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Landslides Induced by Historical and Recent Earthquakes in Central-Southern Apennines (Italy): A Tool for Intensity Assessment and Seismic Hazard

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Abstract

Analysis of distribution of landslides (rock falls and coherent slides), induced by 12 moderate to strong earthquakes occurred in the last three centuries in Central–Southern Apennines, has permitted to investigate the relationship of their maximum distance versus magnitude and ESI epicentral intensity.

For coherent slides, the correlation of magnitude or ESI intensity versus distance is fairly good and consistent with global datasets. Instead, rock falls show a less evident correlation with distance. We stress here the usefulness of such relationships to define the expected scenario of earthquake-induced landslides. However, the data base needs to be improved and enlarged to allow more robust estimates.

Keywords

Earthquake-induced landslides · Intensity scales · Central-Southern apennines

Introduction

The inner sector of Central–Southern Apennines is the most seismic sector of the Italian territory (Fig. 1), characterized in historical times by a number of earthquakes with magnitude around 7 and frequent moderate earthquakes (magnitude around 6).

Events of M � 6 typically cause environmental effects (surface faulting, landslides, liquefactions, ground cracks, hydrological anomalies, etc.) that are a significant independent source of seismic hazard in addition to damages due to ground acceleration.

Many historical documents detail the effects of earthquakes in the Apennines, especially the strong events occurred in the last three centuries, reporting lots of data also on the characteristics of the effects on the natural environment. This extraordinary wealth of information has allowed (1) to identify the most vulnerable regions, i.e., the most prone to hazardous Environmental Effects of Earthquakes (i.e. the effects produced by an earthquake on the natural environment or EEEs) and (2) to evaluate the earthquake intensity (epicentral and local) by means of the ESI intensity scale (Michetti et al. 2007), a recently developed intensity scale only based on EEEs.

This study aims at relating the spatial distribution of seismically-induced landslides with magnitude and with the intensity of the event resulting from the application of the ESI scale.

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Fig. 1 Historical seismicity of Central–Southern Apennines (CPTI 2004). Labels locate the epicentres of the seismic events considered in this study

Background

Seismotectonic Framework of the Apennines

The present tectonic structure of the Apennines is the result of Upper Miocene–Lower Pliocene northeast-verging thrust tectonics (Patacca et al. 1990) overprinted by Late Pliocene to Quaternary northeast–southwest crustal extension, migrating in time and space from west to east; the latter is still active now, as demonstrated by seismic (including palaeoseismic) and morphotectonic evidence (Demangeot 1965; Blumetti et al. 1993; Roberts and Michetti 2004). Geodetic data provide velocities (with respect to stable Eurasia) that imply extension rates of 4–5 mm/year across the Apennines (D'Agostino et al. 2008; Devoti et al. 2008).

Historical catalogues (CPTI 2004; Guidoboni et al. 2007) summarize all available information for several moderate to strong earthquakes affecting Central-Southern Apennines in a time window larger than two millennia, but with good completeness only for the last 500 years.

Seismic hazard maps based on historical seismicity and integrated with paleoseismic evidence locate the areas with highest expected magnitudes (even more than 7) in the inner sector of the Central-Southern Apennines.

Magnitude Versus Landslide Distance: State of the Art

Empirical relationships between earthquake-triggered landslide distribution and magnitude based on a global database (about 40 events in the period 1811–1980) have been proposed by Keefer (1984). These relations were refined by Rodriguez et al. (1999) and Bommer and Rodriguez (2002) using a similar approach based on a larger dataset (almost 80 earthquakes). The last papers also discuss the potential relation between landslides distribution and MM intensity degrees. The best fit of data is given by polynomial curves of second degree.

Other relationships between magnitude and landslide distance were published for regional areas (e.g. Papadopoulos and Plessa 2000, for Greece).

In Italy, Prestininzi and Romeo (2000) related the maximum distance of ground failures collected in the CEDIT database (that includes landslides, fractures, liquefaction, topographic changes) with MCS epicentral intensities. Other empirical relationships were pointed out in previous papers of the Authors of this note (e.g. Porfido et al. 2002, 2007), where the distribution of the number of landslides with distance appears to follow a negative exponential trend (e.g. 1805 and 1980 earthquakes). A similar trend has been highlighted for the 2009 earthquake (Guzzetti et al. 2009; Vittori et al. in prep.).

