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Seismic risk mitigation at Ischia island (Naples, Southern Italy): An innovative approach to mitigate catastrophic scenarios

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ABSTRACT

Ischia island, in the province of Naples, is a densely populated volcanic island, in which small to moderate magnitude earthquakes occur. Due to the very shallow depth of such events (< 2 km), they can generate serious damage and casualties, up to the complete destruction of urban centers located within short epicentral distance. Almost all of the earthquakes at Ischia island occur at shallow depth, beneath the Northern slopes of the Mt. Epomeo horst, which is located very close to the town of Casamicciola. In fact, Casamicciola was completely destroyed by the 1883 earthquake (2313 victims) and experienced intensities up to XI degree on the Mercalli scale. Historical records show that the background seismicity here is almost absent, but larger earthquakes tend to occur in clusters, lasting some decades and with intervals between consecutive events on the order of years to decades. The clustering in time and the very shallow hypocentres, which cause, with respect to tectonic earthquakes of similar magnitude, larger effects though limited to a relatively small area, make the seismicity in this island very peculiar. Despite such destructive record, till now official hazard maps strongly underestimated the seismic hazard in this area. On August 21st 2017, a very shallow earthquake with rather small magnitude struck the area of Casamicciola, killing two people, injuring many more and causing huge damage and partial to total collapse of edifices located just above the earthquake fault.

The maximum acceleration recorded for this earthquake exceeded by more than a factor of two the reference acceleration that should be sustained by edifices, according to official hazard maps. We propose here a complete procedure to assess and mitigate the risk, which can be rapid and economically affordable and, at the same time, can avoid further grief due to possible occurrence of other destructive earthquakes within a short time interval. We describe the most likely building collapse and casualty scenarios, in case that low-to-moderate magnitude earthquakes would occur before the edifices would be appropriately reinforced and secured. Our scenarios demonstrate the urgent need for securing operations. The proposed procedures for assessing seismic hazard and for securing urban areas provide an example that is potentially applicable to the whole Italian peninsula. They may allow in fact the mitigation of the destructive impact of a large number of earthquakes, which in Italy are often characterized by low or moderate magnitudes.

1. Introduction

Seismic risk is very high in Italy. This is due not only to the severity of earthquake magnitudes (Guidoboni et al., 2018), but mainly to the fact that seismic areas are densely populated and rich in masonry edifices, that are often of high historical and architectural value. Several destructive earthquakes have occurred in Italy in the last half-century, with ground accelerations recorded by modern instruments, starting from the 1976 Friuli earthquake (Briole et al., 1986; De Natale et al., 1987). The problem of protecting ancient towns and population from earthquakes, which often produce casualties and destruction even for low-to-moderate magnitude earthquakes, is significant and still unsolved.

Because of the absence of extremely severe earthquakes (magnitudes larger than 7.5 are not reported in historical records), seismic risk mitigation in Italy could be made very effective by retrofitting edifices and making them resistant to the maximum seismic loads, using for instance the concept of maximum credible earthquake (e.g. Panza et al., 2012; Rugarli et al., 2019a). Two problems make it difficult, however, to accomplish this goal in the short term. The first one is the high cost required to secure all the edifices situated in seismic areas. The second one is that, although the hazard maps for the Italian territory are based on a quite accurate and very long (more than 1000 years) historical information, most of the moderate to large earthquakes occurred during

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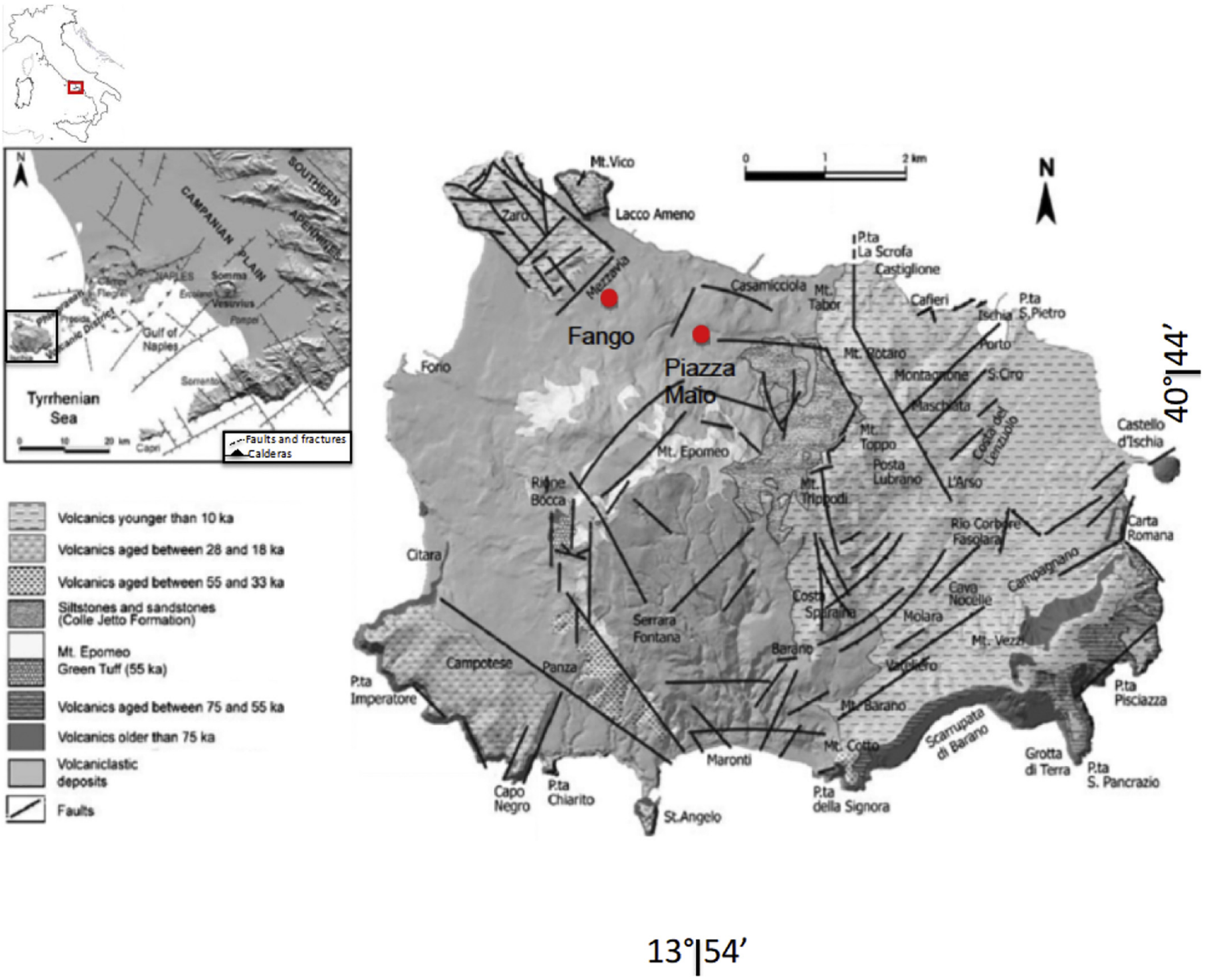


Fig. 1. Volcanological and structural map of Ischia island. In the upper left inset, the tectonic map of Campania Region is schematically shown (modified after Orsi et al., 1996 and de Vita et al., 2010).

the last decades caused seismic accelerations significantly larger than those expected according to the current seismic regulations (for a recent up-to-date analysis of the main causes of this severe drawback see Rugarli et al., 2019a).

In addition to L'Aquila 2009, Emilia 2012 events and the Central Italy seismic crisis that started in 2016 (De Natale et al., 2011; Tramelli et al., 2014; Panza and Peresan, 2016; Cheloni et al., 2017; Rugarli et al., 2019a), a striking example of such problems, reproduced on a smaller scale, is represented by the Ischia island (Fig. 1).

On this island, an earthquake occurred on August 21st, 2017 with magnitude Md = 4.0 (Fig. 2). Its location was changed three times by INGV, before the definitive location on-land, just beneath the town of Casamicciola, was officially released after 4 days from the event (INGV, 2017). Such a delay, with repeated problems in standard location procedures by a local network, was a further indication that seismic hazard in this area has been likely understated, despite several destructive earthquakes occurred in the past. This low magnitude earthquake claimed 2 victims, produced 42 injured, and required the evacuation of 2336 individuals (INGV, 2017). The earthquake was very shallow (with a focal depth of about 2 km) and the earthquake-induced accelerations were locally very strong, though the affected area was very small (about 2 km^2). The historical seismicity of the island (Alessio et al., 1996; Cubellis and Luongo, 1998; Cubellis et al., 2004; Luongo et al., 2006) is concentrated in the same area affected by the August 21st earthquake (the upper part of the town of Casamicciola Terme, see Table 1). The evident underestimation of ground shaking level in the official hazard map makes Ischia an ideal laboratory to deal, at a small scale, with the same problems that represent the national scale issue about seismic risk (Rapolla et al., 2009; Rugarli et al., 2019a).

