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A new dataset and empirical relationships between magnitude/intensity and epicentral distance for liquefaction in central-eastern Sicily

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Abstract
Strong earthquakes can trigger several phenomena inducing soil deformation, such as liquefaction, ground fracturing and landslides, which can often cause more damage than the seismic shaking itself. A research performed on numerous historical accounts reporting descriptions of seismogeological effects in central-eastern Sicily, allowed the authors to update the previous liquefaction datasets. 75 liquefaction-induced phenomena observed in 26 sites, triggered by 14 earthquakes, have been used to define relationships between intensity/magnitude values and epicentral distance from the liquefied sites. The proposed upper bound-curves, at regional scale for central-eastern Sicily, are realized by using the updating liquefaction dataset and also the new CPTI04 Italian earthquake parametric catalogue. These relationships can be useful in hazard assessment to evaluate the minimum energy of an earthquake inducing liquefactions.

Key words *seismo-induced effects – liquefaction dataset – magnitude-distance relationships – geologic hazard – Sicily*

1. Introduction

Liquefaction is one of the most common ground deformation effects of earthquakes and often a major cause of damage and destruction to buildings and infrastructures. Liquefaction evidence is considered geological marker of paleoseismicity (seismites), because sites affected by past liquefaction have the potential to liquefy again.

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Numerous and widespread liquefaction phenomena have been triggered by earthquakes in several places of the world and many studies have revealed a strong relationship between earthquake parameters and maximum epicentral or fault distance from the sites in which liquefaction develops. These studies are useful to engineers and urban planners for seismic hazard assessment and the mitigation of seismic risk (Russ, 1982; Talwani and Cox, 1985; Saucier, 1989; Amick *et al.*, 1990).

Italian historical records offer several descriptions of seismogeological effects which occurred during the last millennium, such as landslides, liquefaction and ground fracturing. These records were used to compile several catalogues and liquefaction prone area maps.

Eastern Sicily is a seismically active area in which some of the most disastrous Italian events, with M_{aw} up to 7.4 (M_{aw} equivalent moment magnitude according to Working Group CPTI04, 2004), have occurred (*e.g.*, the 1169,

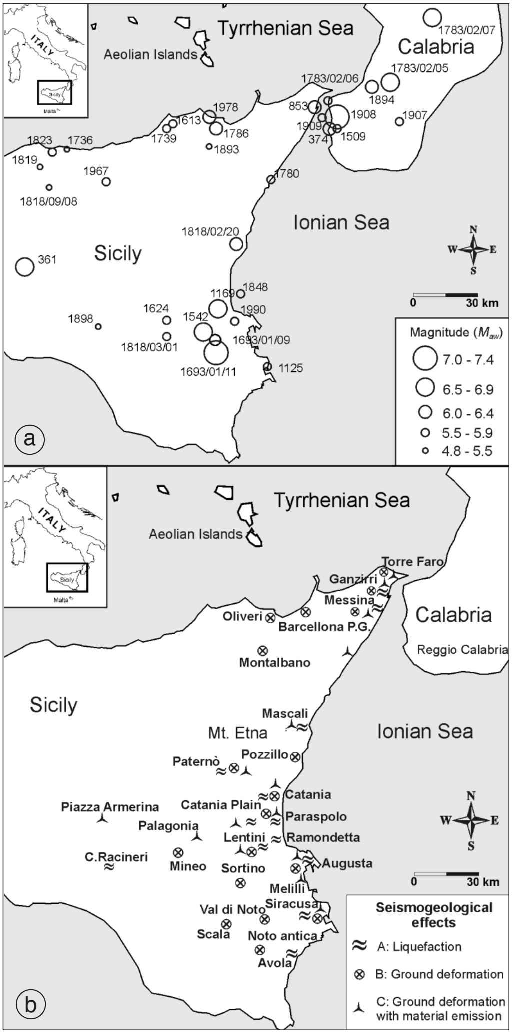

Fig. 1a,b. a) Epicentral map of the earthquakes of central-eastern Sicily and Southern Calabria, data from the Italian Earthquake Parametric Catalogue (Working Group CPTI04, 2004); the circles are earthquake epicentres with magnitudes higher than 4.8. b) Distribution map of the seismogeological effects, classified in table I, retrieved from historical sources (table II).

1693 and 1908 earthquakes) (fig. 1a,b) causing damage, numerous fatalities and triggering several ground failures, as reported by historical sources. This region was also affected by some strong earthquakes occurred in Southern Calabria, such as the 1783 seismic sequences.

Geological evidence of liquefactions (fig. 2a), correlated to some of the strongest earthquakes of Eastern Sicily, were found in the Holocene deposits in the Mascali area, which extends in the eastern flank of Mount Etna, and in the Catania Plain (fig. 1b), both characterized by a continental fluviatile sedimentation environment (Guarnieri *et al.*, 2008).

The aim of this paper is to revise and update the previous liquefaction dataset, and to define empirical relationships, for central-eastern Sicily, between earthquake magnitude/intensity and maximum epicentral distance of liquefied sites, using the earthquake source parameters retrieved from the recent Italian Earthquake Parametric Catalogue (Working Group CPTI04, 2004).

2. Earthquake-induced liquefaction

Earthquake-induced liquefaction is a process by which saturated granular sediment loses its strength, due to ground shaking. Seismic shear waves generated by strong-motion earthquakes produce inter-particle shear stresses which, in saturated soil, can induce significant increasing of pore-water pressures. The increase induces loss of shear resistance of the sediment and the soil can undergo large viscous deformations. This mechanism typically triggers in sandy deposits, even though cases of liquefaction in gravel-rich deposits are documented (Wong *et al.*, 1975; Bezerra *et al.*, 2005).

