



Preliminary data and field observations of the 21st August 2017 Ischia earthquake

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Abstract

On 21st August 2017, an earthquake (M_L 3.6; M_W 3.9; M_d 4.0) struck the municipality of Casamicciola Terme on the island of Ischia, Italy. It was a peculiar earthquake: low magnitude, very superficial (focus depth of about 1.7 km), centered in a high population density area. Despite the island was historically struck by destructive earthquakes during the last centuries, buildings vulnerability in the area was high. Many masonry buildings (main structural typology in Casamicciola Terme and on the island) collapsed or were severely damaged, occasionally exposing the original, dating back to end of nineteenth century, wooden frame that is one of the first examples of code designed anti-seismic structures in Italy. In this study, preliminary data and field observations of the 21st August 2017 Ischia earthquake are given. First, data from the permanent seismic network are used to assess seismic input characteristics and compare them to the known seismic hazard. Building vulnerability is then analyzed via the results of field observations carried out soon after the seismic event, thus providing significant information about quality of materials, construction techniques, structural performance and interpretation of possible damage mechanisms.

Keywords Ischia earthquake · Casamicciola earthquake · Field observations · Seismic risk · Masonry · Earthquake damage survey

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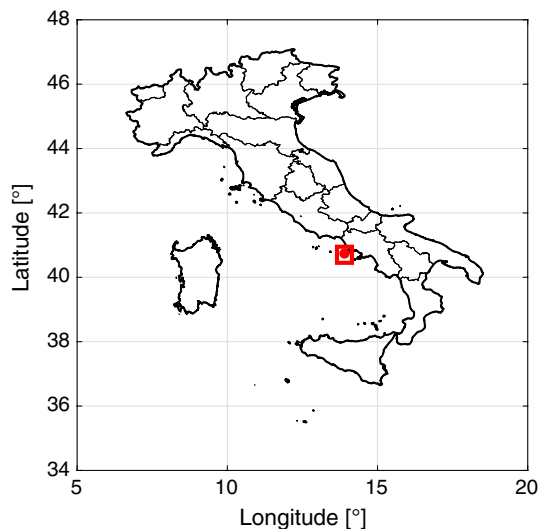
1 Introduction

On Monday, 21st August 2017, an earthquake (Local magnitude M_L 3.6; Moment magnitude scale M_W 3.9; Earthquake duration magnitude M_d 4.0) occurred in Casamicciola Terme on the island of Ischia, in Southern Italy (Fig. 1). The mainshock occurred at 8:57 p.m. local time (6:57 p.m. UTC); the epicenter was located in Casamicciola Terme, near Maio square, with a focus depth of about 1.7 km. The earthquake caused two deaths, forty-two injured people and about 1000 displaced. It was followed by a seismic sequence of almost 20 earthquakes with significantly lower magnitude (De Novellis et al. 2018).

It is noteworthy that for the Italian volcanic areas the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV) usually provides also the earthquake duration magnitude, M_d , because (INGV 2017b): (1) it can be calculated quickly, even if it requires the complete recording of the event; (2) INGV has a special calibration that takes into account the particular conditions of seismic wave propagation within the earth's crust affected by volcanic phenomena. In particular, INGV declared (INGV 2017b) “with regard to the event of Ischia, having occurred within a very superficial and heterogeneous portion of the crust, it has been preferred to use as an estimate of the energy released by the earthquake the Magnitude Duration, which is equal to 4.0. For this estimate, only the stations of the Campania volcanic region were used, so that the characteristics of the rocks that make up the crust of Ischia in terms of seismic wave velocity and attenuation could be taken into account. This does not apply to the magnitude M_L , calculated at all the stations available on the National Seismic Network.”.

Ischia island belongs to the Campi Flegrei volcanic region (Rapolla et al. 2010) near Naples (Fig. 2); other, smaller, islands, Procida and Vivara, also belong to the Campi Flegrei volcanic region. The Campi Flegrei plain (Fig. 2) is delimited by NW-SE trending faults at north-east, that down-thrust the Apennine mountains, and by NE-SW trending faults at north-west and south-east, that form the horsts of Mts. Lattari, Island of Capri, and Mt. Massico, respectively (Paoletti et al. 2013). The origin of the Campanian Plain is related to extensional tectonic events that accompanied the Plio-Pleistocene

Fig. 1 Localization of the area hit by the 21st August 2017 Ischia earthquake



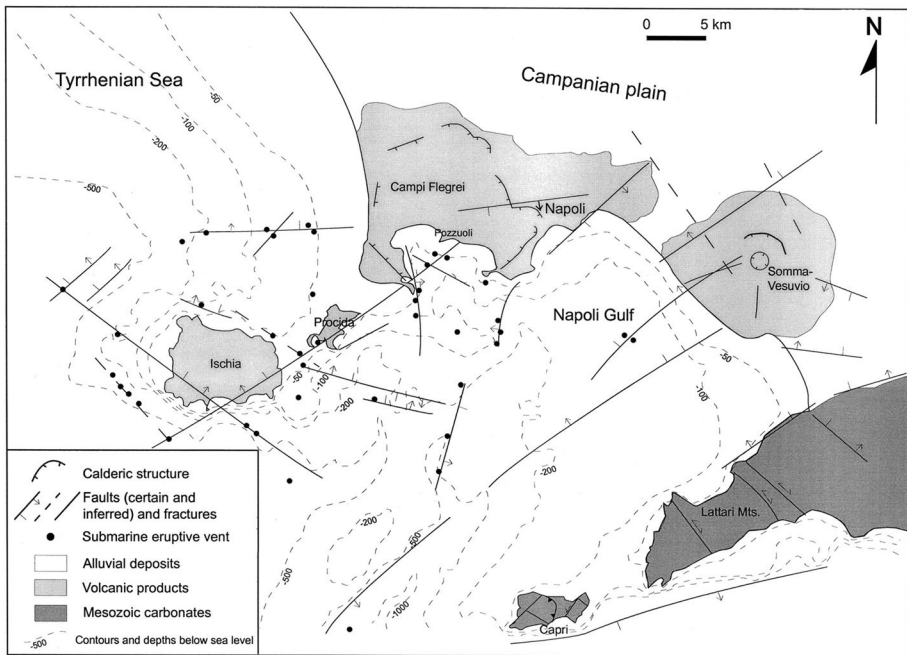
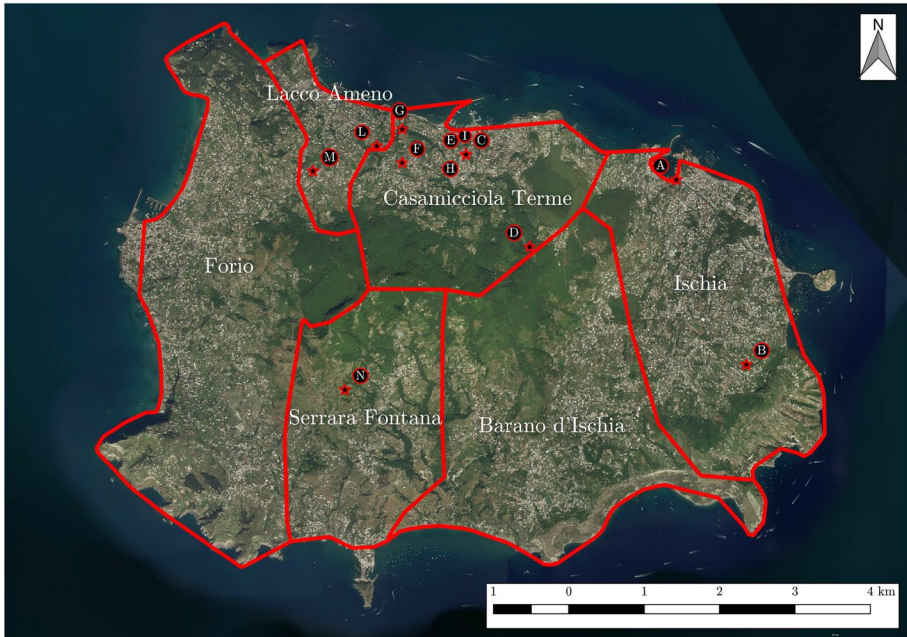


Fig. 2 Structural map of the Campi Flegrei Volcanic Region, showing the active Districts of Somma–Vesuvio and Campi Flegrei. Ischia is located on the westernmost portion of the Campi Flegrei Volcanic District. After Aococella and Funciello (1999). (Fault arrows = dipping side; fault hatches = downthrown side. Depths of isobaths in meters)

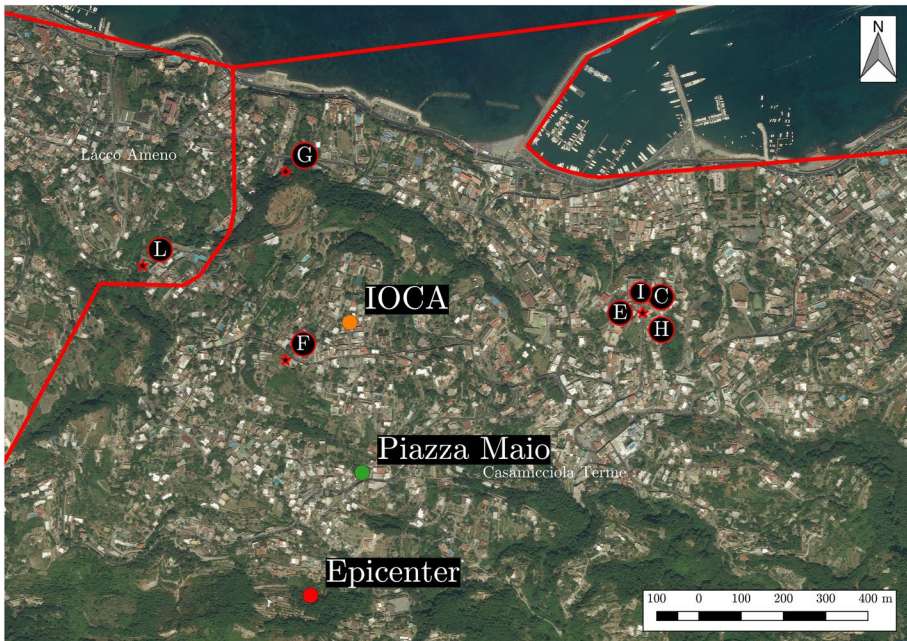
opening of the Tyrrhenian Sea basin and the counter-clockwise rotation of the Italian Peninsula with consequent thinning of its western edge (Scandone 1979; Sartori 2003).

Roughly trapezoidal, Ischia is approximately 10 km east to west and 7 km north to south, with about 34 km of coastline and a surface area of 46.3 km². The island is very densely populated, with 1300 inhabitants per square kilometer (i.e., 60,000 residents). Ischia island is an interesting active volcanic area. It has been home to historical eruptions, earthquakes, and landslide events, sometimes with catastrophic implications (Violante et al. 2003). The island is the surfaced top of a volcanic complex rising about 800 m above sea level at the north–west corner of the Gulf of Naples (Fig. 2). The lowland is located on the eastern slope of the Mt. Epomeo and is aligned with peaks at south-east (Fig. 3). The coastline has steep cliffs with interposed promontories on the southern and northern sides while elsewhere it slopes down to the sea. The geological history of Ischia is complex (Tibaldi and Vezzoli 2004; Paoletti et al. 2009; Caccavale et al. 2017) and may be grouped into five main periods of activity, characterized by distinct volcanological and geochemical features, starting before 200,000 years ago to the present (Chiesa et al. 1987). The interested reader is referred to Alberico et al. (2008) and to Chiesa et al. (1987) for detailed geological information.

The area is historically known as earthquake-prone. During the past, it has been affected by local volcanic and volcano-tectonic earthquakes and by the far-field effect of earthquakes with Moment Magnitude Scale up to 4.7 (Rovida et al. 2016), associated with the tectonic activity of the Southern Apennines fold and thrust belt (Caccavale et al. 2017).



(a)



(b)

Fig. 3 Satellite view of the Ischia island (a). Detail of Casamicciola Terme with the location of the epicenter, Piazza Maio (i.e., Maio Square) and location of the seismic station Ischia-Osservatorio Casamicciola seismic station (Code: IOCA) (b). The black circles markers are referred to the markers reported in Table 2

It must be mentioned that the majority of volcanic earthquakes are characterized by low earthquake energy. This is due to the lack of sufficient stress accumulation, associated with higher-than-normal thermal state of the crust, high medium fracturing, reduction in potential seismogenetic volume and action of concentrated local stress (Carlino et al. 2010). However, in volcanic areas, low magnitude earthquakes occur at low focus depth, thus usually inducing rather large accelerations quickly decreasing with distance from the epicentral area, as compared to deep focus low energy events. It has to be pointed out that magnitudes of shallow seismic events in volcanic areas are associated with higher levels of macroseismic intensity in comparison with tectonic areas, as shown by relationships between Magnitude and Macroseismic Intensity derived for Mt. Etna seismicity (Azzaro et al. 2011). The extension of the damaged area is thus relatively small. Against this fairly well documented geological background, less is documented in the literature on damage to buildings due to past earthquakes.