ESI 2007 Intensity Scale

The ESI 2007 intensity scale (Michetti et al. 2007) classifies earthquake intensity based only on Earthquake Environmental Effects (EEE)., either directly linked to the earthquake source or triggered by the ground shaking. EEEs include surface faulting, regional uplift and subsidence, tsunamis, liquefaction, ground resonance, landslides, rock falls and ground cracks.

The definition of the ESI intensity degrees has been the result of a revision conducted by an International Working Group made of geologists, seismologists and engineers. It has been ratified by INQUA (International Union for Quaternary Research) in 2007.

The use of the ESI 2007 intensity scale, alone or integrated with the other traditional scales affords a better picture of the earthquake scenario, because only environmental effects allow suitable comparison of the earthquake intensity both:

- In time: effects on the natural environment are comparable for a time-window (recent, historic and palaeo seismic events) much larger than the period of instrumental record (last century), and
- In different geographic areas: environmental effects do not depend on peculiar socio-economic conditions or different building practices.

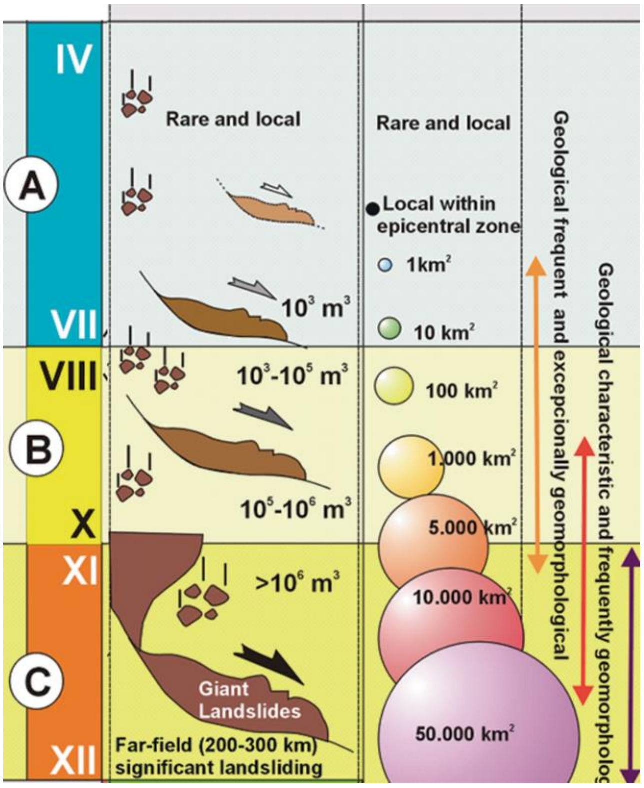

Fig. 2 Schematic picture of the typical landslide size and spatial distribution for ESI intensity degrees ranging from IV to XII (Michetti et al. (2007); Silva et al. (2008))

Thus, the new scale aims at integrating traditional seismic scales:

- For earthquake intensity degree larger or equal to X, when damage-based assessments are extremely difficult (because of tendency to saturation), while environmental effects are still diagnostic;
- In sparsely populated areas, where the effects on man-made structures are lacking and therefore intensity assessments have to be based on the environmental effects, which are the only available diagnostic elements.

The occurrence of landslides is expected from intensity IV ESI. The spatial distribution area of secondary effects (including landslides) allow to estimate the ESI epicentral intensity up to XII (Fig. 2). Furthermore, the growing size (volume, area) of slope movements are considered diagnostic elements for the assessment of the ESI local intensity in the range IV to X.

Landslides Versus Intensity in the Apennines

Landslides Triggered by Selected Earthquakes

We have taken into account 12 earthquakes occurred in the last three centuries, many of which studied in detail by the Authors for macroseismic purposes, with specific focus on the characterization of Earthquake Environmental Effects (Comerci et al. 2009; Esposito et al. 1998, 2000, 2009; Esposito and Porfido 2010; Guerrieri et al. 2007, 2009; Porfido et al. 2002, 2007, 2011; Serva et al. 2007; Vittori et al. 2000, 2011) (Fig. 3).