In this paper we review the main features of Ischia island seismicity and analyze the major problems enlightened by the August 21st earthquake. We further propose a solution capable to address and solve the two significant issues evidenced by this earthquake, which are somewhat representative of the Italian situation: defining reliable seismic hazard maps and securing the urban centers.

2. Seismicity of Ischia island

The Ischia island has been struck several times in the past by moderate-to-strong destructive earthquakes that affected a very limited area, which, in the limits of our knowledge of most historical sources, appears to be roughly always the same. Table 1 reports the historical seismicity in the area: with few exceptions pertaining to the eastern sector of the island, seismicity appears almost totally concentrated in

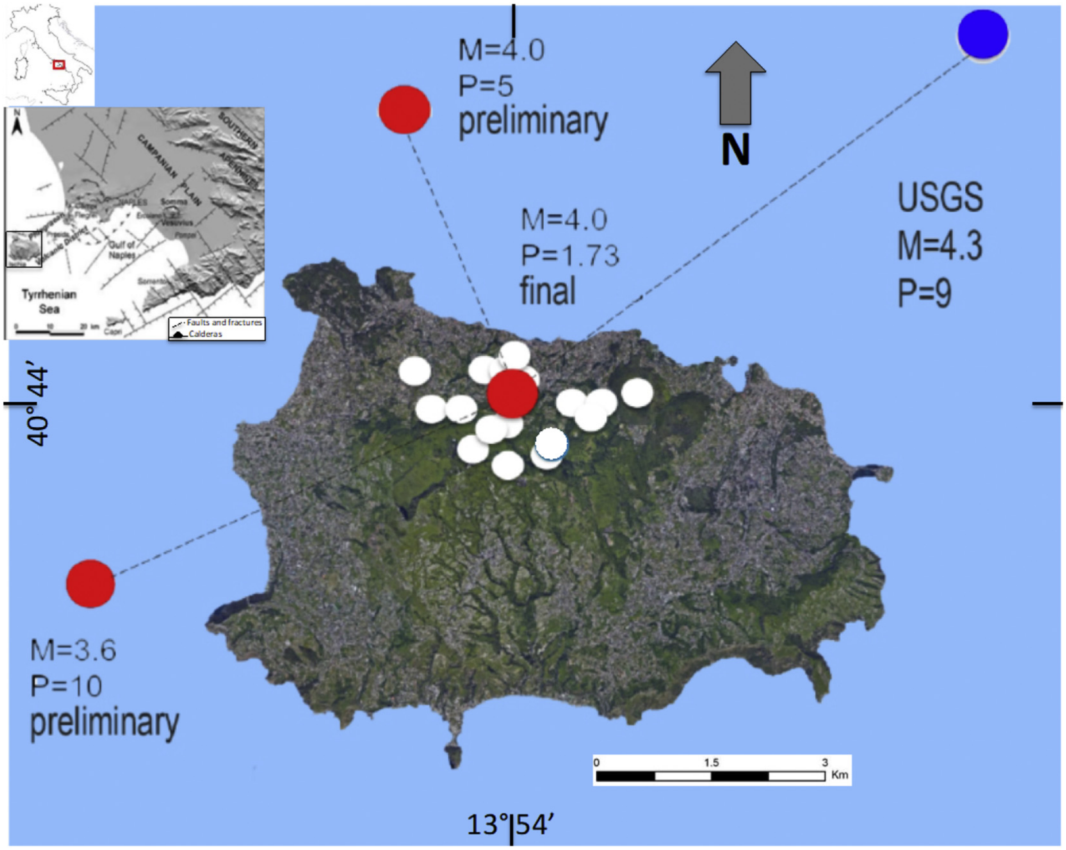


Fig. 2. Recent seismicity at Ischia island since 1993 (M > 1.0). The large red circles represent the locations of the August 21st, 2017 earthquake given by INGV (the position was changed 3 times). The true location, made official 4 days after, is the red circle inland. The final depth and magnitude reported are 1.7 km and Md = 4.0, respectively. The location in blue is the solution given by USGS, which assigned the event a depth of 9 km and magnitude of M = 4.3. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

List of the largest historical earthquakes occurred at Ischia island (modified after Luongo et al., 2006. The intensity values are taken from several sources, the main ones are: Mercalli, 1884; Baratta, 1901; Cubellis and Luongo, 1998; Rovida et al., 2016).

Year	Location	I_{MAX} (MCS)
1275	Casamicciola	IX–**X**
1302	Eastern part of island	VIII
1557	Campagnano	VII–**VIII**
1762	Casamicciola	VII
1767	Eastern part of island	VII–**VIII**
1769	Casamicciola	VIII
1828	Casamicciola	VIII–**IX**
1841	Casamicciola	VII
1863	Casamicciola	VII
1867	Casamicciola	VI–**VII**
1881	Casamicciola	IX
1883	Casamicciola	XI

The year of the first earthquake in the catalogue (originally 1228) has been recently re-evaluated as 1275 (Rovida et al., 2016). The different values of maximum intensity reported for some earthquakes reflect the different estimates reported by different sources. In such cases, to be conservative and consistent with the concept of Maximum Credible Earthquake (MCE) (Rugarli et al., 2019a), we consider the upper intensity bound, shown in bold.

the Casamicciola town area.

Such a seismicity, from previous hypotheses and mainly based on the 1883 earthquake studies (i.e. Alessio et al., 1996; Carlino et al., 2006; Luongo et al., 2006), definitively validated by the contemporary observations from the August 21st 2017 earthquake, appears to be caused by the differential movements of the Epomeo horst, which moves up and down in response to the activity of a magmatic reservoir located at a depth of about 3 km (Luongo et al., 2006; De Novellis et al., 2018; Sbrana et al., 2018). For some reasons, probably linked to the depth of the 'ductile' temperature limit (Luongo et al., 2006; De Novellis et al., 2018), the differential motion of the Epomeo horst (Molin et al., 2003; Carlino et al., 2006; Paoletti et al., 2013) causes seismicity only on the Northern and Northwestern faults, located just beneath the town of Casamicciola. Actually, at Ischia, the trachytic basement is retrieved at about 1 km of depth in the center of the island (Paoletti et al., 2009; Strollo et al., 2015).

Fig. 3 (from INGV, 2017) shows the likely geometry of the main fault causing the earthquakes in this area. The recently proposed model for the main fault, with a dip towards S-SW (De Novellis et al., 2018), is in contrast with the observed fault traces (Emergeo Working Group, 2017; Nappi et al., 2018) that clearly indicate normal faulting dipping N-NE.

In view of the recent observations after the 21st August 2017 Md = 4.0 earthquake, the highly destructive character of the Casamicciola earthquakes can be ascribed essentially to the very shallow depth of the source (< 2 km): considerable accelerations are in fact generated even by events of moderate and small magnitudes. The magnitude estimated by 'fast' methods, like coda duration, may be largely uncertain, even when a well calibrated magnitude-duration curve based on previous earthquakes is available. Actually, in this area there are no instrumental records of previous earthquakes of magnitude larger than 2.5; therefore a magnitude-duration curve calibrated for magnitudes higher than M = 2.5 could not exist. The proposed magnitude Md = 4.0 can be merely indicative, as it was not specified how it could be computed without having a suitable magnitude-duration relation defined at Ischia seismic stations. In fact, for this recent

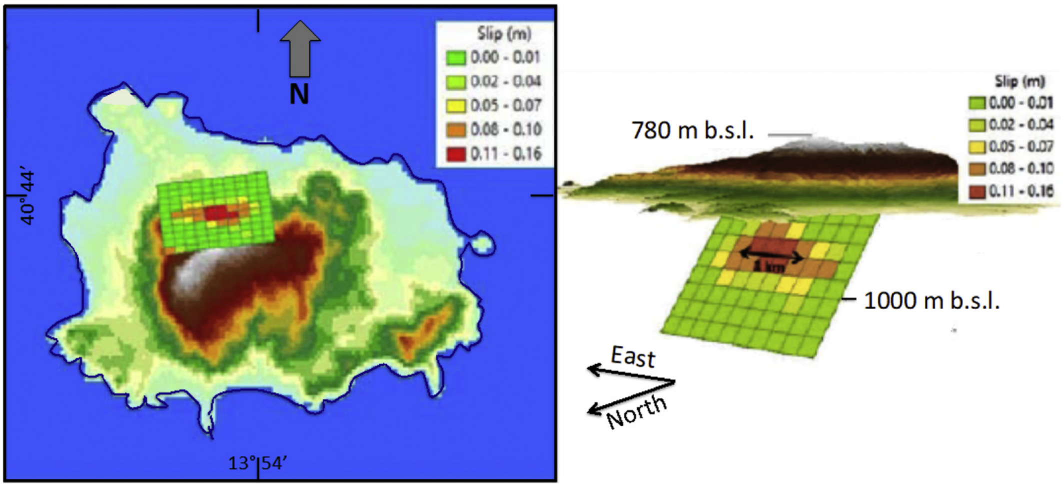


Fig. 3. Reconstruction of a variable slip fault model for the August 21st, 2017 earthquake (INGV, 2017).