The 21st August 2017 Ischia earthquake was a shallow, low energy event. As expected from the previous discussion, it caused high, concentrated damage. The earthquake showed many deficiencies of the building stock in the Casamicciola Terme and Lacco Ameno municipalities. The reasons for such large damage were mainly three: (1) again, low focus depth, (2) local heterogeneous geology, inducing large local amplification effects; (3) large seismic vulnerability of the building stock. According to the visual inspections, a large number of buildings in the area around the epicenter were seriously damaged and unusable. It is noteworthy that these seismic characteristics (e.g., low energy, superficial seismicity with 1–2 km depth, high macroseismic intensity, strong anomalous ground effects in very narrow macroseismic near-fields, frequent ground fracturing and lack of large far-field effects) are common in volcanic areas (e.g., Giudice and Rasà 1992; De Novellis et al. 2018). However, volcanic areas are usually less anthropized than Ischia island leading to a minor seismic risk.

Within this context, the scope of this study is twofold. The main objective is to document damage and explain its main causes, in a rather timely fashion. The second one is to analyze this seismic event and to correlate it to the previous ones. The study of the effects of earthquakes on structures was widely investigated in recent years in Italy (e.g., Nuti et al. 2004; Rasulo et al. 2004; Braga et al. 2015; Fiorentino et al. 2018) and it is of paramount importance for the identification of the main vulnerabilities of buildings.

The paper is therefore composed of three parts. In the first one (Sect. 2), the 21st August 2017 earthquake is analyzed and compared with the seismic history and the seismic hazard model of the Italian Building Code. In the second one (Sect. 3), the building stock, mainly dating from 1950 to 1990, is classified and analyzed from a seismic vulnerability viewpoint. In the last one (Sect. 4), preliminary post-earthquake field-observations of the most severe damage in Casamicciola Terme and Lacco Ameno are described trying to provide possible damage mechanisms according to the different structural types. Finally, based on the field survey, in the Conclusions (Sect. 5) recommendations related to immediate policy following this earthquake are made.

2 21st August 2017 Ischia earthquake: hazard and event characteristics

The focus of the 21st August 2017 earthquake was estimated right after the earthquake, at 10 km depth, about 2 km west of Punta Imperatore, under the sea. The next day, its position was reviewed: the epicenter was moved 2 km north of Lacco Ameno (i.e., 10 km towards NE), with 5 km depth, again under the sea.

Both these estimations conflicted with preliminary field surveys and gathered geological knowledge: severe damage was in fact concentrated in a small area around Maio square in Casamicciola Terme (this will be discussed in Sect. 3), which was far from the estimated epicenter as compared to other, and mainly untouched, densely populated centres (e.g., Forio d'Ischia and Lacco Ameno). Besides, the focus depth was not matching with historical information documented in literature: the crust temperature below about 3 km is too high for rocks to be stressed by relative displacements, given the volcanism of the area (Alberico et al. 2008).

Following a critical press interview (Capone 2017), the focus was moved again and estimated in its final position, i.e., at 1.7 km depth, about 300 m (coordinates 40.74°N and 13.90°E) south of Maio square in Casamicciola Terme (see Fig. 3b). Finally, the magnitude was assessed equal to $M_L 3.6 \pm 0.2$ and $M_d 4.0 \pm 0.3$. The history of the calculated magnitude and epicenter locations for the 21st August 2017 earthquake, taken from INGV (2017a), is reported in Table 1.

The final earthquake assessment was consistent with the island historical seismicity. The structural features of the island are quite complex because deformation patterns in volcanic areas are the result of stresses applied at regional and local scales. The former induces fractures which may constitute preferred pathways for the rise of magma while the latter is induced by the emplacement of magma or by gravity (Acocella and Funicello 1999). This produces a large number of fault systems as shown in Fig. 4. In particular, the NE-SW and

Table 1 History of the calculated magnitude and epicenter locations for the 21st August 2017 earthquake, taken from INGV (2017a)

Location ID	Latitude	Longitude	Magnitude	Depth (km)	Publication time (UTC)	Author
49252001	40.71	13.84	$M_L 3.6$	10	2017-08-21 19:23:06	A
49256941	40.78	13.88	$M_d 4.0$	5	2017-08-21 22:16:47	B
49268411★	40.74	13.90	$M_L 3.6$	2	2017-12-05 11:13:27	C
49355471	40.74	13.90	$M_d 4.0$	2	2017-08-25 12:51:54	B
51070861	40.74	13.90	$M_w 3.9★$	3	2017-10-17 14:08:40	D

★ Best location and best magnitude until now.

A Sala Sismica INGV-Roma

B Sala Operativa INGV-OV (Napoli)

C Bollettino Sismico Italiano INGV

D TDMT-INGV Revised

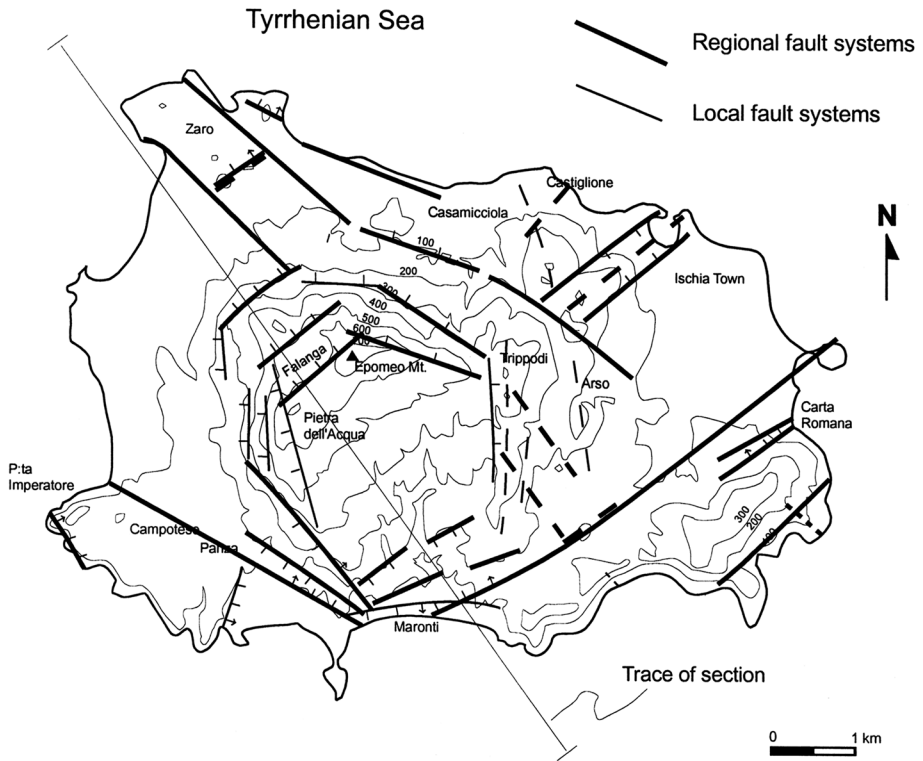


Fig. 4 Location of the main faults of Ischia island (arrows display dipping; hatches on the downthrown side; dashed lines = volcano – tectonic alignments). After Acocella and Funicicello (1999)

NW-SE fractures are widespread throughout the island, both at the borders and away from the dome. The area hit by the 2017 earthquake hosts different regional faults, oriented from NW to SE, that produced a large number of seismic events in the past.

This is confirmed by the analysis of the Parametric Catalogue of Italian Earthquakes (2015-CPTI15; Rovida et al. 2016). The historical seismic activity of the Ischia Island is recognized since the thirteenth century and caused serious damage, thousands of casualties, and often landslides and surface breaks (Carlino et al. 2010; De Novellis et al. 2018). The majority of significant earthquakes occurred in the north and north-west parts of the island, most of them in Casamicciola (Alessio et al. 1996). Starting from 1275 A.D., ten earthquakes with $M_W > 3$ were found, as reported in Table 2. The strongest one occurred in 1980, near the Ischia harbor (marker A in Table 2 and Fig. 3a) producing small damage. The most damaging ones occurred in 1275, 1796, 1828, 1881 and 1883. The damaged areas of the last four earthquakes are shown in Fig. 5. The 1883 earthquake has induced damage to the largest area; all seismic events occurred in the same area. The 1883 Casamicciola earthquake (9:30 p.m. local time, July 28th, 1883; marker G in Table 2) destroyed Casamicciola and led to collapses and heavy damage also in Lacco Ameno and Forio. Light damage was reported throughout the island. The official death toll was between 2313 and 2333 people, with at least 600 tourists, and 762 injured (Cubellis and Carlino 2004). It was peak tourist season, with crowded hotels (the press called it the “earthquake of the

Table 2 Historical seismic events of the area hit by the Ischia earthquake from the Parametric Catalogue of Italian Earthquakes-CPTI15 (Rovida et al. 2016)

Marker	ID	Lon	Lat	Year	I_0	M_w
A	46	40,743	13,942	1275	8–9	4.01
B	340	40,721	13,953	1557	6–7	3.50
C	800	40,746	13,909	1762	6–7	3.50
D	814	40,735	13,919	1767	6–7	3.50
E	966	40,746	13,909	1796	8	3.88
F	1076	40,745	13,899	1828	8–9	4.01
G	1166	40,749	13,899	1841	5–6	3.25
H	1304	40,746	13,909	1863	4	2.87
I	1321	40,746	13,909	1867	4–5	2.99
L	1444	40,747	13,895	1881	9	4.14
M	1481	40,744	13,885	1883	9–10	4.26
N	3235	40,718	13,890	1980	5	4.37

The marker is the location of the epicenter reported on the map (black circles in Fig. 3). ID is the identification number reported in the CPTI15 database (Rovida et al. 2016). I_0 is the epicentral intensity

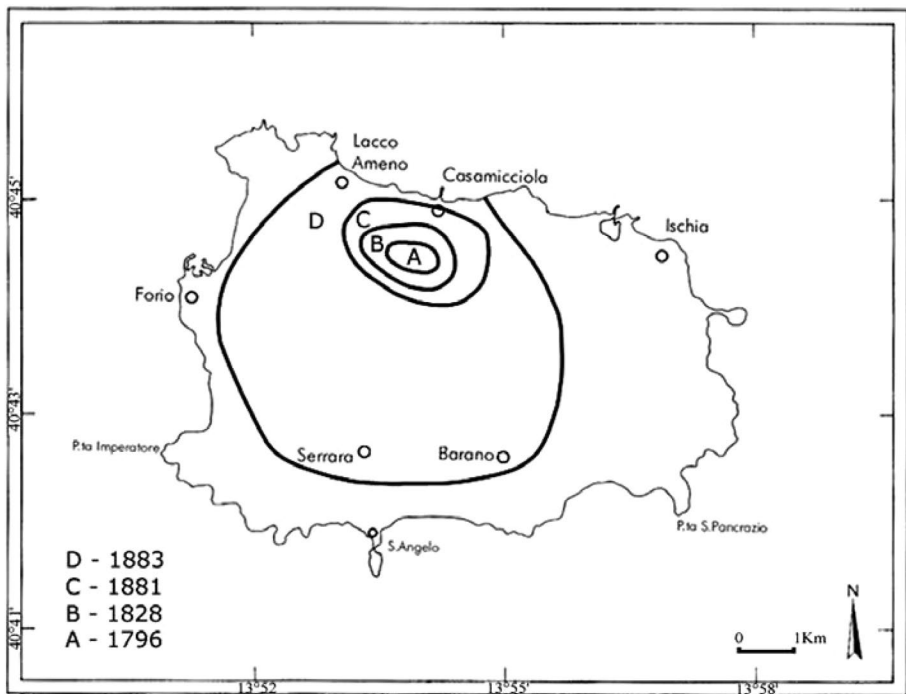


Fig. 5 Damaged areas in 1796, 1828, 1881 and 1883 earthquakes. After Cubellis and Carlino (2004)

rich people”). The earthquake also claimed the lives of Benedetto Croce’s family (a distinguished Italian philosopher and politician), leaving him orphan and lame (Cingari 2000). Finally, it should be highlighted that some earthquakes occurred on the island triggered

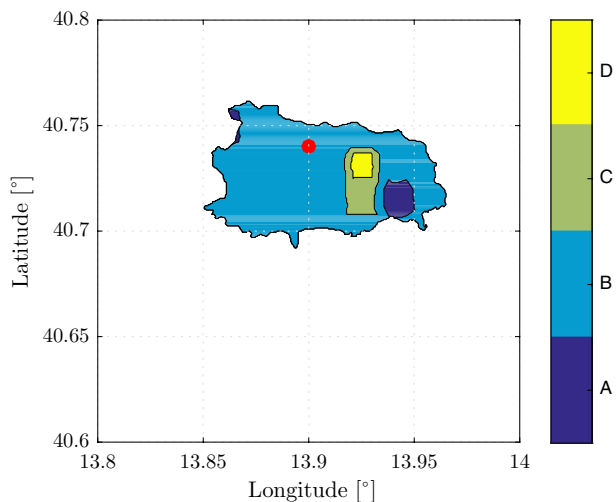
some rock falls and shallow landslides as documented for the 1881–1883 seismic sequence in the vicinity of Mt. Nuovo (Manzo et al. 2006; Rapolla et al. 2010; Paparo and Tinti 2017).

