ShakeDaDO: a data collection combining earthquake building damage and ShakeMap parameters for Italy

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Abstract

In this article, we present a new data collection that combines information about earthquake damage with seismic shaking. Starting from the Da.D.O. database, which provides information on the damage of individual buildings subjected to sequences of past earthquakes in Italy, we have generated ShakeMaps for all the events with magnitude greater than 5.0 that have contributed to these sequences. The sequences under examination are those of Irpinia 1980, Umbria Marche 1997, Pollino 1998, Molise 2002, L'Aquila 2009 and Emilia 2012. In this way, we were able to combine, for a total of the 117,695 buildings, the engineering parameters included in Da.D.O., but revised and reprocessed in this application, and the ground shaking data for six different variables (namely, intensity in MCS scale, PGA, PGV, SA at 0.3s, 1.0s and 3.0s). The potential applications of this data collection are innumerable: from recalibrating fragility curves to training machine learning models to quantifying earthquake damage. This data collection will be made available within Da.D.O., a platform of the Italian Department of Civil Protection, developed by EUCENTRE.

Keywords: ShakeMap, Building Damage, Italian earthquakes, Data Collection

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1. Introduction

This article describes the procedure implemented for the creation of a joint data collection of information on building damage and associated ground shaking (referred to herein as ShakeDaDO) for Italy. The main components used to develop this data collection are Da.D.O. (the Database of Observed Damage, Dolce et al., 2019) compiled by the Italian Civil Protection using damage assessment forms from sequences of past Italian earthquakes [1] and the ground shaking provided by the new implementation of ShakeMap at INGV (Michelini et al., 2020). The data collection was developed in three consecutive steps. The first step involved the refinement of the information on buildings present in Da.D.O.. In the second step, we have recovered from the literature (or accessible web-services) the seismological information of the earthquakes within Da.D.O. to calculate maps of ground shaking with the highest level of accuracy that is currently possible. The latest version of ShakeMap (version 4.0), which implements updated ground motion models and maps of local site corrections, was used for this purpose. Finally, each point of Da.D.O. was paired with the Mercalli–Cancani–Sieberg intensity scale (MCS hereinafter), the ground shaking parameters, the distance between the point under examination and the earthquake source, and the magnitude of the earthquake. The ground motion parameters of interest are: MCS intensity, peak ground acceleration, peak ground velocity, spectral acceleration at 0.3s, 1.0s and 3.0s, and their relative uncertainties. These six parameters are calculated by ShakeMap and were chosen because they give a comprehensive overview of shaking. In particular, these three spectral acceleration are chosen to display the amount of shaking experienced by structures sensitive to low periods, intermediate periods, and long periods.

The publication of the Da.D.O. database (Dolce et al., 2019) has made available a large amount of information on damage data of individual buildings from ten strong sequences of earthquakes that affected Italy since 1980. Around the same time, Michelini et al. (2020) published a new release of ShakeMap for the Italian territory. This implementation is based on the updated ShakeMap code architecture, which implements

[1] available at http://egeos.eucentre.it/danno_osservato/web/danno_osservato

a new and more sophisticated strategy for the integration of real ground motion data and ground motion models (Worden et al., 2020). In addition, it uses the latest ground motion models and an updated site effects map. Michelini et al. (2020) describe the new approach, quantify the consistency between recorded data and the resulting maps and compare the results obtained from the new configuration with the previous one that was fully described in Michelini et al. (2008).

In light of these developments, we have created a single data collection that merges information about the damage and the characteristics of the individual buildings, with the associated ground shaking parameters inferred at the individual points provided by Da.D.O.. Combining these data and applications has allowed the construction of an extensive data collection, the first of its kind for Italy. Its application allows the impact of earthquakes to be addressed through new strategies, such as through the training of machine learning models.

The paper is divided into the following sections:

- refinement of the Da.D.O. database;
- creation of the ShakeMaps for all $M \geq 5.0$ earthquakes belonging to each sequence under examination;
- assemblage of the ShakeDaDO data collection.

In the following, we describe the steps and reasoning that led to the creation of the joint damage/ShakeMap data collection. We also present all of the maps that have been generated and a first statistical analysis of the data distribution.

2. Refinement of the Da.D.O. Database

The damage data in the Da.D.O. database, described in Dolce et al. (2019), required additional processing since it does not include all of the undamaged buildings (except for the Irpinia event which included all the buildings in the affected region). The Italian National Institute of Statistics (ISTAT) census data from either the 1991, 2001 or 2011 census has been used to obtain an estimate of the total number of reinforced concrete and masonry buildings in each municipality at the time of each event. Subsequently, the number of damaged buildings from Da.D.O. has been removed from the total number of buildings to provide an estimate of the number of undamaged buildings. It has not been possible to obtain census data representing the building/dwelling statistics at the time of the Friuli 1976 and Abruzzo 1984 events, and so in these cases it has not been possible to estimate the undamaged buildings and they were thus excluded from further study. For the remaining eight sequences, only those municipalities where the inspection forms made up at least 80% of the estimated total number of buildings in the municipality have been considered in the calculations herein (as it cannot necessarily be assumed that municipalities with few damage forms had few damaged buildings). Due to a lack of municipalities that met this criterion, Emilia 2003 was also excluded from this study. As for the Garfagnana-Lunigiana 2013 earthquake, this earthquake was only recently included in Da.D.O. database. Six historical sequences of events in Italy have thus been analysed herein: Irpinia 1980, Umbria-Marche 1997, Pollino 1998, Molise 2002, L'Aquila 2009 and Emilia 2012. The following fields were extracted from the Da.D.O. Database:

- location (latitude and longitude of the building);
- number of floors/storeys;
- age of construction;
- structure (masonry or reinforced concrete);
- damage (where the original damage descriptions in Da.D.O. were converted to DS0 to DS5 using the approach proposed by Dolce et al. (2019), and where grade DS0 is for no damage; grade DS1 refers to slight damage (e.g., hair-line cracks in few walls); grade DS2 refers to moderate damage (e.g., fall of large pieces of plaster); grade DS3 refers to heavy damage (e.g., large and extensive cracks in walls); grade DS4 refers to very heavy damage (e.g., serious failure of walls) and grade DS5 refers to destruction, the total collapse).

We also added an additional attribute representing the year in which the municipality first entered the seismic zonation classification. However, it is noted that the calculation of undamaged buildings using Census data, as described above, adds a significant number of buildings for the DS0 class which are missing data on the location, number of floors, and age of construction. It was also found that there were also a few damaged buildings from the Da.D.O. database which lacked these attributes. To be able to complete these attributes for these buildings, we adopt the following strategy to generate the missing data: number of storeys and the age of construction are sampled on the basis of the frequency from the same municipality, as available in Da.D.O. database; the location is randomly sampled from the normalised density of population as available in LandScan (2015). In the following the details of the points generated for each historical sequence is given, while in Table 1 a summary is provided.

Table 1: Number and properties of original and added (simulated) buildings in the Da.D.O. database.

	Damage Grade	**Structural Material**	**Buildings Added**	**Origial No. Buildings in Da.D.O.**	**Buildings Added**	**% of Original Buildings Added**
Irpinia 1980	DS0	masonry	163	38095	211	0.6%
		RC [2]	48			
Umbria Marche 1997	DS0	masonry	172	6980	1661	23.8%
		RC	345			
	DS1	masonry	270			
		RC	22			
	DS2	masonry	137			
		RC	2			
	DS3	masonry	307			
		RC	2			
	DS4	masonry	141			
		RC	1			
	DS5	masonry	262			

[2] reinforced concrete

Pollino 1998	DS0	masonry	313	3966	330	8.3%
		RC	6			
	DS1	masonry	6			
	DS2	masonry	1			
		RC	1			
	DS3	masonry	2			
	DS4	masonry	1			
Molise 2002	DS0	masonry	789	14110	903	6.4%
		RC	110			
	DS1	RC	4			
L'Aquila 2009	DS0	masonry	519	52678	1597	3.0%
		RC	781			
	DS1	masonry	102			
		RC	37			
	DS2	masonry	55			
		RC	7			
	DS3	masonry	59			
		RC	11			
	DS4	masonry	14			
		RC	2			
	DS5	masonry	7			
		RC	3			
Emilia 2012	DS0	masonry	174	1866	335	17.9%
		RC	154			
	DS1	masonry	2			
	DS2	masonry	1			
	DS3	masonry	1			
	DS4	masonry	2			
	DS5	masonry	1			

Totals				117695	5037	4.3%

2.1. Irpinia 1980

The Da.D.O. database information on buildings for this earthquake belongs to 41 municipalities. Contrary to what happens for the data of the other sequences, for Irpinia the locations of all the buildings within Da.D.O. are placed at the coordinate of the town hall of the municipality of reference, since more detailed geographical information is not available. To overcome this limitation, we have randomly distributed the buildings within the municipality using the same method described above for the buildings that were lacking location data. As before, the distribution was made on a probabilistic basis, using the population density available in LandScan (2015). For what concerns the buildings with missing data, these are all buildings with damage grade DS0 and they belong to 11 different municipalities; a total of 211 coordinates for these buildings have been simulated. Table S1 in the supplementary material summarises the information on all the buildings for which we have added missing attributes. The final database for Irpinia 1980 is composed of 38,095 data points.