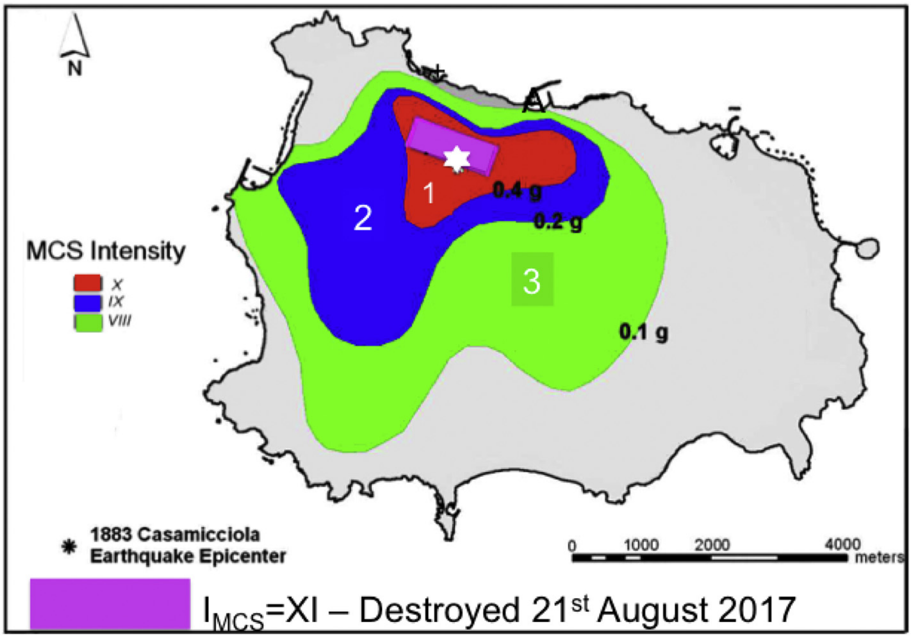


Fig. 4. Isoseismal map (Intensity MCS) for the 1883 event (modified after Luongo et al., 2006). The area 1, in red, is bounded by the intensity X; the area 2, in blue, by the intensity IX; the area 3, in green, by the intensity VIII. Also shown are the levels of ground accelerations deduced for each intensity degree by the empirical relation proposed by Medvedev and Sponheuer (1969). The violet rectangle approximately indicates the zone where the intensity XI was experienced in 1883; it is the same area that had been strongly damaged by the August 21st, 2017 earthquake. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

earthquake the magnitude estimates are quite variable, ranging from Ml = 3.6 (quoted in the preliminary INGV communication), to Mw = 3.9, Md = 4.0 (INGV, 2017) and Mb = 4.3 (USGS). A magnitude as large as 4.4 has been estimated from the geodetic seismic moment and is required to explain the InSAR ground deformation data on the fault (INGV, 2017; De Novellis et al., 2018). Hence, besides the uncertainty in the given magnitude range (3.6–4.4), which exceeds the standard error (σ) affecting magnitudes at global scale (e.g. Båth, 1973), the magnitude of the event was modest. Anyway, the earthquake was very damaging, though in a very limited area. The 2017 earthquake claimed two victims, whereas the one in 1883 caused 2313 casualties and the complete destruction of the town of Casamicciola. Fig. 4 reports the reconstruction of macroseismic intensities associated with the 1883 earthquake (Luongo et al., 2006), where the violet area represents the zone where intensities up to XI (MCS) were reported in 1883, and considerable building collapse was observed after the 2017 earthquake.

Fig. 5 shows the ground accelerations recorded at the Casamicciola observatory (INGV station IOCA, equipped with a velocimeter and an accelerometer). The peak accelerations recorded at Casamicciola were 0.29 g (horizontal) and 0.22 g (vertical), respectively. We can compare the intensity map of Fig. 4 and the recorded peak ground acceleration,

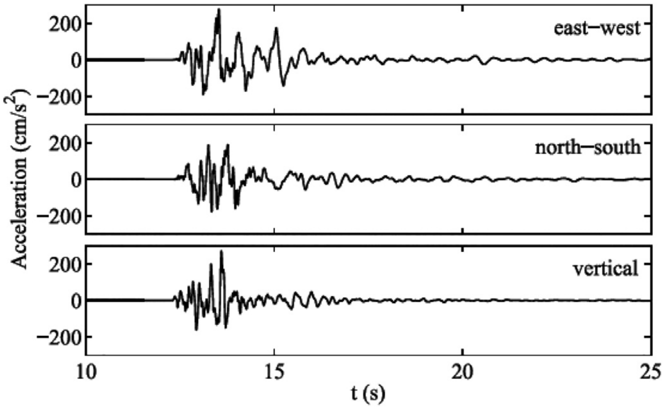


Fig. 5. Ground acceleration waveforms recorded by the accelerometer installed at the Osservatorio Geofisico in the town of Casamicciola (about 1 km from the epicentre). The maximum horizontal acceleration recorded was 0.29 g and maximum vertical acceleration exceeded 0.2 g.

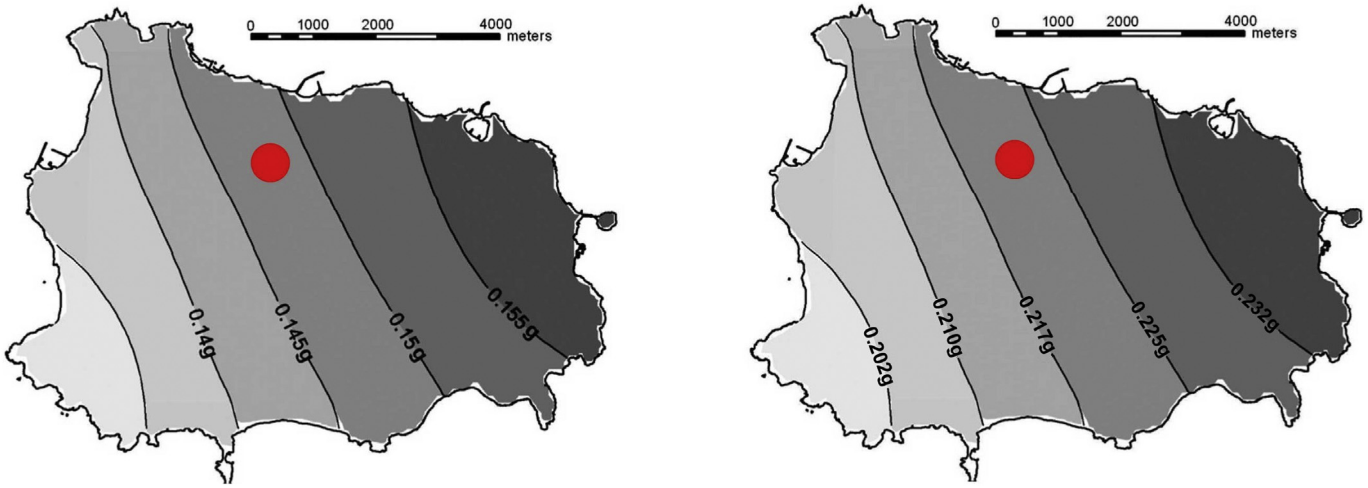


Fig. 6. Peak horizontal accelerations estimated by PSHA at Ischia island (Rapolla et al., 2010). Left: PGA on bedrock. Right: PGA for soil class C, which corresponds to the maximum amplification factor of 1.5. For the site of the accelerometer station IOCA (marked by the red circle), the regulation prescribed soil class B with a maximum amplification factor of 1.2 (Verderame et al., 2017). Only very recently, and well after the occurrence of the 2017 earthquake, the soil class at IOCA has been changed to C. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Detailed list of damaged buildings (or rooms) in various municipalities after the 1883 Casamicciola earthquake (data from Baratta, 1901, extracted from Mercalli (1884) and modified by Guidoboni et al., 2007).