The liquefaction occurrence depends on the local site conditions (soil composition, local stratigraphic and topographic amplification) and on earthquake characteristics, such as magnitude and distance, which control shaking duration (*i.e.* number of cycles and amplitude of imposed shear stress). Usually, the minimum earthquake magnitude value for liquefying sand is estimated to be about 5.5-6 (Ambraseys, 1991; Valera *et al.*, 1994), while for gravel-rich deposits about 7 (Valera *et al.*, 1994).

Earthquake-induced liquefactions commonly produce sedimentary structures such as dikes, sand boils and lateral spreading (Obermeier,

Table I. Classification of the ground features, associated to liquefaction phenomenon. A class embraces the liquefaction features s.s., B class the ground deformation and C class also includes water, gas and bituminous material emission.

A sand boils, sand hills and sand/mud volcano	B Ground deformation	C Ground deformation with material emission
	B1 Ground fracturing	C1 Ground fracturing with gases exhalation
	B2 Ground settlement	C2 Ground fracturing with hot water, bituminous material and/or fluids emission and/or gases exhalation
	B3 Ground fracturing and settlement	C3 Ground fracturing and settlement with water and/or gases exhalation

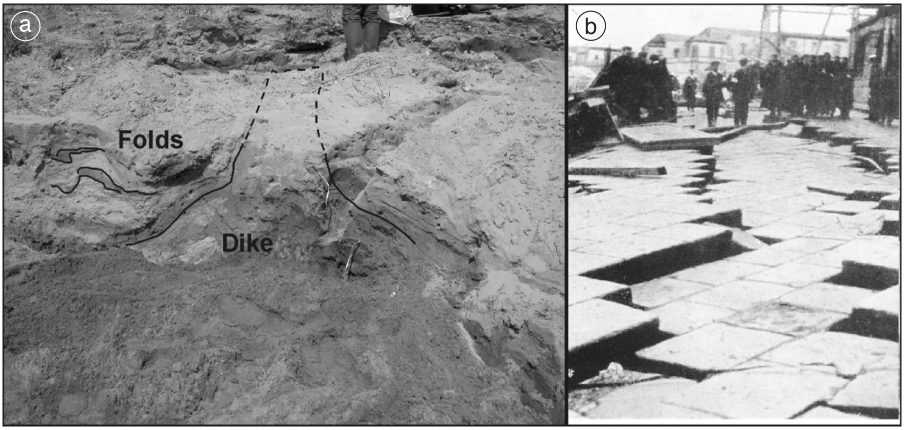

Fig. 2a,b. Examples of liquefaction features in Eastern Sicily: a) surveyed by means of paleo-seismological analysis in the Catania plain (after Guarnieri *et al*., 2008); b) from historical reports, liquefaction in the Messina harbour after the 1908 earthquakes (after Baratta, 1910).

1996) (fig. 2a). These features generally develop near the epicentral area, more numerous and consistent in the mesoseismic area, decreasing systematically with the distance from the epicentre (Obermeier, 1998).

The liquefaction occurs underground and the developed structures not always reach the ground surface. In these cases the seismo-induced liquefaction can be revealed by others associated phenomena such as surface deformation, differential compaction, local swelling or collapse (fig. 2b), differential settlement of building (*e.g.*, Kuribayashi and Tatsuoka, 1975; Galli, 2000); moreover, ground fissures with water or fluids emission, can be superficial evidence of liquefaction.

3. The new dataset of historical liquefaction phenomena in central-eastern Sicily

Italian historical bibliography offers numerous accounts describing seismo-induced effects

Table II. Year, month, day and epicentral area of earthquakes for which liquefaction effects have been observed. Earthquake parameters (latitude and longitude of the epicentre, expressed in fractions of degree, I_o, M_{aw} and M_{as}), from CPTI04 (Working Group CPTI04, 2004). The column *Rt* reports the source of the macroseismic observations: CFTI (Boschi *et al.*, 2000); DOM (Monachesi and Stucchi, 1997) and Azz* refers to Azzaro *et al.* (2007). Sites where liquefaction occurred, their latitude and longitude. The column R_e reports the epicentral distance of the site. Last two columns contain seismically induced observed phenomenon (on the basis of table I classification) and the relative historical sources. New reports and seismo-geological effects are signed by stars.

Earthquake parametres											Recorded phenomenon					
No.	Year	Month	Day	Epicentral area	*Rt*	Lat	Long	I_o	M_{aw}	M_{as}	Site	Lat (s)	Long (s)	R_e (km)	Observed phenomena	Historical sources
1	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Catania	37.380	15.050	7.52	C2	Samperi (1644)
2	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Lentini	37.284	14.998	5.38	C2	Samperi (1644)
3	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Messina	38.187	15.529	106.00	B2*	Cronaca Pisana (13th cent.)
4	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Siracusa	37.082	15.285	34.50	C2	Samperi (1644)
5	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Siracusa	37.082	15.285	34.50	B1	Privitera (1878)
6	1169	2	4	E-Sicily	CFTI	37.32	15.03	10	6.60	6.60	Val di Noto	37.070	15.000	27.76	B1*	Caruso (1781)
7	1542	12	10	SE-Sicily	CFTI	37.22	14.95	10	6.62	6.62	Augusta	37.231	15.221	24.10	A*	BTJN (16th cent.)
8	1542	12	10	SE-Sicily	CFTI	37.22	14.95	10	6.62	6.62	Siracusa	37.082	15.285	26.88	A	BTJN (16th cent.)
9	1624	10	3	Mineo	CFTI	37.27	14.75	8	5.57	5.40	Palagonia	37.326	14.745	6.30	C2*	Mongitore (1743)
10	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Augusta	37.231	15.221	20.53	C2*	Archivio General de Simancas (1693a); Bottone (1718)
11	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Augusta	37.221	15.221	21.07	C1*	Bibl. Comunale di Augusta (17th cent.); Bottone (1718)
12	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Avola	36.908	15.135	26.70	A*	Gubernale (1910)
13	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Catania	37.502	15.087	40.00	B1*	Bottone (1718)
14	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Catania	37.502	15.087	40.00	A	Anonymous (1693); Boccone (1697)
15	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Catania	37.502	15.087	40.00	C2*	Bottone (1718)
16	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Catania Plain	37.502	15.087	32.30	C2	Boccone (1697); Bottone (1718)
17	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Catania Plain	37.502	15.087	32.30	A	Boccone (1697)
18	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Lentini	37.284	14.998	17.33	B1	Bottone (1718)
19	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Lentini	37.284	14.998	17.33	A	Boccone (1697)
20	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Lentini	37.284	14.998	17.33	C2	Bottone (1718)
21	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Mascali	37.757	15.159	70.70	A	Bottone (1718); Boccone (1697)

