

Article

Evaluation of Damages to the Architectural Heritage of Naples as a Result of the Strongest Earthquakes of the Southern Apennines

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Abstract: The city of Naples (Campanian region, Southern Italy) has been hit by the strongest earthquakes located inside the seismogenic areas of the Southern Apennines, as well as by the volcano-tectonic earthquakes of the surrounding areas of the Campi Flegrei, Ischia and Vesuvius volcanic districts. An analysis of the available seismic catalogues shows that in the last millennium, more than 100 earthquakes have struck Naples with intensities rating I to III on the Mercalli–Cancani–Sieberg (MCS) scale over the felt level. Ten of these events have exceeded the damage level, with a few of these possessing an intensity greater than VII MCS. The catastrophic earthquakes of 1456 ($I_0 = XI$ MCS), 1688 ($I_0 = XI$ MCS) and 1805 ($I_0 = X$ MCS) occurred in the Campania–Molise Apennines chain, produced devastating effects on the urban heritage of the city of Naples, reaching levels of damage equal to VIII MCS. In the 20th century, the city of Naples was hit by three strong earthquakes in 1930 ($I_0 = X$ MCS), 1962 ($I_0 = IX$ MCS) and 1980 ($I_0 = X$ MCS), all with epicenters in the Campania and Basilicata regions. The last one is still deeply engraved in the collective memory, having led to the deaths of nearly 3000 individuals and resulted in the near-total destruction of some Apennine villages. Moreover, the city of Naples has also been hit by ancient historical earthquakes that originated in the Campanian volcanic districts of Campi Flegrei, Vesuvio and Ischia, with intensities up to VII–VIII MCS (highest in the Vesuvian area). Based on the intensity and frequency of its past earthquakes, the city of Naples is currently classified in the second seismic category, meaning that it is characterized by “seismicity of medium energy”. In this paper, we determine the level of damage suffered by Naples and its monuments as a result of the strongest earthquakes that have hit the city throughout history, highlighting its repetitiveness in some areas. To this aim, we reconstructed the seismic history of some of the most representative urban monuments, using documentary and historical sources data related to the effects of strong earthquakes of the Southern Apennines on the city of Naples. The ultimate purpose of this study is to perform a seismic macro-zoning of the ancient center of city and reduce seismic risk. Our contribution represents an original elaboration on the existing literature by creating a damage-density map of the strongest earthquakes and highlighting, for the first time, the areas of the city of Naples that are most vulnerable to strong earthquakes in the future. These data could be of fundamental importance to the construction of detailed maps of seismic microzones. Our study contributes to the mitigation of seismic risk in the city of Naples, and provides useful advice that can be used to protect the historical heritage of Naples, whose historical center is a UNESCO World Heritage site.

Keywords: Naples (Southern Italy), historical earthquakes; Southern Apennines; seismic hazard

1. Introduction

Since historical times, the central-southern Apennines chain has generated the strongest earthquakes in Italy. The epicenters of the most energetic events located along this chain have shown a significant alignment in the northwest-southeast direction, parallel to the main direction of the Apennines (Figure 1). The city of Naples has always been exposed to strong earthquakes, and these repeatedly have hit the Southern Apennines from the 15th century to the present (Appendix A Table A1) [1–4]. Our analysis of the available earthquake catalogues and relative scientific papers shows that more than 100 earthquakes with intensities of $I > III$ Mercalli–Cancani–Sieberg (MCS) over the felt level hit the city of Naples in the last millennium. Ten of these events far exceeded the damage threshold, with intensities of VII MCS or greater [5–7]. The strong historical earthquakes that have struck the city since the 15th century (Figure 1) occurred in 1456 ($I_0 = XI$ MCS), 1688 ($I_0 = XI$ MCS), 1694 ($I_0 = X$ MCS), 1702 ($I_0 = X$ MCS), 1732 ($I_0 = X-XI$ MCS), 1805 ($I_0 = X$ MCS), 1930 ($I_0 = X$ MCS), 1962 ($I_0 = IX$ MCS) and 1980 ($I_0 = X$ MCS) [1–3]. Moreover, the city being located between two active volcanic districts, the Somma-Vesuvio to the East, and the Campi Flegrei volcanic field to the West, has been affected also by volcano-tectonic and volcanic earthquakes [8–10] even if characterized by low/moderate magnitude and shallow hypocenters (Appendix A Table A1).

Indeed, in early historical times, the most severe earthquakes to hit Naples originated from the Vesuvian area, including the 62 AD and 79 AD earthquakes [11], which had maximum intensities up to VII–VIII MCS. Naples was also affected by the seismicity related to the eruption of Vesuvio in 1631 [4,12] and more recently by the 9 October 1999 earthquake ($M_d = 3.6$ [13]; $M_w = 3.24$ [14]). Additionally, Naples suffered from the Campi Flegrei earthquakes preceding and accompanying the eruption of Monte Nuovo in 1538 [5,15], and more recently was affected by the 4 October 1983 earthquake ($M = 4.2$ [3]) during the 1982–1984 bradyseismic crisis of Campi Flegrei.

In this paper we present an analysis of the damages that have occurred in Naples due to the strongest earthquakes located in Campania–Molise (Southern Apennines), but we do not take into account the damages of earthquakes that occurred in Vesuvio and Campi Flegrei, for which there is not as much detailed information as for the Apennines earthquakes. The aim is mainly to highlight local seismic hazards and potential heavy damage that could threaten the historical center of Naples and its rich architectural heritage. Based on the intensity and frequency of earthquakes that have occurred in the past, the city of Naples is ranked in the second seismic category, ‘average seismicity’ (Deliberazione Giunta Regionale n.5447 of 2012). The structure of this paper includes an introduction describing the most relevant seismic events that have hit the Neapolitan area, the object of the study, as well as geological structure of the city, highlighting its main characteristics and historical and architectural heritage. Section 2 describes the methodology applied in the study, in which the levels of damage to prestigious monuments of the Naples area are determined and then compared with a density map detailing areas of similar damage. Section 3 illustrates in detail the most important Apennines earthquakes that have hit the city of Naples, including detailed data that are collected in the Appendix A. In Section 4 we analyze and discuss the results of our study. Section 5 outlines the conclusions of our analysis.

The city of Naples is located inside the Campanian Plain, a very large tectonic depression NW-SE elongated, that originated during the extensional regime following the formation of the Southern Apennines [16–19]. The Plain includes the Campi Flegrei and Somma-Vesuvio active volcanic districts to the west and southeast of the city, respectively. In particular, the most important explosive eruptions of the Campi Flegrei volcanic field produced the Campanian Ignimbrite (Figure 2) (Ignimbrite Campana (IC)) (39,000 years) and the Neapolitan Yellow Tuff (Tufo Giallo Napoletano (TGN)) (15,000 years) [20]

lithoid tuffs that represented the main source rocks for most of the ancient and modern buildings inside the urban area of Naples.

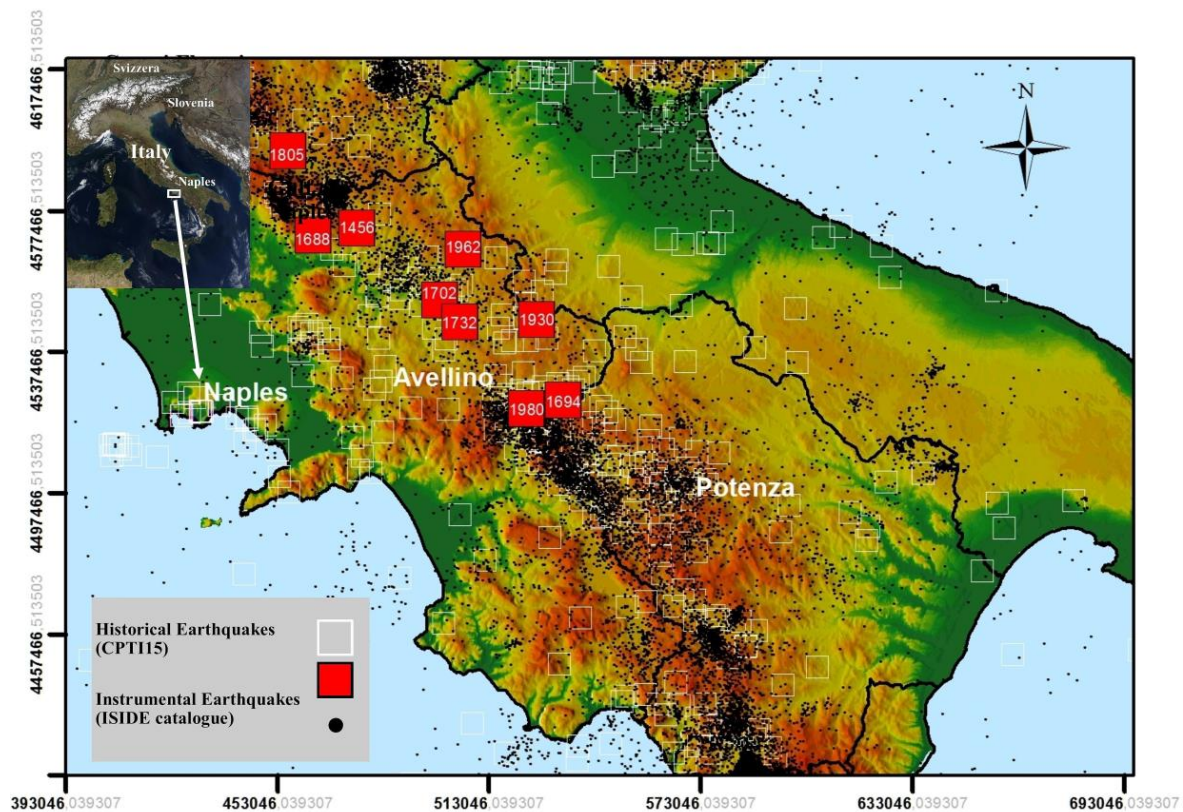


Figure 1. Map of historical earthquake locations (after CPTI15,14). The earthquakes felt in Naples are denoted with a red square, all others are denoted with a white square. The distributions of instrumental quakes from the Italian Seismological Instrumental and Parametric Data-Base (ISIDE) are represented by black dots.