	Casamicciola	Lacco Ameno	Forio	Barano	Serrara Fontana	Total
Houses	672	389	2713 (ROOMS)	1693 (ROOMS)	1159 (ROOMS)	
Collapsed	537 (79.9%)	269 (69%)	1344 (49.5%)	63 (3.7%)	65 (5.5%)	
Damaged	134 (19.9%)	102 (26%)	977 (36%)	1430 (84.4%)	973 (83.9%)	
Undamaged	1 (0.2%)	18 (5%)	392 (14.5%)	200 (11.8%)	121 (10.4%)	
Residents	4300	1800	6800	4600	2000	
Deads	1784	146	345	10	28	2313
Injured	448	93	190	10	21	762

With the exception of Casamicciola and Lacco Ameno, for the other municipalities the table reports the damaged rooms of buildings, and the relative percentages of given damage.

with the official seismic hazard map for the area, reported in Fig. 6. We note, in agreement with Rapolla et al. (2010), that in the official hazard map the estimated horizontal accelerations progressively decrease from East to West, because the seismic hazard in the island is estimated considering only earthquakes occurring in mainland Italy. Moreover, the PGA value estimated by PSHA (for 475 years "return period", i.e. with 10% probability of being exceeded in 50 years) in the area of Casamicciola has the value $0.14\,g < PGA < 0.15\,g$. The site of the station IOCA was assigned, until well after the occurrence of the 2017 earthquake, a soil class B, which corresponds to an amplification factor 1.2 (Verderame et al., 2017). Accordingly, the resulting value of PGA is 0.18 g, so that the observed horizontal peak acceleration is about 60% higher than that forecasted by the hazard map. The maximum vertical acceleration exceeded 0.20 g, more than twice the PSHA estimated value of 0.09 g. Some months after the August 2017 earthquake, for reasons unknown to us, the soil class at IOCA station was changed to C, which implies an amplification factor of 1.5. With the new soil class, the discrepancy between the observed and the forecasted acceleration is less pronounced (from 60% to 30% higher). Still we should recall that the 2017 earthquake is not the strongest earthquake occurred in the area. It was substantially smaller than the largest historical event, occurred in 1883, and also smaller than the 1881 and 1828 earthquakes.

The evident inadequacy of the PSHA seismic hazard map for Ischia poses even larger problems in view of the historical observation that destructive earthquakes on the island have often occurred in clusters, within time intervals of years and decades. The most recent cluster before 2017, started in 1828 (29 casualties), with a moderate size earthquake (slightly larger than the 2017 earthquake), and continued with 5 more events of maximum intensity equal to or larger than I (MCS) = VII. The last two earthquakes occurred in 1881 and 1883 and caused 127 and 2313 casualties, respectively. The 1883 earthquake destroyed completely the town of Casamicciola.

3. Damage scenarios for future earthquakes

The estimation of the casualties due to an earthquake involves an accurate knowledge of the edifice strength, mainly of the masonry ones, which are the most vulnerable (with respect to reinforced concrete). For historical Italian earthquakes, we have generally a very accurate count of victims, but only occasionally a detailed description of damages (i.e. Esposito et al., 1995). In particular, casualties are known to be strongly related to the partial or total collapse of the edifices. This information, however, is almost totally unknown for earthquakes occurred before 1950. For the past destructive earthquakes at Ischia island, we have generally no knowledge of the damage distribution, but only of the number of victims. This is true for all the earthquakes but the 1883, whose damage distribution had been carefully reconstructed by Mercalli (1884; Table 2).

The number of earthquake casualties per year in Italy decreased, in the second half of the 20th century (1951–2000), by an order of magnitude with respect to the first 50 years (1900–1950): 87 with respect to 1204. Such a significant decrease is largely due to the occurrence of lower magnitude earthquakes in the last period, as compared to the first one. However, an important role was also played by the improvements in the building technologies (in addition to the improvements in the rescue efficiency). Actually, based on the statistical analysis of observations from Italian earthquakes, for recent earthquakes the mortality amounts to about 30% of people living in totally collapsed edifices (Lucantoni et al., 2001).

Regarding the 1883 earthquake, we report in Table 2 the total number of buildings and the damages details, in each municipality. From this table, we note that, in the Casamicciola area, the collapse of 537 building produced 1784 victims. We should note that, in Table 2, edifices reported as 'collapsed' include both 'total collapse' and 'partial collapse': the data collected at the time do not allow to discriminate between the two categories. We can however reasonably presume that, in the areas of higher intensity (i.e. Casamicciola and part of Lacco Ameno), the fraction of total collapses has been significantly larger than in the other areas. From the number of residents at that time (about 4300), and the total number of edifices (672) we estimate an average occupancy of 6.4 people per edifice. Using the recent earthquakes mortality statistics, the number of victims today would have been $N = 537 \times 6.4 \times 0.3 = 1031$. This number is substantially lower than the number of victims really occurred in 1883, i.e. 1784.

At present, the number of residents is about double (8250), but we could reasonably assume that most of the edifices built after 1961 (until that year, the population of Casamicciola was of about 4000–4300 people) are much more resistant and, therefore, give a negligible contribution to collapses and hence victims. We will further substantiate later this statement, on technical grounds. Making such assumption, however, and extending the same reduction factor found for Casamicciola to the whole amount of victims claimed by the 1883 earthquake, we could estimate that 1336 victims would be claimed today by an earthquake like the 1883 one.

Using the reduction factor found for Casamicciola might not appear rigorously justified, however, because in the areas farther from the maximum intensities the listed collapses, as already discussed, should be mostly taken as 'partial collapses'. Anyway we can demonstrate this reduction works well, by computing in a more detailed way the casualty estimates out of Casamicciola and Lacco Ameno. We can in fact approximately discriminate, in an indirect way, the percentage of 'people involved in total collapses' in each municipality. To this aim, we make the assumption (which is realistic in the area of maximum intensity) that all the collapses reported at Casamicciola were 'total collapses'. With such an assumption, and with the average occupation per edifice already computed, we note that in 1883 the percentage of casualties compared to the people resident in completely collapsed edifices was about 51%.

If we assume this mortality factor applies equally to all the total collapsed edifices, we can use the relation: C (casualties) = Rc (residents in totally collapsed edifices) x 0.51 to estimate, from the casualties reported in each municipality, the number of residents, Rc, in total collapsed edifices. We can then estimate the number of casualties for an earthquake like the 1883 occurring today, simply multiplying the number Rc computed in the whole island by the factor 0.3 (30%), which represents the mortality index for recent earthquakes (Lucantoni et al., 2001). The total number of forecasted casualties then turns out to be 1341, i.e. approximately the same quantity computed before. We can then compute, based on the ratio between the number of casualties forecasted today and the number observed in 1883, the reduction factor likely due to improved structural features of edifices today (including the structural modifications, i.e. substitution of wooden roofs, to the ancient ones). Using the same reduction coefficient computed for the 1883 event, we can equally estimate the approximate number of victims we would expect if earthquakes like the 1881 or the 1828 ones would occur today: 73 and 16, respectively.

We are confident this method is simple but reliable, because it is based upon a simple analogy and does not need to take into account all the structural features of new buildings. It gives, for the victims of an earthquake comparable with the strongest ones of the past, but occurring today, the results shown in Table 3.

Table 3
Estimates of the likely number of victims for different types of earthquake scenarios, as obtained by the simplified method explained in the text.

Earthquake	Victims
Type 1883	1340
Type 1881	73
Type 1828	16

Another way, somewhat more complex and depending on specific (somewhat arbitrary) assumptions, to estimate the likely number of victims in a future earthquake, is to use the DPM (Damage Probability Matrix) (Zuccaro and Cacace, 2009). In order to apply this method, we use the international classification of buildings in EMS-98 intensity scale (Grünthal, 1998), reported in Table 4. These classes of edifices are the ones defined in order to relate different EMS-98 intensity values to damage scenarios, as reported in Table 5. In the original definition of the EMS-98 intensity scale, terms indicating the frequency of each damage degree are vague (i.e. few, most, etc.). However, they have been tentatively associated to quantitative probabilities by some authors (e.g. Giovinazzi and Lagomarsino, 2004).