Table II. (*continued*)

	Earthquake parametres										Recorded phenomenon					
No.	Year	Month	Day	Epicentral area	*Rt*	Lat	Long	I_o	M_{aw}	M_{as}	Site	Lat (s)	Long (s)	R_e (km)	Observed phenomena	Historical sources
22	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Mascali	37.757	15.159	70.70	C2	Bottone (1718)
23	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Melilli	37.179	15.128	11.60	C1*	Boccone (1697)
24	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Messina	38.187	15.529	127.40	C1*	Bottone (1718)
25	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Messina	38.187	15.529	127.40	B1	Archivio General de Simancas (1693b); Mongitore (1743)
26	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Messina	38.177	15.529	128.10	C2*	Bottone (1718)
27	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Mineo	37.266	14.690	32.83	B1*	Del Bono (1745)
28	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Noto Antica	36.940	15.023	21.06	B1*	Boccone (1697)
29	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Scala	36.900	15.060	25.80	B1*	Del Bono (1745); Bonaiuti (1793)
30	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Paternò	37.566	14.902	49.70	B3*	Bottone (1718)
31	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Piazza Armerina	37.384	14.368	63.90	C2*	Del Bono (1745)
32	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Siracusa	37.082	15.285	24.43	B1	Del Bono (1745)
33	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Siracusa	37.082	15.285	24.43	C2	Boccone (1697); Bottone (1718)
34	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Siracusa	37.082	15.285	24.43	A	Boccone (1697)
35	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Siracusa	37.082	15.285	24.43	C1*	Bottone (1718)
36	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Sortino	37.156	15.027	2.96	B2	Boccone (1697); Bonaiuti (1793)
37	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Sortino	37.156	15.027	2.96	B1	Bonaiuti (1793)
38	1693	1	11	E-Sicily	CFTI	37.13	15.02	11	7.41	7.41	Val di Noto	37.070	15.000	6.90	B2	Boccone (1697)
39	1780	3	28	NE-Sicily	Azz*	37.86	15.31	8	5.60	5.10	Fiumedinisi	38.020	15.380	18.70	C2*	Gallo (1783)*
40	1783	2	5	Calabria	CFTI	38.30	15.97	11	6.91	6.91	Ganzirri	38.258	15.611	31.66	B1	Baratta (1910)
41	1783	2	5	Calabria	CFTI	38.30	15.97	11	6.91	6.91	Messina	38.187	15.549	40.51	C2	Gallo (1783); Lallement (1875)
42	1783	2	5	Calabria	CFTI	38.30	15.97	11	6.91	6.91	Messina	38.187	15.529	40.87	B2	Gallo (1783)
43	1783	2	5	Calabria	CFTI	38.30	15.97	11	6.91	6.91	Messina	38.187	15.529	40.87	B1	Gallo (1783); Corrao (1784)
44	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Paraspolo	37.400	15.080	22.68	B1	Longo (1818)
45	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Paraspolo	37.400	15.080	22.68	A	Longo (1818)
46	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Paraspolo	37.400	15.080	22.68	C2	Longo (1818)

Table II. (*continued*)

				Earthquake parametres							Recorded phenomenon					
No.	Year	Month	Day	Epicentral area	*Rt*	Lat	Long	I_o	M_{aw}	M_{as}	Site	Lat (s)	Long (s)	R_e (km)	Observed phenomena	Historical sources
47	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Paternò	37.566	14.902	20.47	C2	Longo (1818)
48	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Paternò	37.566	14.902	20.47	A	Longo (1818)
49	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Pozzillo	37.660	15.190	8.84	B1	Longo (1818)
50	1818	2	20	Catanese	CFTI	37.60	15.13	9	6.00	6.00	Ramondetta	37.350	15.070	28.24	A	Longo (1818)
51	1848	1	11	Augusta	DOM	37.37	15.154	8	5.48	5.26	Augusta	37.231	15.221	16.23	B1*	Ferruggia Russo (1852)*
52	1848	1	11	Augusta	DOM	37.37	15.154	8	5.48	5.26	Augusta	37.231	15.221	16.23	A*	Ferruggia Russo (1852)*
53	1893	4	22	M. Elicona	DOM	38.02	15.01	7	5.03	4.60	Montalbano	38.020	15.010	0.70	B1*	Riccò (1893)*
54	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Barcellona P.G.	38.146	15.215	58.50	B1*	Giornale di Sicilia (1894)
55	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Ganzirri	38.248	15.611	22.70	B1	Riccò (1907); Baratta (1910)
56	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Ganzirri	38.248	15.601	21.80	C1; C2	Riccò (1907)
57	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Ganzirri	38.248	15.603	22.00	B2	Riccò (1907)
58	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Messina	38.187	15.529	31.41	B2	Riccò (1907)
59	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Messina	38.187	15.529	31.41	B3	Riccò (1907)
60	1894	11	16	S-Calabria	CFTI	38.28	15.87	9	6.05	6.05	Torre Faro	38.266	15.646	19.50	B2*	Riccò (1907)
61	1898	11	2	Caltagirone	DOM	37.23	14.51	6	4.83	4.30	C. Racineri	37.210	14.400	10.33	A	Corriere di Catania (1898)*
62	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Ganzirri	38.258	15.611	13.59	C2	Baratta (1910)
63	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Ganzirri	38.248	15.611	13.49	B2*	Lo Giudice (1909)*; Baratta (1910)
64	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Ganzirri	38.248	15.613	13.70	A*	Lo Giudice (1909)*
65	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Ganzirri	38.248	15.601	13.65	C1*	Lo Giudice (1909)*
66	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Messina	38.187	15.549	11.80	B1	Baratta (1910)
67	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Messina	38.187	15.549	11.59	B2	Franchi (1909); Platania (1909); Baratta (1910)
68	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Messina	38.187	15.549	12.29	A*	Baratta (1910); Sauret and Bousquet (1984)*
69	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Torre Faro	38.266	15.646	13.27	B1*	Baratta (1910)
70	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Torre Faro	38.266	15.646	13.27	B3*	Baratta (1910)
71	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Torre Faro	38.266	15.646	13.34	C2*	Baratta (1910)
72	1908	12	28	S-Calabria	CFTI	38.15	15.68	11	7.24	7.24	Torre Faro	38.266	15.646	13.50	B2*	Baratta (1910); Platania (1909)
73	1978	4	15	Patti Gulf	CFTI	38.15	14.983	9	6.06	6.06	Oliveri	38.124	15.060	7.37	B1*	Gazzetta del Sud (1978)
74	1990	12	13	SE-Sicily	CFTI	37.27	15.121	7	5.68	5.26	Augusta	37.231	15.221	9.70	B1	De Rubeis *et al.* (1993)
75	1990	12	13	SE-Sicily	CFTI	37.27	15.121	7	5.68	5.26	Augusta	37.231	15.225	9.15	A	De Rubeis *et al.* (1993)