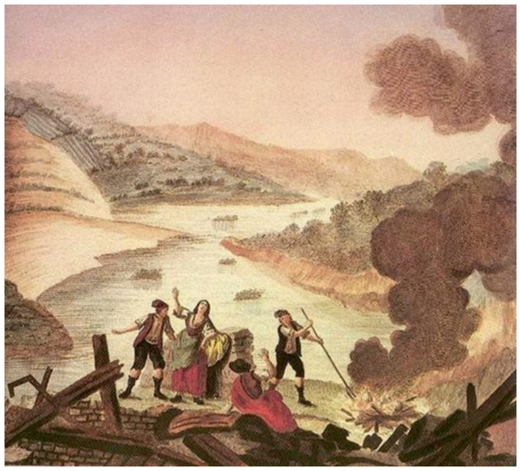

Fig. 3 A landslide triggered by the 1783 Calabrian seismic sequence damned the S. Cristina narrow valleu and formed a temporary lake (Sarconi 1784)

The 1783 Calabrian seismic sequence (Ms ¼ 6.9; I_o ¼ XI MCS; I_o ¼ X-XI ESI) was characterized by a 3 years long sequence and five main shocks generated by individual fault segments of regional WNW-ESE trends. The 1783 multiple event started at the beginning of February and went on until the end of March, reaching a release of energy on March 28 with assessed macroseismic magnitude M ¼ 6.9. More than 30,000 lives were lost and 200 localities were completely destroyed by the February 5 main shock. The epicentral area was located on the Gioia Tauro plain, at the western foot of the northern Aspromonte mountain.

The shock produced spectacular ground effects, both primary and secondary, such as tectonic deformations, ground fractures, liquefactions phenomena, tsunamis, hydrological changes and diffuse landslides of large size, which in most cases dammed the rivers creating more than 200 new temporary lakes (Porfido et al. 2011). A great density of mass movements occurred in the area bounded by Santa Cristina d'Aspromonte, Molochio-Cittanova and Palmi (Cotecchia et al. 1986). The most common landslides were earth-block type, translational and rotational movement affecting the Plio-Pleistocene deposits of Gioia Tauro Plain (Cotecchia et al. 1986). Nevertheless, a reliable dataset of rock fall distribution is not available.

The 1805 July 26 Molise earthquake (Ms ¼ 6.6; I_o ¼ X MCS; I_o ¼ X ESI) affected mostly the Molise region, where at least 30 municipalities, located in the Bojano plain and the eastern foot of the Matese massif, were nearly totally destroyed (Esposito et al. 1987).

About one hundred seismically induced environmental effects are known for the 1805 earthquake mostly in the near-field area although some were reported as far as 70 km from the epicentre (Esposito et al. 1987; Porfido et al. 2002, 2007; Serva et al. 2007).

The earthquake triggered at least 26 slides: mainly rock falls, topples, slumps, earth flows and slumpearth flows. Among the largest of them were the earth flow of San Giorgio la Molara (Benevento), which affected the course of the Tammaro River, the earth flow of Acquaviva di Isernia, the rotational slide at San Bartolomeo in Galdo (Benevento), and a rotational slide-flow at Calitri (Avellino) (Esposito et al. 1987, 1998).

The 1857 December 16 Basilicata earthquake (Ms ¼ 7.0; I_o ¼ X-XI MCS scale; I_o ¼ X–XI ESI) caused extensive damage over an exceptional large area; high values of intensities, X and XI MCS, were observed over an area of 900 km^2, killing about 13,000 people and causing severe damages to man-made works and to the environment.

This event was characterized by multiple main shocks; the second shock, felt two minutes after the first one, with higher energy (Branno et al. 1985). Earthquake-induced environmental effects were recorded over a large area extending from the Vallo di Diano (Campania) to the Val d'Agri (Basilicata).