2.2. Umbria–Marche 1997

The Da.D.O. database data for this earthquake belong to 12 municipalities. For the buildings with missing attributes, these belong to 12 different municipalities, and 1661 coordinates have been simulated. Table S2 in the supplementary material summarises the information on all the buildings for which we have added missing attributes. For this event there are some municipalities for which buildings with damage grades other than DS0 have also been generated, such as Fiastra, Monte Cavallo and Pieve Torina; the type of structure of the simulated buildings are mainly reinforced concrete for damage grade DS0, and masonry for the other damage states. The final database for Umbria-Marche 1997 is composed of 6980 data points.

2.3. Pollino 1998

The Da.D.O. database data for this earthquake belong to 6 municipalities. The buildings with missing attributes belong to 6 different municipalities, and 330 coordinates have been randomly simulated. Table S3 in the supplementary material summarises the information on all the buildings for which we have added missing attributes, which are mainly masonry buildings with damage grade DS0. The final database for Pollino 1998 is composed of 3966 data points.

2.4. Molise 2002

The Da.D.O. database data for this earthquake belong to 16 municipalities. The buildings whose attributes have been simulated belong to 13 different municipalities, and a total of 903 coordinates have been simulated. Table S4 in the supplementary material summarises the information on all the buildings for which we have added missing attributes. As for Pollino 1998, the majority of simulated buildings are masonry with no damage (DS0). The final database for Molise 2002 is composed of 14,111 data points.

2.5. L'Aquila 2009

The Da.D.O. database data for this earthquake belong to 38 municipalities. The buildings with missing attributes belong to 32 different municipalities, and a total of 1597 coordinates have been simulated. Table S5 in the supplementary material summarises the information on all the buildings for which we have added missing attributes. As for Umbria–Marche 1997, for this earthquake, the simulation of buildings not only includes those belonging to the DS0 class but also some of the other categories. The municipalities of Castel del Mare, Pietracamela and Calascio showed this behaviour. In the regional capital, L'Aquila, the damage grade with by far the largest number of buildings to simulate is DS0, with a reinforced concrete structure type. Contrary to other earthquakes, several points belonging to class DS1 have also been simulated. The final database for L'Aquila 2009 is composed of 52,679 data points.

2.6. Emilia 2012

The Da.D.O. database data for this earthquake belong to just 2 municipalities. The buildings with missing attributes belong to both municipalities, and 335 coordinates have been randomly simulated. Table S6 in the supplementary material summarises the information on all the buildings for which we have added missing attributes. The main damage grade of buildings with missing attributes is DS0, in equal part of structure type masonry and reinforced concrete; only a very limited number of buildings in other damage grade is simulated. The final database for Emilia 2012 is composed of 1866 data points.

3. ShakeMaps

This section describes the generation of the ground shaking maps to be associated with the historical sequences in the Da.D.O. database. Some of the sequences that are of interest for this study are complex, consisting of several earthquakes with comparable magnitudes, and which are spatially very extended. This characteristic could influence the shaking suffered by the different zones where buildings are located. We have therefore calculated all the ShakeMaps related to events with magnitude $M \geq 5.0$, which occurred during the whole sequence, and not just those associated to the mainshock. For the seismological information, we used the Engineering Strong-Motion (ESM) database (Luzi et al., 2016). The ESM website gives the possibility to download through a web service the peak values of the ground motion parameters in a format suitable for ShakeMap. The ground motion variables we considered are macroseismic intensity in MCS scale, PGA, PGV, SA 0.3s, SA 1.0s and SA 3.0s. Moreover, ESM gives the possibility to download the extended fault if it is available in the literature. For stronger earthquakes, there are several solutions for the extended fault in the literature, and it is not always straightforward to define which is the best choice. In ShakeMap applications, the extended fault has an impact on the magnitude and shape of shaking, especially in the near field. This work has decided to select the input data for the ShakeMap calculation from a single database (ESM). In this way, we have aligned ourselves with the choice made in ESM for the extended fault associated with the earthquake.

Michelini et al. (2020) describe the adopted ground motion models and the new map of V_{S30} for the site effects. The software implemented is the ShakeMap version 4.0 (Worden et al., 2020). Below we describe the main features of the earthquakes we have considered and show the most relevant ShakeMaps that have been calculated.

3.1. ShakeMaps for Irpinia 1980

There are 3 earthquakes with a magnitude greater than 5.0 for this sequence, as shown in Table 2, with information on location, magnitude, fault and number of stations available. Only for the first earthquake, the one with the larger magnitude, the extended fault model is available. Also, for this earthquake, 21 stations have recorded the ground motion, while for the other two earthquakes only few stations recorded the event.

Table 2: List of the earthquakes with $M \geq 5.0$ for the Irpinia 1980 sequence

Origin Time	Magnitude	Fault	Number of Stations
1980-11-23 18:34:53	6.9	Ameri et al. (2011)	21
1980-11-24 00:24:00	5.0	–	4
1980-11-25 17:06:44	5.0	–	2

Logically, the considerable difference in magnitude between the first earthquake and the other two implies that the main earthquake with magnitude M 6.9 is responsible for the damage reported in the Da.D.O. database. Figure 1 instead shows the distribution of the Da.D.O. points on panel *a*, while in panel *b* the ShakeMaps in MCS intensity of the main earthquake. Figure S1 in the supplementary material shows the ShakeMaps for all the ground motion values. The 1980 Irpinia earthquake was undoubtedly the most devastating earthquake in Italy since the Second World War. According to the most reliable estimates, it caused about 280,000 displaced people, about 9,000 injured and 3,000 dead. The earthquake affected three regions, Campania, Basilicata and Puglia, with an area aligned along fault strike longer than 60 km featuring MCS intensity higher than IX.

3.2. ShakeMaps for Umbria–Marche 1997

The seismic sequence of Umbria–Marche 1997, which affected parts of the two regions of central Italy, began in September 1997 and ended in March 1998. On 26th

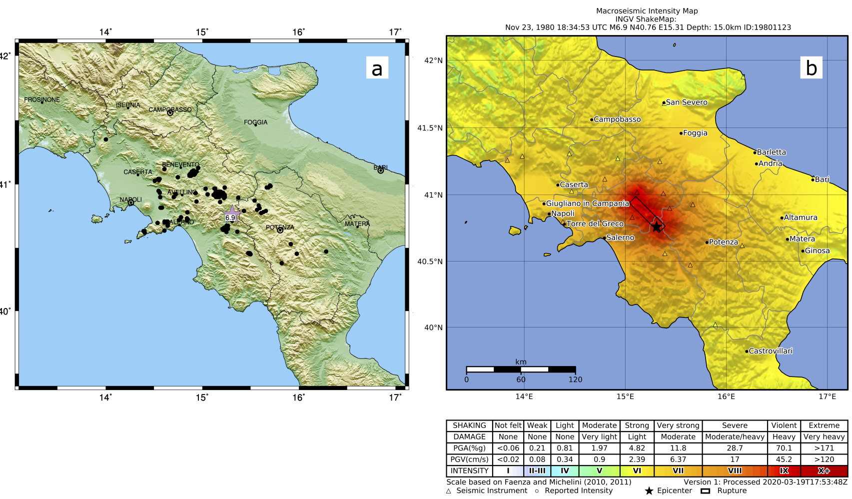

Figure 1: 23th November, 1980 Irpinia, M 6.9 earthquake. Panel *a*: Distribution of the Da.D.O. points; Panel *b*: ShakeMap for MCS intensity scale.