which are reported in catalogues (Berardi *et al.*, 1991; Galli and Ferreli, 1995; Romeo and Delfino, 1997; Boschi *et al.*, 2000; Galli, 2000; Prestininzi and Romeo, 2000); these have also been used to draw maps of liquefaction-prone areas of Italy (Galli and Meloni, 1993) and, at local scale, of historical liquefaction-induced phenomena in the Catania area (Azzaro, 1999).

This paper presents an updated dataset of liquefaction phenomena in central-eastern Sicily, realized through the revision of historical accounts, retrieved from the aforementioned catalogues and through an original research of historical primary sources. Besides liquefaction structures developing at the surface (*i.e.* sand boils, dikes and mud volcanoes), effects directly connected to the liquefaction mechanism at depth (fig. 2b) have also been reported. Soil deformation phenomena related to liquefaction, according to the classification of Galli (2000) and to geological and geomorphologic criteria, have been chosen, *i.e.* ground fissuring, collapse and surface settlements occurred in recent alluvial depositional areas, flat enough to suggest a their deep liquefaction-induced origin. For example Bottone (1718) describes the effects observed during the 1693 earthquake in the Catania plain as follows: «*la terra si aprì in modo spropositato… Da questa fenditura fuoriuscì una polla di acqua calda: si osservò che ciò era avvenuto in molti luoghi della pianura*» (The ground surface excessively opened… The crack ejected hot water: this phenomenon was observed in several places of the plain). Using the same criteria, exhalation of gases and fluids occurred together with sediment liquefaction, as described for 1908, 1894 and 1783 earthquakes by Lo Giudice (1909) and Baratta (1910), have been included.

The ground features, associated to liquefaction phenomenon, have been classified into three groups: A class, liquefaction features s.s.; B class, ground deformation; C class, ground deformation with emission of material (table I).

The new dataset (table II) collects 75 liquefaction effects observed in 26 sites triggered by 14 earthquakes occurred in central-eastern Sicily and Southern Calabria, from 1169 A.D. to 1990 A.D., and also contains the new earthquake parameters, location, epicentral intensity I_o (MCS), magnitude, M_{aw} (equivalent moment magnitude) and M_{as} (surface wave magnitude), reported by the CPTI04 Catalogue (Working Group CPTI04, 2004) and the epicentral distance R_e, for each liquefied site. The epicentral intensity (I_o) varies from 6 to 11 MCS (table II); the magnitude M_{aw} from 4.83 to 7.41; and the M_{as} from 4.3 to 7.41.

Table III. Number of liquefaction cases for M_{aw} interval. Column 3 is the number of events that induced liquefaction, to be compared with the total number of events existing in the CPTI04 earthquake catalogue (Working Group CPTI04, 2004) for magnitude interval classes at the same epicentral distance.

M_{aw} interval	No. liquefactions	No. events	Events in CPTI04
7.0-7.5	40	2	2
6.6-6.9	11	3	4
6.0-6.5	15	3	6
5.6-5.9	3	2	6
5.0-5.5	4	3	75
4.6-4.9	1	1	62

Table III summarises the frequency of occurrence of liquefaction phenomena for magnitude classes. 69% of observed liquefaction features are induced by earthquakes with $M_{aw} \geq 6.6$; while 24% are related to M_{aw} ranging from 5.6 to 6.5 and only 7% for M_{aw}<5.5.

4. Relationships between magnitude/intensity *versus* epicentral distance (R_e)

Several studies have been carried out to acquire empirical relationships between earthquake source parameters (magnitude, intensity, etc.) and maximum epicentral or fault distance of liquefied sites at regional scale and worldwide. These relationships are useful tools both in geotechnical applications, such as microzonation studies and hazard assessment at the regional scale, and in seismic application, *i.e.* for the evaluation of the minimum energy of an earthquake capable to induce liquefaction and of the minimum magnitude of paleo-earthquakes which have caused liquefaction in a given site, finally for the recognition of the probable mesoseismic zone.