Primary and secondary geological effects were recognized both in the near and far field. Forty-three landslides phenomena have been localized and classified. The most common slides were rock fall (Atena Lucana, Teggiano, Montesano sulla Marcellana, Grumento Nova, Marsico Vetere) and topless and subordinately rotational slides (Viggiano, Polla), earth flows (Pignola), and slump earth flows (Bella, Muro Lucano), Mallet (1861), Esposito et al. (1998), Porfido et al. (2002).

On 1905 September 8, a large earthquake (Ms ¼ 7.1; I_o ¼ XI MCS; I_o ¼ X-XI ESI) occurred in the Southern part of the Calabria region. It extensively ruined several villages located in the northern part of the Capo Vaticano peninsula within an area that suffered a MCS intensity greater than IX, causing the death of 557 people. The earthquake was characterized by different epicenters both inland, near to Vibo Valentia, and offshore not far from the coastline, suggesting as capable faults the Vibo and Capo Vaticano normal fault segments (Catalano et al. 2008).

The event induced a great number of effects on the environment in a wide area: large landslides, accompanied by several cracks and fractures and liquefaction features occurred in several places within the epicentral area, hydrological variation (changes in flow and in the temperature of springs and rivers) were also observed over the entire Calabria region both in the near and far field. This event also generated a tsunami that inundated the whole northern coast of the peninsula from Vibo to Tropea with an estimated height of waves of about 1–2 m.

The earthquake triggered at least 40 slides: mainly slump earth flows (Belmonte Calabro, Caraffa di Catanzaro, Cessaniti, Gizzeria, Martirano, Piscopio, Mileto ecc.) and subordinately rock falls (Aiello Calabro, Caulonia, Conidoni, San Leo, Tiriolo, Zungri) (Chiodo and Sorriso-Valvo 2006; Tertulliani and Cucci 2008; Porfido et al. 2011).

The 1908 December 28 Southern Calabria-Messina earthquake (Ms ¼ 7.2; I_o ¼ XI MCS; I_o ¼ X-XI ESI) is one of the strongest seismic events that struck Italy during the XXth century and the most ruinous in terms of casualties (at least 80,000). The epicenter was located at sea in the Messina Straits. The location of seismogenic fault is still an open issue (Valensise et al. 2008; Aloisi et al. 2009) and therefore the corresponding distance was not evaluated.

The impact of the earthquake was particularly catastrophic in Reggio Calabria and Messina cities, damages have been more intense and widespread along the Calabrian coast, between south of Reggio Calabria and south-west of Scilla (Comerci et al. 2009; Porfido et al. 2011). In Sicily the most damaged area was the coast from its easternmost tip to south of Messina. Some minutes after the earthquake, a destructive tsunami inundated both sides of the Strait, with a run up that rose above 10–13 m.

More than 400 environmental effects were catalogued (Caciagli 2008; Comerci et al. 2009). Among them, particularly relevant were the changes in elevation along both sides of the Strait, partly due to the settlement of loose sediments and artificial filling (e.g., Messina and Reggio Calabria harbor areas), and partly ascribed to landslides and tectonic slip. Portions of the coast were lost, especially on the Calabrian side, most of them eroded by the tsunami. Landslides and rockfalls occurred in many Sicilian and Calabrian localities (especially between Reggio C. and Bagnara C.). A submarine telephone cable between Gallico (Calabria) and Gazzi (Sicily) was cut likely by a slide.

The 1930 July 23 Irpinia earthquake (Ms ¼ 6.7; I_o ¼ X MCS; I_o ¼ IX-X ESI) occurred in the most seismic part of the Southern Apennines. The earthquake affected a wide area of 36,000 km^2, comprising the regions of Campania, Puglia and Basilicata. The studies of seismically-induced ground effects benefited from numerous historical and scientific sources, and allowed recognition of primary effects (surface faulting), secondary effects (fractures, landslides, settlements, hydrological changes, variations in the chemical and physical activity related to the volcanic and/or thermal zones).

