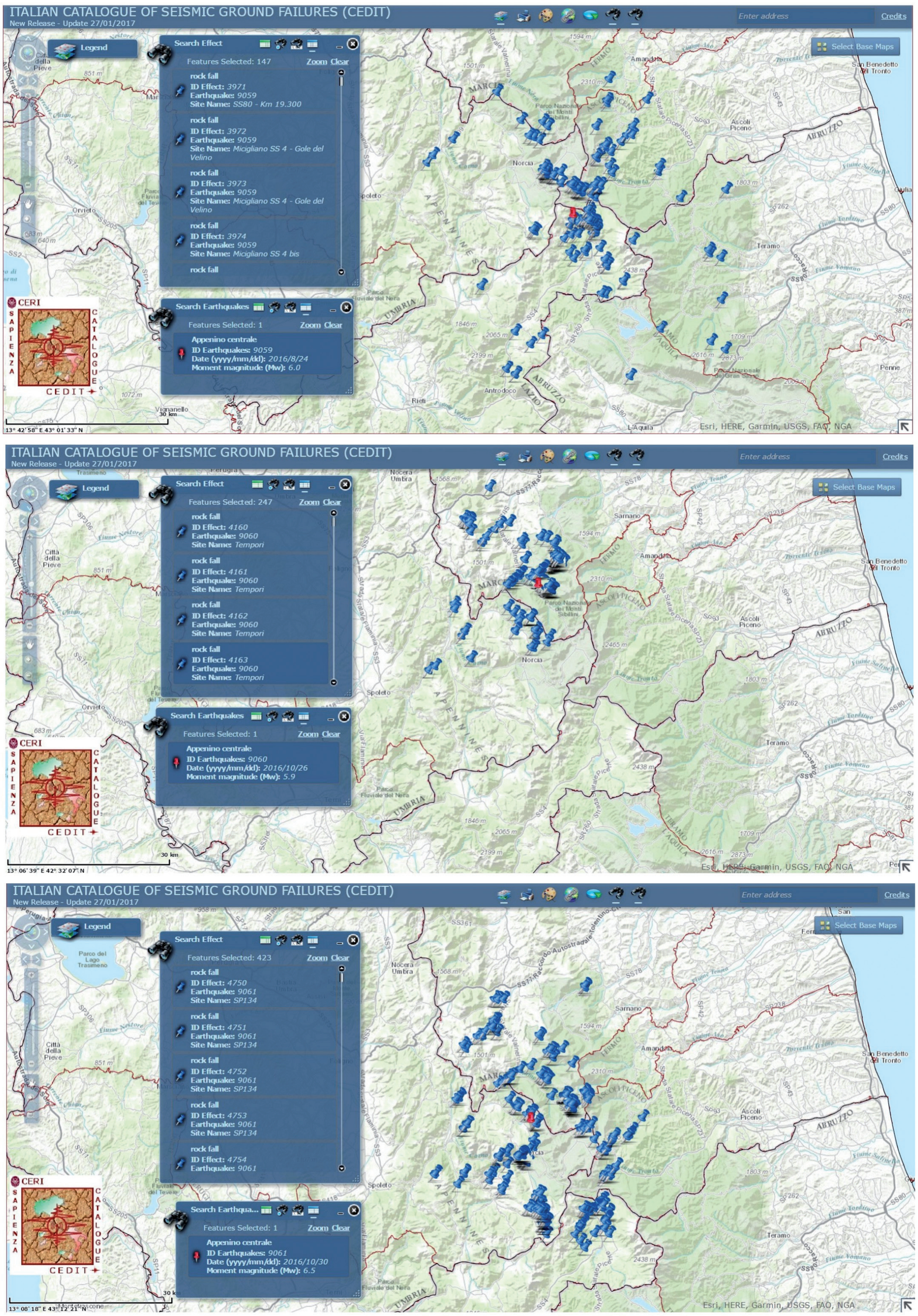

Fig. 8 - Screen shots from the CEDIT web-GIS available on the http://www.ceri.uniroma1.it/cn/gis.jsp web-site showing (from up to down) the distribution of the ground effects induced by the: 24/08/2016 Mw 6.0 Amatrice earthquake, the 26/10/2016 Mw 5.9 Castelsantangelo sul Nera earthquake, the 30/10/2016 Mw 6.5 Norcia earthquake (the blue symbols indicate the inventoried effects and the red symbols the earthquake epicenters)