September in the night, there was the first of the three main earthquakes (M 5.7), while in the late morning of the same day there was the second earthquake (M 6.0). This second event was responsible for the fall of the Giotto and Cimabue vault in the Basilica of St. Francis in Assisi, which killed four people. The third main event (M 5.6) on 14th October caused the lantern in the Town Hall of Foligno to collapse. Overall, there are 8 earthquakes with magnitude greater than 5.0 that have occurred in the time span September 1997 to April 1998, as shown in Table 3.

Table 3: List of the earthquakes with $M \geq .0$ for the Umbria–Marche 1997 sequence.

Origin Time	Magnitude	Fault	Number of Stations
1997-09-26 00:33:11	5.7	Hernandez et al. (2004)	15
1997-09-26 09:40:24	6.0	DISS (2010)	21
1997-10-03 08:55:20	5.2	–	11
1997-10-06 23:24:51	5.4	–	17
1997-10-12 11:08:35	5.2	–	13

1997-10-14 15:23:09	5.6	Hernandez et al. (2004)	28
1998-03-21 16:45:09	5.0	–	11
1998-04-03 07:26:36	5.1	–	14

A fault model is available for the three larger earthquakes. The number of stations that have recorded the earthquakes changes considerably during the sequence. In fact, after the 26th September, several other stations belonging to temporary networks were installed, which allowed for a good coverage of the near field for the 14th October earthquake.

Figure 2, panel *a*, shows the spatial distribution of earthquakes and the points of the Da.D.O. database. As can be seen from the figure, the points of the Da.D.O. database fall all in the Marche region. An important thing to observe in the figure is that there are some points in the database that are very close to the third largest event of the sequence (M 5.6 occurred on 14th October 1997, pink star in Figure 2, panel *a*) to the south, whereas other Da.D.O. points are affected by the earthquakes of 26th September 1997, M 6.0 and M 5.7, dark green and violet stars in Figure 2, panel *a*. Figure 2, panels *b,c,d*, shows the ShakeMap for the 3 mainshocks of the sequence, in MCS intensity scale. Figures S2, S3, S4 in the supplementary material show the ShakeMaps for all the ground motion values. From the three figures, it is possible to notice that the second earthquake on September 26 (M6.0) caused the most damage in area located northern respect to the epicentres, with values of macroseismic intensity in the epicentral zone corresponding to grade IX of the MCS scale. The area in which the effects of the earthquake equal to grade VIII-IX is 20 km long, along the north-west direction of the fault. The third earthquake (M 5.6) which occurred further south, on the other hand, shows an extended area of several km where the macroseismic intensity reaches grade VIII. The same area in previous earthquakes had shown macroseismic intensity equal to degree VI-VII on the MCS scale.

3.3. ShakeMaps for Pollino 1998

The sequence relating to the earthquake that struck Calabria in 1998 has only one earthquake with a magnitude greater than 5.0. Table 4 summarises the characteristics of

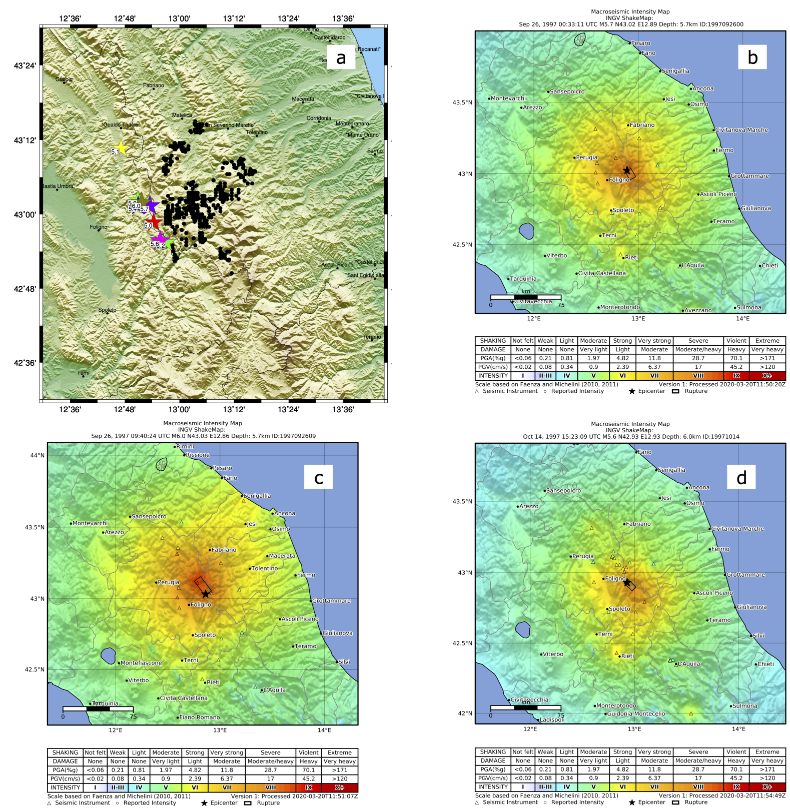

Figure 2: Umbria-Marche 1997 earthquake sequence. Panel *a*: data points (solid black circles) and earthquakes (stars) with $M \geq 5.0$. Panel *b*: ShakeMap for the first 26[th] September 1997 Umbria-Marche earthquake in MCS intensity scale. Panel *c*: ShakeMap for the second 26[th] September 1997 Umbria-Marche earthquake in MCS intensity scale. Panel *d*: ShakeMap for the 14[th] October 1997 Umbria-Marche earthquake in MCS intensity scale.

this earthquake. No extended fault model is available for this earthquake of moderate size; it was only registered by 5 stations.

Table 4: The Pollino 1998 earthquake with $M >= 5.0$

Origin Time	**Magnitude**	**Fault**	**Number of Stations**
1998-09-09 11:28:00	5.6	–	5

Figure 3 instead shows the distribution of the Da.D.O. points on panel *a*, while on panel *b* the ShakeMap in MCS intensity. Figure S5 in the supplementary material shows the ShakeMaps for all the ground motion values.

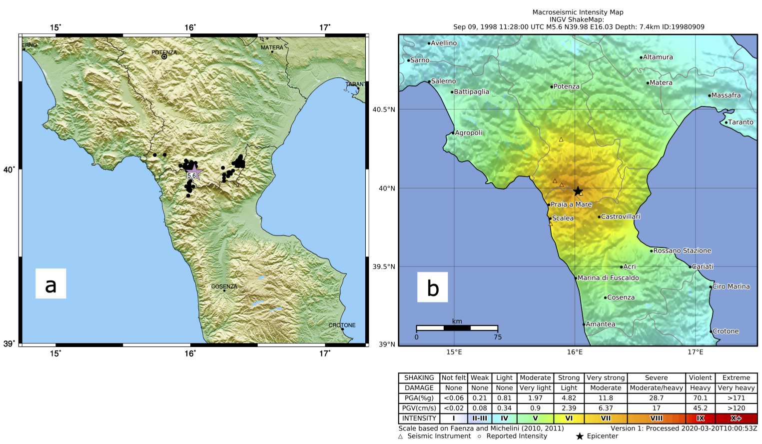

Figure 3: 9th September, 1998 Pollino, M 5.6 earthquake. Panel *a*: Distribution of the Da.D.O. points; Panel *b*: ShakeMap for MCS intensity scale.

The area of Pollino, in Calabria, has already been the scene of significant earthquakes in the past. The epicentre is located between the municipalities of Castelluccio Inferiore, Castelluccio Superiore and Lauria. The epicentre zone shows macroseismic intensity values equal to grade VII-VIII of the MCS scale.

3.4. ShakeMaps for Molise 2002

The earthquakes with magnitude greater than 5.0 that occurred during the seismic sequence of 2002 in Molise are two they are close both spatially and temporally and also have the same magnitude. Table 5 summarizes the characteristics of these earthquakes. Also in this case, as with the 1998 Pollino earthquake, not many stations recorded the earthquake. The faults are available for both earthquakes and come from the DISS (2010) and 10 stations recorded the events, but in both cases, they are located far from the epicenters. The earthquake of Molise in 2002 is composed of two earthquakes of the same size that occurred between 31st October and 1st November 2002, with the epicentre located in the province of Campobasso, between the towns of San Giuliano di Puglia, Colletorto, Santa Croce di Magliano, Bonefro, Castellino del Biferno and Provvidenti.