Kuribayashi and Tatsuoka (1975) obtained the correlation between maximum epicentral distance of liquefied sites and associated magnitude for strong earthquakes of Japan. Ambraseys (1991) considered both epicentral and fault distance to compute the relationships between moment-magnitude and distance for 137 liquefaction events scattered around the world. Papadopoulos and Lefkopoulos (1993) obtained a bounding equation revisiting the worldwide curves proposed by Ambraseys (1991), adding their Greek data and other liquefaction observations in several places of the world. Recently, the magnitude upper bound method was applied by Galli (2000) to historical liquefactions induced by 61 earthquakes occurred in Italy from 1117 A.D. to 1990 A.D. The author related epicentral intensity I_o (MCS), magnitude M_s and equivalent moment magnitude M_e, reported in the previous version of the Italian parametric catalogue (Working Group CPTI99, 1999), to the epicentral distance R_e; finally, magnitude M_s to the epicentral distance R_e considering only the instrumentally observed values for the period 1900 A.D.-1990 A.D. Prestininzi and Romeo (2000) found for the whole Italian territory maximum epicentral distances at which ground failures occur as a function of epicentral intensity, distinguishing induced ground effects in topographic changes, liquefaction, landslides and fractures.

The regional dataset realized in this work has been used to find local relationships between earthquake source parameters, M_{aw}, M_s and I_o from CPTI04 (Working Group CPTI04, 2004) and the epicentral distance of the liquefied sites (R_e). We selected these parameters because most of the historical earthquakes have not instrumental data; M_{aw} is the parameter that could be linked to the earthquake energy being computed from I_o and the extension of the felt area (Gasperini *et al.*, 1999).

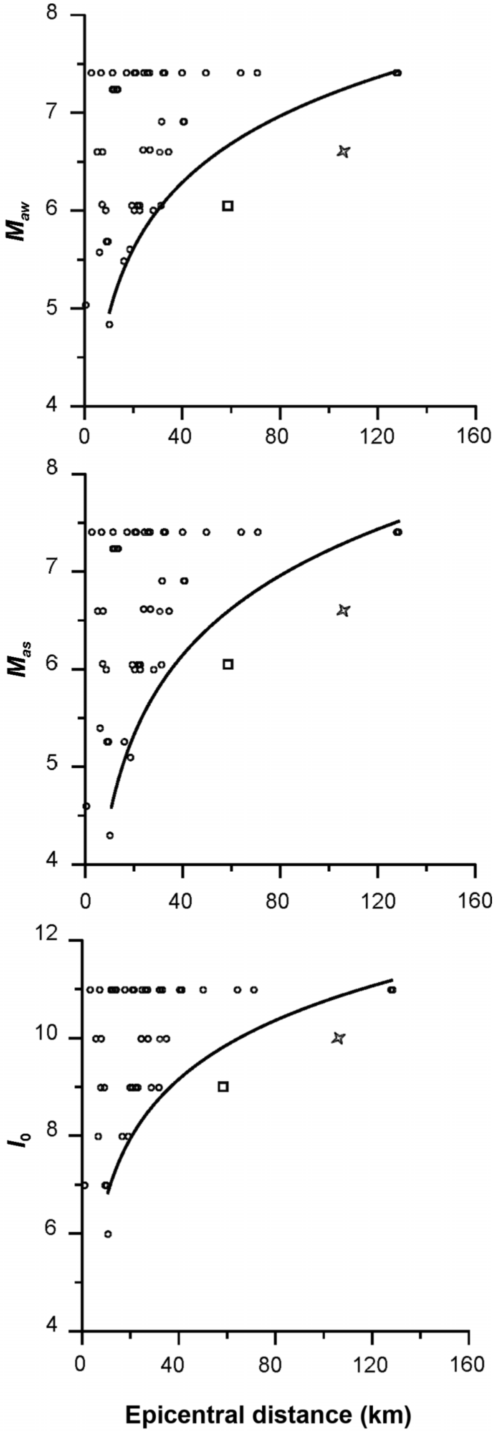

Fig. 3. Distribution of earthquakes that induced liquefaction effects for the period 1169-1990 in terms of epicentral distances and M_{aw} values, M_{as} values and I_o values. M_{aw}, M_{as} and I_o are from CPTI04 (Working Group CPTI04, 2004). The upper bound equations are reported in the text as eq. (4.1), eq. (4.2) and eq. (4.3), respectively. The polygons correspond to the anomalous points: star to the Messina site for the 1169 earthquake; square refers to Barcellona site for the 1894 earthquake.

In the magnitude/intensity-epicentral distance graphs, the point distribution shows the area of occurrence of liquefaction effects (fig. 3), the best-fit of the farthest points gives the upper bound-curves, delimiting liquefaction-prone areas, whose equations (1, 2 and 3) are reported below

$$M_{aw} = (2.67 \pm 0.04) + (0.98 \pm 0.01)\ln(R_e) \quad (4.1)$$

$$M_{as} = (1.85 \pm 0.28) + (1.16 \pm 0.06)\ln(R_e) \quad (4.2)$$

$$I_o = (2.77 \pm 0.32) + (1.73 \pm 0.06)\ln(R_e) \quad (4.3)$$

5. Discussion

The upper bound curves (M_{aw}, M_s and I_o *versus* R_e) obtained for central-eastern Sicily show a similar trend and highlight that lower intensity earthquakes have caused liquefaction at very close distance from the epicentre (<10 km); 43% of the observations occurred with low-medium magnitude (intensity VIII-IX MCS) within 50 km from the epicentre. Finally the events with M_{aw}>6.6 (intensity X-XI) induced liquefaction at great distances, particularly earthquakes with M_{aw}>7.0 and intensity XI (MCS) can trigger liquefaction as far as ~130 km from the epicentre (fig. 3).

Only two points fall out of the upper bound curve, in the area where no liquefaction is predicted. One of these points refers to ground fracturing observed in the Messina seaport during the 1169 earthquake and another point refers to a ground fracture observed near the Barcellona P.G. village after the 1894 earthquake (fig. 3). These sites are both located in north-eastern Sicily. Liquefaction at such exceptionally great distance from the epicentres, as observed for the previous two sites (table II and fig. 3), may be due to local geological characters, but may also be explained with both mislocation and a magnitude/intensity wrong estimate of the 1169 and 1894 earthquakes.