occurred on 2016-2017 in the Central Apennines (Martino *et alii*, 2016) that culminated with the 30 October 2016 Mw 6.5 Norcia earthquake and included the 24/08/2016 Mw 6.0 Amatrice earthquake, the 26/10/216 Mw 5.9 Castelsantangelo sul Nera earthquake and the 18/01/2017 Mw 5.5 Capitignano earthquake. After this sequence, 817 earthquake-induced ground effects were inventoried by the CERI research team (Martino *et alii*, 2016); 99% of the inventoried effects consist in landslides and 1% only of ground cracks. Among landslides, 698 consist in disrupted ones (*sensu* Keefer, 1984), i.e. 633 rock falls and 65 rock slides, (Fig. 8) that originated from man-made road cuts for more than 50% of the inventoried cases.

Since the ‘80s, the higher accuracy in effect location allowed one to obtain much more reliable distribution scenarios of earthquake-induced landslides. The reliability of data for this earthquake makes it possible to infer more accurate information on the spatial distribution of ground effects as shown by the distribution of induced landslides obtained by Martino *et alii* (2014) along a section across the NE dipping seismogenic normal fault of the Irpinia earthquake (Fig. 9). This distribution is peaked within 10 km astride the earthquake source area and is more widespread on the hanging wall of the fault than on the footwall, as a result of the activation of another fault antithetic to the main one (Westaway & Jackson, 1984; Bernard & Zollo, 1989).

The highest accuracy of earthquake-induced landslide location is available since the most recent 1997 Umbria-Marche and 2009 L’Aquila earthquakes, where 194 and 93 landslides were inventoried representing 68% and 55% of the induced ground effects respectively (Fig. 10).

The spatial distribution of the inventoried effects related to the last seismic sequence of the Central Apennines (including the Mw 5.5 18th January 2017 Capitignano earthquake) demonstrated that the CEDIT-derived distance vs. magnitude curve for Italy (Martino *et alii*, 2014) is strongly reliable to constrain the areas that can be involved in future earthquake-induced ground effects (Fig. 11). This is a very good example of how an historical dataset well supports actual evidences and can operate in a prevision perspective.

Based on the data inventoried in the CEDIT catalogue, the likelihood of observing ground effects given a MCS site intensity can be derived. The absolute frequencies for landslides has been used to derive a probability curve according to the Weibull distribution, which is aimed at simulating the reaching of failure states. This statistic indicates that a probability of exceedance equal to 50% for earthquake-induced landslides corresponds to a MCS site intensity of about 7.5 (Fig. 12). The probability trends can be interpreted as measures of the progressive increase of the seismic shaking required to trigger landslides. This probabilistic output demonstrates how collecting historical data can contribute to the evaluation of the earthquake-induced hazard in a natural risk perspective.