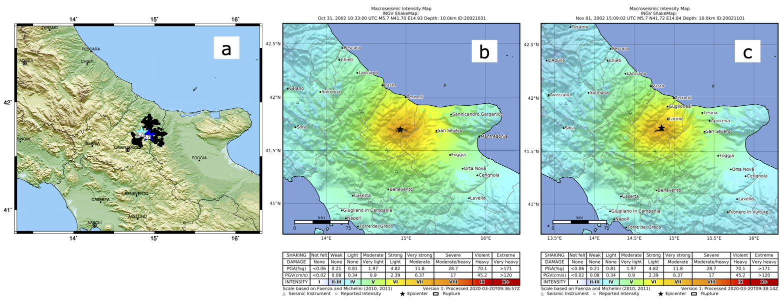

Figure 4: Molise 2002 earthquake sequence. Panel *a*: data points (solid black circles) and earthquakes (stars) with $M \geq 5.0$. Panel *b*: ShakeMap for the first 31st October 2002 Molise earthquake in MCS intensity scale. Panel *c*: ShakeMap for the first 1st November 2002 Molise earthquake in MCS intensity scale.

Table 5: List of the earthquakes with $M \geq 5.0$ for the Molise 2002 sequence.

Origin Time	Magnitude	Fault	Number of Stations
2002-10-31 10:33:00	5.7	DISS (2010)	11
2002-11-01 15:09:02	5.7	DISS (2010)	10

Figure 4 instead shows the distribution of the Da.D.O. points on panel *a*, while the ShakeMap related to these earthquakes in MCS intensity scale are presented on panels *b* and *c*. Figures S6 and S7 in the supplementary material show the ShakeMaps for all the ground motion values for these two earthquakes. In the first event, the effects of the earthquake reached a value equal to grade VIII on the MCS scale, while they were slightly lower for the second event.

3.5. ShakeMaps for L'Aquila 2009

There are 8 earthquakes with a magnitude greater than 5.0 that have occurred during this sequence, and they all occurred in the time span from 6th April to 13th April 2009. Table 6 shows the main data underlying ShakeMap. Comparing the number of data recorded data from these earthquakes with previous events, it is clear that the number of stations has increased. After the first earthquake, as happens when a damaging earthquake occurs, INGV and other research institutes and universities have installed many stations in the epicentre area. In this way, we can generate more constrained ShakeMaps in the epicentral area. It should be noted that the higher number of stations in the first earthquake depends on the fact that the ShakeMap for earthquakes with magnitude greater than 6 is more spatially extended than the others.

Table 6: List of the earthquakes with $M \geq 5.0$ for the L'Aquila 2009 sequence.

Origin Time	**Magnitude**	**Fault**	**Number of Stations**
2009-04-06 01:32:40	6.1	Ameri et al. (2012)	62
2009-04-06 02:37:04	5.1	–	18
2009-04-06 23:15:36	5.1	–	23
2009-04-07 09:26:28	5.1	–	26
2009-04-07 17:47:37	5.5	Gallovič et al. (2014)	56
2009-04-09 00:52:59	5.4	–	50
2009-04-09 19:38:16	5.2	–	44
2009-04-13 21:14:24	5.0	–	48

The main shock, which occurred on 6^{th} April 2009, was felt throughout central-southern Italy. This event is currently the most severe earthquake, in terms of the number of victims and damage, of the 21st century in Italy. Also, in the city of L'Aquila, several strategic buildings, such as the Prefect's Office, the Regional Hospital, the headquarters of the University, the Police Headquarters and the Student House suffered severe damage. The city of L'Aquila and the entire basin of L'Aquila, since the fourteenth century, has always been subject to earthquakes of severe or medium intensity. Three other significant earthquakes struck the area, all with a macroseismic intensity value equal to the grade IX of the MCS scale. Figure 5 panel *a*, shows the distribution of the different earthquakes with respect to the points of the Da.D.O. database. The important thing to note in the figure is that there are several earthquakes north of L'Aquila, near the Campotosto, with a maximum magnitude of M 5.4 that could affect the damage to the database of buildings located in the northern area. We show as an example the maps for 3 earthquakes in the sequence. The first one is for the mainshock M 6.1 of 6th April 2009 (Figure 5, panel *b*). The maximum macroseismic intensity reaches the values of IX of MCS scale, in the direction south-east for the city of L'Aquila. The village of Onna, located in this area, was destroyed. The second one shows the shaking related to the earthquake M 5.5 of 7th April, which affected the southernmost part of the aftershock area (Figure 5, panel *c*), with a maximum of macroseismic intensity equal to VIII of MCS intensity. Finally, the ShakeMap of the earthquake with M 5.4 of 9th April 2009 is presented, which occurred in the northernmost part of the area affected by the sequence (Figure 5, panel *d*). The epicentral area of this earthquake suffers a macroseismic intensity equals to grade VIII of MCS scale. Figures S8, S9, S10 in the supplementary material show the ShakeMaps for all the ground motion values.

3.6. ShakeMaps for Emilia 2012

The sequence that hit the Emilia region in 2012 had two main shocks of comparable magnitude but quite distant spatially, and several other earthquakes with magnitude greater than 5.0 (see Figure 6, panel *a*). The seismic sequence has affected the Po Valley region, an area where strong earthquakes occur at medium-low frequency. But historical information has shown that already in the past earthquakes had happened in the area, as in 1579 (M 5.4) with a maximum macroseismic intensity equal to grade VIII and 1639 (M 5.3) with a maximum intensity equal to grade VII-VIII of the MCS scale.

Table 7: List of the earthquakes with $M \geq 5.0$ for the Emilia 2012 sequence.

Origin Time	**Magnitude**	**Fault**	**Number of Stations**
2012-05-20 02:03:50	6.1	Pezzo et al. (2013)	270
2012-05-20 03:02:47	5.1	–	125
2012-05-20 13:18:01	5.2	–	96
2012-05-29 07:00:02	6.0	Paolucci et al. (2015)	280
2012-05-29 10:55:56	5.5	Pondrelli (2002)	198
2012-05-29 11:00:22	5.5	Ekström et al. (2012)	71

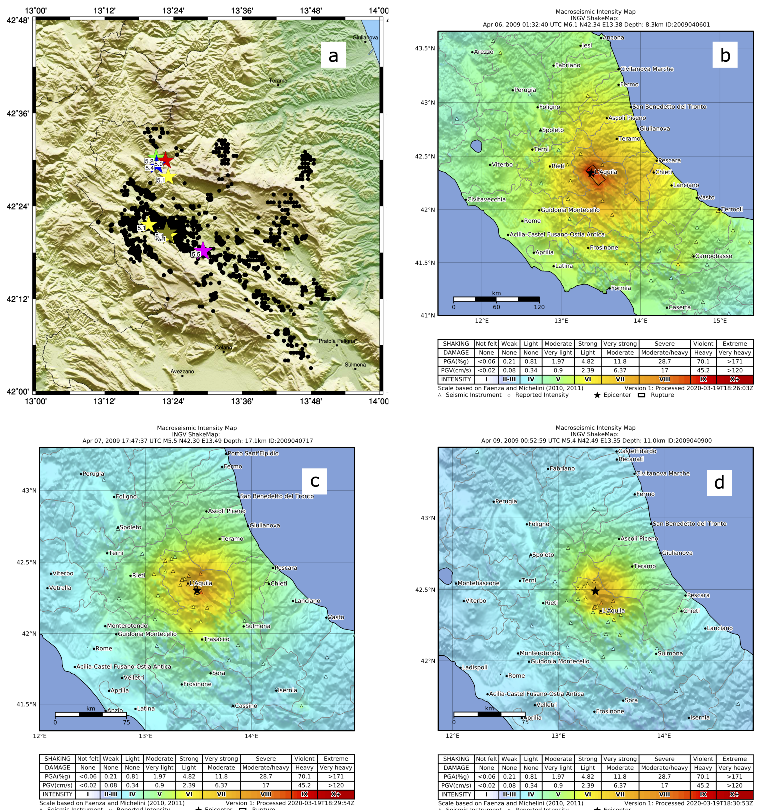

Figure 5: L'Aquila earthquake sequence. Panel *a*: data points (solid black circles) and earthquakes (stars) with $M \geq 5.0$. Panel *b*: ShakeMap for the 6$^{\text{th}}$ April 2009 L'Aquila earthquake, in MCS intensity scale. Panel *c*: ShakeMap for the 7$^{\text{th}}$ April 2009 L'Aquila earthquake in MCS intensity scale. Panel *d*: ShakeMap for the 9$^{\text{th}}$ April 2009 L'Aquila earthquake in MCS intensity scale.