We may tentatively consider, for a first estimate, only the most exposed zone between Piazza Maio in Casamicciola and Fango in Lacco Ameno (see Fig. 1). This area has been the most heavily damaged (and hence closed to people) also as a consequence of the 2017 earthquake, and it is the area where the seismogenic fault is located (Nappi et al., 2018).

Here, presently we can estimate the following vulnerability distribution for the edifices: n. 100 class A, 230 class B and 350 class C buildings. By the DMP matrix, we got the number of total or partial collapsed edifices as in Table 6 and Table 7, respectively.

Ascribing victims only to the total collapse, hypothesizing an average occupation factor of 6.4 people per edifice as in 1883 and a mortality index of 30% of people involved in total collapses, we get a total of 178 victims in such a limited, highly exposed area. Considering that, in 1883, the number of total victims was about double with respect to the number of victims in this highly exposed area, we can estimate in about 356 the total number of victims, for a future earthquake like the 1883 one. Table 8 reports the estimated numbers of victims, computed by the DMP matrix approach, for any scenario based on the strongest earthquakes of the XIX Century. It is noteworthy that such a low number is likely underestimated. In fact, the Zuccaro and Cacace (2009) DMP matrix implies that an intensity I(MCS) = XI causes the total collapse of 36.6% of class A edifices. Actually, even if all the edifices of Casamicciola in 1883 were of class A, the number of total collapses should have been $672 \times 0.366 = 245$, with respect to an observed number of 537 (more than double). The DMP matrix, in fact, does not work well in estimating the damages in a very small area ($< 1\ \mathrm{km}^2$), because this method has been developed analyzing the distribution of damage level over areas wide several tens of km^2. Then that value could be assumed as a lower bound estimate.

We can hence state that the most likely number of victims for a future earthquake like the 1883 would be in the range 356–1336, probably closer to the upper bound. Using the Zuccaro and Cacace (2009) DMP matrix approach to estimate the number of victims also for earthquakes like those of 1881 and 1828, we get, respectively, 82 and 32 victims. Although the number of victims for a 1883 type earthquake may appear strongly underestimated using the DMP approach, the estimated numbers of victims for 1881 and 1828 type earthquakes are larger than the number computed with the alternative procedure. This effect is partially explained by the fact that, in the case of smaller earthquakes like 1828 and 1881, the victims would be almost all

Table 4
Definition of vulnerability classes for edifices: combination of vertical and horizontal structural features (Grünthal, 1998).

Horizontal structures	Vertical structures			
	Poor masonry	Medium masonry	Good masonry	Reinforced concrete
Archway system or mix	A	A	A	
Wooden ceiling with or without chain	A	A	B	
Ceiling in I-beams with or without chains	B	B	C	
Ceiling in reinforced concrete	B	C	C	C
Reinforced buildings	C	D	D	D
Anti-seismic original buildings	D	D	D	D

Table 5
Definition of damage scenarios for different values of EMS-98 macroseismic intensities (Grünthal, 1998).

Damage intensity EMS98	0	1	2	3	4	5
	None	low	Medium	Serious	Very serious (partial collapse)	Total collapse
VII			Many B, few C	Many A, few B	Few A	
VIII			Many C, few D	Many B, few C	Many A, few B	Some A
IX			Many D, few E	Many C, few D	Many B, few C	Many A, few B
X			Many E, few F	Many D, few E	Many C, few D	Most A, many B, few C
XI			Many F	Many E, few F	Most of C, many D, few E	Almost all A, most B, many C, few D

Table 6
Building classes of totally collapsed houses in the past earthquakes.

Event	Intensity	Building class			Total
		A	B	C	
1883	XI	37	40	12	89
1881	X	20	7	0	27
1828	IX	8			8

Table 7
Building classes of partially collapsed houses in the past earthquakes.

Event	Intensity	Building class			Total
		A	B	C	
1883	XI	41	92	49	182
1881	X	37	36	10	82
1828	IX	26			26

Table 8
Estimates of the likely number of victims for different types of earthquake scenarios, based on the DMP matrix approach (Zuccaro and Cacace, 2009).

Earthquake	Intensity	Victims
Type 1883	XI	356
Type 1881	X	82
Type 1828	IX	32

concentrated in the most exposed zone (Piazza Maio-Fango). As a consequence, the multiplication by 2 required to consider victims of adjacent areas is not justified anymore.

It must be noted from these scenarios that, even simply abandoning the most exposed area (actually evacuated because severely damaged by the 2017 earthquake), can significantly decrease the total number of victims, mainly for less severe scenarios like the 1881 and 1828 ones.

4. Urgent planning for securing urban areas

Since the past seismicity shows the occurrence of clustered destructive events, the August 21st, 2017 earthquake makes it clear that two urgent steps should be undertaken: (1) securing the edifices (mostly masonry) in the urban areas most prone to experiencing large macroseismic intensities; and (2) re-elaborating a seismic hazard map for Ischia island, taking into account the maximum (spectral) accelerations that can be produced by local earthquakes and that should be used in the design of new buildings and possibly in the retrofitting of the existing ones.

The elaboration of a plan for securing edifices in the most hazardous areas is a priority in order to avoid collapses of large numbers of old, masonry edifices, in case of earthquakes stronger than the one of 21st August 2017. This is crucial in view of past experiences, which show that larger magnitude earthquakes tend to occur clustered in time, with periods of larger seismicity lasting several decades. Securing the present edifices is also crucial because Ischia is a renowned location for international tourism, and its population during the summer months may increase 10 times. In the following, therefore, we present a plan for securing the urban areas, in order for the edifices to resist to earthquakes like the 1883 one, which, to our knowledge, has been the maximum local earthquake recorded on the island. For such an earthquake, we do not have a precise estimation of the magnitude, but we have an accurate isoseismal map (Mercalli, 1884). Regarding its magnitude, we can make an inference based on the maximum intensity and on the estimated magnitude of the 21st August 2017 earthquake. Comparing the maximum intensity of the 2017 earthquake with the 1883 earthquake and assuming the magnitude $M = Md = 4.0$ for the recent event (actually, it was quoted as an Md), the magnitude of the 1883 event could be tentatively estimated to lie between $M = 5$ and $M = 6$ (or equivalently $M = 5.5 \pm 2\sigma$). Whereas refining the magnitude estimation for the 1883 earthquake would result useful for estimating possible ground accelerations and hence hazard maps for that event, an urgent plan for securing edifices in the most risky areas should rely on intensities only, because these already include the effects of source, travel paths, and site effects (Ambraseys, 1988). The procedure we propose is to take advantage from the well-established observations worldwide that relate masonry edifice types, seismic intensities, and structural damages. Table 4 reports the International classification of masonry edifices (Grünthal, 1998), whereas Table 5 shows the level of damage suffered by each class of edifices as a function of the intensity (Grünthal, 1998).

The intensities reported in Table 4 are in the IEMS-98 scale, because they are calibrated internationally with this scale, whereas in Italy it is much more common to use the MCS scale. Approximately, the following relations hold: I(MM) ~ (5/6) I(MCS) and I(MM) ~ I(MSK) ~ I(EMS-92), where I(EMS-92) is the intensity scale defined by the European Seismological Commission in 1992, I(MM) is the modified Mercalli scale, and I(MSK) is the Medvedev, Sponheuer, Karnik scale (Decanini et al., 1995; Dolce et al., 2005). However, given the approximations implicit in our methodology, slight differences in the intensity scales are not relevant in this first approximation.