The earthquake caused many sliding phenomena, which mainly affected the rural area and, to a lesser extent, the towns around the epicentral area. At least, 26 landslides were triggered by the earthquake. Large landslides struck Aquilonia (Avellino) and San Giorgio la Molara (Benevento). The former was a reactivation of a slump-earth flow, along the north side of the Rione San Pietro, that forced the abandonment of the entire village (Esposito et al. 2000a). The latter was a 1 km wide and 3 km slump within the Argille Varicolori formation, on the left bank of the Tammaro River, that dammed a short section of the river. Other noteworthy landslides occurred at Ariano Irpino, Vallata, Montecalvo Irpino, Lacedonia, Rocchetta S. Antonio and Acerenza (Esposito et al. 1998; Porfido et al. 2002).

The 1980 November 23 Campania–Basilicata earthquake (Ms ¼ 6.9; I_o ¼ X MCS; I_o ¼ X ESI) affected 800 localities over a large area of the Southern Apennines, killing 3,000 people. This event was felt nearly everywhere in the Italian peninsula, from Sicily to Emilia Romagna and Liguria (Postpischl et al. 1985).

The review of more than 100 technical and scientific publications has allowed to locate and classify 200 landslides over a total area of 22,000 km^2. About 47 % of the landslides were rock falls/toppling, 20 % rotational slides, 20 % slump-earthflows, 3 % rapid earth flows, 9 % left undefined (Cotecchia 1986; Esposito et al. 1998; Porfido et al. 2002, 2007). The largest rock falls occurred mostly in the epicentral area, with volumes ranged from 1,000 to 10,000 m^3 as well as slump-earth flow that affected some historical centre in the Apennines. The largest one (23 million m^3) affected Calitri (Avellino) and its recent urban expansion. Even larger were the mudflows at Buoninventre(30 million m^3), near Caposele and Serra d'Acquara, Senerchia (28 million m^3).

The September–October 1997 Colfiorito seismic sequence (Mw ¼ 6.0; I_o o ¼ VIII-IX MCS; I_o ¼ VIII-IX ESI) struck the Umbria and Marche regions (Central Italy). Three main events occurred on 26 September at 00:33 and 09:40 GMT, and 14 October with magnitude Mw equal to 5.8, 6.0 and 5.4, respectively; furthermore hundreds of minor but significant events were also recorded. Primary and secondary effects were observed, including surface faulting phenomena, landslides, ground fractures, compaction and various hydrological phenomena.

Landslides, which were the most recurrent among the phenomena induced, consisted mainly of rock falls (Stravignano Bagni, Sorifa, Val Nerina), and subordinately of rotational (Afrile, Foligno, Acciano, Monte d'Annifo), which were generally mobilised by the inertia forces during the seismic motion (Esposito et al. 2000; Guerrieri et al. 2009; Guzzetti et al. 2009).

On 1998 September 9, a moderate earthquake (Mw ¼ 5.7; I_o ¼ VII MCS; I_o ¼ VIII ESI) hit the Southern Apennines at the NW margin of the Pollino Massif, between Basilicata and Calabria regions. Historical towns, such as Lagonegro, Lauria and Castelluccio suffered significant damage (I ¼ VIII MCS). Several ground effects followed the shock, and a rock fall, far from the epicenter, on the road between Cersuta and Acquafredda claimed one life.

Landslide phenomena consisting in rock fall, toppling, rotational slides and earth slumps were observed in Castelluccio Inferiore and Superiore, Fardella, Lauria, Maratea, Monte Alpi, Nemoli, Noepoli, Rivello, Rotonda, Tortora. Trecchina and Viggianello territories (Michetti et al. 2000).

The 2002 October 31, San Giuliano di Puglia, earthquake (Mw ¼ 5.8; I_o ¼ VII-VIII MCS; I_o ¼ VIII ESI) caused relevant damages to some villages in Southern Molise (San Giuliano di Puglia, Bonefro, Colletorto), including the tragic collapse of a school at San Giuliano that killed 27 children.

Environmental effects (Vittori et al. 2003) included mainly ground cracks, but also slope movements and hydrological anomalies. Seismically induced landslides consisted mainly in rotational slides (e.g. Castellino sul Biferno) but also translational slides even at significant distance from the epicenter (e.g., Salcito). Rock falls were not surveyed in a systematic way.