The main reliefs of the urbanized area of Naples include ancient eruptive centers originating the hills of Capodimonte, Vomero, Pizzofalcone, Posillipo and Camaldoli (Figure 2). These were the results of activity from about 70 explosive monogenetic volcanoes as well as down-faulting displacement associated with the collapse of the Campi Flegrei caldera [21,22].

The very intense urbanization of Naples has been almost continuous over time, and architectural development and consequent anthropic activities have nowadays hidden the ancient eruptive centers, making their relative volcanic morphologies rather undetectable.

The stratigraphic setting of the urban area is very complex and mainly characterized by a cover of loose pyroclastic and reworked material lying on Neapolitan Yellow Tuff (TGN) sequence, with lateral and vertical heterogeneities due to the presence of different erupted products, and vertical and lateral variation in lithification grades [23].

The main outcropping deposits in the urban area of Naples, as regards the areal extension, are pyroclastic ashes, lapilli and pumice dating less than 15,000 years, which therefore erupted after the TGN setting, as well as some reworked pyroclastics, as shown on the Geological Map of Naples (Figure 2) [24]. The lithified deposits of IC and TGN very rarely outcrop inside the urban area.

As the city of Naples is located next to the western area of the Southern Apennines, it has consistently been exposed to the strong historical earthquakes that repeatedly have hit the mountain chain and its villages. Moreover, as the city is enclosed by two great active volcanic districts (i.e., the Somma-Vesuvio and Campi Flegrei volcanic fields), it has also been affected by the seismic activity (even at low/moderate magnitudes) of volcano-tectonic and volcanic earthquakes, an issue that persists

to the present day [20,25–27]. In particular, the Campi Flegrei area, near the city, has undergone considerable deformations and almost continuous subsidence due to several bradyseismic phases over the past two millennia [28].

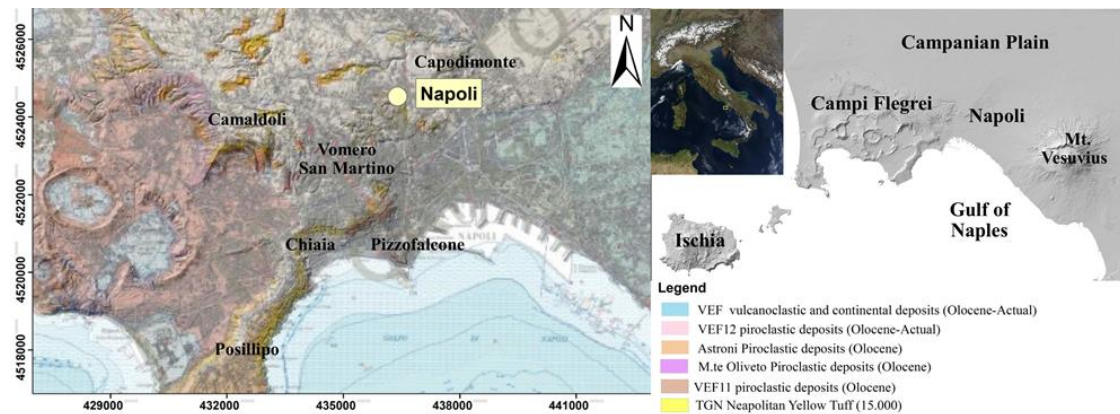


Figure 2. Geological Map of Naples extracted from the Geological Map of Italy, 1:50,000 (Sheet Naples n. 446–447).

Settlements in the Gulf of Naples date back to a very ancient age due to its mild climate, the fertility of its soil and its abundance of landings and natural harbors.

The city has been influenced in its urban development by the arrival of various peoples and cultures, from its Greek foundations, Roman conquest, Byzantine domination, Norman and Swabian dominations and alternating French and Spanish dynasties to the present era [29,30]. Such multiethnic influence has given Naples a unique reality that is rich in history and culture both in terms of its urban layout as well as its art and traditions. The historic center of Naples represents an exclusive example of a vertical stratified city, and its architecture is based on overlapping of different architectural styles [31]. It has been possible to reconstruct the historical events of many parts of the city with greater precision due to the numerous archaeological findings that have been found over the years. Parthenope, the first nucleus of the future Naples, was founded by the Cumans in the eighth century BC on Echia Mountain, and is presently known as Pizzofalcone [32].

The harbor was located to the east of the city, near the present-day Municipio Square, and there Castel Nuovo (as known as Maschio Angioino) became the headquarters of the medieval age and one of the most important symbols of the city. At the beginning of the sixth century BC, the city was rebuilt as Neapolis, meaning “new city”, and was conceived similarly to the city of Cuma [32]. Due to the privileged relationship with Athens, Naples became one of the largest ports in the Mediterranean Sea, with unchanged urban development until the middle of the first century BC [33]. Following the influences of Athens and Syracuse, the political and social equilibrium of Naples was compromised towards the end of the fifth century BC by the expansion of the Oscii people, who conquered both the territories of the Etruscans in northern Campania and the territories of the Cumans [32]. In 327 BC, the city of Naples was strongly contended between the Sanniti and Romans. Rome had the strongest influence, reducing the city’s Greek traditions and habits [32]. From the first century BC until approximately the first century AD, Roman high society went to Naples for rest and recreation. It was precisely in this period that Naples was enriched with refined Roman villas. In the Augustan age, Naples was hit with the catastrophic earthquakes of 62 AD and 79 AD and the eruption of Vesuvius [2,34,35].

Many churches were built during the empire of Constantine in the fourth century, such as San Giovanni Maggiore and San Giorgio Maggiore. In 533 AD, the church of Santa Maria Maggiore alla Pietrasanta was built in the historical center of Naples [36,37].

Naples was attracted the attention of the Byzantine and Gothic peoples following the crisis of the Roman empire. The Byzantines conquered Naples in 534 AD, and thereafter became a Byzantine

province for the next six centuries, during which the Duchy of Naples was established. Numerous monasteries were built in the city during this time, including the Greek monastery of San Sebastiano. Moreover, several churches were located on the hills of the interior or on the islands, such as the hill of Monte Echia or the islet of Megaride. Between 780 and 790 AD [37], the Byzantine bishop Stephen II built the church of San Gaudioso [36,37]. In the centuries of ducal government, Naples often found itself in contrast with the Lombards and Saracens and also had to face repeated contrasts with the pontifical state. The defensive wall was enlarged to protect Naples against attacks and heavy population growth. In the 9th and 10th centuries, the churches of Santi Severino e Sossio (10th century) and Santa Maria Donnalbina were built. In 1137, the Duchy was conquered by the Normans who later formed the Kingdom of Sicily.

Guglielmo I of Sicilia was responsible for the construction of Castel Capuano (1176) and for the restoration and expansion of Castel dell’Ovo by building the tower later known as Normandy.

After the Norman period, Naples was subjected to Swabian domination. Thanks to Federico II of Swabia, Naples regained strong central power, thanks in particular to the establishment of the first State University of History.

During the subsequent Angevin domination, Charles I and Charles II of Anjou reorganized the city of Naples, with urban planning interventions aimed at creating a port city [38].

At the end of the 13th and beginning of the 14th centuries, numerous churches were built as a result of kings’ subsidies [29,30,36,37], including the churches of San Agrippino (1265), San Lorenzo Maggiore (1270), Santa Maria La Nova (1279), San Domenico Maggiore (1283), Sant’Agostino Maggiore (1287) and San Pietro Martire (1294), the monastery of Santa Chiara (1310) and the Santa Maria Assunta Cathedral (1270–1313). In addition, Charles I of Anjou was responsible for the construction of a new fortress, Castel Nuovo (known as Maschio Angioino) (1279), which was located by the sea, right near the creek that previously hosted the port of Naples. The construction of the Santa Maria del Carmine church dates back to the end of the 13th century, thanks to the contributions of Roberto d’Angio’ who donated the land in 1270, although historical sources report the date of the start of construction as the 12th century [36,37]. During the Angevin domination, the church of Santissima Annunziata Maggiore (1318, but completely rebuilt and enlarged in 1513), Castel Sant’Elmo (1329–1343), Certosa di San Martino (1325–1368, located at Vomero hill) and Castello del Carmine (1382) were built [36,37].

During the Catalan–Aragonese kingdoms (15th century), the church of Santa Maria di Monteoliveto (Sant’Anna dei Lombardi) was built (1411) and subsequently enlarged during the kingdom of Alfonso V of Aragona. He also restored Castel Nuovo, which had been damaged by continuous wars, and added an exemplary Triumph Arch and the famous throne room. Subsequently, the city of Naples underwent considerable expansion, with the construction of a new wall with 22 cylindrical towers [36,37]. Alfonso V of Aragona made the city of Naples a true capital of the Mediterranean [29,30]. During the Ferdinando kingdom, many monuments were built [39]: Palazzo Carafa d’Andria (in the early 15th century), Porta Capuana (1484), the Como Palace (Museo Filangieri) (1464 and 1490), the Diomede Carafa Palace (1470) and the facade of the San Severino palace (about 1470) of the Salerno princes. The currently facade of the church of Gesù Nuovo was rebuilt in 1584, as well as the actual lower church of Santi Severino e Sossio (1490). The urban situation is described in detail in the Tavola Strozzi dated at the end of 15th century (Figure 3).