The 1275–1980 seismic events (Table 2) were apparently uncorrelated with eruptions, but may be related to periodic reactivation of the tectonic structure. The seismicity can thus be linked to a local stress field, probably generated by volcanic processes. Since the active-quietescent periods of the island seem to be marked by Mt. Epomeo uplift, monitoring of the long-term deformation of the resurgent block is fundamental for understanding the state of the Ischia volcanic system (Luongo et al. 2010).

The soil classification is usually based on the shear wave velocity averaged among the soil layers in the top 30 m ($V_{s,30}$) of the site. In particular, the Italian Building Code (NTC; MIT 2008) and the Eurocode 8 (CEN 2004) classify soil types in four classes (from A to D), depending on $V_{s,30}$. Three further special soil types are considered, named E, S1 and S2, where strong amplification and/or soil liquefaction is foreseeable. The last three classes will not be considered in the following as they require other parameters than $V_{s,30}$ to be identified. The shear wave velocity can be estimated using the 1:100,000 geological map of Italy compiled published by the Geological Survey of Italy (Luzi et al. 2011; Vanzi et al. 2015). The estimation of shear wave velocity $V_{s,30}$ reported in Michellini et al. (2008) is used to evaluate the soil class using the classification reported in Fig. 6. In particular, the majority of the territory is classified as class B (also the area hit by the 2017 earthquake) while some limited areas are classified as A, C and D.

The Italian Building Code (NTC; MIT 2008) defines the seismic action in terms of elastic acceleration response spectrum approximating the probabilistic uniform hazard spectra for 10751 nodes (in a reference grid with step of 0.05° in a ED50 Datum leading to an almost regular grid spaced around 5.5 km in the Cartesian coordinate system) and for 9 return periods (ranging from 30 to 2475 years). The parameters defining the elastic acceleration response spectra are: the maximum horizontal ground acceleration, a_g , the maximum spectral acceleration normalized with respect to a_g , F_0 , the period indicating the beginning of the constant velocity branch of the spectrum, T_c^* , and the factor that takes into account the stratigraphic and topographic conditions, S . These are reported in Fig. 7 for

Fig. 6 Map of the soil classes for Ischia island according to the Italian Building Code (NTC; MIT 2008) or the Eurocode 8 (CEN 2004) estimated using the shear wave velocity $V_{s,30}$ in Italy from Global $V_{s,30}$ Map Server of the USGS. The red dot indicates the epicenter of the event



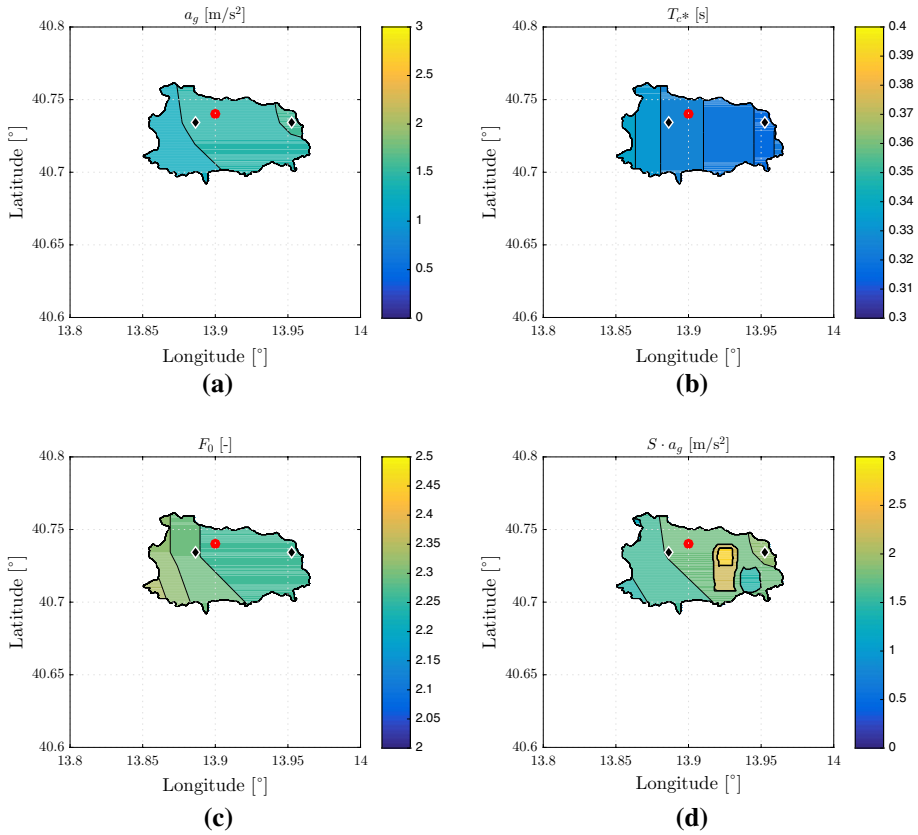
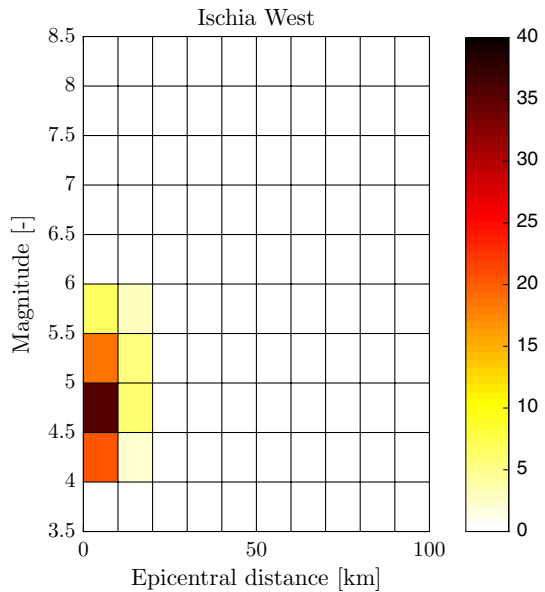


Fig. 7 a_g (a), T_C^* (b), F_0 (c), $S \cdot a_g$ (d) with 10% probability of exceedance in 50 years (return period 475 years) according to Italian Building Code (NTC; MIT 2008) for the Ischia island. The red dot indicates the epicenter of the seismic event of the 21st August 2017. The black squares indicate the location of the nodes coming from the Italian Building Code (NTC; MIT 2008)

a return period equal to 475 years. In particular, it is visible that the maximum horizontal ground acceleration considering the soil effect is around 2 m/s^2 with peaks up to 3 m/s^2 where amplifications due to the soil are predicted. However, the seismic ground classification reported in Fig. 6 may be inaccurate at this small scale and is intended as the best available proxy to the real one.

The 475 years return period disaggregation of the peak ground acceleration for Ischia West (Lat: 40.7343, Lon: 13.8862, ID: 33639) is shown in Fig. 8. For the same local soil conditions, the intensity of the ground shaking at the site mainly depends on the magnitude, M , and source-to-site distance, R , of the causative event (Bazzurro and Allin Cornell 1999). The disaggregation was performed according to the procedure reported in Spallarossa and Barani (2007). The disaggregation of the peak ground acceleration is available only at grid points (shown in Fig. 7); in Fig. 8, it is only reported the closest grid point to the epicenter. However, it is noteworthy that negligible differences were found between the east and west parts of Ischia, with differences lower than 1%. Seismic hazard in Ischia is mainly dependent on local and low energy events, with a magnitude in the range 4–5.5, and epicentral distance smaller than 10 km. This is compatible with the 2017 Ischia earthquake.

Fig. 8 Disaggregation of the peak ground acceleration, a_g , with return period 475 years for Ischia West (LAT: 40.7343, LON: 13.8862, ID: 33639). Data from <http://esse1-gis.mi.ingv.it> (INGV-DPC 2006)



The strong motion record of the 21st August 2017 earthquake was provided by the INGV Engineering Strong Motion Database (Luzi et al. 2016). The only station available on the Ischia island was the Ischia-Osservatorio Casamicciola (Code: IOCA; Soil class: B; Lat: 40.7458 and Lon: 13.9008; altitude: 123 m above sea level). The station was very close to the epicenter and the focus, respectively at about 0.6 and 1.8 km. Accordingly, non-synchronous earthquake signal characteristics cannot be evaluated. However, they are only important for long structures such as bridges (Lavorato et al. 2017) that are not present on Ischia island.

The acceleration time histories and the 5% damped elastic response spectra are shown in Fig. 9 while Table 3 reports some features of the strong motion. Arias intensity (I_A) is a duration related intensity measure that represents the total earthquake input energy per unit weight for a set of undamped elastic oscillators with frequencies uniformly distributed from zero to infinity (Arias 1970). It is the area under the square of ground acceleration, $a(t)$, and it can be an indicator of potential destructiveness in ground motions:

$$I_A = I_A(t_{max}) \Rightarrow I_A(t) = \int_0^t a^2(\tau) d\tau \tag{1}$$

where t_{max} is the total duration of the time series. The largest values of I_A are in the HNE component while in the HNN and HNZ lower values are observed (Table 3). The significant-duration SD is defined as the time elapsed between two specific energy levels expressed in terms of $I_A(t)$. In the following, it will be considered SD_{5-95} that is the time interval between 5 and 95%. In this case, a short significant duration, between 2.7 and 3.6 s, has been found for the three components, as expected for a low magnitude event. The cumulative absolute velocity (CAV) is defined as the integral of the absolute value of an acceleration time series, which is mathematically represented by the following equation (Benjamin et al. 1988):

Fig. 9 Acceleration time histories for the three components (HNE: East component; HNN: North component; HNZ: Vertical component) for the Ischia-Osservatorio Casamicciola seismic station (Code: IOCA) for the 21st August 2017 earthquake. The red asterisks indicate the absolute maximum. (Data provided by INGV-Osservatorio Vesuviano)

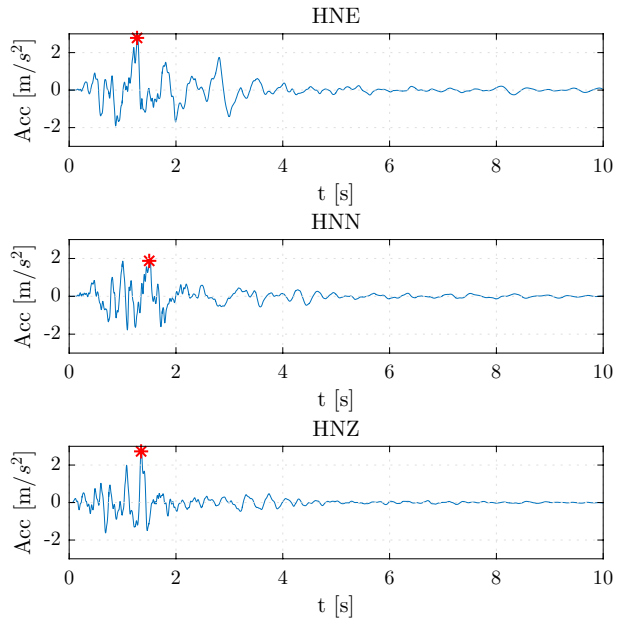


Table 3 Arias intensity, I_A , strong-motion duration SD_{5-95} , RMS acceleration, cumulative absolute velocity, CAV , Housner spectrum intensity (damping equal to 5%), SI , peak ground acceleration, PGA , peak ground velocity, PGV , peak ground displacement PGD , for the three components for the Ischia-Osservatorio Casamicciola seismic station (Code: IOCA) for the 21st August 2017 earthquake. (HNE: East component; HNN: North component; HNZ: Vertical component)

Direction	[-]	HNE	HNN	HNZ
I_A	[m/s]	0.3933	0.2217	0.1993
SD_{5-95}	[s]	2.8500	3.5900	2.7350
RMS acceleration	[m/s ²]	0.0307	0.0231	0.0219
CAV	[m/s]	2.950	2.1904	1.7299
SI	[m]	0.6623	0.4345	0.2551
PGA	[m/s ²]	2.7514	1.8814	2.7082
PGV	[m/s]	0.1779	0.1146	0.1177
PGD	[m]	0.0231	0.0172	0.0146

$$CAV = \int_0^{t_{max}} |a(t)| dt \tag{2}$$

Again, CAV assumes the largest values in the HNE component and lower values for the HNN and HNZ components (Table 3). The Housner spectrum intensity is defined as the integral of the pseudo-spectral velocity, $S_V(t)$, over the period range of 0.1–2.5 s:

$$SI = \int_{0.1\text{ s}}^{2.5\text{ s}} S_V(T) dT \tag{3}$$

Similarly to *CAV*, *SI* presents the largest values in the HNE component (0.66 m) and lower values for the HNN (0.44 m) and HNZ (0.25 m) components (Table 3). The peak ground acceleration (Table 3) was around 2.7 m/s^2 , 1.9 m/s^2 and 2.7 m/s^2 for the East, North and vertical directions, respectively.