Moreover, the liquefaction prone areas show a lack of data for $6 \leq M \leq 7.4$ and $9 \leq I_o \leq 11$ and epicentral distance between 40 and 120 km (fig. 3), indicating that the earthquakes with these magnitude intervals (1169, 1542, 1783, 1894, 1908 and 1978 events) could have triggered liquefaction outer from the study area. This lack of data could be due to the inevitable incompleteness of the dataset, assembled from historical accounts, and to the fact that the study region not always embraces the entire mesoseismic area of the analyzed earthquakes. In fact the epicentres of the 1783 and 1894 earthquakes are localized in Southern Calabria; the 1908 event is located in the Messina Strait; the 1169 and 1542 sources are close to the south-eastern coast of Sicily, finally the 1978 epicentre is located in the Tyrrhenian Sea (fig. 1).

Comparing ours upper bound curves to previous ones of several regions of the world

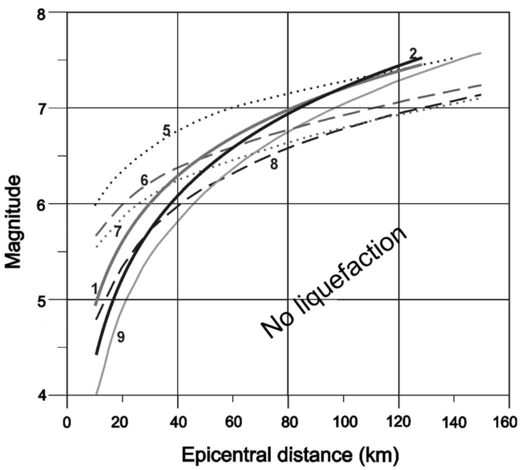

Fig. 4. Comparison between different upper bound curves from literature and those proposed in this paper: continuous dark grey line (1) and continuous black line (2) are related to ours M_{aw} and M_{as} relationships, respectively; dot black line (5) is related to M values from Kuribayashi and Tatsuoka (1975); dashed grey line (6) to M_w from Ambraseys (1991); dot light grey line (7) to M_s from Papadopulos and Lefkopulos (1993); dashed black line (8) to M_e (equivalent magnitude) values and continuous light grey line (9) to M_s ones from Galli (2000).

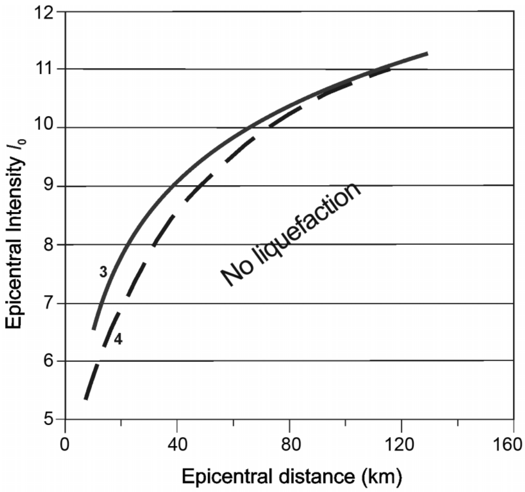

Fig. 5. Comparison between the upper bound curves concerning epicentral intensity I_o provided by Galli (2000), dashed line (4), and that proposed in this paper, continuous line (3).

(Kuribayashi and Tatsuoka, 1975; Ambraseys, 1991; Papadopoulos and Lefkopoulos, 1993) and of the Italian country (Galli, 2000), it is possible to observe a good correspondence of the curve trends as it regards the surface wave magnitude M_s *versus* R_e curve (9) from Galli (2000) (fig. 4) and between our I_o *versus* R_e curve and Galli's one (fig. 5). Mismatch found with the M_e (equivalent magnitude) *versus* R_e curve (8) (fig. 4) can be explained with the different source parameters used by the authors.

6. Conclusions

The analysis performed on historical sources has enriched previous compilations of liquefaction-induced phenomena that occurred during the last millennium in central-eastern Sicily. New data have been introduced and some of the known historical accounts have been reconsidered also including environmental effects directly connected to the liquefaction mechanism, chosen on the basis of geological and geomorphologic criteria.

The new dataset contains 75 liquefaction phenomena triggered by 14 earthquakes, with I_o>6 (MCS) and M_{aw}>4.6, in 26 sites of central-eastern Sicily, and source parameters retrieved from the new Italian earthquake catalogue (Working Group CPTI04, 2004).

Most of the liquefactions are connected to earthquakes with magnitude more than 5.4; only under peculiar site condition, can liquefactions be triggered by earthquakes with M_{aw} value less than 5.4, as observed for the 1893 Montalbano Elicona earthquake (M_{aw}=5.03) and the 1898 Caltagirone earthquake (M_{aw}=4.83).

The updating of the previous catalogues of liquefaction effects and the use of the data retrieved from the Parametric Catalogue (CPTI04), allowed us to obtain a version, at regional scale, of the upper bound curves, M_{aw}, M_{as} and I_o *versus* R_e, for central-eastern Sicily.

Liquefaction effects described at great distance suggest that the studied area is particularly sensitive to these kinds of phenomena, probably due to the seismological characters of the region and to the distribution of Holocene deposits. Moreover, liquefaction effects that fall out of the bound-curve could reveal mislocation and/or wrong magnitude estimate of historical seismic events such as for the 1169 and 1894 earthquakes.

These relationships may be considered a tool for evaluating the minimum energy of an earthquake inducing liquefaction effects, useful in paleoseismic analyses and hazard evaluation, *i.e.* for engineering applications and for the Civil Protection Department, especially in areas subject to industrial and urban growth.

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REFERENCES

Ambraseys, N.N. (1991): Engineering seismology, *Int. J. Earthq. Eng. Struct. Dyn*, **17**, 1-105.