Between the 16th and 17th centuries, the fortification walls were built to the south of Naples [29,30]. Under Spanish domination, the kingdom of Carlo V (and the regency of his viceroy Don Pedro de Toledo) subjected Naples to further transformations in which the quarters of Toledo and the present Spanish quarters were built, in order to accommodate the Spanish military garrisons. At the beginning of the 16th century further work of transformation and fortification of Castel Nuovo (Maschio Angioino) and the construction of Palazzo Pignatelli di Monteleone were made by the Bourbons. During the 16th and 17th centuries, the churches of Gesù Vecchio dell’Immacolata di Don Placido (1554), San Tommaso d’Aquino (1567 but destroyed in 1932), San Liguoro/San Gregorio Armeno (1572), San Severo out of the walls (1573), Gesù Nuovo (1584), Madonna della Pietà dei Turchini (1592), San Filippo Neri

(Gerolamini) (1592), San Filippo e Giacomo (1593), San Paolo Maggiore (1538–1630), Santa Maria della Sanità or San Vincenzo (1602–1614), Santa Maria della Verità/Sant’Agostino degli Scalzi (1603), Santa Maria ai Monti (1606–1654), Santa Teresa degli Scalzi (1604), San Michele Arcangelo dei Mercedari a Port’Alba (1620), San Nicola alla Carità (1647) and la Croce di Lucca were built [36,37]. Construction of the Regio Arsenal dates back to 1577, but it was destroyed in the early 1900s, while the construction of Palazzo Carafa di Maddaloni is dated to 1580. In the 17th century, the Church of Santa Maria Donnalbina (ninth century) and the Church of Santa Maria Maggiore alla Pietrasanta (sixth century) were rebuilt, and in 1667 the construction of the Presidio di Pizzofalcone began. In 1600, the building of the Palazzo Reale (Royal Palace) took place [39], and was subsequently expanded in 1734 when Naples became the capital of the kingdom with Charles III of Bourbon. The final transformations took place in Ferdinand’s time between 1838 and 1858 with a general restoration of the neoclassical style. In 1919 this was largely dedicated to the National Library, where the oldest wing was used as a Museum of Historic Property.



Figure 3. Tavola Strozzi: view of Naples depicting the Aragonese fleet re-entering the port on 12 July 1465 after the defeat of the Angevin Navy at Ischia on 7 July. (Attributed to F. Rosselli—Museo Nazionale di San Martino, Naples, Italy.)

During the 20th century, many other changes and renovations were carried out, both in the Municipio Square and in the oldest city center [30].

As can be seen from the synthetic historical and architectural excursus reported so far, the uniqueness of Naples and above all of its historical center stems largely from the use of the ancient Greek path of road that has been preserved to the present day. Because of this, the historic center of Naples was declared a human heritage site in 1995 by UNESCO, and was included on its list of protected properties.

Our analysis has allowed us to reconstruct the seismic history of some of the most representative urban monuments of Naples, and to perform a seismic macro-zoning of the ancient center of the city in order to reduce future seismic risk. A methodology already widely tested for assessing the damage level of some cities affected by both historical and relatively more recent earthquakes was adopted [40,41].

2. Methodology

In the last 1000 years, the Southern Apennines have been the source area of strong earthquakes that have had a considerable impact on the city of Naples, exceeding the threshold of damage. In this paper we consider the level of damage suffered by the city of Naples and its monuments as a result of the strongest earthquakes that have affected it throughout its history, highlighting recurrences in some areas. We reconstructed the seismic history of some of the most representative urban monuments in Naples using a methodology already widely tested that assesses the damage level of cities that have been affected both historically and relatively more recently by earthquakes [5]. We determined the level of damage in certain Neapolitan structures relative to historical earthquakes, distinguishing three different classes of damage (Table 1): minor damage (MD) (slight damage; surface cracks, light

non-structural damage); serious damage (SD) (large and extensive cracks, moderate structural damage, heavy non-structural damage and occasionally partial collapses); and great damage/collapse (GD) (heavy cracks, very heavy damage, heavy structural damage, partial and in some case total collapse).

Table 1. Level of damage by historical earthquakes, distinguishing among three different classes of damage.

MD (Minor Damage)	SD (Serious Damage)	GD (Great Damage/Collapse)
slight damage; surface cracks, light non-structural damage	large and extensive cracks, moderate structural damage, heavy non-structural damage and occasional partial collapses	heavy cracks, very heavy damage, heavy structural damage, partial and in some cases total collapse

The classification of damage suffered by buildings of Naples was carried out by means of the expressions and terms used in the historical sources (i.e., “leviter lesa”, “leggiemente lesa” and “picciola parte patita” for minor damage; “plurimum laceratum” and “tutto lesionato” for serious damage; and “a fundamentis devastatum”, “gittato a terra” and “totalmente rovinato” for great damage). This analysis was possible thanks to the damage descriptions by several authors who used recurring verbs, adjective and adverbs that defined increasing damage levels [40–45].

For each earthquake studied in this paper, tables are presented in the Appendix A that show the original name of the monument whose damage is known, the type of building, the year of construction (and in some cases reconstruction), the level of damage suffered following the earthquake and the geographic coordinates. The damage reported by all buildings was mapped for each earthquake examined (Figures 4–6). Moreover, we generated a density map allowing the identification of areas with the same damage value for all examined historical earthquakes. For this purpose, we used the ArcGIS (version 10.8) Silverman algorithm, which calculates a magnitude-per-unit area from point features that fall within a neighborhood around each cell [46].

The final results were interpreted and are commented upon in this paper, with a discussion of the usefulness and value of our study to improving the literature about seismic risk in the city of Naples.

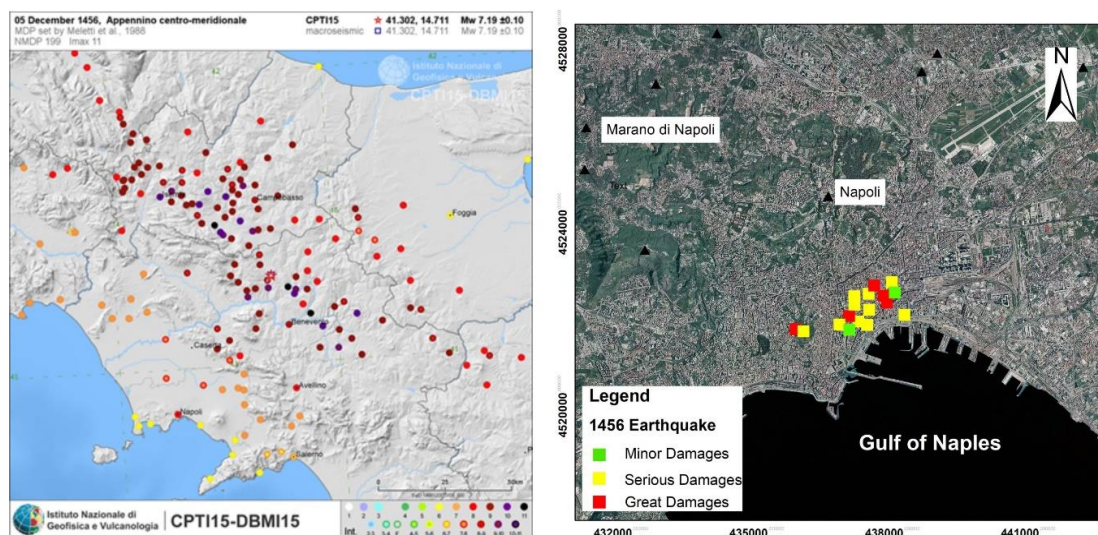


Figure 4. Map of the 1456 Mercalli-Cancani-Sieberg (MCS) macroseismic intensity (modified from [1]) on the left; map of the damage to Naples from the earthquake of 5 December 1456 on the right.

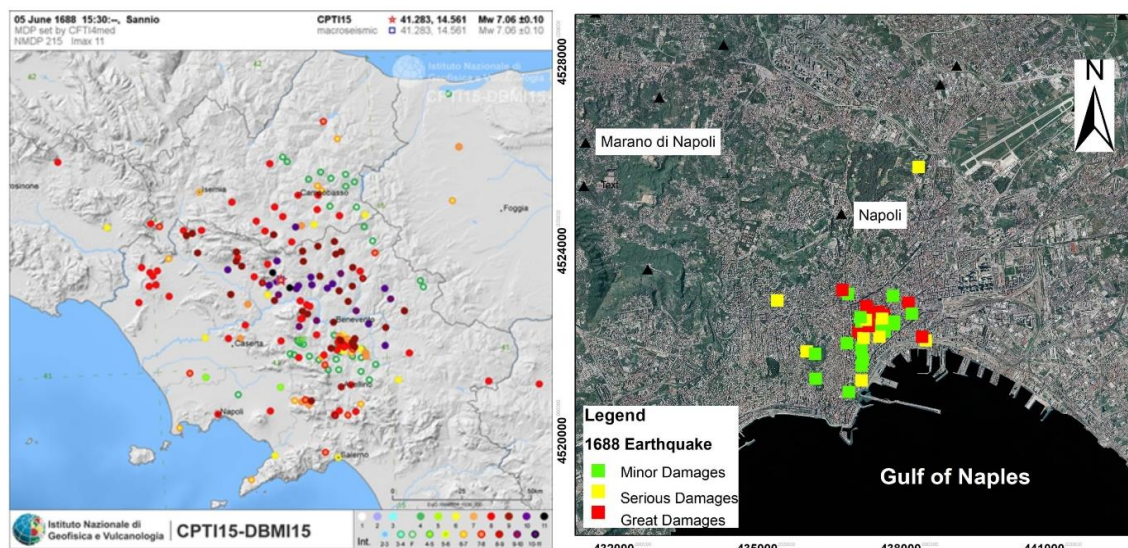


Figure 5. Map of the 1688 MCS macroseismic intensity (modified from [1]) on the left; map of the damage to Naples from the earthquake of 5 June 1688 on the right.