In Fig. 10 acceleration, velocity and absolute and relative energy input elastic spectra of the three components are shown for critical damping equal to 5%. Measured elastic response spectra indicate peak values equal to 7.4 m/s^2 ($T = 0.5 \text{ s}$), 8.0 m/s^2 ($T = 0.17 \text{ s}$) and 8.5 m/s^2 ($T = 0.27 \text{ s}$) for the East, North and vertical directions, respectively. Despite IOCA instrument epicenter proximity, the area around the IOCA instrument was considerably less damaged than the one around the epicenter (see Sect. 4). Based on this observation, it can be assumed that, in the area around the epicenter, the earthquake was sensibly more intense than what the response spectra in Fig. 13 show.

The energy input spectra reported in Fig. 10 are expressed in form of equivalent velocity (Uang and Bertero 1990):

$$V_E(T) = \sqrt{2 \int (\ddot{u}_g(t) + \ddot{u}(t, T)) \dot{u}_g(t) dt}$$

$$V'_E(T) = \sqrt{2 \int \ddot{u}_g(t) \dot{u}(t, T) dt}$$
(4)

where $V_E(T)$ and $V'_E(T)$ are the absolute and relative equivalent velocity, respectively, \ddot{u}_g and \dot{u}_g are the ground acceleration and velocity, respectively, and \ddot{u} and \dot{u} are the relative acceleration and velocity of the system with respect to the ground. The significant difference between $V_E(T)$ and $V'_E(T)$ (Fig. 10) can be considered as representative of directivity effects (e.g., Kalkan and Kunnath 2008; De Luca et al. 2014). Finally, the strong motion (Fig. 9) was analyzed using a multi-component pulse classification algorithm (Shahi and Baker 2014) and classified as a non-pulse-like ground motion.

After the earthquake, it is important to estimate the return period of the seismic event. In the following, the Italian code (NTC; MIT 2008) will be used as a benchmark to estimate the signal return period as recorded at the IOCA station. Two benchmark parameters have been chosen: *PGA* and elastic response spectra in the 0–2 s range. Figure 11 shows the hazard curves in terms of *PGA* for the eastern (green lines) and western (blue lines) parts of the island (black dots in Fig. 7) according to the Italian Building Code (NTC; MIT 2008). The *PGA* is shown for soil type A (dashed lines), B (thin solid lines) and B plus topographic amplification of 1.2 (thick solid lines). The east side has a slightly larger seismic hazard. In addition to the hazard, Fig. 11 shows the maximum values of the *PGA* recorded in the two directions (HNE and HNN) from the IOCA seismic station for the 21st August 2017 earthquake (vertical dashed lines). Neglecting topographic effects and soil type B matching (i.e., the soil where the IOCA station is located), the return period is approximately 2000 years (i.e., the intersection of the colored thin solid lines with the vertical dashed line at the right). With topographic effects considered, return period may be estimated as 1000 years.

A more structurally meaningful estimation can be performed in terms of elastic response spectra. This was done by finding the return period giving the minimum of the sum of squares of the difference between the code elastic response spectrum

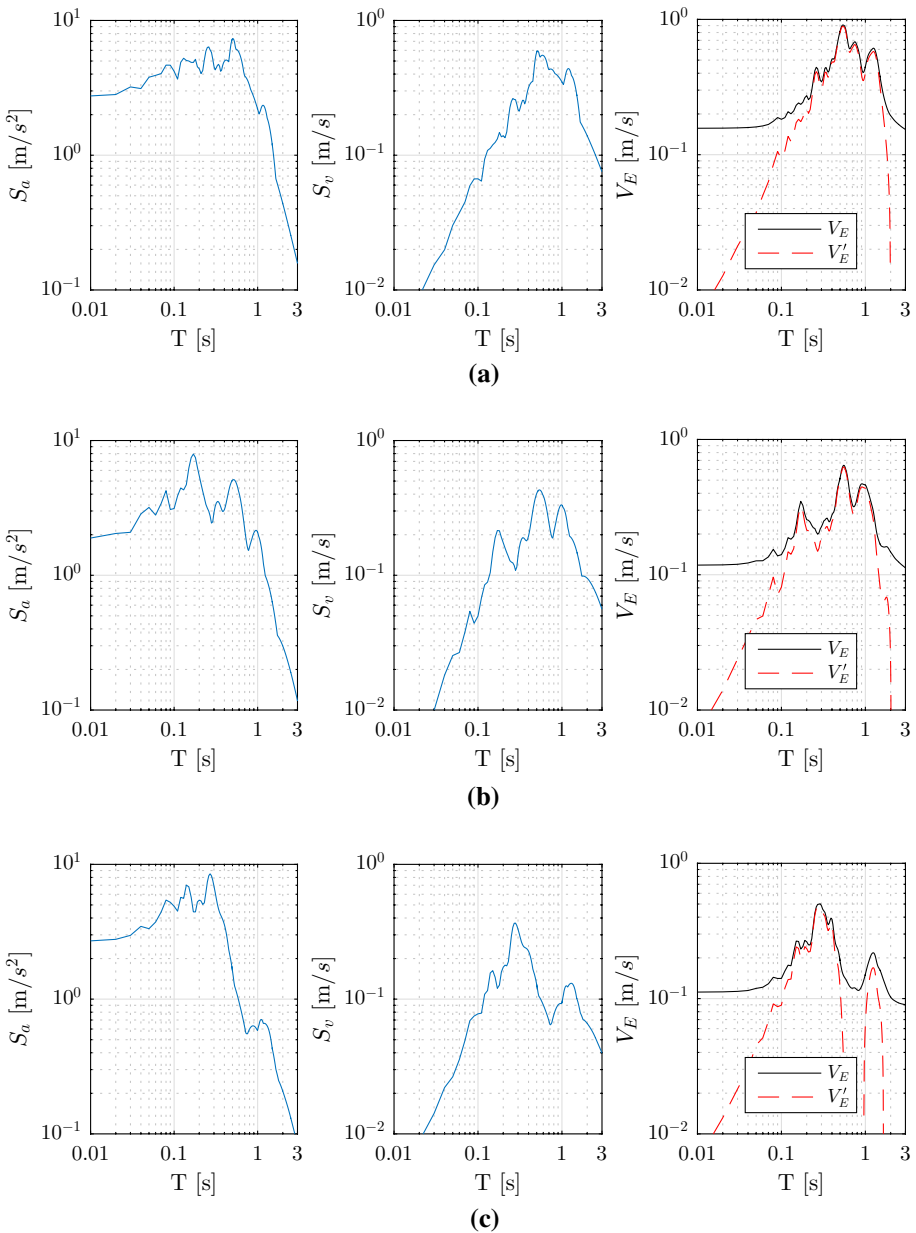


Fig. 10 Acceleration (S_a), velocity S_v , and relative, V'_E , and absolute, V_E , equivalent velocity spectra (damping equal to 5%) for the East component (a) North component (b) and Vertical component (c) for the Ischia-Osservatorio Casamicciola seismic station (Code: IOCA) for the 21st August 2017 earthquake

according to the Italian Building Code (NTC; MIT 2008), $S_{a,NTC}$, and the measured elastic response spectrum, S_a , at the IOCA station:

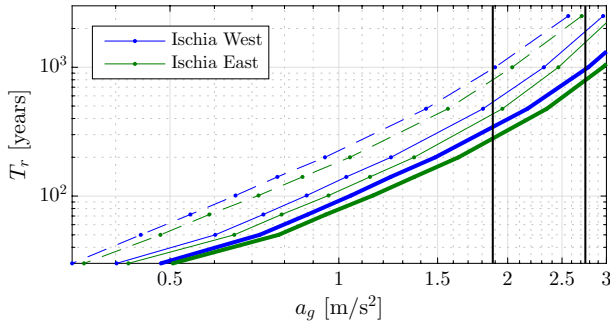


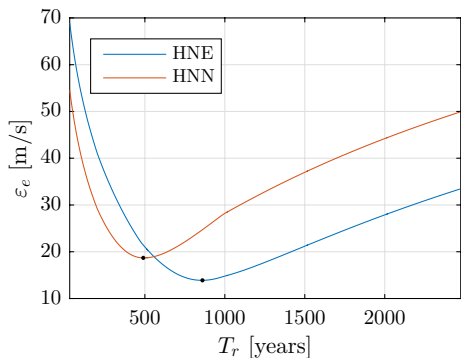
Fig. 11 Hazard curves in terms of a_g for Ischia Island according to the Italian Building Code (NTC; MIT 2008). The colored dashed lines are the hazard curve on soil type A and neglecting the topographic effects. The colored thin solid lines are the hazard curve on soil type B and neglecting the topographic effects. The colored thick solid lines are the hazard curve on soil type B and considering topographic effects (i.e., topographic amplification factor equal to 1.2). The vertical black solid lines are the maximum values of PGA recorded by the Ischia-Osservatorio Casamicciola seismic station (Code: IOCA) for the two directions (HNE and HNN) for the 21st August 2017 earthquake

$$T_r \Rightarrow \min \left\{ \varepsilon_e(T_r) = \sqrt{\int_0^{2s} [S_a(T) - S_{a,NTC}(T, T_r)]^2 dT} \right\} \tag{5}$$

Solving Eq. 5 the following assumptions were done: (1) only fundamental periods, T , in the range of 0–2 s were considered; (2) topographic effects were neglected; (3) 5% of damping ratio was considered; (4) soil was assumed of type B as for the Ischia-Osservatorio Casamicciola seismic station (Code: IOCA). Equation 5 was solved for the two horizontal directions finding a return period of 660 years in the North component and 860 years in the East component (Fig. 12) and the maximum is assumed as representative return period. Accordingly, the estimated return period at the IOCA station has thus been equal to 860 years.

It is noteworthy that the estimation of the return period using the hazard model of the Italian Building Code (NTC; MIT 2008) can be only considered as a benchmark number for the risk assessment procedure. As a matter of fact, this hazard model does not properly account for the volcanic regions because of the lack of proper earthquake recurrence

Fig. 12 Variation of ε_e (Eq. 5) for different T_r for the East component (HNE) and North component (HNN). The two black dots on the curves are the minimum of the function $\varepsilon_e(T_r)$



model within the seismogenic zone and attenuation relations. In fact, if the estimated return period at the IOCA station using the elastic spectrum of the Italian Building Code (NTC; MIT 2008), i.e., 860 years, is compared with the historical data reported in Table 2, it can be observed a large overestimation. Observing Table 2, it can be seen that five events ($N = 5$) with $M_w \geq 4$ occurred between 1275 and 1980, resulting in very rough terms in an estimation of the average return period equal to:

$$T_r = \frac{\Delta t}{N - 1} = \frac{1980 - 1275}{4} = 176 \text{ years}$$

This indicates the need for the definition of an appropriate model of seismic hazard for the volcanic regions and in this specific case for Ischia Island.

Figure 13 shows a comparison of the measured and design elastic response spectra according to the Italian Building Code (NTC; MIT 2008) and Eurocode 8 (CEN 2004) type 1 and 2, with 5% damping, 860 years return period, soil class B (i.e., the same soil class as the IOCA instrument). In particular, Eurocode 8 (CEN 2004) considers two different types of spectral shapes (type 1 and type 2) for varying seismicity conditions. In this regard, provisions of Eurocode 8 (CEN 2004) state: “If the earthquakes that contribute most to the seismic hazard defined for the site for the purpose of probabilistic hazard assessment has a surface wave magnitude, M_s , not greater than 5.5, it is recommended that the Type 2 spectrum is adopted”. In this case, being the analyzed earthquake characterized by a low magnitude, type 2 should be adopted.

Looking at Fig. 13, it can be seen that the Italian Building Code (NTC; MIT 2008) and Eurocode 8 (CEN 2004) type 1 vertical spectra strongly underestimate the vertical effects. This is probably due to near-field effects (Grimaz and Malisan 2014) that are not considered by the uniform hazard spectrum (e.g., Demartino et al. 2018). On the other hand, as expected, Eurocode 8 (CEN 2004) type 2 spectrum gives a better estimate of the measured response spectrum.