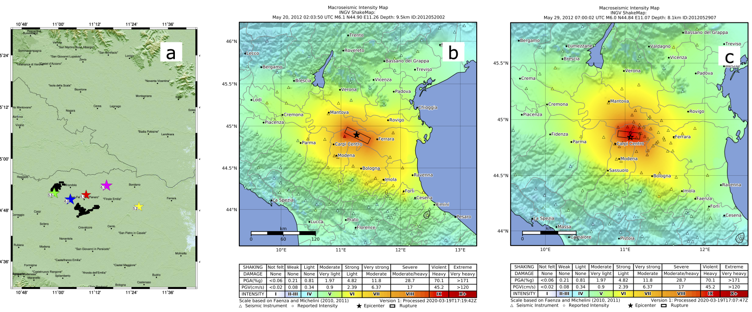

Figure 6: Emilia 2012 earthquake sequence. Panel *a*: data points (solid black circles) and earthquakes (stars) with $M \geq 5.0$. Panel *b*: ShakeMap for the 20th May 2010 Emilia earthquake in MCS intensity scale. Panel *c*: ShakeMap for the 29th May 2010 Emilia earthquake in MCS intensity scale.

Table 7 and Figure 6 show an overview of the data used to calculate the ShakeMap and the spatial distribution of the epicentres of the earthquakes with respect to points in the Da.D.O. database. For this sequence, we use the extended source for four out of six earthquakes. The number of stations we have at our disposal is significantly higher than those of earthquakes that occurred several years ago. Moreover, after the first earthquake of the sequence, we notice an improvement in the station coverage in the epicentral area, allowing a better constraint of the shaking. The earthquakes caused massive damage to rural and industrial buildings, water pipelines, historical buildings and monuments and old stone buildings. The most damaged provinces are those of Modena and Ferrara, where the territory affected has an area of about 1800 square kilometres. We show as an example the maps in MCS intensity scale for 2 earthquakes in the sequence, related to the strongest earthquakes in the sequence (Figure 6 panels *b* and *c*), while Figures S11 and S12 in the supplementary material show the ShakeMaps for all the ground motion values.

4. Preparation of the damage and ground motion data collection

The last step in developing ShakeDaDO data collection consists of associating the building damage to the level of the ground shaking experienced at the same location, defined by the coordinates in the processed version of the Da.D.O. database described in Section 2, to produce the ShakeDaDO data collection. To this end, we have implemented the following strategy. For each point of the Da.D.O. database, we have associated the maximum shaking that occurred during the whole sequence as determined by the calculated ShakeMaps, as described in Section 3. In this way, we have tried to take into account the occurrence of several earthquakes in close time and space. The six variables quantifying the ground shaking are treated separately and independently of each other. This choice implies that, for example, the same Da.D.O. point may have the maximum shaking for the PGA ground value that is associated with an earthquake from the sequence that is different to the earthquake leading to the maximum PGV. Each ground motion variable is associated with the epicentral distance and the magnitude. It is to be noted that the new ShakeMap configuration (Worden et al., 2020) allows for the calculation of the ground motion values directly at the sought target point. The shaking value is also associated with the uncertainty, as specified in Worden et al. (2018). Finally, each building contained in the Da.D.O. database is associated with the damage grade description, as available in Da.D.O. database (Dolce et al., 2019) and described in section 2, and the maximum ground shaking values of the six shaking parameters as derived from the largest events of the sequence. Whilst it would be have been very useful to use the date of damage evaluation in the ShakeDaDo data collection (to ensure that all of the main events preceding the damage were included), this data is not publicly available within Da.D.O.. Typically, damage surveys for large numbers of buildings can take weeks to complete, and so it was felt to be appropriate to include all the ground shaking from the potentially damaging aftershocks in the days following the main event. The only event for which a wider range of time has been considered is the Umbria-Marche sequence, which occurred over a period of 6 months. The damage data is likely to have been collected following each of the large events in this sequence, but as mentioned previously, the actual damage survey date for each building in the

Da.D.O. database is not available.

Table 8 provides the final list of parameters in the ShakeDaDO data collection, where for reasons of privacy the actual location in terms of latitude and longitude is not provided.

Table 8: List of the parameters in ShakeDaDO data collection

Parameters
Earthquake Identifier
Number of Storeys
Average Year of Construction
Structural Material
Year of Seismic Classification of the Municipality
classification-age of construction code as:
0 building constructed before the seismic regulations;
1 building constructed after the seismic regulations;
2 building constructed after 2000;
Vs,30
Damage Grade
MCS max
Uncertainty of MCS max
Distances between earthquake and Da.D.O. datapoint for the MCS couple
Distance Code (R_{JB} [3] if the fault is available, R_{epi} [4] otherwise) for the MCS couple
Magnitude for the MCS couple
PGA max $[ln(g)]$
Uncertaintyof PGA max $[ln(g)]$
Distances between earthquake and Da.D.O. datapoint for PGA couple
Distance Code (R_{JB} if the fault is available, R_{epi} otherwise) for PGA couple

[3] R_{JB} is distance to the surface projection of the rupture

[4] R_{epi} is the epicentral distance

Magnitude for PGA couple
PGV max $[ln(cm/s)]$ Uncertainty of PGV max $[ln(cm/s)]$ Distances between earthquake and Da.D.O. datapoint for PGV couple Distance Code (R_{JB} if the fault is available, R_{epi} otherwise) for PGV couple Magnitude for PGV couple
SA 0.3s max $[ln(g)]$ Uncertainty of SA 0.3s max $[ln(g)]$ Distances between earthquake and Da.D.O. datapoint for SA 0.3s couple Distance Code (R_{JB} if the fault is available, R_{epi} otherwise) for SA 0.3s couple Magnitude for SA 0.3s couple
SA 1.0s max $[ln(g)]$ Uncertainty of SA 1.0s max $[ln(g)]$ Distances between earthquake and Da.D.O. datapoint for SA 1.0s couple Distance Code (R_{JB} if the fault is available, R_{epi} otherwise) for SA 1.0s couple Magnitude for SA 1.0s couple
SA 3.0s max $[ln(g)]$ Uncertainty of SA 3.0s max $[ln(g)]$ Distances between earthquake and Da.D.O. datapoint for SA 3.0s couple Distance Code (R_{JB} if the fault is available, R_{epi} otherwise) for SA 3.0s couple Magnitude for SA 3.0s couple

It is noted that for the Irpinia 1980 and Pollino 1998 earthquakes there is only one earthquake responsible for the damage. For the sequence relating to Emilia 2012, the earthquake with magnitude 6.1 on 20$^{\text{th}}$ May is too far from the points in the Da.D.O. database compared to the other strong earthquake in the sequence, which occurred on 29$^{\text{th}}$ May (see Figure 6). This spatial distribution implies that the Da.D.O. points, for all the ground motion variables, are associated with the 29$^{\text{th}}$ May earthquake. For the other four sequences the situation is not linear, and is described in more detail in the

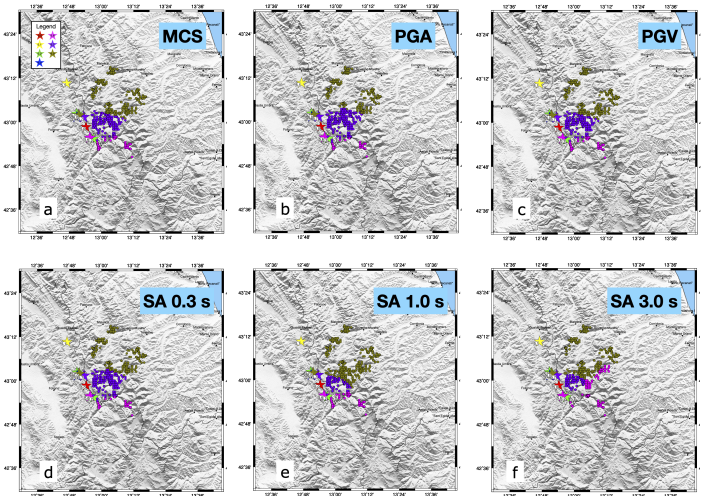

Figure 7: Association of the Da.D.O. points to the earthquakes ground shaking for the Umbria–Marche 1997. Stars: earthquakes (coloured according to the legend in panel *a*), dots: points in Da.D.O. database. The color of the dots indicates which earthquake the dot has been coupled with, for MCS (Panel *a*), PGA (Panel *b*), PGV (Panel *c*), SA 0.3s (Panel *d*), SA 1.0s (Panel *e*), SA 3.0s (Panel *f*).

following sections.