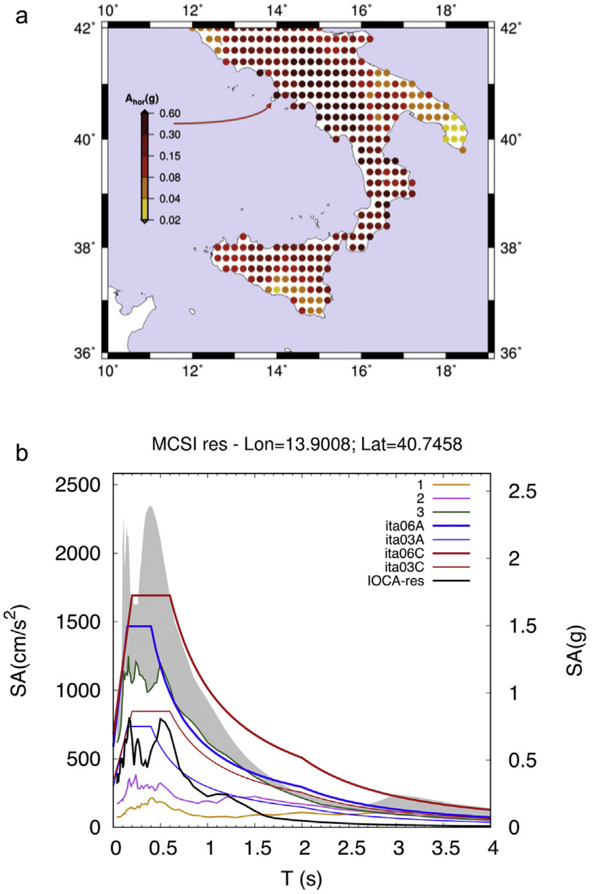
From Table 5, for each intensity level we can infer what are the classes of edifices suffering only slight damage with negligible probability of collapse. It is easy to evidence, for instance, that in zones experiencing intensity up to X, only edifices belonging to class D are negligibly affected by collapse. In zones with intensities lower than IX, the edifices of class C are only marginally affected by collapse. In zones with intensities lower than VIII, the class B edifices only rarely collapse. It is then natural to plan a strengthening of all the edifices lying in the areas affected in 1883 by intensities VIII and higher. In areas delimited by the intensity of degree X, all the edifices must be of class D or higher. Therefore, all the edifices A, B, and C must be structurally reinforced to belong to class D. In areas delimited by the intensity IX, all the class A and B edifices must be reinforced to belong to class C, and in the areas delimited by the intensity VIII the class A edifices must be reinforced to become class B at least. In order to maintain a higher caution, we suggest that in the areas VIII the class A edifices be reinforced to become class C, and that the owners of class B edifices be incentivized, although not compelled, to reinforce their edifices to become class C at least.

5. Towards a new reliable seismic hazard map

Considering the shortcomings of the official hazard map for the area, which strongly underestimated the accelerations observed for the August 21st, 2017 earthquake, it is imperative to define a new hazard map with realistic and reliable predictions of maximum accelerations. The official seismic hazard maps used for Italy are based on the PSHA method (Probabilistic Seismic Hazard Assessment). However, this method has several problems, well described by many authors (e.g. Rugarli et al., 2019a and references therein). In particular, it is known the underestimation of peak accelerations for short distances from the seismogenic faults, and the complete failure in the case when a given fault does not produce any earthquake in the time interval during which the historical catalogue is reliable. A more powerful method, which is gaining progressively more favor with the improvement of the specific knowledge about active faults, is the Neo-Deterministic Seismic Hazard Assessment (NDSHA) (Panza et al., 2001, 2012; Zuccolo et al., 2008; Fasan et al., 2016; Magrin et al., 2017; Rugarli et al., 2019a). NDSHA computations for the Italian territory have been already obtained in a variety of cases. Several ground shaking maps for Italy have been published, based on the computation of synthetic seismograms for different hypotheses about the properties of the source and of the regional structural models (Panza et al., 2001, 2012). Analyses of the uncertainties in the definition of sources with historical seismicity demonstrate (Rugarli et al., 2019b) that the unique 1000-year long Italian earthquake catalogue, acting as the experimental set, is within errors almost everywhere matched or enveloped by the sources identified within the seismogenic nodes defined by morphostructural zonation and pattern recognition techniques (Panza et al., 2012; Gorshkov et al., 2002, 2004), if their magnitude is incremented by 0.5, i.e. twice the global standard deviation of magnitude (Båth, 1973).

The ground motion map of horizontal accelerations (Design Ground Acceleration - DGA) is reproduced in Fig. 7. The DGA class assigned to the grid point closer to the Ischia island is 0.3–0.6 g. It is significantly higher than (i.e. well enveloping) the maximum acceleration observed for the 21st August 2017 seismic event.

Fig. 7b shows the comparison between observed and synthetic response spectra:



	source	M_w	edi (km)	depth (km)	strike (°)	dip (°)	rake (°)	sre (°)	slon (°E)	slat (°N)
1	sz 0928 bb	7.0	37.8	15.0	254	47	158	10	14.3	40.9
2	sz 0928 bb	6.7	24.0	10.0	254	47	158	29	14.1	40.9
3	sz 0928 bb	5.9	5.1	10.0	254	47	158	253	13.9	40.7

Fig. 7. (a) The map of Design Ground Acceleration computed by the NDSHA approach (Rugarli et al., 2019b). Note that the grid node very close to Ischia island is assigned a ground acceleration $0.3 < a < 0.6$ g. (b) Comparison between observed and synthetic response spectra at IOCA site. IOCA-res spectrum is obtained from the resultant of the horizontal components of the recorded acceleration of the August 21st, 2017 seismic event. The ita06A and ita03A curves represent the EC8-based spectra normalized to the class of DGA (0.3–0.6 g) expected (for soil class A) at the nearest grid point to Ischia according to the NDSHA map of (a) (see also Panza et al., 2001, 2012). Similarly, for EC8 soil class C, curves ita06C and ita03C are given. The grey band represents the MCSI, as defined by Rugarli et al. (2019a), that is controlled by three sources: curves 1 and 2 are the median spectra obtained from hundred realizations of the rupturing process for the two sources located in inland Campania, while curve 3 represents the median spectrum for the scenario of a M = 5.9 earthquake located in Ischia (at an epicentral distance of 5.1 km).

- IOCA spectrum is obtained from the composition of the horizontal components of the recorded acceleration of the 21st August 2017 seismic event;
- ita06A and ita03A curves represent the EC8-based spectra normalized to the class of DGA (0.3–0.6 g) expected (for soil class A) at the grid point nearest to Ischia according to the NDSHA map of Fig. 7 (see also Panza et al., 2001, 2012); similarly, for EC8 soil class C, curves ita06C and ita03C are given;
- curves 1, 2 and 3 are the median spectra obtained from hundred realizations of the rupture process for three specific sources (as specified at bottom of Fig. 7b). Sources 1 and 2 are located in inland Campania, while source 3 is located in Ischia and characterized by M = 5.9.

Source 3 is the main responsible, at least for periods shorter than 2.5 s, for the MCSI obtained at the chosen site, as shown by the grey band in Fig. 7b. Actually, as described by Rugarli et al., 2019a, at each period, SA values computed from different scenarios are compared and the maximum is chosen. Thus, the MCSI at different periods can be controlled by different scenarios affecting the site of interest. Each scenario provides a distribution of possible values (e.g. because of the semi-stochastic nature of the source model). MCSI should be set equal to their envelope or, alternatively, at the cost of reducing safety level, it could be arbitrarily set equal to a given percentile. Following Rugarli et al. (2019a) the grey band shows, at each period, the distribution between the median and the 95th percentile.

6. Discussion and conclusions

The case of Ischia island is a small-scale paradigm for the mitigation of seismic risk in Italy, because the earthquakes occur always in a limited area beneath the town of Casamicciola and at very shallow depths (less than about 2 km). The main peculiarity of these earthquakes, which poses markedly different problems with respect to the Apennine or Alpine earthquakes, is that for reasons not yet understood the largest earthquakes ($M > 3$) occur in clusters whose typical duration intervals are of several decades (about 5 decades for the last cluster, from 1828 to 1883). For instance, the devastating earthquake occurred at Casamicciola in 1883 caused 2313 casualties and was preceded 2 years earlier (1881) by a slightly lower magnitude event, which caused about 127 casualties. Six earthquakes with I(MCS) ≥ VII occurred in that time interval. Such feature makes it very crucial and urgent to strengthen the edifices which are likely to collapse if a maximum credible earthquake (MCE) occurs, whose magnitude might exceed, within experimental errors, that of the 1883 earthquake.

Based on details of damaged and collapsed buildings compiled after the 1883 earthquake, we can estimate the number of victims for a similar earthquake scenario. Although the modern buildings are more resistant than in 1883, and applying different recent statistics, we still get very catastrophic scenarios, claiming from several hundreds to more than 1300 victims. Applying similar concepts to less catastrophic scenarios, namely the 1828 and 1881 earthquakes, we may still expect several tens of victims (up to about 80, if an earthquake similar to 1881 would occur today).