Figure 14 shows the ratio between elastic response spectra (damping 5%) in the vertical and horizontal directions (i.e., HNE and HNN), namely V/H ratio. The largest value is 3.4,

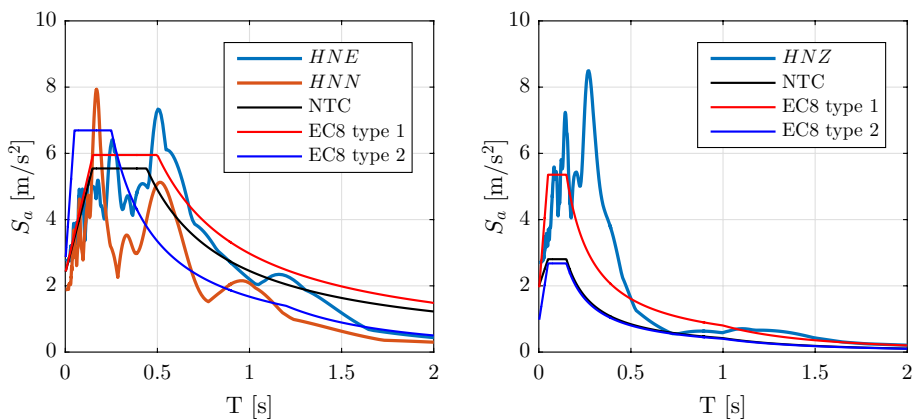


Fig. 13 Comparison of the measured elastic response spectra (HNE: East component; HNN: North component; HNZ: Vertical component) and design elastic response spectra of the Italian Building Code (NTC; MIT 2008) and Eurocode 8 (CEN 2004) type 1 and 2 evaluated with return period 860 years for damping equal to 5%, soil class B for the horizontal (left) and vertical (right) components of the event of the 21st August 2017 earthquake at Ischia

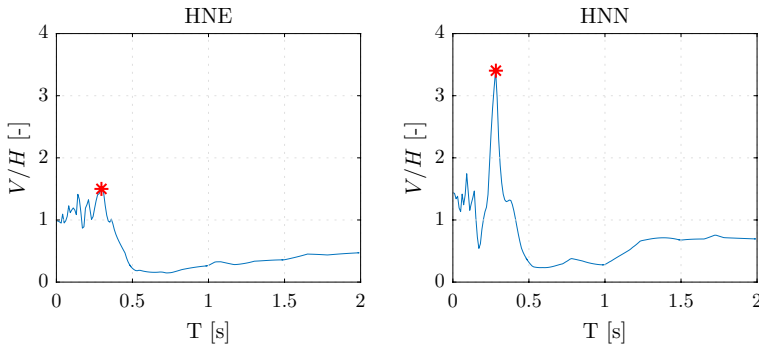


Fig. 14 V/H PGA ratio in terms of spectral components for the two horizontal components (HNE: East component; HNN: North component) for the Ischia-Osservatorio Casamicciola (code: IOCA) for the 21st August 2017 earthquake. The red asterisks indicate the absolute maximum

at a fundamental period equal to 0.28 s in the north direction. At zero period (i.e., PGA), the ratio is within 0.98 (east) and 1.44 (north). Literature V/H PGA ratios (e.g., Collier and Elnashai 2001; Bozorgnia and Campbell 2016) indicate values above 1 within a 5 km radius of earthquake source, higher than $2/3$ within 25 km; they further show dependence on earthquake magnitude. The V/H PGA ratios of the Ischia earthquake appear to confirm these findings (the IOCA seismic station was 600 m away from the epicenter).

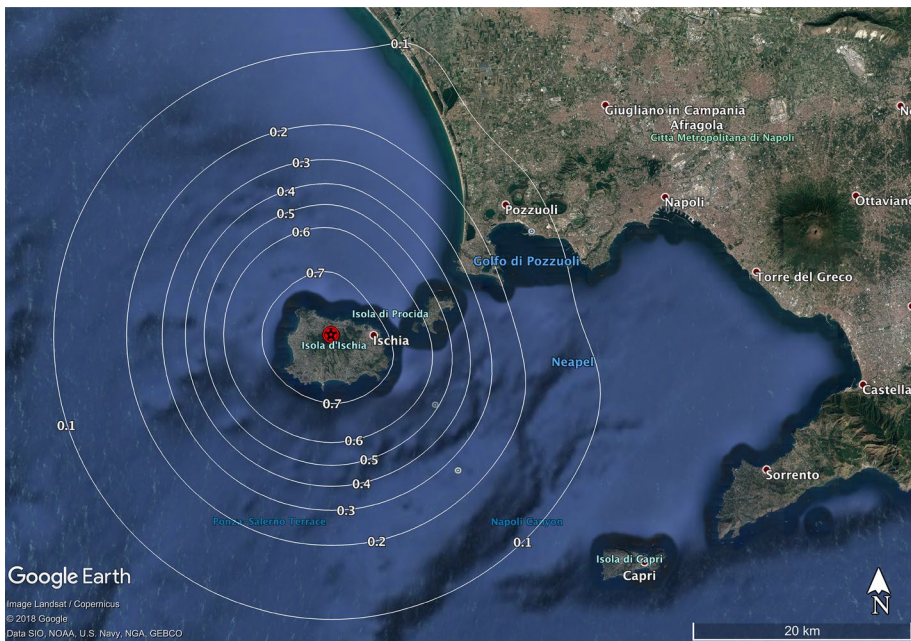


Fig. 15 ShakeMap for the 21st August 2017 Ischia earthquake. Event location and magnitude from INGV seismic center, peak ground motion data from INGV (red star). Intensities expressed in terms of PGA [m/s^2]. The blue triangle indicates the seismic station of Pozzuoli (code: CPIS). (From Google Earth)

Figure 15 shows the ShakeMap for August 21, 2017, Ischia earthquake in terms of PGA (Michelini et al. 2008). Almost the whole island experienced horizontal PGA values larger than 0.9 m/s^2 . This particular shakemap, however, is pretty non-informative. Results are biased, as the almost circular iso-accelerations curves show, because only two seismic stations were near the epicenter: (1) Ischia-Osservatorio Casamicciola (code: IOCA) and (2) Pozzuoli (code: CPIS, around 20 km from the epicenter).

Finally, it is also interesting to report information on the macro-seismic intensity of the 21st August 2017 Ischia earthquake. In particular, a survey after the earthquake made by the QUEST [QUick Earthquake Survey Team, Azzaro et al. (2017)] of INGV was used to estimate the macroseismic intensity according to the European Macroseismic Scale (EMS). Table 4 reports the EMS intensities estimated to the different area of the Ischia island. This result confirms that the high level of damage (EMS 8) was mainly observed near the epicenter in Casamicciola Terme. As it will be shown in Sect. 4, only the area of Casamicciola near the epicenter was severely damaged by the earthquake. The damage was lighter in Lacco Ameno (near the epicenter) (EMS 7) and even smaller in the Marina di Casamicciola (near the sea) (EMS 6). The remaining part of the island was rated $\text{EMS} < 6$ (i.e., slightly damaging).

It is noteworthy that seismicity in volcanic areas shows that earthquakes generally have a low magnitude and they do not produce serious damage (e.g., McNutt 2005). However, sometimes, as in the case of Ischia island, earthquakes occurring in volcanic areas have been associated with low seismic energy events and high intensities (e.g., De Novellis et al. 2018). In fact, looking in detail the macroseismic intensities in the area of Casamicciola caused by the 2017 earthquake (Table 4 in terms of MCS intensity) and the historical seismic events (Table 2 in terms of EMS intensity), large values of the epicentral intensity were observed compared with the magnitude of the causing events. For instance, the 1883 Casamicciola earthquake reached an epicentral intensity of $I_o 9 - 10$ for a magnitude $M_w 4.26$. Using the estimations obtained by the $I_o - M_w$ relationship calibrated from macroseismic data at a national scale (Gasperini 2004), a magnitude $M_w 4.26$ (1883 Casamicciola earthquake, Table 2) and $M_w 3.9$ (21st August 2017 Ischia earthquake, Table 1) correspond to an estimate of the epicentral intensity equal to $I_o 5$ and $I_o 4$, respectively. These predictions are quite smaller with the observed values of the epicentral intensities: $I_o 9 - 10$ (Table 2) and $I_o 8$ (Table 4), respectively. On the other hand, if the $I_o - M_w$ relationship calibrated from the Volcanic region of Mount Etna in Italy, it is estimated an epicentral intensity equal to: $M_w 4.26 \rightarrow I_o 7$

Table 4 EMS intensity for the different areas of Ischia island (see Fig. 3a for the location of the different municipalities). Adapted from Azzaro et al. (2017)

Location	EMS intensity	Description
Casamicciola Terme (near the epicenter)	8	Heavily damaging
Lacco Ameno (near the epicenter)	7	Damaging
Casamicciola (near the sea)	6	Slightly damaging
Serrara Fontana	5–6	Strong-slightly damaging
Lacco Ameno	5	Strong
Forio	4–5	Largely observed-strong
Bararo d' Ischia	4–5	Largely observed-strong
Ischia	4	Largely observed

and $M_w 3.9 \rightarrow I_o 6-7$ (Azzaro et al. 2011) and $M_w 4.26 \rightarrow I_o 8$ and $M_w 3.9 \rightarrow I_o 7-8$ (Giampiccolo et al. 2007). Unfortunately, due to the limited number of events, such relationships are not available for Ischia island. In any case, the latter intensities are more consistent with the observed values indicating and confirming the specificity of the seismic events in volcanic regions.

3 Building stock

As already noticed, the largest damage occurred in the Casamicciola Terme municipality, and marginally in the Lacco Ameno municipality, both located in the northern part of the island (Fig. 3a). Statistical data on the building stock may be useful to frame the case study and are given in the following. Then, the results of field observations carried out by the authors will be presented in the next Section.

Looking at the historical background, it should be noted that the construction systems used in the island are partly the results of provisions developed over time, in order to withstand the effects of earthquakes. Before the 1881 earthquake, houses were generally built with rooms side by side at ground level, often on basements used as wine-cellars. These masonry buildings were mainly constructed of rubble stone and heavy blocks, which were easily available around settlement areas. These constructions were non-engineered and not earthquake resistant; moreover, no standards were available for materials quality and construction details.

The two major historical earthquakes, 1881 and 1883 (see Sect. 2 for detailed information), were characterized by ground-motion directionality (inferred through a detailed survey of the damage structures carried out soon after the earthquake) with preferential East–West direction at Casamicciola and North–South direction at Lacco Ameno (Abbate et al. 1980). In particular, it was observed that in these settlements the most damaged buildings were those with their sides parallel to the preferred directions of transmission of the seismic waves (Abbate et al. 1980). In particular, after the 1883 earthquake, a committee of the government surveyed the area hit by the earthquake and found a large number of vulnerabilities in the building (Penta 1964). In particular, the survey highlighted: insufficient foundations; houses with three and four floors above ground built with poor quality (irregularly shaped pieces) tuff masonry and with low-quality mortar (i.e., low-quality lime, partly substituted by clayey soil); roofs not secured to the structure; terraces made with a 30 cm thick layer at the last floor; detrimental effect of the iron end-plate anchors installed during the 1881 earthquake.

Consequently, in accordance with this evidence, new measures for town planning and anti-seismic building were adopted. After the catastrophic 1883 earthquake, new houses were built, characterized by a rectangular shape and following a “seismic orientation” that is with the short sides oriented along the preferred directions of transmission of the seismic waves (Abbate et al. 1980). At the same time, damaged houses were replaced by constructions with wooden beam frameworks (Penta 1964), strengthened with x-bracings. Roofs were light, often made of corrugated iron. This construction typology, named “*casa baraccata alla Beneventana*”, is the first anti-seismic building technique introduced in the island (Abbate et al. 1980; D’Aprile et al. 2013). Its origins, however, date back to 1783 and was introduced by Ferdinando IV, a Bourbon family king of Naples (Ruggieri et al. 2013).