The 2009 April 6 L'Aquila earthquake (Mw ¼ 6.3; MCS I_o ¼ IX; ESI I_o ¼ IX), which rocked the Abruzzo region, in Central Apennines is part of a seismic sequence active from December 2008 to October 2009. The epicenter for the main shock was located near L'Aquila. Two M > 5 aftershocks followed on 7 April (ML 5.3, Mw 5.6, epicenter about 10 km southeast of L'Aquila) and on 9 April (ML 5.1, Mw 5.4, epicenter near Lake Campotosto).

Damages were concentrated on the historical town of L'Aquila which, together with many villages in the surrounding area. The death toll reached 308.

The earthquake produced a widespread set of geological effects on the natural environment. Clear evidence of surface faulting was found along the Paganica fault (Guerrieri et al. 2010; Vittori et al. 2011), and secondary effects have been mapped over an area of about 1000 km^2, mostly gravitational movements and ground fissures, and secondarily liquefactions and hydrological anomalies (Blumetti et al. 2009).

Regarding slope movements, rock falls in calcareous slopes (Fig. 4) and artificial cuts have been the most common type of effect Sliding phenomena have also occurred, threatening in some cases the viability of important roads. The scenario includes also some local peculiar effects, like the ground failures along the shores of the Lake Sinizzo.

Empirical Relationships

Similarly to Keefer (1984), we have measured for each earthquake the maximum distance of coseismic slides and rock falls from either the causative fault and the epicentre (Table 1).

Then, such distances have been plotted versus magnitude and versus ESI epicentral intensity (Figs. 5 and 6) with the aim to find a potential correlation.

Fig. 4 Two rock falls triggered by the 2009 L'Aquila earthquake at San Demetrio ne' Vestini (above) and Fossa (below)

Table 1 Maximum distances of coseismic rock falls and slides from epicentre and from the fault plane for the 12 earthquakes considered in this study. M_{aw} are from CPTI04

			Rock falls		Slides	
Earthquake	M_{aw}	ESI I_o	Epic	Fault	Epic	Fault
1783.02.05	6,9	X–XI	–	–	13	16
1783.03.28	6,6	X	–	–	70	70
1805.07.26	6,6	X	80	60	100	82
1857.12.16	7	X–XI	86	48	66	30
1905.09.08	7,1	X–XI	49	51	116	115
1908.12.28	7,2	X–XI	36	–	180	–
1930.07.23	6,7	IX–X	15	23	77	52
1980.11.23	6,9	X	50	43	118	97
1997.09.26	6	VIII–IX	25	20	19	15
1998.09.09	5,7	VIII	23	26	16	18
2002.10.31	5,8	VIII	–	–	36	35
2009.04.06	6,3	IX	45	37	46	38

Concerning coherent slides (Fig. 5), a quite good correlation is evident with either magnitude and ESI intensity ($R^2 > 0.8$). In general, these data are quite consistent with the Keefer's envelope (black dashed line in Fig. 5 above), which is based on a global data base. However, substantial deviations (above Keefer's envelope) do exist for some earthquakes (e.g., 1805, 1908, 2002 events).

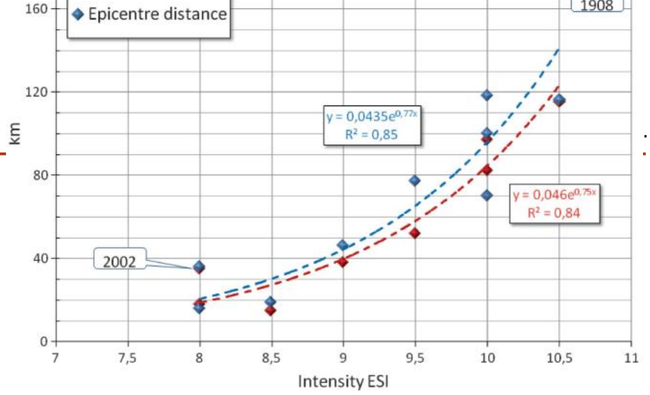

Fig. 5 Relationships between maximum fault distance (in red) and epicentral distance (in blue) of coseismic coherent slides versus magnitude (above) and ESI epicentral intensity (below). Black bold dashed line in the upper graph is the envelope curve of Keefer (1984)

Instead, rock fall data only show a weak trend (Fig. 6). In our opinion, this is due to the very diverse susceptibility to coseismic rock fall/collapse, which is controlled by precise lithological and morphological factors. Moreover, maximum distances for rock falls are always lower than those typically expected for similar magnitudes (see envelope line of Keefer 1984 in Fig. 6 above). Such evidence points out the incompleteness of collected data, especially for historical earthquakes.