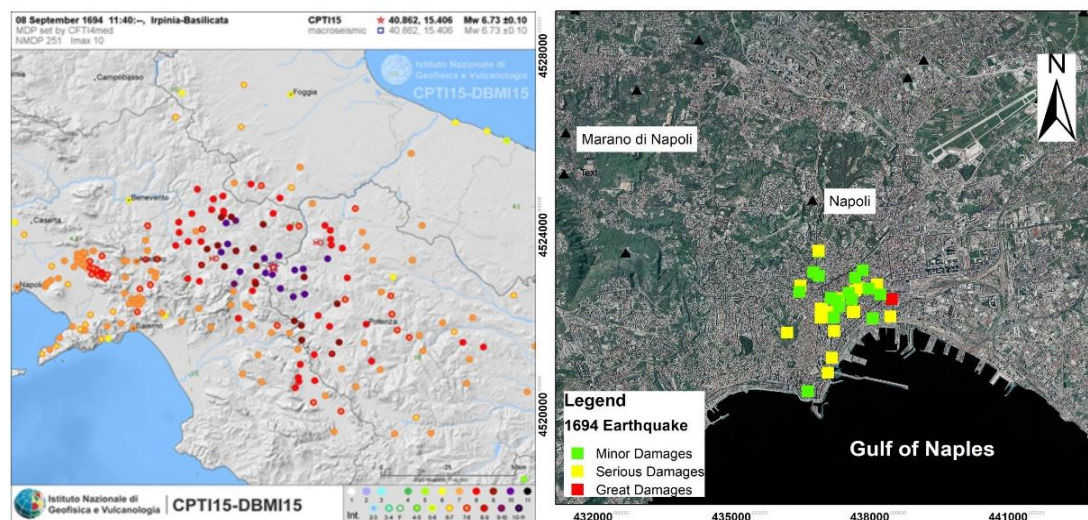


Figure 6. Map of the 1694 MCS macroseismic intensity (modified from [1]) on the left; map of the damage to Naples from the earthquake of 8 September 1694 on the right.

3. Historical Earthquakes of the Southern Apennines Felt in Naples

The strongest historical earthquakes to have struck the city of Naples since the beginning of the 15th century (Figure 1) were in 1456 ($I_0 = \text{XI MCS}$), 1688 ($I_0 = \text{XI MCS}$), 1694 ($I_0 = \text{X MCS}$), 1702 ($I_0 = \text{X MCS}$), 1732 ($I_0 = \text{X-XI MCS}$), 1805 ($I_0 = \text{X MCS}$), 1930 ($I_0 = \text{X MCS}$), 1962 ($I_0 = \text{IX MCS}$) and 1980 ($I_0 = \text{X MCS}$) [1–3]. Devastating effects were inflicted upon the historical Neapolitan urban area as a result of these seismic events, and damages reaching levels of up to VIII MCS have been recorded [6,7].

During the 20th century, the city of Naples was hit by three major earthquakes (in 1930, 1962 and 1980) originating in the Southern Apennines. The last of these events is still deeply engraved in the collective memory, due to the high number of casualties, of about 3000, and the almost complete destruction of some nearby Apennines villages.

The main seismological and macroseismic parameters of the earthquakes that hit the city of Naples in the previous centuries are listed in Appendix A Table A1. Between 1293 and 2002, 178 recorded events hit Naples, about ninety of which had an epicentral intensity of $I_0 \geq \text{VII MCS}$. Ten events struck Naples severely, exceeding a damage level greater than VII MCS [6,7]. The 5 December 1456 earthquake

is considered one of the most catastrophic events to have occurred in Italy during historical times, and had an epicentral intensity of XI MCS and a magnitude $M_w = 7.2$ [14,42]. It was a very complex event, with five main shocks triggered along the axis of the Apennines [47] along a narrow belt ranging from the Abruzzi to Campania regions. The seismogenic area inside Benevento province was the nearest to Naples, and caused high levels of damage. The earthquake's destruction covered a large region (Figure 4), with an intensity $I \geq IX$ MCS and more than 90 localities affected in Central and Southern Italy, killing at least 60,000 people. In Naples, the earthquake resulted in 100 casualties. Damages were widespread, many buildings were damaged and streets were blocked. Historical sources report that damage occurred above all to the most important castles, fortresses, churches and monasteries of the time (Appendix A Table A2). Great and serious damages were recorded in Naples (Figure 4). In detail, collapses occurred in Castel Sant'Elmo, Castel Capuano and the churches of San Agostino, San Pietro Martire, San Lorenzo, Santa Chiara, San Giovanni Maggiore, Santa Maria Maggiore alla Pietrasanta, San Domenico and San Severino. Moreover, even the bell towers of San Agrippino and the Cathedral fell down; the Certosas of San Martino and Monte Oliveto monasteries, located outside the walls, were severely damaged (Appendix A Table A2). The severity of the impact in the city of Naples was estimated to be equal to VIII MCS [5,42,47].

Another devastating earthquake that affected the whole Campania region occurred on 5 June 1688, with its epicenter inside the Sannio area (Figure 5). This earthquake was characterized by an epicentral intensity of $I_0 = XI$ MCS, presumably in the Cerreto Sannita and Civitella Licinio villages, and a value of magnitude $M_w = 7.06$ and $I_0 = X$ on the basis of the Environmental Seismic Intensity (ESI-07) scale [48]. The earthquake resulted in a high number of casualties, with some chronicles reporting as many as 10,000 deaths. Moreover, many environmental effects such as fractures, landslides, liquefaction phenomena and hydrological variations were observed that in some cases, together with the diffuse damage to the housing stock, led to total relocation of some Apennines villages like Cerreto Sannita [6,48]. The level of damage was very high throughout Naples (Figure 5), with a number of deaths somewhere between 35 and 50 people. Chronicles have reported severe and widespread damage, especially to the churches of the city (Appendix A Table A3). Of the church of San Paolo, an anonymous contemporary source reported that "in the atrium below the Church of San Paolo dei Teatini ... the magnificent arch has dropped together with the large and ancient columns, which they were said to form the famous temple of Castor and Pollux, only four left standing, but almost falling, so far 19 people have been quarried from ruin".

The collapse of the frames of some private buildings and damages to Castel Sant'Elmo, Castel Capuano, Castel Nuovo, the fortress of Torrione del Carmine, the Sala del Tesoro and the Royal Palace also occurred. The last revision proposed by the authors of DBMI15 [1] assigned a VIII MCS to Naples.

On 8 September 1694, a strong earthquake struck a wide area of Southern Italy between the Campania and Basilicata regions. Unlike the 1456 and 1688 earthquakes, the epicentral area was located between Irpinia and Basilicata (Figure 6), with $I_0 = X$ MCS, $M_w = 6.73$ and $I_0 = X$ ESI-07 [43,48,49]. The seismogenic source located in Campania and Basilicata, relatively more distant than the source zones of the 1456 and 1688 earthquakes, caused a lower damage level in Naples (Figure 6), evaluated as VII MCS. The number of deaths was considerable, about 6000 in total, although only one dead and one wounded were reported in Naples. The earthquake caused moderate damage throughout the Neapolitan urban fabric, with only a single collapse at Porta Nolana. Widespread damage occurred to the ecclesiastical buildings (Appendix A Table A4), and more or less serious damages occurred to the Cathedral and the churches of Girolomini, Santa Maria Maggiore, San Paolo Maggiore dei Teatini, Santi Severino e Sossio churches, among others. Much damage to public buildings was observed, including to Castel Nuovo (Maschio Angioino) and Castel Capuano. In the Royal Arsenal, seven arches and its central pillars lanes were damaged, while the Real Presidio of Pizzofalcone, which was already undergoing repairs, suffered damage to some walls that had to be reinforced with iron chains. Moreover, the noble palaces of the Duke Carafa of Maddaloni, the Duke Carafa of Andria and of the Duke Pignatelli of Monteleone suffered considerable damage.

In the following century, the city of Naples was hit by two strong events that took place on 14 March 1702 and 29 November 1732; both these epicenters were located between the Irpinia and Sannio areas, with damage levels evaluated to have an intensities of VI and VII MCS, respectively.

The 26 July 1805 earthquake is also known as “the earthquake of Sant’Anna”, since it occurred on the day dedicated to celebrating this saint. The epicentral area was located in the Molise region (Figure 7), where at least 19 villages suffered almost complete destruction, with epicentral intensity $I_0 = X$ MCS, $M_w = 6.73$ and $I_0 = X$ ESI-07 (Figure 7) [48,50]. According to official chronicles, 5573 people died and 1583 were injured. There was widespread damage in Naples (Figure 8), with collapses and deep fractures requiring shoring of housing. The damage level was equal to VII–VIII MCS (Appendix A Table A1). The major damages were related to part of today’s historical center (Appendix A Table A5) [44]. Indeed, Castel Nuovo (Maschio Angioino), the big building of Regj Studj, the Reale Albergo de’ Poveri, the Gesù Vecchio Church and the buildings of the Prince of Angri, of Roccella, of Sangro, of Duca della Regina and many others over the district of Pizzofalcone suffered serious damage. Moreover, some churches like the Cathedral, Sant’Agostino alla Zecca and San Demetrio also suffered severe damages. The strong earthquake produced many environmental effects throughout the whole area hit by the quake, especially in the epicentral area of the Bojano plain, with surface faulting, fractures, landslides and hydrological variations. In the Bay of Naples and along the coastal areas of Gaeta (in Latium) and Sorrento peninsula (in Campania), located very far from the epicentral area, changes in sea level equivalent to a low-energy tsunami were observed [45,48,50,51].