These efficient, for life safety, anti-seismic details were extensively used in the period immediately following the 1883 event; later, as the memory faded, they were progressively

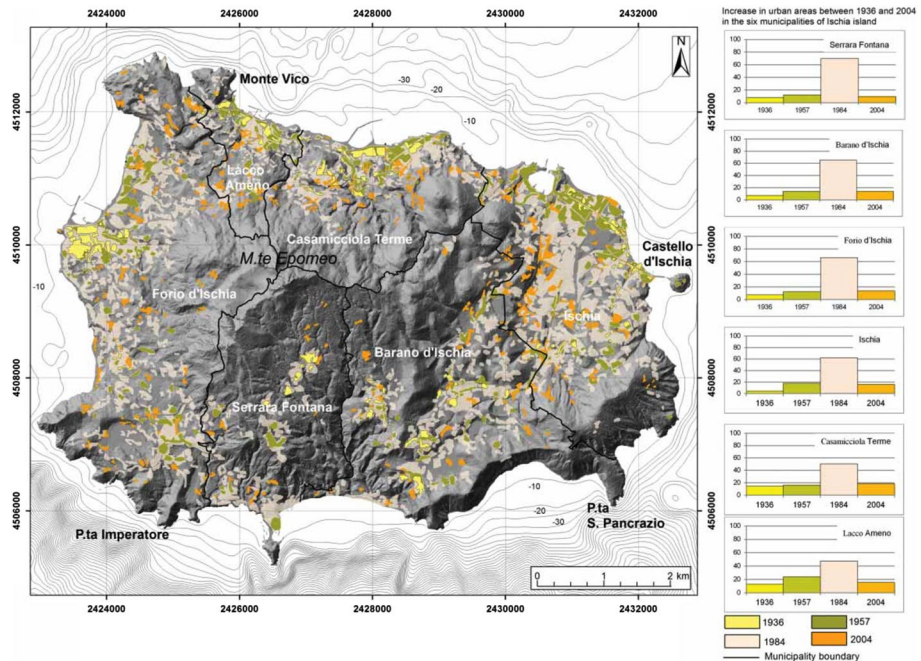


Fig. 16 Urban development at Ischia Island from 1936 to 2004 (right). Percentage of total urban area for the different municipalities (left). After Alberico and Petrosino (2014)

discarded in favor of simpler, cheaper and faster methods. The favorite construction material was tuff, readily available.

Looking at the last century, the extent of the urbanized areas at 1936, 1957, 1984 and 2004 for Ischia Island is reported in Fig. 16 together with the percentage of total urban area for the different municipalities. It can be observed that the highest increase in the urbanized area occurred in 1984. Moreover, it is evident that the area hit by the 21st August 2017 Ischia earthquake is mainly covered by urbanized areas realized after 1957.

After the August 2017 earthquake, masonry buildings were the most damaged (see Sect. 4). This was expected, since, according to the official cadastral data (15th General Census of the Population and Dwellings; ISTAT 2012), masonry constructions are the most common system. Data are relative to census tracts, and classify buildings by construction type (RC, Masonry, Other), storeys (1, 2, 3, 4 or more), age (since before 1919–2011) and are shown in Fig. 17. Data are shown for the whole island and for Casamicciola Terme and Lacco Ameno (municipalities mainly hit by the earthquake). Casamicciola Terme hosts about one-eighth of the residential buildings on the island. The surveyed sample shows homogeneous typologies throughout the island: low rise, pre-1990's, masonry buildings. As it will be shown in the following, this is the structural typology mainly observed in the post-earthquake survey.

Figure 18 reports the number of the residential building stock for Casamicciola Terme for masonry (Fig. 18a) and reinforced concrete (Fig. 18b) in terms of time of construction and number of storeys. It can be observed that before 1945, in Casamicciola Terme almost the totality of the building was masonry building, the most frequent typology having 2

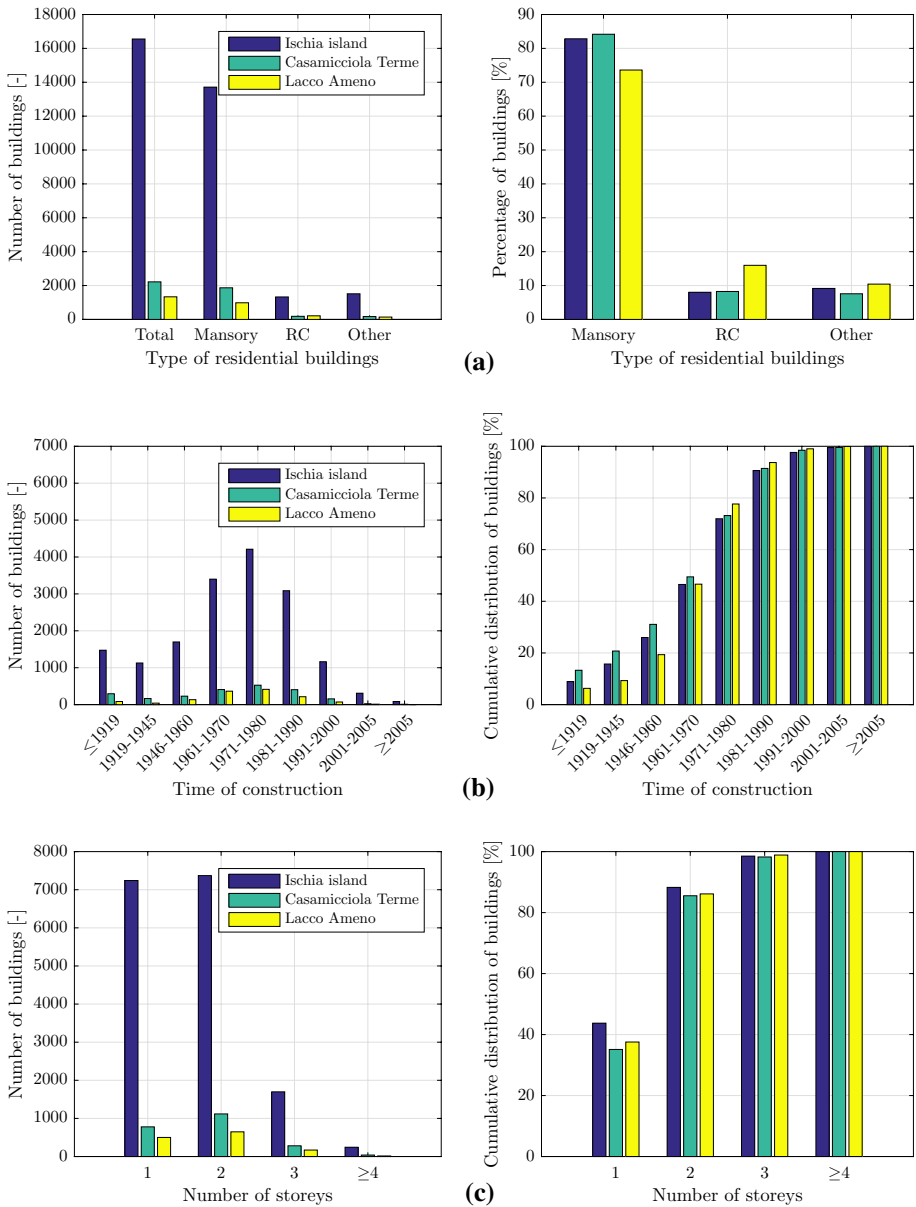


Fig. 17 Number and frequency distribution of the residential building stock in terms of type of structural typology (a), time of construction (b) and number of storeys (c) for the island of Ischia, Casamicciola Terme and Lacco Ameno from 15th General Census of the Population and Dwellings (ISTAT 2012)

storeys. Moreover, the majority of the residential buildings were realized in the period 1946–2000. Masonry buildings are dominated by 1 and 2 storeys while reinforced concrete by 2 and 3 storeys. Also according to the data reported in Fig. 17, it can be clearly seen

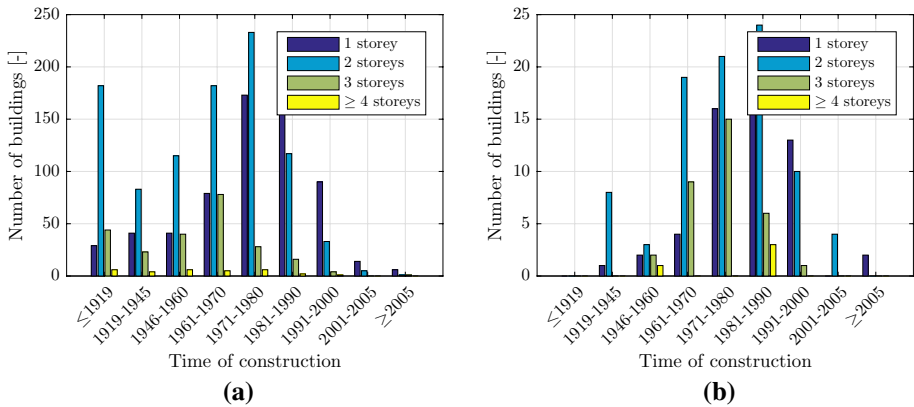


Fig. 18 Number of the residential building stock for Casamicciola Terme for masonry (a) and reinforced concrete (b) in terms time of construction and number of storeys from 15th General Census of the Population and Dwellings (ISTAT 2012)

Table 5 Average market value (k€/m²) for three different building typology for the six municipalities on the Ischia Island for the second semester of the year 2016

Municipality	Average market value (k€/m ²)		
	Apartments	Economic apartments	Villas
Barano d’Ischia	3.9–5.8	2.6–4.0	4.4–6.7
Casamicciola Terme	4.8–7.4	3.4–5.2	5.7–8.7
Forio	5.0–7.5	3.5–5.2	5.7–8.6
Ischia	5.5–8.3	3.8–5.8	6.3–9.4
Lacco ameno	5.3–8.0	3.7–5.5	5.4–8.2
Serrara Fontana	5.3–8.0	3.4–5.1	6.1–9.2

that for the most part the building stock is composed of masonry buildings realized in the period 1946–2000 having less than 3 storeys.

Buildings market values for the six municipalities of the Ischia island are in Table 5 (*Osservatorio del Mercato Immobiliare, 2016, AgenzieEntrate 2016*). The study of the exposed economic values is of paramount importance in the seismic risk assessment since economic losses can be dominant (e.g., Demartino et al. 2017). Against the background of the whole Campania region (the administrative region where Ischia island is located), with an average market value of 2000€/m², buildings values in Ischia are relatively high, being the island a popular tourist destination, with up to 6 million visitors per year. Market values have obviously been a powerful incentive for the intense, and sometimes disrespectful of town-planning and structural safety regulations, building activity.

Data on other types of networks (e.g., water, electric power and transportation networks) are not analyzed since no damage was recognized (see Sect. 4) although this issue is of fundamental importance in seismic risk analyses (e.g., Nuti et al. 2007, 2009, 2010).

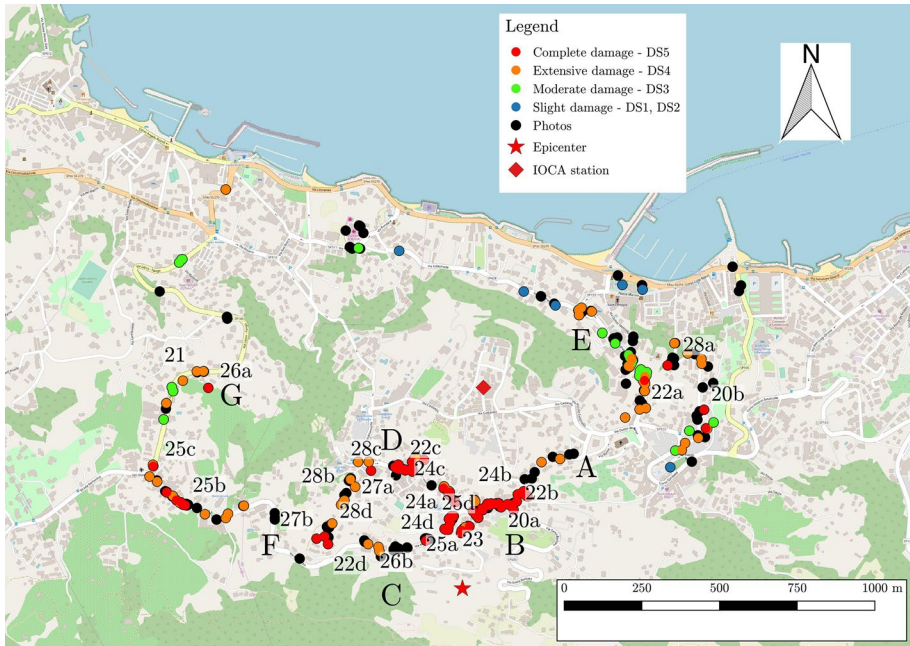


Fig. 19 Location of the photos taken and itinerary covered during the in-situ survey (black circles). Location of the epicenter (red star) and of the IOCA seismic station (red diamond). The different color on the circles indicates a rapid classification (slight, moderate, extensive, complete) of the observed damage. The identifiers composed by a number and/or a letter are the figure numbers reported in Sect. 4 and represent the location of the photos

4 Damage observed

Field observations after the 2017 earthquake in Ischia are coherent with the historical and statistical data background (see Sect. 3). The rapid inspection was carried out along the paths shown in Fig. 19, on August 22nd (the morning after the earthquake) and August 31st. Approximately 130 buildings were surveyed mainly paying attention to the damaged one. Almost the totality of buildings was of masonry type confirming the cadastral information (see Figs. 17 and 18). Inspection sites are shown with circles in Fig. 19. Inspections were mainly visual, from the outside of buildings. Occasionally, when permitted by safety and owners, they were carried out inside the buildings. Information on structural performances and construction methods was locally recorded, allowing evaluations on material quality and on the exhibited seismic vulnerability of the building stock.