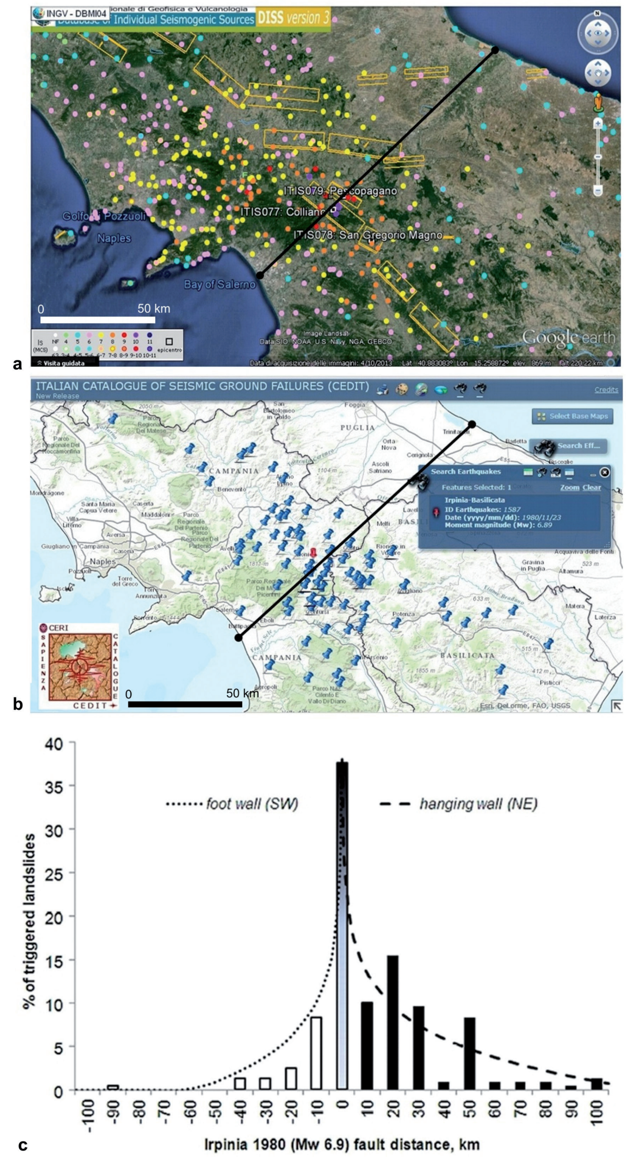

Fig. 9 - a) Macroseismic field and seismogenetic sources from the DISS3.1.1. (2010) database referred to the 1980 Irpinia earthquake (modified from Martino et alii, 2014). b) Distribution of ground effects induced by the Irpinia earthquakes inventoried in the CEDIT catalogue. c) Distribution of landslides induced by the 1980 Irpinia earthquake projected along the SW-NE cross section (solid black line in panels a) and b))

LOOKING AHEAD TOWARD THE FUTURE: MAPPING HAZARD SCENARIOS FOR EARTHQUAKE-INDUCED LANDSLIDES

Several studies have been devoted to investigate the modeling of the seismic susceptibility of slopes to undergo failure. Starting from the pioneering work of Wilson & Keefer (1985) to the most recent ones in terms of susceptibility or hazard (Miles & Keefer, 2009, Jibson & Michael, 2009, Chousianitis *et alii*, 2016), many of them are focused on the spatial analysis of seismically-induced landslides In these studies, landslides affecting soil and rock are usually faced separately due to the different failure mechanisms as well as to the different way to manage the spatial data (raster vs. vector data); rarely distinctions are done between first-time slides and reactivations (*sensu* Hutchinson, 1988). Following a preliminary approach proposed by Bozzano *et alii* (2013), the novel Probabilistic Approach to pRovide Scenarios of earthquake-Induced slope FAiLures (PARSIFAL) was proposed by Esposito *et alii* (2016). It provides the possibility to: i) integrate outputs referred to different mechanisms into a unique mapping, ii) to