In the 20th century, three catastrophic earthquakes with $I_0 \geq IX$ MCS occurred in one of the main seismogenic zones located in the Southern Apennines. Events on 23 July 1930 and 21 August 1962 occurred in Irpinia; the earthquake of 23 November 1980 occurred at the border between Irpinia and Basilicata.

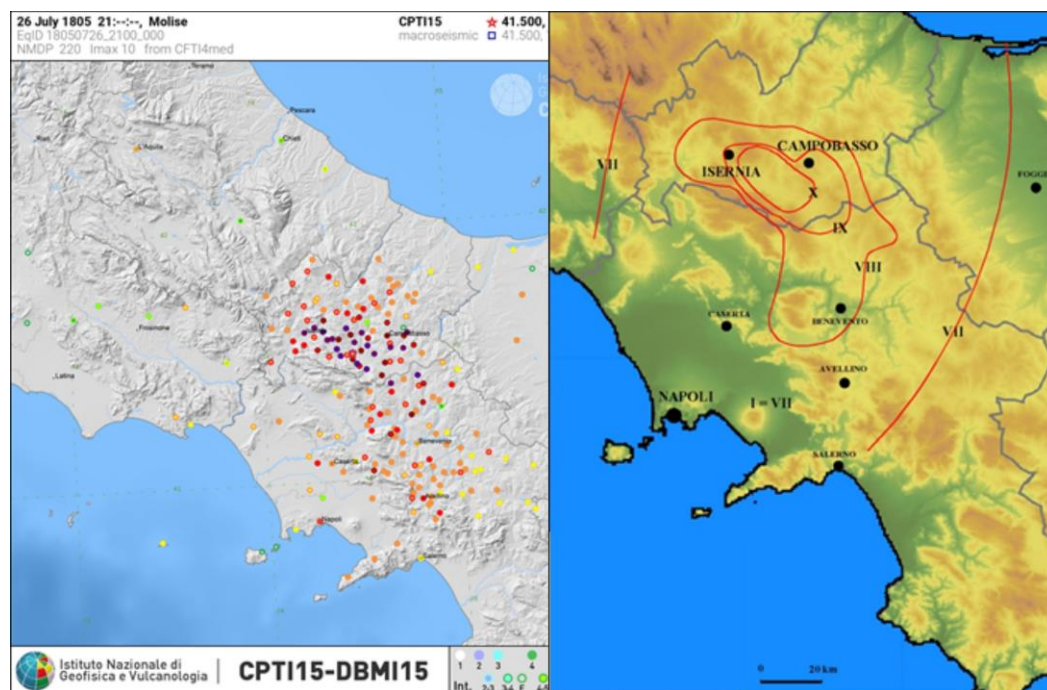


Figure 7. Map of the 1805 MCS macroseismic intensity (modified from [1]) on the left; isoseismal map of the 1805 Bojano earthquake (modified from [50]) on the right.

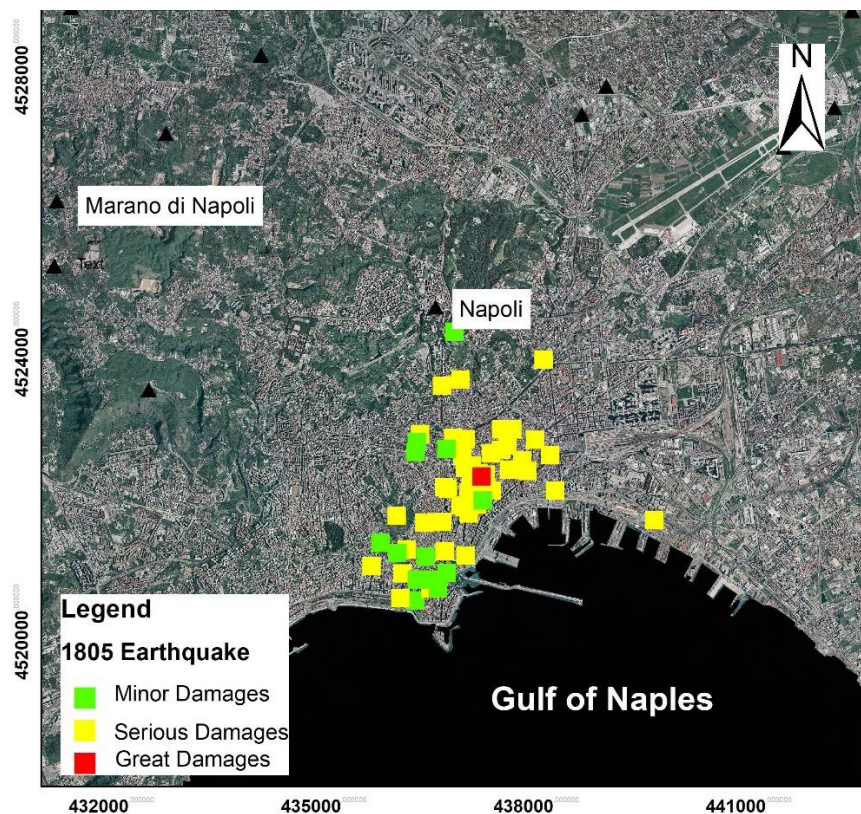


Figure 8. Map of damages caused in Naples by the 26 July 1805 earthquake.

The 1930 earthquake struck the Campania, Puglia and Basilicata regions. The epicentral area was located between the northern Irpinia and Puglia regions, with $I_0 = X$ MCS, $6.67 M_w$ and $I_0 = X$ ESI-07 scale [14,48,51–54]. The most damaged villages were located along the axis of the Apennines Chain, including Ariano Irpino, Lacedonia, Villanova del Battista, Scampitella, Trevico and Aquilonia, with values of $I = IX-X$ MCS. The earthquake led to the deaths of 1424 people, with 4624 injured and about 100,000 being left homeless in the aftermath.

In Naples, widespread damage occurred to housing stock and, in particular, four houses in the Courts area collapsed as well as the Casanova Bridge, with four casualties. The intensity value in Naples was VII MCS.

On 21 August 1962, a violent earthquake of $M_w = 6.15$ struck Campania, on the border between the Sannio and Irpinia regions, with an epicentral intensity of IX MCS [14,55]. The most affected towns were Ariano Irpino, Casalbore, Melito Irpino and Montecalvo Irpino in the province of Avellino; and Apice, Ginestra degli Schiavoni, Molinara, Reino and San Giorgio la Molara in the province of Benevento. The event was characterized by some premonitory shocks that deterred people from staying inside of their homes, ultimately reducing the number of deaths to only 17.

In the city of Naples, the earthquake resulted in five deaths, only one of which was a direct consequence of collapse. Moreover, there were collapses in the gutters of some buildings and serious damage to the Duca D'Aosta and Thaon de Revel dam, as well as to the Calata Villa del Popolo and Vittorio Veneto docks. Minor damages were widely observed in the historical center, and in the Vomero hilly zone. The intensity values assigned to Naples were VI–VII MCS.

The final catastrophic event to devastate Southern Italy over the past 100 years is known as the Irpinia-Lucania earthquake, and it occurred on 23 November 1980 (Figure 1). It was characterized by an $I_0 = X$ MCS (Figure 9), $M_w = 6.9$ and $I = X$ ESI [14,48,56]. It was felt throughout Italy, from southern Sicily in the South, to Emilia Romagna and Liguria in the North, with the epicenter between the Campania and Basilicata regions, which were the most damaged regions. The number of destroyed

homes was 75,000, while about 275,000 were seriously damaged. The earthquake led to a loss of nearly 3000 lives and damage to about 800 villages. Castel Nuovo di Conza, Conza della Campania, Lioni, Santomenna, San Mango sul Calore, San Michele di Serino and Sant'Angelo dei Lombardi were almost completely destroyed. In Naples, this event produced widespread and serious damages (Figure 9), reaching an intensity of VII MCS [56]. About 18,000 stability analyses were carried out throughout the city, equal to 80–85% of the entire housing stock. The most damaged areas were found in the old city (Appendix A Table A6) [5–7,56–58].

A residential tower collapsed in the Poggioreale area, where 52 people were killed. Among the most important monumental buildings seriously damaged by the earthquake was the Reale Albergo dei Poveri (one of the largest in Europe), where the infirmary, part of the refectory and some of the surrounding rooms on the first and second floor collapsed [56].

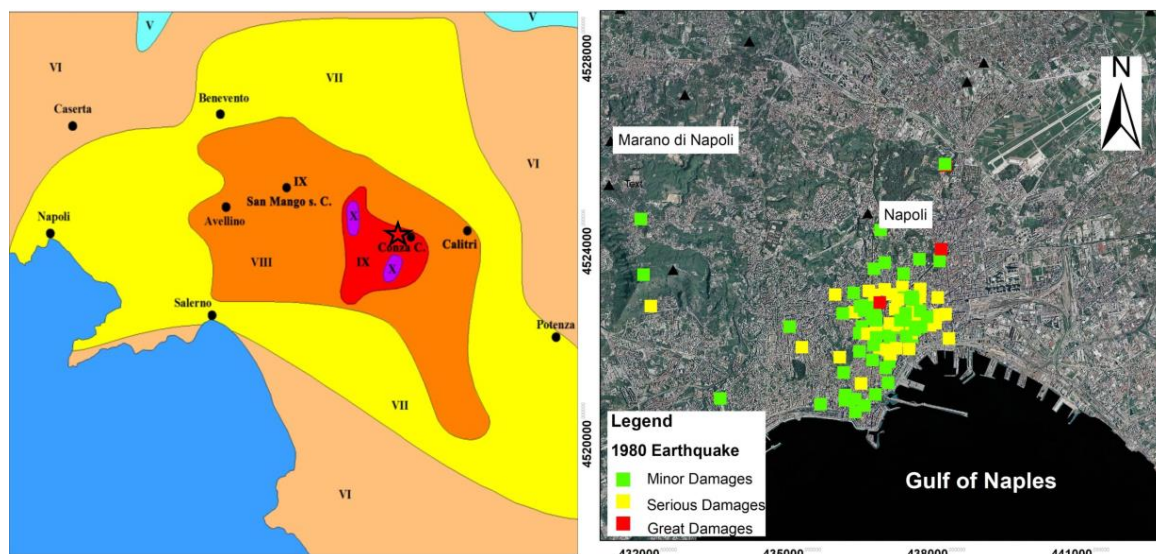


Figure 9. Isoseismal map of the November 1980 Irpinia-Basilicata earthquake [4,56,59] (on the left). The different colors are related to the different values of MCS macroseismic intensity, and the black star is the location of the epicenter. Map of the damage caused in Naples by the earthquake on 23 November 1980 (on the right).