Conclusions

Analysis of distribution of landslides (rock falls and coherent slides), induced by 12 moderate to strong earthquakes occurred in the last three centuries in Central–Southern Apennines, has permitted to investigate the relationship of their maximum distance versus magnitude and ESI epicentral intensity.

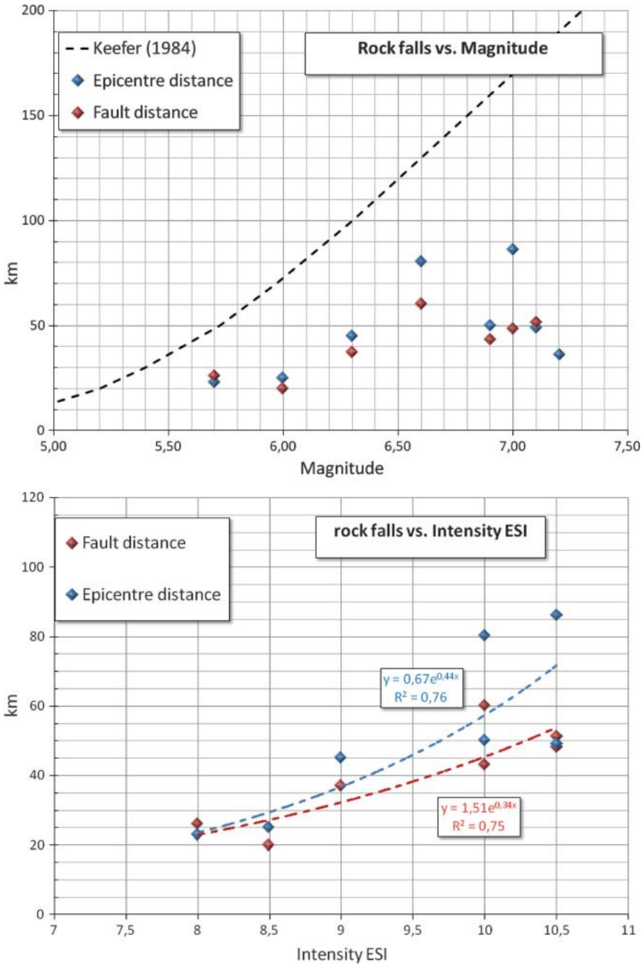

Fig. 6 Maximum fault distance (in red) and epicentral distance (in blue) of rock falls versus magnitude (above) and versus ESI epicentral intensity (below). Bold dashed line in the upper graph is the envelope curve of Keefer (1984). The point distribution is too scattered here to assess reliable trend lines

For coherent slides, the correlation of magnitude versus distance is fairly good and consistent with global datasets (e.g. Keefer 1984; Rodriguez et al. 1999).

For rock falls, maximum distances increase with magnitude, as expected and commonly observed in earthquakes. However, the correlation is much less evident, most likely influenced by local lithological and morphological factors as well as by the incompleteness of data base.

Moreover, although ESI intensity values are actually discrete categories (not numbers), based on the correlation already established between intensities and magnitudes (e.g., CPTI 2004), we have explored their correlation with maximum distance of rock falls and coherent slides. Resulting correlations seem to be reasonably good, for either coherent slides and rock falls.

Being based only on the effects of earthquakes on the natural environment and independent from seismological parameters or damage-based intensity assessments, we stress here the usefulness of such a tool to define the expected scenario of earthquake-induced landslides, especially in sparsely populated areas or where seismic hazard assessment is based only on pre-instrumental seismicity. However, the data base needs to be improved and enlarged to allow more robust estimates.

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