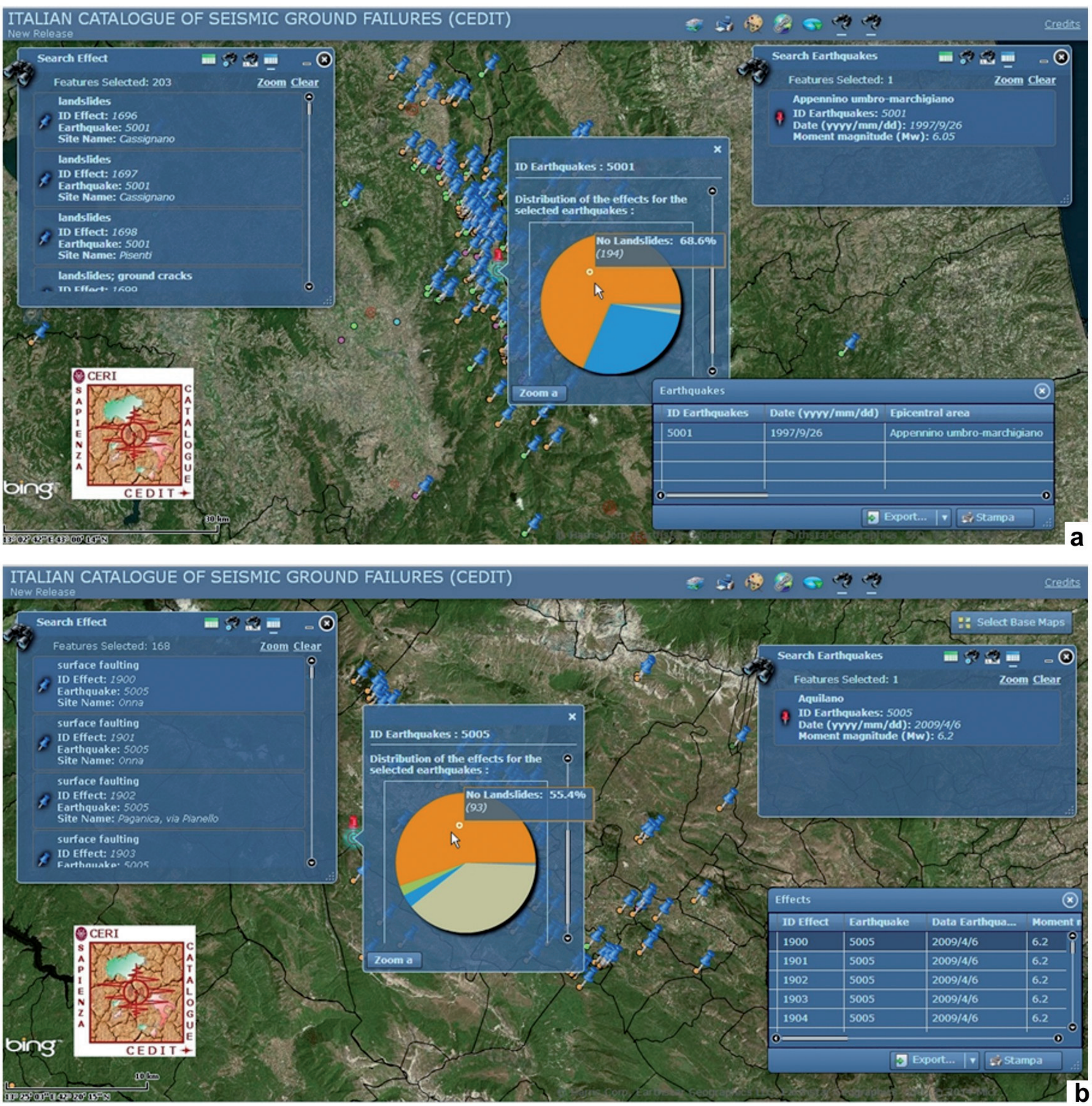

Fig. 10 - Screen shots from the CEDIT web-GIS available on the http://www.ceri.uniroma1.it/cn/gis.jsp showing the distribution of the ground effects induced by the 1997 Umbria-Marche earthquake (a) and by the 2009 L'Aquila earthquake (b) with the related pie graphs reporting the percentages of inventoried ground effects (including landslides)