4. Results and Discussion

The strongest earthquakes of the Southern Apennines, such as those in 1456 ($I_{max} = XI$ MCS, $M_w = 7.2$), 1688 ($I_{max} = X$ MCS, $M_w = 6.7$) and 1805 ($I_{max} = X$ MCS, $M_w = 6.7$), reached Naples at a maximum macroseismic intensity of $I = VIII$ on the MCS scale, with considerable damage to the architectural heritage of the historical center specifically, as in the case of Castel Nuovo, as well as to the ecclesiastical heritage more generally. Meanwhile, the earthquakes of 8 September 1694, 23 July 1930 and 23 November 1980 caused a lower damage level of VII MCS in the urban area of Naples (Appendix A Table A1).

We distinguished the levels of damage relative to historical earthquakes as belonging to three different classes of damage: minor damage (MD), serious damage (SD) and great damage/collapse (GD). In detail, the levels of damage of the 1456 and 1688 earthquakes were great and serious, concentrated in a very restricted area of the historical center of Naples (Figures 4 and 5, respectively). The 1805 earthquake resulted in a serious level of damage spread over a wider area of the historical center of the city (Figure 8), while the 1980 earthquake produced a serious level of damage that was widespread (Figure 9) in the historical center but also included minor damage diffused in the suburban areas (Figure 9). According to the different effects that the earthquakes had on the historical buildings of Naples, an original damage-density map has been elaborated upon in this paper (Figure 10), synthesizing all of the damage data on the architectural heritage that were collected ad hoc for

comparison in our study. Figure 10 shows the way in which the damage repeats and overlaps in the same areas, with the greatest damages in the historic center of Naples covering an area of 17 km² and representing the most vulnerable portion of the city.

Several pieces of the most famous Neapolitan architectural heritage are located in this area, including the castles/fortresses of Castel Capuano, Castel Nuovo (Maschio Angioino) and Castel Sant’Elmo, and the churches of the Cathedral, Santa Chiara, San Domenico Maggiore, San Lorenzo Maggiore, Santa Maria La Nova, San Paolo Maggiore and the Albergo dei Poveri, all of which suffered the greatest damages as a result of historical earthquakes (Figure 11). In detail, among the castles/fortresses of medieval age between the 11th and 13th centuries, Castel Sant’Elmo is the one that reported the greatest damage due to the earthquake of 1456, while Castel Capuano suffered the most significant damage from the earthquake of 1688. Moreover, Castel Capuano was the most affected by all of the historical earthquakes generally, as it suffered serious damages following the 1456, 1694 and 1805 earthquakes. Castel Nuovo (Maschio Angioino) was seriously damaged by the seismic events of 1688, 1694 and 1805.

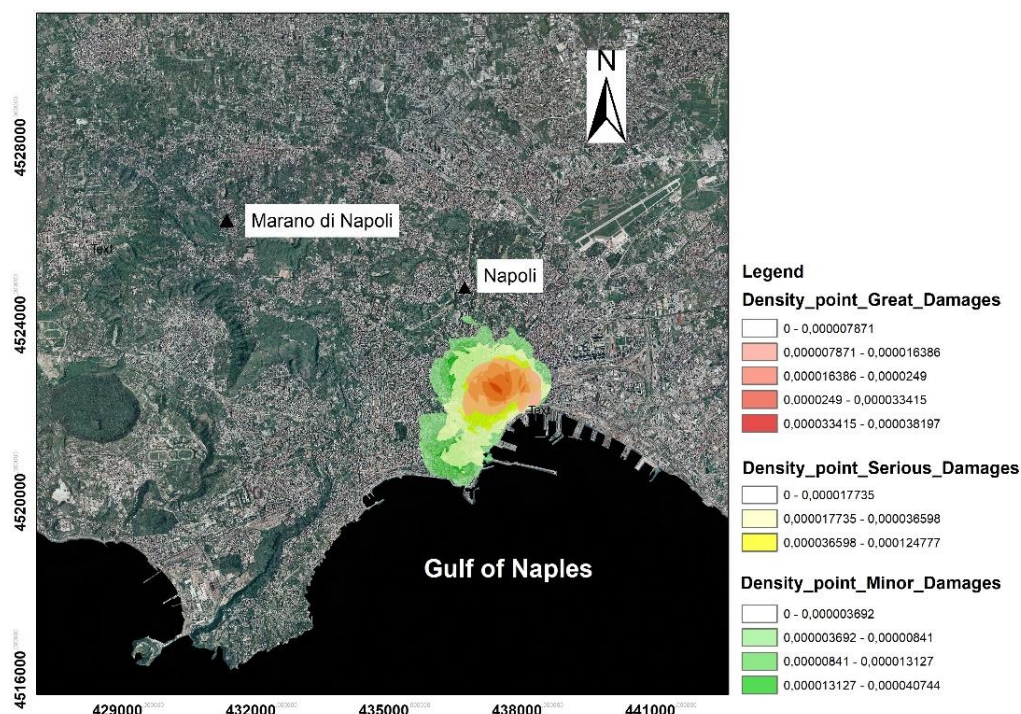


Figure 10. The map shows the areas with the same damage, represented as a density value, for all historical earthquakes felt in the city of Naples.

Considering the damage suffered by the churches, we observed that the Duomo (13th century), Santa Chiara (14th century), San Domenico Maggiore (13th century), San Lorenzo Maggiore (13th century), Santa Maria La Nova (13th century) and San Paolo Maggiore (16th century) churches suffered damage from almost all of the strong earthquakes under consideration (Figure 11). The Church of San Paolo Maggiore suffered great damage following the earthquake of 1688 and minor damage following the earthquake of 1694. The historical monumental building of the Albergo dei Poveri, among the largest buildings in Europe (18th century), showed a different damage compared to the churches and castles/fortresses as it had severe damage only resulting from the 1805 earthquake, and partial collapses due to the 1980 seismic event.

Our study shows that the vulnerability of buildings repeatedly damaged by earthquakes depends on very complex factors that go beyond the magnitude of the earthquakes themselves, the distance from the epicenter and the condition of the building, but also the geological substrate on which they were built, which in some cases can amplify the shaking due to the earthquake [5,23,59,60].

From this perspective, the seismic history of the recent past teaches us that other major events could also occur in the future and affect the city of Naples and its historical heritage again. Therefore, the “prevention” and preservation of architectural heritage appears to be the correct solution, together with respect for the regulations surrounding the construction of buildings in seismic zones. Accordingly, it is necessary to think about the methods of intervention, especially to reduce the risk of damage and/or the collapse of historical and monumental buildings. Therefore, a collective effort involving interdisciplinary action could address administrations and demand that they take prompt actions in order to protect the historical center of Naples, which was declared a World Heritage Site by UNESCO in 1995: “... considering that the site is of exceptional value. It is one of the most ancient cities in Europe, whose contemporary urban fabric preserves the elements of its long and eventful history. Its setting on the Bay of Naples gives it an outstanding universal value which has had a profound influence in many parts of Europe and beyond”.