AMICK, D., R. GELINAS, G. MAURATH, H. CANNON, D. MOOR, E. BILLINGTON and H. KEMPINEN (1990): Paleoliquefaction features along the Atlantic seabord, *U.S.N.R.C*, Washington DC 20555 NRC FIN D 1682, NUREG/CR-5613 RA.

ANONYMUOS (1693): *Vera relazione di quello che è successo nell'ultimo terremoto in Sicilia* (veritable ralation de ce qui s'est passé dans le dernier tremblement de terre en Sicile), Toulon.

ARCHIVIO GENERAL DE SIMANCAS (1693a): *Relazione del governatore del Porto di Messina B. Bazan al Vicerè di Napoli sui danni causati in Sicilia dai terremoti del 9 e 11 gennaio*, 1693, Secretarìa de Estado, Negociòn de Sicilia, legajo 3507 (1693-94), Consultas decretos y notas, no. 4.

ARCHIVIO GENERAL DE SIMANCAS (1693b): *Relazione dei luoghi che hanno sofferto in Sicilia nei Terremoti dal nove di gennaio fino al cinque di febbraio del 1693 che si sono sentite ventuno scosse, le primi tre grandi e le altre più lievi*, Palermo febbraio 1693, Secretarìa de Estado, Negociòn de Sicilia, legajo 3507 (1693-94), Consultas decretos y notas, no. 11.

AZZARO, R. (1999): Liquefaction induced features for the scenario earthquake in the Catania area, in *The Catania Project: Earthquake Damage Scenarios for High Risk Area in the Mediterranean*, edited by E. FACCIOLI and V. PESSINA (CNR - Gruppo Nazionale per la Difesa Terremoti, Roma), 42-45.

AZZARO, R., F. BERNARDINI, R. CAMASSI and V. CASTELLI (2007): The 1780 seismic sequence in NE Sicily (Italy): shifting an underestimated and mislocated earthquake to a seismically low rate zone, *Nat. Hazards,* **42** (1), 149-167.

BARATTA, M. (1910): *La Catastrofe Sismica Calabro Messinese* (28 dicembre 1908), Roma, **2**, 211-426.

BERARDI, R., C. MARGOTTINI, D. MOLIN and A. PARISI (1991): Soil liquefaction: case histories in Italy, *Tectonophysics*, **193**, 141-164.

BEZERRA, F. H. R., V. P. DA FONSECA, C. VITA-FINZI, F.P. LIMA-FILHO and A. SAADI (2005): Liquefaction-induced structures in Quaternary alluvial gravels and gravelly sediments, NE Brazil, *Eng. Geol.*, **76**, 191-208.

BIBLIOTECA COMUNALE DI AUGUSTA (17th cent.): *Cronaca dei terremoti del 9 e 11 gennaio 1693 scritta da una monaca del Monastero di S. Caterina di Augusta* (ms), Raccolta Blasco, vol. 638.

BOCCONE, P. (1697): *Intorno il terremoto della Sicilia seguito l'anno 1693,* Museo di Fisica, Venezia 1697, pp. 31.

BONAIUTI, V. (1793): Particolarità intorno al tremuoto che ruinò la Sicilia nel 1693, in *Compendio delle Transazioni Filosofiche della Società Reale di Londra*, parte 1 (Storia Naturale), tomo 1 (Vulcani e Tremuoti), 33-43, Venezia.

BOSCHI, E., E. GUIDOBONI, G. FERRARI, P. GASPERINI, D. MARIOTTI and G. VALENSISE (2000): Catalogue of strong Italian earthquakes from 461 a.C. to 1997, *Ann. Geofis.*, **43** (4), 843-868 and CD-ROM.

BOTTONE, D. (1718): *De immani Trinacrie terremotu. Idea historico-physica, in qua non solum telluris concussiones transacte recensetur, sed novissime anni 1717*, Messina.

BTJN (16th cent.): *Lettera from Yosef Ha-Kohen to Yishaq ha-Kohen*, Raccolta epistolare KM 55 (ms), The Jewish National and University Library.

CARUSO, G.B. (1781): *Storia di Sicilia*, p. II, libro V, p. 360, Palermo.

CORRAO, A. (1784): *Memoria sopra i tremuoti di Messina accaduti nell'anno 1783*, Messina.

Corriere di Catania (1898), Novembre, Catania.

Cronaca Pisana (13th cent.), in *Italia sacra* edited by F. UGHELLI, **10**, Venezia 1722.

DEL BONO, M. (1745): *Discorso sull'origine dé tremuoti, in cui si esamina di proposito una nuova Opinione intorno alla cagione di essi*, Palermo.

DE RUBEIS, V., C. GASPARINI, A. MARAMAI and A. ANZIDEI (1993): Il terremoto siciliano del 13 Dicembre 1990, in *Contributi allo studio del terremoto della Sicilia orientale del 13 Dicembre 1990*, Roma, 9-44.

FERRUGGIA-RUSSO, S. (1852): *Memoria sul tremuoto degli 11 gennaro 1848*, Siracusa, pp. 61.

FRANCHI, S. (1909): Il terremoto del 28 dicembre 1908 a Messina, in rapporto alla natura del terreno ed alla riedificazione della città, *Boll. Comit. Geol. Ital.,* 4th series, **10**, 111-157**.**

GALLI, P. (2000): New empirical relationships between magnitude and distance for liquefaction, *Tectonophysics*, **324**, 169-187.

GALLI, P. and L. FERRELI (1995): A methodological approach for historical liquefaction research, *Paleoseismol., Assoc. Eng. Geol. Spec. Publ.*, **6**, 36-48.

GALLI, P. and F. MELONI (1993): Nuovo catalogo nazionale dei processi di liquefazione avvenuti in occasione dei terremoti storici in Italia, *Il Quaternario*, 271-292.

GALLO, A. (1783): Lettera istorico-fisica dé terremoti accaduti in Messina nel mese di febbraio di quest'anno 1783, scritta dal Sig. D. Andrea Gallo, Messina 8 Marzo, in *Dei terremoti di Messina e di Calabria dell'anno 1783, Memorie e riflessioni*, edited by M. AUGUSTI, Bologna, 7-18.