4.1. Umbria–Marche 1977 Data Collection

The sequence under examination consists of several earthquakes. Figure 7 shows which earthquakes the different points of the Da.D.O. database are associated with, for the 6 ground shaking variables.

The MCS parameter (panel *a* in Figure 7) shows that the Da.D.O. points to the north are associated with the shaking caused by the earthquake with largest magnitude (M 6.0 of 26th September 1997), the dark green points in the Figure. In purple there are highlighted the Da.D.O. points associated with the first earthquake with M 5.7 that also occurred on 26th September 1997. While the pink points further south are associated with the 14th October 1997, M 5.6 shock. The association of the Da.D.O. points concerning the different earthquakes in the sequence is substantially the same for the other ground motion variables, with the exception of SA 3.0s. In this case, the

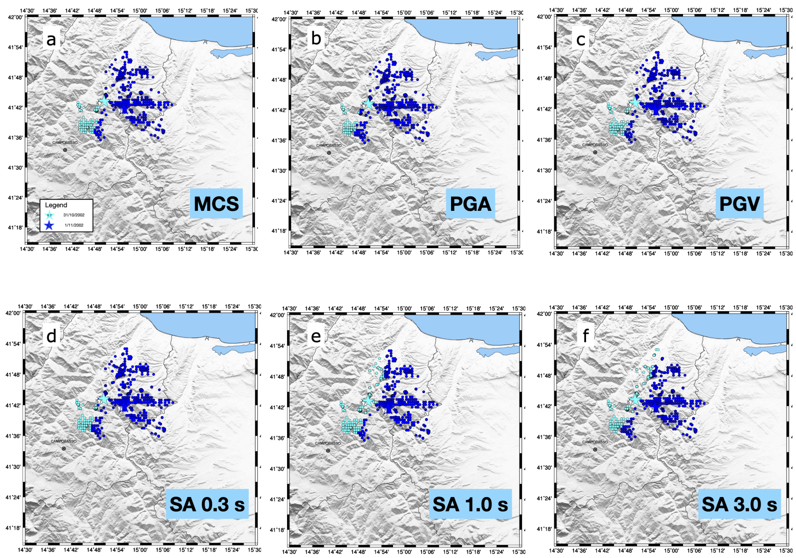

Figure 8: Association of the Da.D.O. points to the earthquakes ground shaking for the Molise 2002. fStars: earthquakes (coloured according to the legend in panel *a*), dots: points in Da.D.O. database. The color of the dots indicates which earthquake the dot has been coupled with, for MCS (Panel *a*), PGA (Panel *b*), PGV (Panel *c*), SA 0.3s (Panel *d*), SA 1.0s (Panel *e*), SA 3.0s (Panel *f*).

earthquake of 14th October 1997 M 5.6 has greater values, as can be seen from Figure7 (panel *f*) where the contribution of this shock (highlighted with pink dots) also extends in the north-eastern direction. Probably, for this earthquake, the source mechanism enhanced these longer periods.

4.2. Molise 2002 Data Collection

The sequence under examination consists of 2 earthquakes close in space and with the same magnitude. Figure 8 shows which earthquakes the different points of the Da.D.O. database are associated with, for the 6 ground shaking variables.

From the MCS map (panel *a* in Figure 8), we can see that the earthquake of 31st October 2002 has higher shaking values than the one that occurred a few days later, on 1st November 2002. Consequently, all the buildings surveyed by Da.D.O. that are to the east and north of the two earthquakes are associated with the maximum shak-

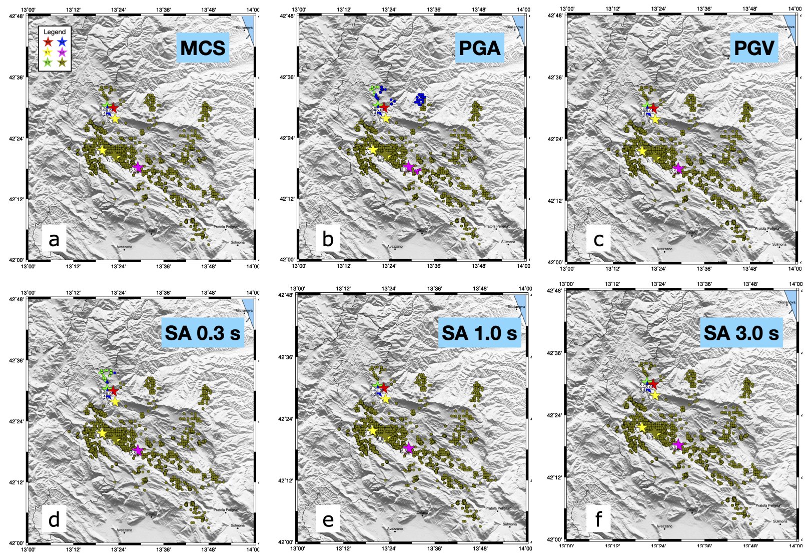

Figure 9: Association of the Da.D.O. points to the earthquakes ground shaking for the Molise 2002. Stars: earthquakes (coloured according to the legend in panel *a*), dots: points in Da.D.O. database. The color of the dots indicates which earthquake the dot has been coupled with, for MCS (Panel *a*), PGA (Panel *b*), PGV (Panel *c*), SA 0.3s (Panel *d*), SA 1.0s (Panel *e*), SA 3.0s (Panel *f*).

ing of the first earthquake. The association of the Da.D.O. points with respect to the two earthquakes in the sequence is substantially the same for the other ground motion variables.

4.3. L'Aquila 2009 Data Collection

The sequence under examination consists of several earthquakes. Figure 9 shows which earthquakes the different points of the Da.D.O. database are associated with, for the 6 shaking parameters.

The points in the Da.D.O. database relating to the L'Aquila 2009 earthquake are associated mainly with the mainshock, M 6.1 of 6th April 2009. Only a few points to the north are, for the PGA and SA 0.3s maps, associated with earthquakes of magnitude M 5.2 and M 5.4 that occurred further north than the main event.

5. Final Data Collection

This data collection is one of the first attempt to combine engineering information collected and harmonized in Da.D.O. Dolce et al. (2019) with ground shaking data. The University of Cambridge has recently developed a platform (Spence et al., 2011) with similar purposes as ShakeDaDO. The main difference, however, is that ShakeDaDO provides data with a higher level of detail and completely disaggregated. There are six ground shaking variables: MCS scale intensity, PGA, PGV and SA at 0.3s, 1.0s and 3.0s. As noted above, the shaking was calculated using the new version of ShakeMap, with the latest seismological data and information. Each shaking value is associated with its uncertainty. The final assembled data collection consists of 117,695 data points; of the resulting table each row is associated with a building. For each building, the information available is the type of structure, the number of storeys, the age of construction, and the class of damage. The year in which the municipality was classified as a seismic zone, as well as the value of Vs,30, that can be useful to get an idea of the type of soil on which the building is built, are also available in the database. We note, however, that the Vs,30 data is extracted from the Vs,30 grid used in ShakeMap, and it is not provided from direct measurements.

Figures 10 and 11 summarises the data collection according to the building characteristics. Three-quarters of the available data come from the sum of the information of the earthquakes of Irpinia 1980 and L'Aquila 2009, while few data come from the earthquakes of Emilia 2012 and Pollino 1998 (see Figure 10, panel *a*).