The observed damage is classified using an adapted version of the European Macro-seismic Scale EMS98 (Grünthal 1998), that defines six vulnerability classes (A to F) and five damage grades (1–5) based on the level and on the extension of structural and non-structural damage in the buildings. In this study, only four damage grades adapted from the EMS98 classification are used: (1) slight (minor or no damage observed—EMS98 DS1, DS2), (2) moderate (damage not significantly affecting the capacity of the structure without falling of non-structural elements—EMS98 DS3), (3) extensive (damage significantly affecting the capacity of the structure but far from the limit of partial collapse—EMS98 DS4) and (4) complete (damage significantly affecting the capacity of the structure

Table 6 Damage level according to EMS98 (Grünthal 1998) assigned to masonry buildings

	Damage level					Total
	DS1, DS2	DS3	DS4	DS5		
Number of buildings	11	23	43	66	143	

bringing and close to the limit of partial or total collapse—EMS98 DS5). A similar procedure was previously adopted to rapidly identify and characterize damage patterns observed after recent earthquakes (e.g., Fiorentino et al. 2018).

The result of the rapid damage estimation is shown in Fig. 19 and Table 6. It should be highlighted that the data summarized herein derives from a rapid inspection and they should be considered as qualitative rather than quantitative. The observation of the map allows for making the following considerations: the damage was observed along paths A–B, B–C, B–D. Damage increased visibly moving from point A to B and from point G to F, i.e., getting closer to the epicenter. Based on this evidence, it can be argued that even a distance of 300 m made the difference between generally damaged (points A and F) or generally collapsed (points B, C and D) areas. It can be seen that the majority of the damage was localized in a very small area with approximately 400 m radius. Accordingly, the derivation of a statistical model of the damage distribution, although of remarkable importance for risk assessment, do not fall within the scope of this study because the population of buildings is too small to provide a robust estimation and, rather, deserve a statistical analysis of a large number of earthquakes events. The proposed methodology aims at defining the damage in the small area hit by the earthquake and to identify possible damage mechanisms and vulnerability factors.

During the in-situ survey, damage to three main construction typologies was recognized: (1) “*casa baraccata alla Beneventana*”; (2) leaf tuff masonry constructions; (3) hollow cement bricks technology, sometimes called *Cellublok*, often with no reinforcement nor cast-in-situ concrete within the hollow parts. The first two typologies date back to about 1950’s while the last one is more recent. The most frequent typology was the second one (around 70% of the cases). No damage on RC buildings was observed during the survey although this typology is not so common in the area hit by the earthquake (see Sect. 3). Large damage to dry stone masonry retaining walls was observed. Moreover, it is noteworthy that geological coseismic effects have been induced over an area with approximately 900 m radius (Azzaro et al. 2017; EMERGEO and Nappi 2017), among which fractures and small rock falls.

The survey highlights that existing buildings on the island are characterized by a high seismic vulnerability. Materials and construction techniques are unable to provide suitable earthquake resistance, due to lack of connection between external and internal units of the wall section (i.e., lack of headers); lack of proper connection between interlocking walls in correspondence of corners; high percentage of openings. The low energy 2017 earthquake has been an important reminder (luckily, in a very small area) of the urgency to retrofit buildings in volcanic areas characterized by moderate seismicity.

In the following, the main damage observed in the four structural types before-mentioned will be described and possible explanation of the damage mechanism will be given. The location of the photos reported in the following is reported in Fig. 19 with an identifier representing the Figure number.

4.1 “Casa baraccata alla Beneventana” constructions

The “*casa baraccata alla Beneventana*” constructions were conceived as an anti-seismic system and they take their name from the city of Benevento where they were used for the first time (Barucci 1990). The “*muratura alla beneventana*” consists of a wooden frame with infill masonry (i.e., a timber braced frame system used as reinforcement for the wall), and can be distinguished from other types of so-called “*baraccate*” masonries for the finishing mortar that covers both the frame buffers.

Generally speaking, this structural typology showed better seismic performances with respect to more recent masonry structures realized with poorly construction practice. Figure 20a showed a typical example of complete damage (i.e., separation between infill and frame) of a “*Casa baraccata alla Beneventana*” construction (two storeys) located in piazza Maio near the epicenter (see Fig. 3b). The damage was mainly localized at



(a)



(b)

Fig. 20 Complete damage of “*Casa baraccata alla Beneventana*” constructions: **a** piazza Maio (Lat: 40.7425–Lon: 13.9013); **b** viale Paradisiello (Lat: 40.7451–Lon: 13.909)

the corner of the building unit just below the roof system made of light corrugated roof panels supported by timber beams. It can be clearly observed the beneficial effect of the timber frame that continued to support the roof system also when the upper part of the masonry was totally damaged. Similar observations can be done for the case reported in Fig. 20b although it can be clearly seen that the original structure was modified with the addition of reinforced concrete parts such as the balcony, the third floor and the presence of new openings.

4.2 Leaf tuff masonry constructions

Tuff masonry structures have been built since old times in countries located in the Mediterranean areas; they represent a significant part of the existing masonry building inventory of Central-Southern Italy, including historical architecture (Marcari et al. 2007). The majority of the masonry buildings in the area hit by the 21st August 2017 Ischia earthquake are of this typology. Partial collapses were frequently observed in vulnerable rural and unreinforced tuff masonry buildings.

Figure 21 shows the case of an undamaged leaf tuff masonry construction. It can be clearly seen the presence of iron tie rods in the upper part of the wall that are installed in to keep them from succumbing to lateral forces. Similar seismic performances were observed in other constructions with iron tie rods. Accordingly, it can be inferred that the presence of tie rods in leaf tuff masonry constructions can be a good seismic retrofitting technique provided that tuff units are dressed and a transverse connection between leaves is provided by headers.

Figure 22 shows the case of extensive damage of leaf tuff masonry constructions. In particular, it can be seen the typical in-plane storey shear mechanism that is recognizable by the presence of diagonal cracks appearing between the openings. The shear mechanism is probably due to the poor quality of masonry and the high percentage of openings. It is important to notice that in many cases the high percentage of openings is due to recent modifications of the original structural system. Moreover, the presence of overhang elements such as balconies (e.g., Fig. 22c, d) was a vulnerability factor.

Fig. 21 Undamaged leaf tuff masonry construction with iron tie rods-via provinciale Lacco Fango (Lat: 40.7462–Lon: 13.8899)



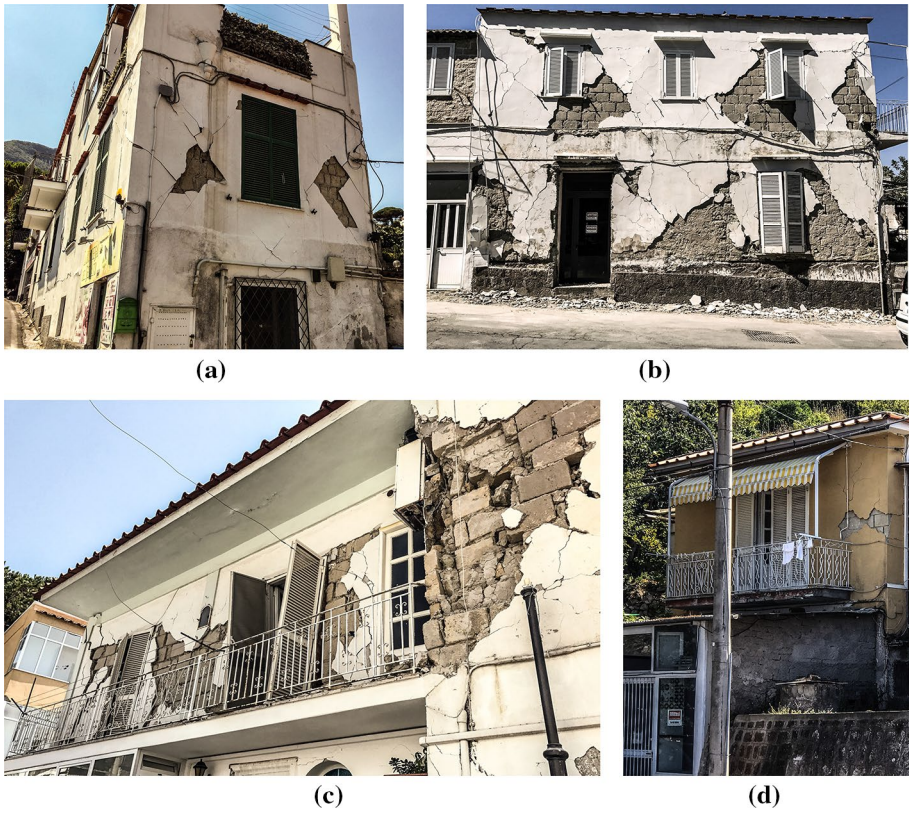


Fig. 22 In-plane storey shear mechanism of leaf tuff masonry constructions: **a** via Principessa Margherita (Lat: 40.7452–Lon: 13.9068); **b** near piazza Maio (Lat: 40.7423–Lon: 13.902); **c** near piazza Maio (Lat: 40.7436–Lon: 13.8976); **d** via Montecito (Lat: 40.7412–Lon: 13.8968)

Fig. 23 Failure of the outer wythe of wall: via Epomeo (Lat: 40.742–Lon: 13.9006)





Fig. 24 Damage at building corners: **a** via Montecito (Lat: 40.742–Lon: 13.8995); **b** viale Ottringolo (Lat: 40.7428–Lon: 13.9023); **c** via D’Aloisio (Lat: 40.7434–Lon: 13.8976); **d** via Montecito (Lat: 40.7419–Lon: 13.8995)

Figure 23 reports the out-of-plane failure of the outer wythe of a leaf tuff masonry wall at the first level around one small opening due to lack of connection between blocks and between outer and inner wythes of walls. The two-storey structure is made of tuff masonry with the top level realized in a subsequent time (the different masonry adopted is well visible in the Figure). It can be observed that masonry at the upper level is made of dressed units and did not suffer disintegration.

Figure 24 depicts the case of damage at building corners in the upper part. It is characterized by the formation of a masonry wedge, mainly due to inertial forces (Casapulla et al. 2018). Moreover, in Fig. 24a, it is possible to observe that the damage is induced

by the thrust of roof elements. In Fig. 24c, the formation of a masonry wedge involved rocking-sliding motions along the cracks on the interlocked orthogonal walls.

The damage of the corners can be explained by the presence of openings near the corners and lack of connection between orthogonal walls, highlighting the incompatibility of deformations of the walls in two orthogonal directions of loading. The mechanism characterized by the overturning of the corner around a horizontal hinge occurred only when that corner of the building was free, without any adjacent structures, hence, for buildings isolated or positioned at the end of a block. In some cases it can be clearly seen the poor quality of masonry (Fig. 24a, b, d). Also in the case of a light roof system, it can be observed a damage at building corners although in the case of low quality of the masonry (Fig. 24a).