GASPERINI, P., F. BERNARDINI, G. VALENSISE and E. BOSCHI (1999): Defining seismogenic sources from historical earthquake felt report, *Bull. Seismol. Soc. Am.*, **89**, 94-110.

Gazzetta del Sud (1978), Aprile 27, a. 27, n. 115, Messina.

Giornale di Sicilia (1894), Novembre 24/25, Palermo.

GUARNIERI, P., C. PIRROTTA, M.S. BARBANO, P.M. DE MARTINI, F. GERARDI, D. PANTOSTI and A. SMEDILE (2008): Paleoseismic investigation of historical liquefactions along the Ionian coast of Sicily, *J. Earthq. Eng.* (in press).

GUBERNALE, G. (1910): *Brevi cenni sulla città di Avola*, Modica.

KURIBAYASHI, E. and F. TATSUOKA (1975): Brief reviewer of liquefaction during earthquakes in Japan, *Soil Foundations*, **15** (4), 81-92.

LALLEMENT, M. (1785): Relation envoyée par M. Lallement, viceconsult de France a Messine, au ministre, in *J.C.R. de Saint-Non, 'Vojage pittoresque à Naples et en Sicile'*, **vol. 4**, parte I, pp. 5-10.

LO GIUDICE, P. (1909): I laghi di Ganzirri e del Faro (Messina) dopo il terremoto del 28 Dicembre 1908, *Riv. Mensile Pesca Idrobiol.*, Anno XI, Luglio-Agosto, 7-8.

LONGO, A. (1818): *Memoria storico-fisica sul tremuoto dé 20 febbraio 1818*, Catania 1818.

MONACHESI, G. and M. STUCCHI (1997): DOM4.1, un database di osservazioni macrosismiche di terremoti di area italiana al di sopra della soglia del danno, *GNDT, Rapporto Interno*, Milano-Macerata.

MONGITORE, A. (1743): Istoria cronologica de' terremoti di Sicilia, in *Della Sicilia Ricercata nelle Cose più Memorabili,* **2**, 345-445, Palermo.

OBERMEIER, S.P. (1996): Use of liquefaction-induced features for paleoseismic analysis- An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes, *Eng. Geol.*, **44**, 1-76.

OBERMEIER, S.P. (1998): Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, U.S.A., *US Geol. Surv.,* MS 955, 12201 Sunrise Valley Drive, Reston, VI 20192, U.S.A.

PAPADOPOULOS, G.A. and G. LEFKOPULOS (1993): Magnitude-distance relations for liquefaction in soil from earthquakes, *Bull. Seismol. Soc. Am.*, **83**, 925-938.

PLATANIA, G. (1909): Il Maremoto dello Stretto di Messina del 28 dicembre 1908, *Boll. Soc. Sism. It.*, **13**, 369-458.

PRESTININZI, A. and R. ROMEO (2000): Earthquake-induced ground failures in Italy, *Eng. Geol.*, **58** (3-4), 387-397.

PRIVITERA, S. (1878): *Storia di Siracusa antica e moderna* (ristampa anastatica, Sala Bolognese), Napoli, 1878.

RICCÒ, A. (1893): Periodo di attività geodinamica dal 22 aprile alla fine di maggio1893, *Boll. Acc. Gioenia Sc. Nat.*, n.s., **33**, 16-17.

RICCÒ, A. (1907): Il terremoto del 16 novembre 1894 in Calabria ed in Sicilia. Parte I: Relazione sismologia, in *Ann.Uff. Meteor. Geodin. Ital.*, s. II, **19** (1897), 7-261.

ROMEO, R. and L. DELFINO (1997): *Catalogo Nazionale degli Effetti Deformativi del Suolo Indotti da Forti Terremoti*, CEDIT, Rapporto Tecnico SSN/RT/97/04.

RUSS, D.P. (1982): Style and significance of surface deformation in the vicinity of New Madrid, Missouri, in *Investigations of the New Madrid, Missouri, earthquake region*, edited by F.A. MCKEOWN and L.C. PAKISER, *US Geol. Surv., Prof. Paper 1236*, 95-114.

SAMPERI, P. (1644): *Cronologia della gloriosa Vergine Madre di Dio Maria protettrice di Messina*, Messina, 1644.

SAUCIER, R.T. (1989): Evidence for episodic sand-blow activity during the 1811-1812 New Madrid (Missouri) earthquake series, *Geology*, **17**, 103-106.

SAURET, B. and J.C. BOUSQUET (1984): Manifestations d'instabilité du sol dans la zone epicentrale du seisme de Messine de 1908: le role de la liquefaction, *Mouvements de Terrains*, Papers of the Colloquium, **83**, 54-70.

TALWANI, P. and J. COX (1985): Paleoseismic Evidence for Recurrence of Earthquakes near Charleston, South Carolina, *Science*, **229**, 379-381.

VALERA, J.E., M.L. TRAUBENIK, J.A. EGAN and J.Y. KANESHIRO (1994): A practical perspective on liquefaction of gravels, in *Ground Failures Under Seismic Conditions*, edited by S. PRAKASH and P. DAKOULAS, *Am. Civil. Eng. Geotech., Spec. Publ.*, **44**, 241-257.

WONG, R.T., H.B. SEED and C.K.CHAN (1975): Cyclic loading liquefaction of gravely soils, *J. Geotech, Eng. Am. Soc. Civil Eng.*, 277-283.

WORKING GROUP CPTI99 (1999): *Catalogo Parametrico dei Terremoti Italiani* (ING, GNDT, SGA, SSN, Bologna), pp. 92.

WORKING GROUP CPTI04 (2004): *Catalogo Parametrico dei Terremoti Italiani, versione 2004, CPTI04* (INGV, Bologna), (available on line at http://emidius.mi.ingv.it/CPTI/).

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