Concerning the type of structures, here divided only in masonry (denoted as *mu* in Figure) and reinforced concrete (denoted as *ca* in Figure), we find that three-quarters of the buildings surveyed in Da.D.O. database are of the masonry type, while only a quarter is in reinforced concrete (panel *c* of Figure 10). The damage grades are also not equally populated. DS0 is by far the most populated, while few buildings have suffered damage falling within the DS4 and DS5 categories (panel *b* of Figure 10). A significant portion of the buildings have just a few floors, with a considerable peak for the two or three-storey buildings (the sum of which reaches three-quarters of the total dataset). Very tall buildings, on the other hand, are not numerically relevant (panel *a*

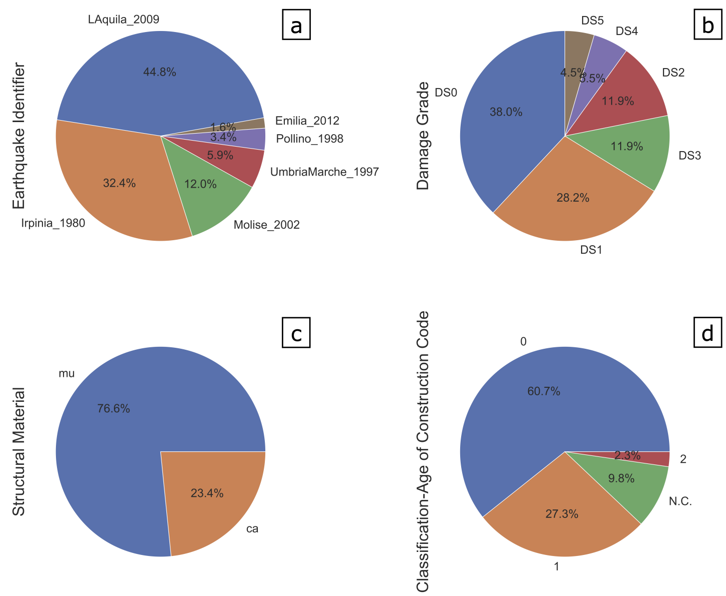

Figure 10: Distribution of the different categories in the ShakeDaDO data collection. Panel *a*: Earthquake Identifier; Panel *b*: Damage Grade; Panel *c*: Structural Material; Panel *d*: Classification-Age of Construction Code. "N.C." (Not compiled) implies that no information was available for that building in this category.

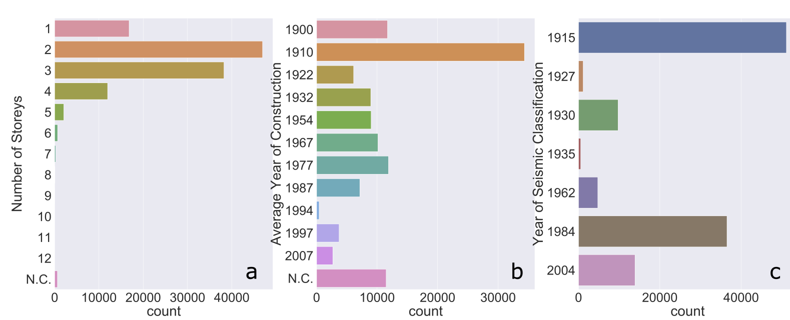

Figure 11: Distribution of the different categories the ShakeDaDO data collection. Panel *a*: Number of Storeys; Panel *b*: Average Year of Construction; Panel *c*: Year of Seismic Classification. "N.C." (Not compiled) implies that no information was available for that building in this category.

of Figure 11). More than a third of the buildings were built before 1910, while there are about 6% constructed after 1990 (panel *b* of Figure 11). The panel *c* in Figure 11 shows the year of seismic classification of the municipalities. Slightly less than half of the buildings belong to cities that have been classified since 1915. A second big slice of buildings (about 30%) belongs to municipalities that have been classified after 1984. About 12% of the buildings belong to the cities that have been classified after 2004. The combination of information on the age of construction and the year of seismic classification has defined the parameter "Classification Age" (in panel *d* in Figure 10). 61% of the buildings were built before the municipality entered seismic classification, against 27% of buildings constructed afterwards.

Going a little more into the details of the data collection elements, Figures 12 and 13 show how the different features are distributed in the six different seismic sequences. Figure 12, in panel *a*, shows the damage distribution. DS05 and DS04 are numerically relevant for the earthquakes of Irpinia 1980, Umbria Marche 1997, Molise 2002 and L'Aquila 2009, while it is nearly absent in the earthquakes of Pollino 1998 and Emilia 2012. The DS0 and DS1 grades are the most represented for all earthquakes. At the same time, class DS03 is more populated then class DS02 for the earthquakes in Umbria Marche 1997, Molise 2002 and Pollino 1998. As far as vertical structures are concerned, in all sequences and in a somewhat similar way, masonry buildings (defined as *mu* in Figure) are more abundant than reinforced concrete ones (defined as *ca*, panel *b* in Figure 12). Finally, in panel *c* of Figure 12, we see for all earthquakes a very high number of 2- and 3- storey buildings, while only for L'Aquila 2009 and Molise 2002, 4-storey buildings are also numerically relevant. If we analyse the features related to the age of the buildings, from Figure13 panel *a*, we can say that there is for the Irpinia 1980 a considerable part of the buildings that had been built before 1900. This earthquake is also the only one in which the number of buildings without this information is high. As far as the sequences of Umbria Marche 1997, Pollino 1998 and Emilia 2012 are concerned, we observe a relatively pronounced peak of buildings built in 1910, and then very few other constructions. A similar situation also exists for the earthquakes of Molise 2002 and L'Aquila 2009. Still, in these cases, especially in the areas affected by the sequence of L'Aquila 2009, there are a significant number of buildings built in

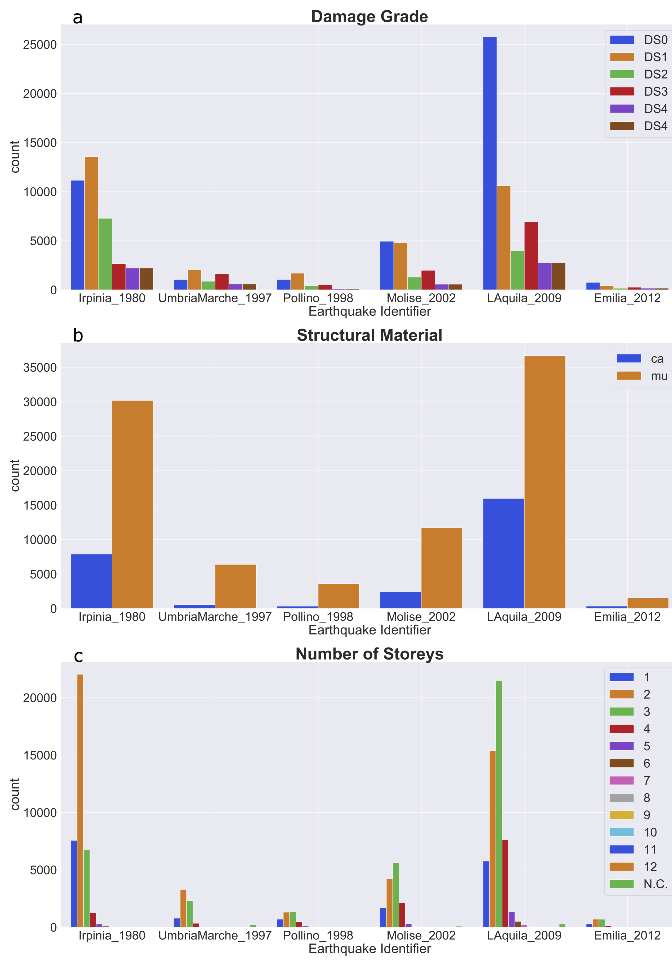

Figure 12: Distribution of the different categories in the data collection with respect to the Earthquake Identifier. Panel *a*: Damage Grade; Panel *b*: Structural Material; Panel *c*: Number of Storeys. ”N.C.” (Not compiled) implies that no information was available for that building in this category.