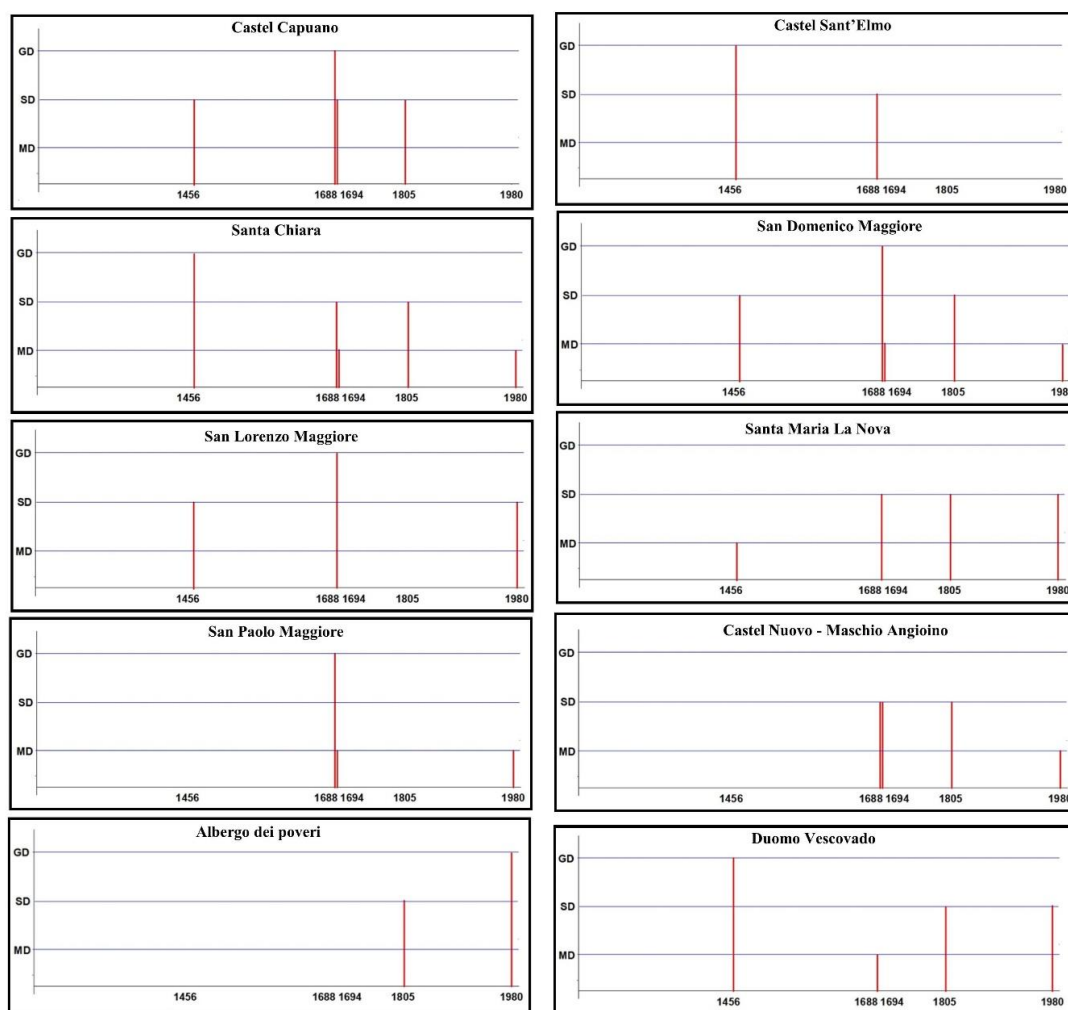


Figure 11. The graphs show the damage that the castles, historical buildings and churches suffered as a result of the historical earthquakes of the Southern Apennines.

5. Conclusions

The collected documentary and historical sources consulted has allowed us to evaluate the damage suffered by the historical buildings of Naples following the strongest historical earthquakes of the Apennines (Appendix A Table A1), and to perform the seismic macro-zoning of the ancient center of city (Figure 10). The damage level of the historical earthquakes of 5 December 1456, 5 June 1688 and 26 July 1805 have caused the highest level of damage (VIII on the MCS scale) in the historical center of city.

Moreover, we want to emphasize that the methodology used in this paper has allowed us to identify and classify the monumental buildings examined, a seismic history that has never been carried out by other authors. The same methodology can be extended and applied to other socio-cultural contexts globally [61].

The other result of significant scientific interest in this study is the density map of damages (Figure 10), which, for the first time, provides evidence of the areas of the historic center of Naples that are architecturally the most vulnerable to damage from strong earthquakes in the future (Figure 11). These data can be of fundamental importance for the construction of detailed maps of seismic microzonation by the technicians in charge (e.g., engineers, architects and geologists).

In conclusion, our study could be considered to contribute to the mitigation of seismic risk in the city of Naples [23,57,60], and provides useful advice on the protection of the historical heritage of Naples, whose historical center is a UNESCO World Heritage Site.

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Appendix A

Table A1. The table contains the strong historical earthquakes of the Southern Apennines and the earthquakes of the Neapolitan volcanic areas that were affected in the city of Naples [1, 8, 9, 10, 12].

Date	Epicentral Area	I ₀	M _w	I Naples	References
1293 09 04	Sannio-Matese	8–9	5.80	7	1
1349 09 09	Lazio-Molise	10	6.80	7–8	1
1386 03 17	Napoli	7–8	3.75	7–8	1
1406 09 16	Napoli	5	3.12	5	1
1456 12 05	Appennino centro-meridionale	11	7.19	8	1
1456 12 30 08 20	Appennino centro-meridionale			7	1
1457 01 08	Napoli	6	3.37	6	1
1457 02 10	Capua	5–6	4.40	3	1
1466 01 15 02 25	Irpinia-Basilicata	8–9	5.98	5	1
1468 05 26	Napoli	4		4	10
1470 01–1472 09	Pozzuoli	7			10
1475 08 11	Napoli	4–5		4–5	10
1496 11 09	Napoli	4		4	10
1498 10 07	Campi Flegrei (Pozzuoli)	5–6	3.25	5	1; 10
1498 10 19	Campi Flegrei (Pozzuoli)	5–6		5	10
1498 10 20	Campi Flegrei (Pozzuoli)	7	3.63	3	1; 10
1499 03 18 00 45	Napoli	4–5		4–5	10
1499 03 18 01 45	Napoli	5	3.12	5	1; 10
1505 05 18 08 55	Campi Flegrei (Agnano)	8 [5]	3.75	6	1; 10
1508 01 25 15 20	Napoli	4–5		4–5	10
1508 04 25	Pozzuoli	8			10

Table A1. Cont.

Date	Epicentral Area	I ₀	Mw	I Naples	References
1508 07 19 08 55	Napoli	5	3.12	5	1; 10
1517 03 29 19	Irpinia	7–8	5.33	5	1
1520 01 28 23 50	Campi Flegrei (Pozzuoli)	6–7	3.50	5	1; 10
1536 08 07	Napoli	5	3.12	5	1; 10
1537 02 14	Campi Flegrei (Pozzuoli)	7–8 [5]	3.50	4	1; 10
1538 04 20	Napoli	6 [5]	3.25	6	1; 10
1538 09 20	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 22	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 23	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 24	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 25	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 26	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 27	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 28 06 00	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 28 17 30	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 29 11 00	Campi Flegrei (Pozzuoli)	5–6	3.25	4	1; 10
1538 09 29 18 30 (eruption)	Campi Flegrei (Pozzuoli)	8	3.88	5	1; 10
1560 05 11 04 40	Costa Pugliese centrale	8	5.66	3	1
1561 07 31 20 10	Penisola sorrentina	8	5.56	7	1
1561 08 19 15 50	Vallo di Diano	10	6.72	4–5	1
1564 07	Campi Flegrei	4–5 (5)	3.12	5–6	1; 10
1566 05 06 22 45	Napoli	5	3.12	5–6 [5]	1; 10
1568 12 27	Campi Flegrei (Pozzuoli)	6	3.37	4–5	1; 10
1570 04 30 23 06	Campi Flegrei (Pozzuoli)	6–7	3.50	5	1; 10
1570 06 17	Pozzuoli	4–5		4	10
1575 06 05 20 30	Napoli	5–6	3.25	6–7	1
1580 06 09 07 10	Campi Flegrei (Pozzuoli)	4–5		4	10
1582 06 05 07 08	Campi Flegrei (Pozzuoli)	8	3.88	5	1; 10
1601 08 10 UT	Napoli	5	3.12	5	1
1616 01 12 20 20 UT	Napoli	5	-	5	8
1616 12 07/08 20 05 UT	Napoli	5		5	8
1620 03 20 UT	Napoli	5		5	8
1621 08 10 00 40 UT	Napoli	5		5	8
1622 02 25 05 40 UT	Napoli	5		5	8
1622 04 10 UT	Napoli	5		5	8
1622 11 06 18 55 UT	Napoli	5		5	8
1622 11 06 21 25UT	Napoli	4		4	8
1626 03 10 00 40 UT	Napoli	6–7		6–7	8
1626 03 10 22 15 UT	Napoli	4		4	8
1626 03 15 19 05 UT	Napoli	4		4	8
1626 03 22 05 15 UT	Napoli	3		3	8
1626 09 08 04 55 UT	Napoli	3		3	6
1626 10 21 13 45 UT	Napoli	3		3	8
1626 10 27 12 40 UT	Napoli	3		3	8
1626 11 02 23 15 UT	Napoli	4		4	8

Table A1. Cont.

Date	Epicentral Area	I ₀	Mw	I Naples	References
1627 07 30 10 50	Capitanata	10	6.66	5	1
1630 04 02 06 50 UT	Napoli	5		5	8
1631 12	Area Vesuviana	5–6	3.25	5–6	1
1631 12 15 21UT	Area Vesuviana	5–6		3	8
1631 12 15 23UT	Area Vesuviana	7			8
1631 12 17	Area Vesuviana	7	5.17		4
1638 03 27 15 05	Calabria centrale	11	7.09	3	1
1646 05 31	Gargano	10	6.72	5	1
1657 01 29 02	Capitanata	8–9	5.96	4–5	1
1685 05	Penisola Sorrentina	5–6	4.73	5	1
1687 04 25 00 30	Penisola Sorrentina	6	4.63	5	1
1688 06 05 15 30	Sannio	11	7.06	8	1
1688 07 23	Capitanata	7–8	5.33	3	1
1688 08 14	Beneventano	6–7	4.86	3	1
1692 03 04 22 20	Irpinia	8	5.88	5	1
1694 09 08 11 40	Irpinia-Basilicata	10	6.73	7	1
1694 10 09	Avellino	5–6	4.40	3	1
1702 03 14 04 30	Sannio-Irpinia	6–7	4.86	5	1
1702 03 14 05	Sannio-Irpinia	10	6.56	6	1
1702 04 02 06 20	Sannio-Irpinia	6–7	4.86	4–5	1
1703 01 14 18	Valnerina	11	6.92	3–4	1
1703 01 16 13 30	Appennino laziale-abruzzese			3	1
1703 02 02 11 05	Aquilano	10	6.67	3	1
1706 11 03 13	Maiella	10–11	6.84	4–5	1
1720 08 28	Cassinese	5–6	4.35	5	1
1731 03 20 03	Tavoliere delle Puglie	9	6.33	5	1
1731 10 17 11	Tavoliere delle Puglie	6–7	4.86	4–5	1
1732 11 29 07 40	Irpinia	10–11	6.75	7	1
1733 05 15 00 30	Puglia			3	1
1735 01 26	Casertano	5	4.16	3–4	1
1737 03 31 17 20	Monti di Avella	7	5.10	4	1
1739 02 12 21 30	Tavoliere delle Puglie	5–6	4.40	3	1
1739 02 27 04 20	Benevento	5–6	4.40	4	1
1741 08 06 13 30	Irpinia	7–8	5.44	4	1
1742 08 17	Napoli	5–6	3.25	5–6	1
1743 02 20	Ionio settentrionale	9	6.68	4–5	1
1756 10 22 14	Napoletano	6–7	3.50	6–7	1
1760 12 23	Area vesuviana	6–7	3.50	4–5	1
1777 06 06 16 15	Tirreno meridionale			4–5	1
1779 10 01 00 45	Napoletano	6	3.37	4	1
1779 12 12	Napoletano	6	3.37	3	1
1783 03 28 18 55	Calabria centrale	11	7.03	4	1
1794 06 12 22 30	Irpinia	7	5.26	5	1
1794 06 15	Area vesuviana	4	2.87	3	1

Table A1. Cont.