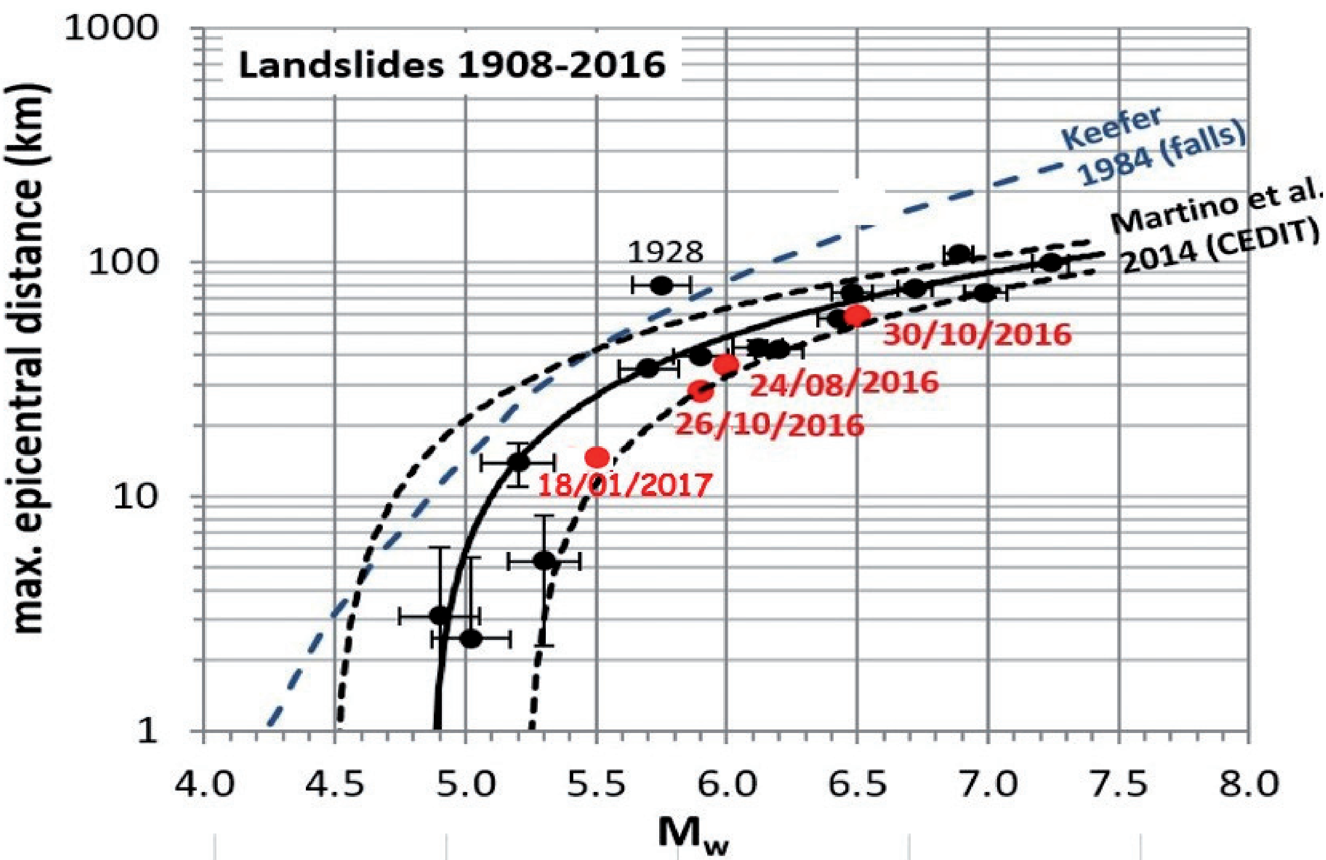

Fig. 11 - Maximum expected distance for earthquake-induced rock falls and rock slides from the Keefer *(1984) global dataset and the* Martino *et alii (2014) CEDIT inventory. The red dots are related to the effects inventoried after the 2016-2017 seismic sequence of the Central Apennines*

distinguish first-time slides and reactivations for analytical computations, ii) take into account seismic hazard combined with saturation conditions, iii) take advantage from the Probabilistic Seismic Hazard Approach and the Deterministic Seismic Hazard Approach by merging them, vi) create comprehensive maps of hazard-controlled scenarios of earthquake-induced landslides.