Figure 13: Distribution of the different categories in the data collection with respect to the Earthquake Identifier. Panel *a* : Average Year of Construction; Panel *b*: Year of Seismic Classification; Panel *c*: Classification-Age of Construction Category. "N.C." (Not compiled) implies that no information was available for that building in this category.

other years. The areas affected by these six sequences have a very different seismic classification history (Figure 13 panel *b*). Referring to the area affected by the Irpinia earthquake, many buildings belong to municipalities that entered the 1930 and 1984 seismic regulations. The regulations of 1930 substantially affect the Irpinia area, which classified a large part of the territory after the destructive earthquake of 23rd July 1930, Mw 6.7. The 1984 regulations were the first to classify a large part of the Italian region, as reflected in Figure 13, panel *b*, where all areas have some municipalities classified in that year. A particular situation concerns the L'Aquila area. Most of the buildings belong to cities that were classified seismically already in 1915, following the devastating earthquake in Marsica on 13th January 1915, Mw 7. Finally, the area affected by the Emilia 2012 only entered into the last seismic regulations, dated 2004. The union of the information of panels *a* and *b* of Figure 13, leads us to the definition of code to understand if a building was built before the seismic regulations (panel *c*, Figure13). As already mentioned in commenting on the previous two panels in Figure 13, Italy has a fairly old building stock, where except for L'Aquila 2009, a large proportion of the buildings was built without the seismic regulations in place.

As regards the seismological information, for each of the 6 shaking parameters under examination, in addition to the value of the variable itself and the relative uncertainty, the distance between site and epicenter and the magnitude of the event under examination are also provided. The distance used is R_{JB} when the finite source is available, and epicentral distance in other cases.

Figure 14 shows the histograms of the ground motion variables included in the data collection. The intensity values range between a minimum of 6.0 and a maximum of 9.0 on the MCS scale. With the exclusion of two prominent peak at 7.4 and 8.3, the intensities distribute rather homogeneously for intensities larger than 6.5. Instead, data with MCS less than 7.0 are less abundant.

Looking at ground motion data, PGA has a predominant peak at 0.3 g, a second smaller peak at 0.2 g, and it ranges between 0.02g and 0.45g. The values of PGV from 5 to 9 cm/s are all equally highly populated. A second peak is at 24 cm/s. Values between 10 cm/s and 26 cm/s are distributed over a plateau of frequencies that are comparable to each other. At the same time, values from 28 cm/s to 44 cm/s are also

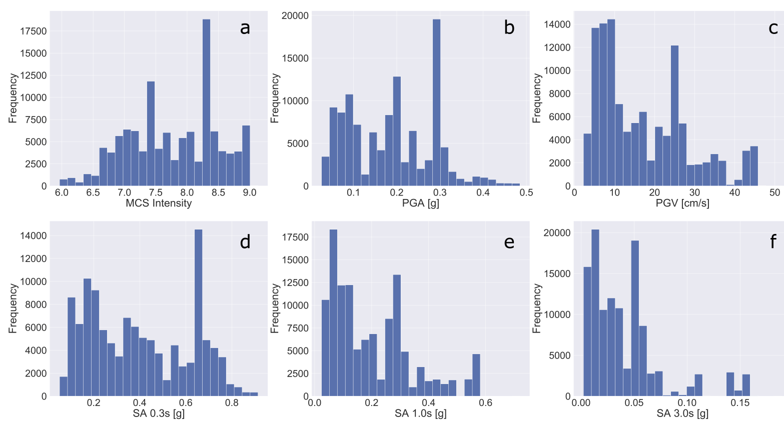

Figure 14: Distribution of the different ground motion parameters in the data collection. Panel *a*: MCS; Panel *b*: PGA; Panel *c*: PGV; Panel *d*: SA 0.3s; Panel *e*: SA 1.0s, Panel *f*: SA 3.0s.

spread over a plateau but with a much lower frequency. SA at 0.3s has a peak at 0.7; the values of this variable range between 0.05 g and 1 g, with an almost uniform distribution. SA at 1.0s has a predominant peak at 0.07 g and a smaller peak at 0.3 g. The ranges of values are between 0.03 g and 0.6 g. SA at 3.0s has two predominant peaks 0.015g and at 0.05 g, and it ranges between 0.003 g and 0.075 g; there are some values of SA 0.3s higher, but their frequency is negligible.

Figure 15 shows the scatterplot of the six ground motion values according to distance, differentiated according to the earthquake identifier. What we can deduce from the figure is that Pollino 1998 and Emilia 2012, which are the two least populated sequences of the data collection have a different ground motion distribution. Pollino 1998 has points that are further away as if the majority of the inhabited centres were not close to the epicentre. On the contrary, Emilia 2012 has many points very close to the epicentre, and no point is more than 80 km away. The data for the earthquake in L'Aquila 2009 and Umbria Marche 1997 are those that show a greater scatter. In fact, for the same distance, there are shaking values that cover a wide range. The data relative to Irpinia 1980 are instead those with less scatter. The greatest shaking values

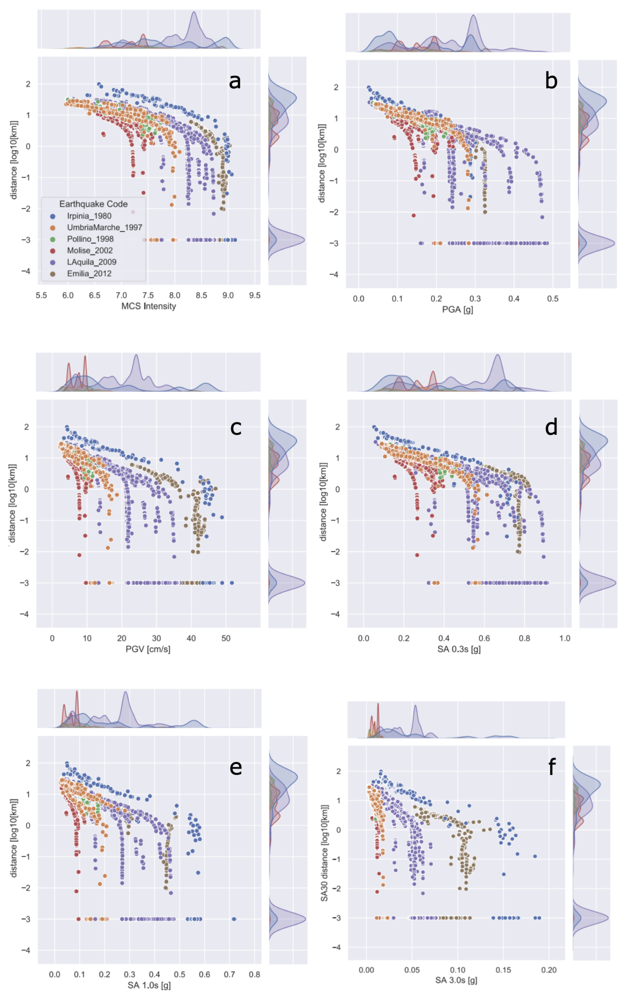

Figure 15: Distribution of the different ground motion parameters in the data collection. Panel *a*: MCS; Panel *b*: PGA; Panel *c*: PGV; Panel *d*: SA 0.3s; Panel *e*: SA 1.0s; Panel *f*: SA 3.0s.

for all six variables are those of Irpinia 1980, followed by Emilia 2012, L'Aquila 2009 and Umbria Marche 1997.

6. Conclusions and Future Applications

The ShakeDaDO data collection presented in this work combines for the first time damage data and peak ground shaking for Italy within a single structure allowing further research and applications to be undertaken by the community. In particular, the analysis of the relative dependencies between parameters or, possibly, deep dependencies between sets of parameters could lead to fast, euristic determinations of earthquake impact. Overall, we believe there are multiple possible applications. For example, there has been a significant effort since the publication of the Da.D.O. database to produce empirical fragility functions for the Italian building stock (e.g. DelGaudio et al., 2017, 2018; Rosti et al., 2020a,b)). However, these efforts have been limited by a lack of ground shaking data for many of the events in the Da.D.O. database. We thus believe that the ShakeDaDO data collection can help greatly improve the research related to the development of empirical fragility functions in Italy. We also expect this database to be useful to test new and benchmark existing applications of new applications of Machine Learning, which is an emerging field in seismic hazard and risk assessment, see for example Xie et al. (2020); Riedel et al. (2015). The ShakeDaDO data collection, derived from the information in the Da.D.O. database, will be distributed within the Da.D.O. GIS platform.

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Data and Resources

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