For this reason, we consider urban securing in this area a compelling operation, which should be very timely and rapid. The simplest way to significantly decrease the risk of casualties would be to prevent people from coming back in the area affected by the 2017 earthquake (actually completely evacuated because all the buildings collapsed or are severely damaged). In fact, that is the most exposed area for all the earthquake scenarios. Besides such a recommendation, at least in the short-mid term, we propose two lines of actions: one to quickly secure the urban areas most affected by the 1883 scenario, the other to elaborate a reliable hazard map, which must be used to design new edifices that can resist the maximum credible ground accelerations. As the most urgent action, we propose to consolidate the edifices lying in the areas affected by I(MCS) ≥ VIII during the 1883 earthquake, in order to have, in each intensity area, only the classes of edifices that should not collapse with such a seismic intensity. We stress that securing the most risky area, which is very limited, would have a high relevance for civil safety at a reasonable and affordable cost (we made a rough estimate in the range 50–100 M€). As to the elaboration of a new hazard map able to reliably estimate the maximum credible earthquake accelerations, the most promising method is NDSHA, since it has demonstrated to overcome the strong underestimation of ground accelerations obtained by the present map based on PSHA (for a recent review see Rugarli et al., 2019a and references therein). A reliable seismic hazard map should, however, take into account also the local seismogenic sources of the main historical earthquakes, (1828, 1881, 1883) and, not last, of the 2017 event, of which the surface faulting is known (Emergeo Working Group, 2017; Nappi et al., 2018). All these goals can be equally afforded by the NDSHA methodology, by estimating the maximum credible seismic input.

The only limitations to obtain a very accurate and reliable hazard map are posed by the, at present, unavoidably imperfect knowledge of the geometry and mechanism of the seismic sources involved. In fact, as an example, the most recent papers analyzing the 2017 earthquake source, report very different results, both for fault dip and earthquake mechanism (De Novellis et al., 2018; Nappi et al., 2018; Calderoni et al., 2019). However, as shown in Fig. 7b, NDSHA may cope with such kind of uncertainties and supply reliable ranges of hazard estimates.

The problem posed by the seismicity of the island of Ischia provides a striking example, at a relatively small scale, of what should be accomplished for the entire Italian territory. To begin this process in Ischia is, however, of the utmost urgency, because we know from the historical seismicity that earthquakes like the one of 2017 generally occur in swarms, with inter-event times of several years and global duration of several decades. Ischia is a renowned international tourism brand, and can become a good case study in which to test and calibrate reliable seismic mitigation procedures, and enforce risk mitigation actions to be extended to the national scale.

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References

Alessio, G., Esposito, E., Ferranti, L., Mastrolorenzo, G., Porfido, S., 1996. Correlazione tra sismicità ed elementi strutturali nell'isola d'Ischia. Il Quaternario 9 (1), 303–308 (in Italian).

Ambraseys, N.N., 1988. Engineering seismology. The first Mallet-Milne lecture. Earthq. Eng. Struct. Dyn. 17 (1), 1–105 September.

Baratta, M., 1901. I terremoti d'Italia. Saggio di storia, geografia e bibliografia sismica italiana (ristampa anastatica, Sala Bolognese 1979). Torino, (in Italian).

Båth, M., 1973. Introduction to Seismology. Birkhäuser Verlag, Basel.

Briole, P., De Natale, G., Gaulon, R., Pingue, F., Scarpa, R., 1986. Inversion of geodetic data and seismicity associated with the Friuli earthquake sequence (1976–1977). Ann. Geophys. 4 (B 4), 481–492.

Calderoni, G., Di Giovambattista, R., Pezzo, G., Albano, M., Atzori, S., Tolomei, C., Ventura, G., 2019. Seismic and geodetic evidences of a hydrothermal source in the Md 4.0, 2017, Ischia earthquake (Italy). J. Geophys. Res. Solid Earth 124, 5014–5029. https://doi.org/10.1029/2018JB016431.

Carlino, S., Cubellis, E., Luongo, G., Obrizzo, F., 2006. On the mechanics of caldera resurgence of Ischia Island (southern Italy). In: Troise, C., De Natale, G., Kilburn, C. (Eds.), Mechanisms of Activity and Unrest at large Calderas. Geological Society 269. Special Publications, London, pp. 181–193.

Cheloni, D., De Novellis, V., Albano, M., et al., 2017. Geodetic model of the 2016 Central Italy earthquake sequence inferred from InSAR and GPS data. Geophys. Res. Lett. 44, 6778–6787. https://doi.org/10.1002/2017GL073580.

Cubellis, E., Luongo, G., 1998. Il terremoto del 28 luglio 1883 a Casamicciola nell'Isola di Ischia – Il contesto fisico. In: Monografia n 1, Presidenza del Consiglio dei Ministri, Servizio Sismico Nazionale. Istituto Poligrafico e Zecca dello Stato, Rome, Italy, pp. 49–123 (in Italian).

Cubellis, E., Carlino, S., Iannuzzi, R., Luongo, G., Obrizzo, F., 2004. Management of historical seismic data using GIS: the Island of Ischia (southern Italy). Nat. Hazards 33, 379–393.

De Natale, G., Madariaga, R., Scarpa, R., Zollo, A., 1987. Source parameter analysis from strong motion records of the Friuli, Italy, earthquake sequence (1976–1977). Bull. Seismol. Soc. Am. 77 (4), 1127–1137.

De Natale, G., Crippa, B., Troise, C., Pingue, F., 2011. Abruzzo (Italy) earthquakes of April 2009: heterogeneous fault slip models and stress transfer from accurate inversion of Envisat-InSAR data. Bull. Seismol. Soc. Am. 101 (5), 2340–2354. https://doi.org/10.1785/0120100220.

De Novellis, V., Carlino, S., Castaldo, R., et al., 2018. The 21 August 2017 Ischia (Italy) earthquake source model inferred from seismological, GPS, and DInSAR measurements. Geophys. Res. Lett. 65 (5). https://doi.org/10.1002/2017GL076336.

de Vita, S., Sansivero, F., Orsi, G., Marotta, E., Piochi, M., 2010. Volcanological and structural evolution of the Ischia resurgent caldera (Italy) over the past 10 k.y. In: Groppelli, G., Viereck-Goette, L. (Eds.), Stratigraphy and Geology of Volcanic Areas. Vol. 464. Geol. Soc. Am. Sp. Pap, Boulder, CO, pp. 193–241.

Decanini, L., Gavarini, C., Mollaioli, F., 1995. Proposta di definizione delle relazioni tra intensita' macrosismica e parametri del moto del suolo, Atti 70 Convegno

L'ingegneria sismica in Italia. 1. pp. 63–72 (in Italian).

Dolce, M., Martelli, A., Panza, G.F., 2005. Proteggersi dal terremoto: le moderne tecnologie e metodologie e la nuova normativa sismica. Seconda edizione. 21mo Secolo. pp. 336 ISBN 88-87731-28-4 (in Italian).

Emergeo Working Group, Nappi, R., Alessio, G., Belviso, P., Gaudiosi, G., Marotta, E., Nave, R., Peluso, R., Siniscalchi, V., Civico, R., et al., 2017. The August 21, 2017 Isola di Ischia (Casamicciola) Earthquake: Coseismic Effects. https://doi.org/10.5281/zenodo.1003188.

Esposito, E., Laurelli, L., Porfido, S., 1995. Damage pattern in historical centres: Isernia, an example in Southern Italy. Ann. Geophys. 38 (5–6). https://doi.org/10.4401/ag-4061.

Fasan, M., Magrin, A., Amadio, C., Romanelli, F., Vaccari, F., Panza, G.F., 2016. A seismological and engineering perspective on the 2016 Central Italy earthquakes. Int. J. Earthq. Impact Eng. 1, 395–420. https://doi.org/10.1504/IJEIE.2016.10004076.

Giovinazzi, S., Lagomarsino, S., 2004. A macroseismic method for vulnerability assessment of buildings. In: Proc. 13th World Conference on Earthquake Engineering, Vancouver, Canada, paper 896 (CD-Rom).

Gorshkov, A.I., Panza, G.F., Soloviev, A.A., Aoudia, A., 2002. Morphostructural zonation and preliminary recognition of seismogenic nodes around the Adria margin in peninsular Italy and Sicily. J. Seismol. Earthq. Eng. 4, 1–24.