Figure 25 reports the case of the collapse of leaf tuff masonry construction or a portion of construction. In particular, Fig. 25a depicts the collapse of a portion of a two-storey building that was characterized by an irregular L shaped footprint leading to torsional effects. In the part that remained standing, the typical in-plane storey shear mechanism is well visible. The collapse was probably induced by the poor quality of masonry and

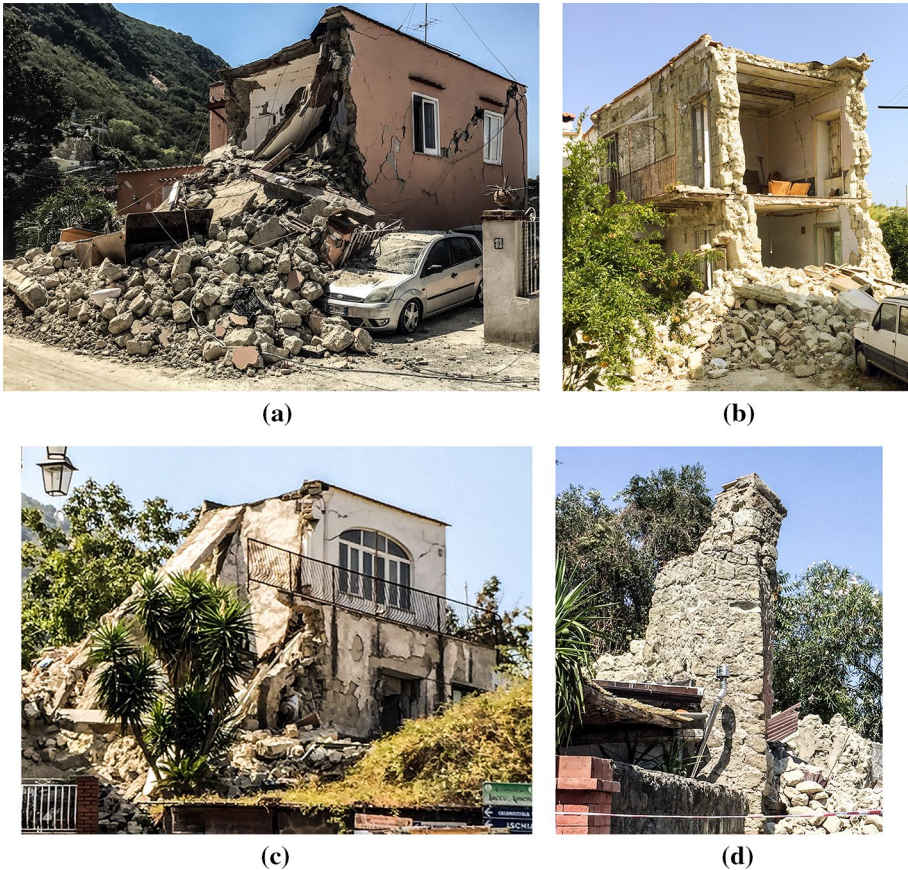


Fig. 25 Collapse of leaf tuff masonry construction: **a** via Montecito (Lat: 40.7419–Lon: 13.8995); **b** via Montecito (Lat: 40.7425–Lon: 13.8893); **c** via Borbonica (Lat: 40.7435–Lon: 13.8882); **d** piazza Maio (Lat: 40.7425–Lon: 13.9011)

the presence of RC roof and RC stringcourse. The floors badly connected with the walls didn't block the out-of-plane mechanism generating the final collapse of the portion of the building. Figure 25b shows the collapse of a portion of a two-storey building with composite steel-concrete floors. It can be clearly seen that the first floor breaks the vertical continuity of the wall (the steel beam is continuous from the balcony to the opposite wall). Similarly, Fig. 25c, d show the collapse of a portion of two-storey buildings. Also in these cases, the collapse is due to the floors badly connected with the walls and poor quality of masonry. It should be noticed that the examples of collapsed buildings reported herein are representative of low-quality buildings with non-seismic designed structures if not even non-designed.

Finally, Fig. 26a shows the damage occurred to the “*Chiesa di santa Maria dei Suffragi*”, which was assigned to a D4 damage level. It is possible to notice the shear mechanism on the lateral wall, the partial roof collapse and the extensive damage of the upper part of the bell tower. In particular, the damage mechanism in the upper part of the bell tower is a horizontal sliding failure due to local reduction of the masonry section inducing a local discontinuity. A similar mechanism was also observed in the masonry chimney pot where breaking at the roofline was observed (Fig. 26b). It should be highlighted that, although slight seismic activity can cause masonry chimney damage, it remains one of the most commonly ignored items during earthquake-preparedness efforts.

4.3 Cellublok constructions

A common type of construction in Ischia Island is the hollow cement bricks technology, sometimes called *Cellublok*. Concrete hollow blocks are usually made from cast concrete (e.g. Portland cement and aggregates, usually sand and fine gravel, for high-density blocks). The typical *Cellublok* construction is formed by a concrete foundation and

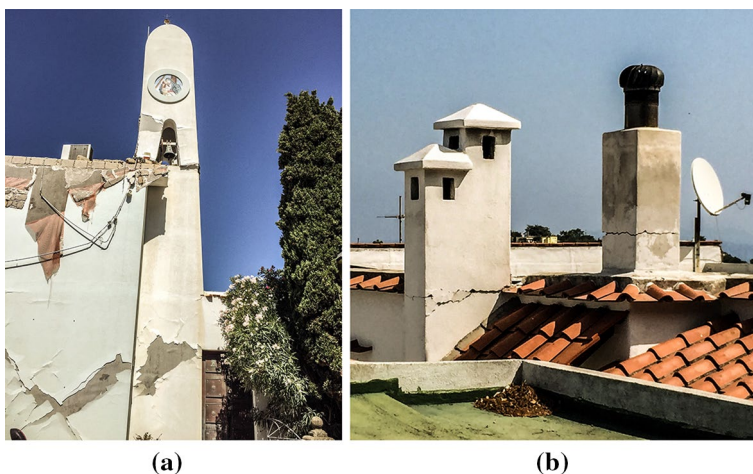


Fig. 26 Damage of: **a** the bell tower of the “*Chiesa di santa Maria dei Suffragi*” via provinciale Lacco Fango (Lat: 40.7458–Lon: 13.8903); **b** masonry chimney pot-via Montecito (Lat: 40.7413–Lon: 13.8964)

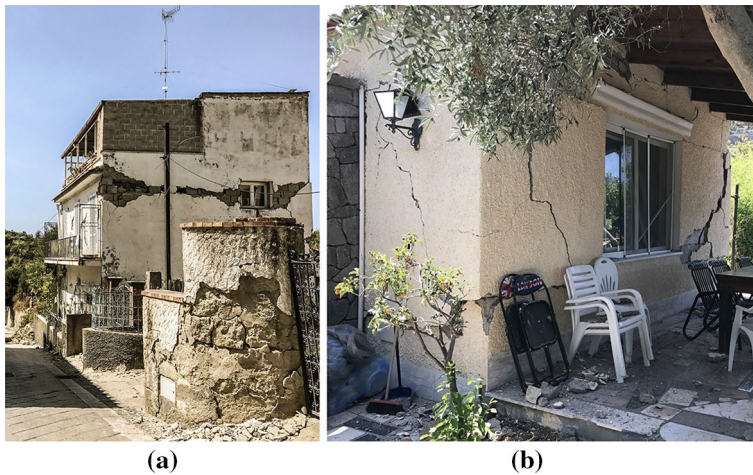


Fig. 27 Damage of a Cellublok constructions: **a** three storeys building-via D'Aloisio (Lat: 40.7434–Lon: 13.8978); **b** single storey building near via Montecito (Lat: 40.7415–Lon: 13.8947)

hollow concrete slab with a concrete block wall on the perimeter. It is very common to have no reinforcement nor cast-in-situ concrete within the hollow parts. Figure 27 shows the damage on two buildings of *Cellublok* construction-type of three storeys (Fig. 27a) and single storey (Fig. 27b), respectively. Figure 27a depicts a typical horizontal sliding failure probably due to the high percentage of openings and to a poor quality of mortar with no reinforcement. The shear cracking in the wall reported in Fig. 27b shows the low quality of the mortar, highlighting the incompatibility of deformations among the different blocks.

4.4 Dry stone masonry retaining walls

During the survey, collapse phenomena of dry stone masonry cantilever retaining walls were observed in the investigated area. This structural typology made of stones without any mortar to bind them together is quite diffused on Ischia Island for retaining walls. Built by skilled masons, dry stone walls rely on careful selection and positioning of stones for their integrity. Figure 28 shows four different examples of collapses of dry stone masonry walls used for retaining walls. Due to the absence of mortar, the collapse (i.e., partial wall overturning) occurred in the out-of-plane direction due to the low moment capacity of the wall generated by the negligible tensile strength. In all the observed collapses, the masonry was found disrupted after the collapse. In many cases, the debris leads to the blockage of some street sections (Fig. 28) creating problems for the emergency services and disaster recovery responses. On the other hand, reinforced concrete retaining walls exhibited a good seismic response without damage observed.

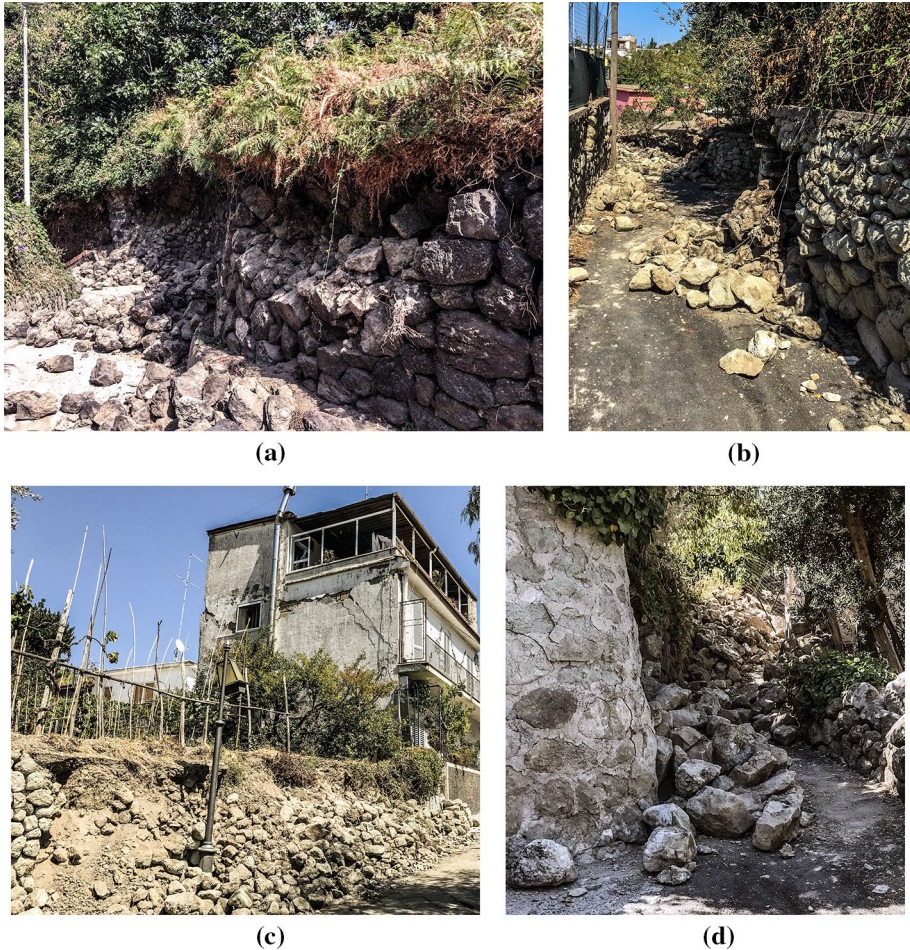


Fig. 28 Collapse phenomena of dry stone masonry retaining walls: **a** via Paradisiello (Lat: 40.7465–Lon: 13.908); **b** near via D’Aloisio (Lat: 40.7428–Lon: 13.8956); **c** near corso Garibaldi (Lat: 40.7435–Lon: 13.8974); **d** via Iasolino (Lat: 40.7417–Lon: 13.8949)

5 Conclusions

The August 21st, 2017, Ischia earthquake was a shallow (1.7 km), low energy (M_L 3.6; M_W 3.9; M_d 4.0) event, of volcanic origin. It was centered in a high population density area and was very damaging in a very small area with approximately 400 m radius. The only recording instrument on the island (IOCA seismic station) was 600 m from the epicenter, and recorded a maximum horizontal PGA equal to 0.29 g, corresponding to a return period equal to 860 years, when compared with the elastic spectrum derived according to the Italian code hazard estimation (MIT 2008). However, looking at historical data, it can be roughly estimated a return period of 176 years for events with a magnitude $M_d \geq 4$ indicating that this type of seismic event is common in Casammicciola. Field observations in the area around the recording instrument showed considerably less damage with respect to the epicentral area indicating a rapid attenuation of the seismic action.

Using the data from cadastral information and from the photographic survey, a tentative identification of the most common structural types damaged in the small area hit by the earthquake was carried out and a possible identification of the damage mechanisms and vulnerability factors given. Buildings are mainly one and two storeys masonry ones, built between about 1890 and 1990. Casamicciola Terme was, in fact, destroyed by the 1883 earthquake. Masonry can be classified into three types: so-called *case baraccate alla Benevanta*; tuff masonry; hollow cement bricks called *Cellublok*. The main damage observed is in-plane storey shear mechanism, failure of the outer wythe of wall, building corners in the upper part. The epicentral area buildings sustained heavy damage and collapses. Damage was obviously lighter moving away from the epicenter, but there was such a strong correlation with epicentral distance that even a few hundreds of meters increase made the difference between strongly and weakly damaged areas. It must be emphasized that topographic amplification played a role: the epicenter happened to be at the top of a hill at 110 m above sea level, where Maio Square is located. No damage to reinforced concrete buildings was found. It can also be pointed out that large damage was typically observed in low-quality buildings with non-seismic designed structures or even non-designed. Additionally, large damage (i.e., partial wall overturning) to dry stone masonry retaining walls were largely observed; this is probably due to the absence of mortar in the wall.

The event sadly confirmed that in Italy major earthquake return periods are higher than the human memory: older buildings (*case baraccate*) performed better with respect to more recent buildings, raised up without seismic details provisions. This advocates for compulsory and closely monitored building regulations, with special reference to modern, capacity design-based ones, that, through ductility and implicit safety margins, minimize damage also under very adverse scenarios, as was the case for the 2017 Ischia earthquake (code-based return period higher than 860 years, although in a very limited area).

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