To arrive at a more suitable probabilistic approach for defining the seismic input and depict earthquake-induced landslide scenarios, Esposito *et alii* (2016) experienced the coupling of PSHA and DSHA by hazard de-aggregation, a powerful but sensitive tool to derive which earthquake scenarios (in terms of magnitude-distance pairs) contribute the most to hazard for a given return period. Since hazard de-aggregation is driven by the choice of the magnitude-distance bins, different bins lead to different scenarios. Moreover, hazard de-aggregation is significant when applied to individual seismogenic structures, but not when applied to zones of diffuse seismicity, where the earthquake scenarios are usually given by the lowermost magnitudes (that have the highest frequency of occurrence) at the shortest distances (that produce the highest ground motion values). In this regard, one can take advantage from the aforementioned Database of the

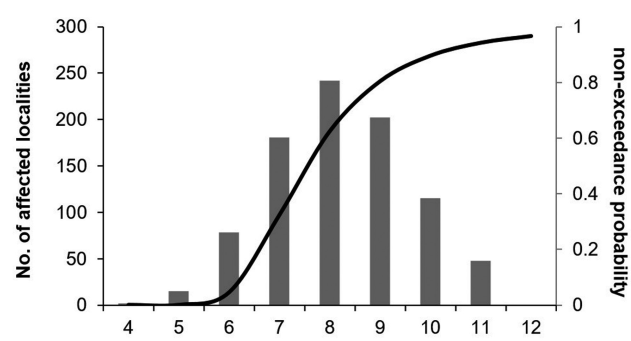

Fig. 12 - Frequency distribution and non-exceedance probability (Weibull distribution) of site intensity for localities affected by earthquake-induced landslides

Italian Seismogenic Sources (DISS 3.1.1; DISS Working Group, 2010). In the PARFISAL, seismic scenarios are formulated on a probabilistic basis to provide uniform seismic loads for each seismogenic structure. Thus, formal landslide hazard maps regarding the seismic shaking are drawn.

For a comprehensive mapping, PARSIFAL proposes univocal relations among kinematic units (i.e. landslide prone or landslide