Gorshkov, A.I., Panza, G.F., Soloviev, A.A., Aoudia, A., 2004. Identification of seismogenic nodes in the Alps and Dinarides. Boll. Soc. Geol. Ital. 123 (1), 3–18.

Grünthal, G. (Ed.), 1998. European Macroseismic Scale 1998 (EMS-98). Cahiers du Centre Européen de Géodynamique et de Séismologie 15, Centre Européen de Géodynamique et de Séismologie, Luxembourg.

Guidoboni, E., Ferrari, G., Mariotti, D., Comastri, A., Tarabusi, G., Valensise, G., 2007. CFTI4 Med, Catalogue of Strong Earthquakes in Italy (461 B.C.-1997) and Mediterranean Area (760 B.C.–1500). INGV-SGA.

Guidoboni, E., Ferrari, G., Mariotti, D., Comastri, A., Tarabusi, G., Sgattoni, G., Valensise, G., 2018. CFTI5Med, Catalogo dei Forti Terremoti in Italia (461 a.C.–1997) e nell'area Mediterranea (760 a.C.–1500). Istituto Nazionale di Geofisica e Vulcanologia (INGV) https://doi.org/10.6092/ingv.it-cfti5. (in Italian).

INGV, 2017. Gruppo di Lavoro INGV sul terremoto dell'isola di Ischia. Rapporto di sintesi preliminare sul Terremoto dell'isola d'Ischia (Casamicciola) M4.0 del 21 agosto 2017 (6 settembre 2017). https://doi.org/10.5281/zenodo.886045. (in Italian).

Lucantoni, A., Bosi, V., Bramerini, F., De Marco, R., Lo Presti, T., Naso, G., Sabetta, F., 2001. Il rischio sismico in Italia. Ing. sismica 1, 5–36 XVIII (in Italian).

Luongo, G., Carlino, S., Cubellis, E., Delizia, I., Iannuzzi, R., Obrizzo, F., 2006. Il terremoto di Casamicciola del 1883: una ricostruzione mancata. In: Alfa Tipografia, Napoli, (in Italian).

Magrin, A., Peresan, A., Kronrod, T., Vaccari, F., Panza, G.F., 2017. Neo-deterministic seismic hazard assessment and earthquake occurrence rate. Eng. Geol. 229, 95–109.

Medvedev, S.V., Sponheuer, W., 1969. Scale of seismic intensity. In: Proc. World Conf. Earthquake Engr. A-2, 4th, Santiago, Chile, pp. 143–153.

Mercalli, G., 1884. L'isola d'Ischia ed il terremoto del 28 luglio 1883. Mem. Ist. Lombardo, Scienze Mat. e Nat. XV, 99–154 Milano (in Italian).

Molin, P., Acocella, V., Funiciello, R., 2003. Structural, seismic and hydrothermal features at the border of an active intermittent resurgent block: Ischia island (Italy). J. Volcanol. Geotherm. Res. 121, 65–81.

Nappi, R., Alessio, G., Gaudiosi, G., Nave, R., Marotta, E., Siniscalchi, V., Civico, R., Pizzimenti, L., Peluso, R., Belviso, P., et al., 2018. The 21 August 2017 MD 4.0 Casamicciola earthquake: first evidence of coseismic normal surface faulting at the Ischia volcanic island. Seismol. Res. Lett. 89 (4), 1323–1334. https://doi.org/10.1785/0220180063.

Orsi, G., De Vita, S., di Vito, M., 1996. The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration. J. Volcanol. Geotherm. Res. 74 (3-4), 179–214. https://doi.org/10.1016/S0377-0273(96)00063-7.

Panza, G.F., Peresan, A., 2016. Difendersi dal terremoto si può: l'approccio neo-deterministico. EPC Editore, Roma (in Italian).

Panza, G.F., Romanelli, F., Vaccari, F., 2001. Seismic wave propagation in laterally heterogeneous anelastic media: theory and applications to seismic zonation. Adv. Geophys. 43, 1–95. https://doi.org/10.1016/S0065-2687(01)80002-9.

Panza, G.F., La Mura, C., Peresan, A., Romanelli, F., Vaccari, F., 2012. Seismic hazard scenarios as preventive tools for a disaster resilient society. Adv. Geophys. 53, 93–165. https://doi.org/10.1016/B978-0-12-380938-4.00003-3.

Paoletti, V., Di Maio, R., Cella, F., Florio, G., Mocka, K., Roberti, N., Secomandi, M., Supper, R., Fedi, M., Rapolla, A., 2009. The Ischia volcanic island (Southern Italy): inferences from potential field data interpretation. J. Volcanol. Geotherm. Res. 179, 69–86. https://doi.org/10.1016/j.jvolgeores.2008.10.008.

Paoletti, V., D'Antonio, M., Rapolla, A., 2013. The structural setting of the Ischia island within the neapolitan volcanic area: inferences from geophysics and geochemistry. J. Volcanol. Geotherm. Res. 249, 155–173. https://doi.org/10.1016/j.jvolgeores.2012.10.002.

Rapolla, A., Di Fiore, V., Di Nocera, S., Matano, F., Paoletti, V., Tarallo, D., 2009. The April 2009 Abruzzi, Italy, earthquake: impact on site seismic hazard estimation. EOS Trans. Am. Geophys. Union 90 (45), 410–411. https://doi.org/10.1029/2009EO450002.

Rapolla, A., Paoletti, V., Secomandi, M., 2010. Seismically-induced landslide susceptibility evaluation: application of a new procedure to the island of Ischia, Campania Region, Southern Italy. Eng. Geol. 114 (1–2), 10–25. https://doi.org/10.1016/j.enggeo.2010.03.006.

Rovida, A., Locati, M., Camassi, R., Lolli, B., Gasperini, P., 2016. CPTI15, the 2015 Version of the Parametric Catalogue of Italian Earthquakes. https://doi.org/10.6092/INGV.IT-CPTI15.

Rugarli, P., Amadio, C., Peresan, A., Fasan, M., Vaccari, F., Magrin, A., Romanelli, F., Panza, G.F., 2019a. Neo-Deterministic Scenario-Earthquake Accelerograms and Spectra: a NDSHA approach to seismic analysis. In: Jia, J., Paik, J.K. (Eds.), Chpt. 6 in "Engineering Dynamics and Vibrations: Recent Developments". CRC Press, Boca Raton, Florida, USA, pp. 187–241. https://doi.org/10.1201/9781315119908-6. ISBN 978-1-4987-1926-1.

Rugarli, P., Vaccari, F., Panza, G.F., 2019b. Seismogenic nodes as a viable alternative to seismogenic zones and observed seismicity for the definition of seismic hazard at regional scale. Vietnam Journal of Earth Sciences 41 (4), 289–304.

Sbrana, A., Marianelli, P., Pasquini, G., 2018. Volcanology of Ischia (Italy). J. Maps 14 (2), 494–503.

Strollo, R., Nunziata, C., Iannotta, A., Iannotta, D., 2015. The uppermost crust structure of Ischia (southern Italy) from ambient noise Rayleigh waves. J. Volcanol. Geotherm. Res. 297, 39–51.

Tramelli, A., Convertito, V., Pino, N.A., Piochi, M., Troise, C., De Natale, G., 2014. The 2012 Emilia, Italy, Quasi-consecutive triggered mainshocks: implications for seismic hazard. Seismol. Res. Lett. 85 (5). https://doi.org/10.1785/0220140022.

Verderame, G.M., Del Gaudio, C., Di Domenico, M., Ricci, P., 2017. Rapporto relativo ad una preliminare predizione del danno agli edifici residenziali di Casamicciola Terme e Lacco Ameno a seguito del sisma del 21.08. 2017, ore 20.57, M = 4.0. Reluis Report, Dip. Strutture per l'Ingegneria e l'Architettura, University of Naples Federico II (in Italian).

Zuccaro, G., Cacace, F., 2009. Seismic Casualty Evaluation: The Italian Model and Application to the L'Aquila Event in Human Casualties in Earthquakes: Progress in Modelling and Mitigation. edited by Robin Spence, Emily So, Charles Scawthorn. pp. 171–184. https://doi.org/10.1007/978-90-481-9455-1_12.

Zuccolo, E., Vaccari, F., Peresan, A., Dusi, A., Panza, Martelli A. e G.F., 2008. Neo-deterministic definition of seismic input for residential seismically isolated buildings. Eng. Geol. 101 (3–4), 89–95. https://doi.org/10.1016/j.enggeo.2008.04.006.