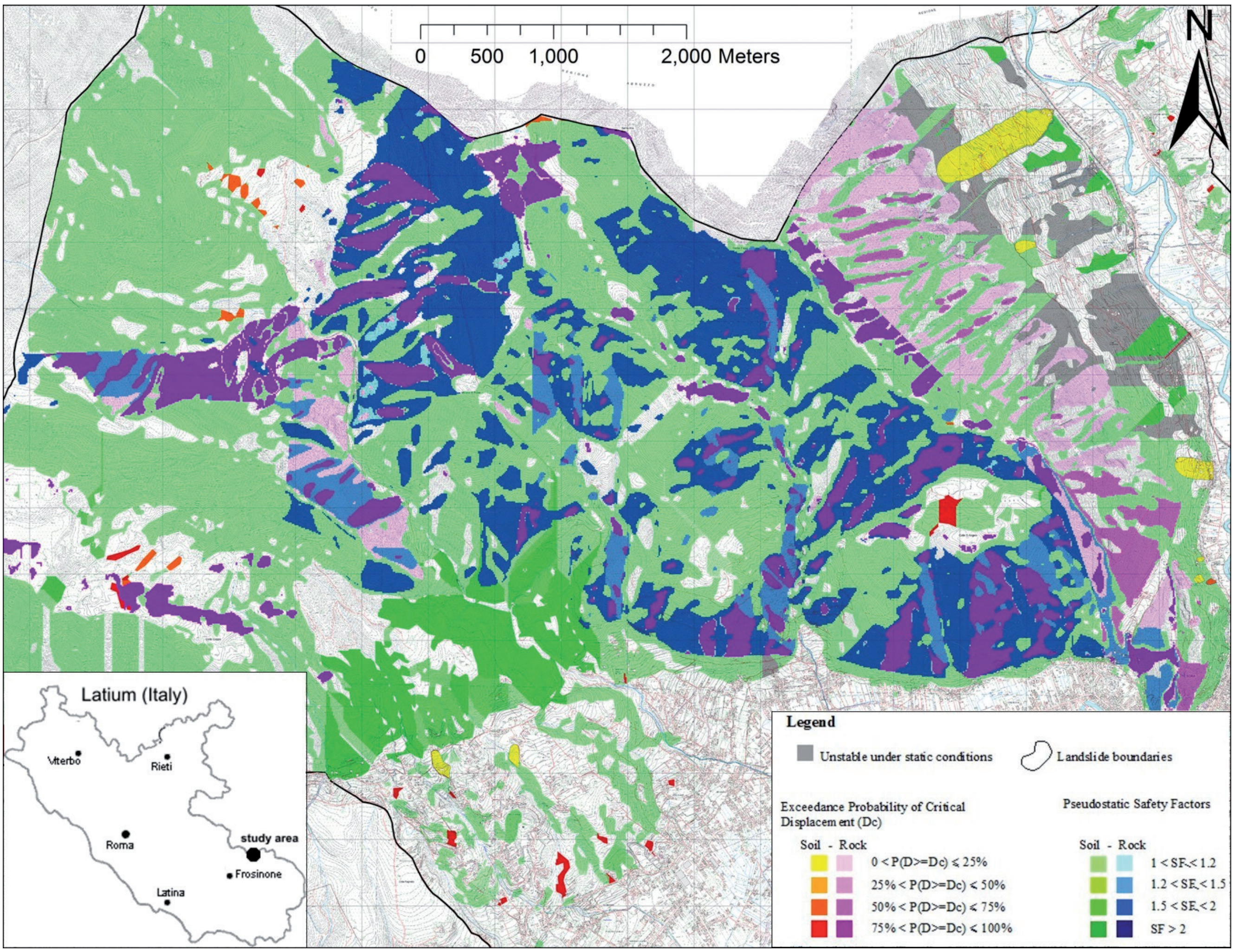

Fig. 13 - Example of earthquake-induced landslide hazard mapping (modified from Esposito *et alii, 2016) obtained through the PARSIFAL approach applied to the Municipality of Sora (Frosinone, Italy)*

existing volumes) and territorial ones. Moreover, even though different kinematic units can be distinguished corresponding to a probability of exceedance or a safety factor value, the landslide hazard maps contain the integrated information with respect to all the investigated conditions. Thus, they provide a general overview of the stability conditions under seismic and hydraulic scenarios and are therefore suitable for the planning of the land use (e.g. micro zonation studies, as addressed by the official document of the Gruppo di Lavoro per la MS, 2008 – "Indirizzi e Criteri per la Microzonazione Sismica") as well as for site-specific analyses.

The local expected ground-motion is expressed by natural time-histories selected according to seismic scenarios in terms of seismic source characteristics, recording site conditions, shaking parameters and spectral shape similarity. PARSIFAL represents an original approach for managing the multi-hazard associated to earthquakes. It was applied so far to some Municipality territories in the Latium region (Esposito *et alii*, 2016). Nevertheless, the methodology is adaptable to any geological context where basic geographical and geological data are either suitable or can be detailed by specific technical surveys (Fig. 13). The CERI is now going to apply the PARSIFAL in some of the Municipality areas of eastern Latium Region which were strongly felt by the 2016-2017 seismic sequence.

CONCLUSIONS

Earthquake-induced landslides represent a multi-hazard in a natural risk perspective since they are induced by a hazardous event (the earthquake), but represent hazardous events by themselves; therefore, they can induce other damaging effects, like river damming or tsunamis. For the Italian territory, the awareness of this kind of “domino effect” derives from several historical documents that were recently inventoried in a catalogue (CEDIT), presently available on-line for free consultation. Based on this catalogue, landslides represent almost 56% of the earthquake-induced ground effects since 1100 A.D. to Present. Considering the strongest earthquakes of the last centuries, more than 50% of ground effects often correspond to landslides; this is the case of the 1980 Irpinia earthquakes as well as of the 2009 L’Aquila earthquake and the seismic sequence of the Central Apennines occurred on 2016-2017. Moreover, the derived statistic indicates that a probability of exceedance equal to 50% for earthquake-induced landslides corresponds to a MCS site intensity of about 7.5. Looking ahead to the future, in view of prevention strategies for natural risk mitigation, the very recent approach PARSIFAL has been recently proposed to provide a comprehensive mapping of earthquake-induced first-time slope failures and landslide re-activations. The PARSIFAL experiences a probabilistic approach, which allows to account for earthquake-induced landslide scenarios at a Municipality spatial scale.

ACKNOWLEDGMENT

To my friend and colleague Roberto Romeo

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Received January 2017 - Accepted May 2017