Date	Epicentral Area	I ₀	Mw	I Naples	References
1805 07 26 21	Molise	10	6.68	7–8	1
1805 10 13 22	Pianura Campana	7	5.10	3	1
1806 08 26 07 35	Colli Albani	8	5.61	3–4	1
1814 11 25	Beneventano	5–6	4.40	3	1
1817 04 17	Potentino	4–5	3.97	3	1
1821 11 22 01 15	Costa molisana	7–8	5.59	3	1
1826 02 01 16	Potentino	8	5.74	3	1
1826 10 26 18	Salento	6–7	5.22	3	1
1832 03 08 18 30	Crotone	10	6.65	3	1
1836 04 25 00 20	Calabria settentrionale	9	6.18	3–4	1
1836 11 20 07 30	Appennino lucano	8	5.86	5	1
1841 02 21	Gargano	6–7	5.17	3	1
1846 08 08	Potentino	6–7	5.18	3	1
1851 08 14 13 20	Vulture	10	6.52	5	1
1851 08 14 14 40	Vulture	7–8	5.48	3–4	1
1853 04 09 12 45	Irpinia	8	5.60	4	1
1857 12 16 21 15	Basilicata	11	7.12	6	1
1858 03 07 14	Campania meridionale	7–8	5.39	3	1
1858 05 24 09 20	Tavoliere delle Puglie	4–5	4.35	3	1
1861 12 09	Torre del Greco	5–6	3.25	3	1
1870 10 04 16 55	Cosentino	9–10	6.24	3	1
1874 12 06 15 50	Val Comino	7–8	5.48	4	1
1875 12 06	Gargano	8	5.86	6–7	1
1881 09 10 07	Chietino	7–8	5.41	3	1
1882 06 06 05 40	Isernino	7	5.20	5	1
1883 07 28 20 25	Isola d'Ischia	9–10	4.26	5	1
1893 01 25	Vallo di Diano	7	5.15	3–4	1
1895 02 01 07 24 3	Monti del Partenio	5	4.29	3–4	1
1895 08 09 17 38 2	Adriatico centrale	6	5.11	3	1
1901 07 31 10 38 3	Sorano	7	5.16	3–4	1
1903 05 04 03 44	Valle Caudina	7	4.69	3	1
1903 12 07 05 58	Beneventano	4–5	4.14	3	1
1905 03 14 19 16	Avellinese	6–7	4.90	4–5	1
1905 08 25 20 41	Valle Peligna	6	5.15	3	1
1905 09 08 01 43	Calabria centrale	10–11	6.95	3–4	1
1905 11 26	Irpinia	7–8	5.18	3–4	1
1907 12 18 19 21	Monti Picentini	5–6	4.52	3	1
1908 12 28 04 20 2	Stretto di Messina	11	7.10	3	1
1910 06 07 02 04	Irpinia-Basilicata	8	5.76	4	1
1913 10 04 18 26	Molise	7–8	5.35	4	1
1915 01 13 06 52 4	Marsica	11	7.08	5	1
1922 12 29 12 22 0	Val Roveto	6–7	5.24	3	1
1923 11 08 12 28	Appennino campano-lucano	6	4.73	3	1
1924 03 26 20 50	Sannio	4	4.06	3	1
1924 05 09 05 48	Irpinia	4	4.71	3–4	1

Table A1. Cont.

Date	Epicentral Area	I ₀	Mw	I Naples	References
1927 05 25 02 50	Sannio	6	4.98	4	1
1930 04 27 01 46	Salernitano	7	4.98	4	1
1930 07 23 00 08	Irpinia	10	6.67	7	1
1930 10 30 07 13	Senigallia	8	5.83	3	1
936 04 03 18 42	Valle Caudina	5–6	4.25	3	1
1948 08 18 21 12 2	Gargano	7–8	5.55	3	1
1962 08 21 18 19	Irpinia	9	6.15	6–7	1
1971 05 06 03 45 0	Irpinia	6	4.83	4	1
1973 08 08 14 36 2	Appennino campano-lucano	5–6	4.75	3	1
1975 06 19 10 11	Gargano	6	5.02	4	1
1979 09 19 21 35 3	Valnerina	8–9	5.83	4	1
1980 06 14 20 56 5	Marsica	5–6	4.96	3	1
1980 11 23 18 34 5	Irpinia-Basilicata	10	6.81	7	1
1980 12 03 23 54 2	Irpinia-Basilicata	6	4.83	4	1
1981 01 09 00 12 4	Irpinia-Basilicata	5–6	4.36	3–4	1
1981 02 14 17 27 4	Monti di Avella	7–8	4.88	5–6	1
1982 03 21 09 44 0	Golfo di Policastro	7–8	5.23	4	1
1983 10 04 08 09	Campi Flegrei	6	4.0	5–6	9
1984 05 07 17 50	Monti della Meta	8	5.86	5–6	1
1996 04 03 13 04 3	Irpinia	6	4.90	3	1
1999 10 09 05 41 0	Area vesuviana	5	3.24	4	1
2002 11 01 15 09 0	Molise	7	5.72	3–4	1

Table A2. The historical buildings of Naples damaged by the earthquake of 1456 [5,42]. MD = Minor Damage; SD = Serious Damage; GD = Great Damage.

Original Name	Type of Building	Age of Building (Century)	Damages	Long. Lat. (UTM)
Certosa di San Martino	Church/Monastery	14th	SD	4521651 436027
Duomo/Vescovado	Cathedral	13th	GD	4522649 437588
Sant' Agostino alla Zecca	Church	13th	GD	4522283 437870
Sant' Agrippino a Forcella	Church	13th	GD	4522431 437800
Sant' Anna dei Lombardi/Santa Maria di Monteoliveto	Monastery	15th	SD	4521801 436820
Santissima Annunziata Maggiore a Forcella	Church	13th rebuilt 16th and 18th	MD	4522498 438049
Santa Chiara	Church/Monastery	14th	GD	4521985 437035
San Domenico Maggiore	Church	13th	SD	4522232 437151
San Giovanni Maggiore	Church	4th rebuilt in 6th	SD	4521869 437242
San Lorenzo Maggiore	Church	13th	SD	4522474 437466
Santa Maria del Carmine Maggiore	Church/Monastery	12th	SD	4522010 438260
Santa Maria Maggiore alla Pietrasanta	Church	17th	SD	4522415 437148
Santa Maria La Nova		13th	MD	4521684 437042
San Pietro Martire	Church	13th	SD	4521789 437434
Santi Severino e Sossio	Church /Monastery	10th	SD	4522122 437478
Castel Capuano	Fortress Castle	12th	SD	4522729 437980
Castel Sant'Elmo	Fortress Castle	14th	GD	4521698 435848

Table A3. The historical buildings of Naples damaged by the 1688 earthquake [5–7,14]; MD = Minor Damage; SD = Serious Damage; GD = Great Damage.

Original Name	Type of Building	Age of Building (Century)	Damages	Long./Lat. (UTM)
Certosa di San Martino	Church	14th	MD	4521651 436027
Croce di Lucca		16th	SD	4522364 437090
Gesù Nuovo (ex palazzo Sanseverino di Salerno)	Church	16th	GD	4522111 436931
Gesù Vecchio	Church	16th rebuilt in 17th	SD	4522009 437369
Madonna della Pietà/Madonna della Pietà dei Turchini	Church	16th	MD	4521402 436995
Sant'Agostino degli Scalzi/Santa Maria della Verità	Church	17th	GD	4522994 436593
Santissima Annunziata Maggiore a Forcella	Church	13 rebuilt in 16th and 18th	MD	4522498 438049
Sant'Antonio delle Monache a Port'alba	Church	16th	MD	4522421 436973
Santissimi Apostoli		5th	MD	4522875 437657
Santa Chiara	Church	14th	SD	4521985 437035
San Diego all'Ospedaletto/Spedaletto/San Giuseppe Maggiore/	Church/Monastery	16th	MD	4521526 437022
San Domenico Maggiore	Church	13th	GD	4522232 437151
San Filippo e Giacomo	Church	16th	MD	4522245 437383
San Gaudioso	Church	8th demolished in 20th	GD	4522654 437097
San Giorgio Maggiore	Church	4th–5th rebuilt after 17th	MD	4522332 437677
San Gregorio Armeno/S. Liguoro	Church	8th rebuilt in 16th	SD	4522390 437425
San Lorenzo Maggiore	Church	13th	GD	4522474 437466
Santa Maria del Carmine Maggiore	Church/Monastery	12th rebuilt in 13th	GD	4522010 438260
Santa Maria Donnalbina	Church	9th rebuilt 17th	MD	4521772 436991
Santa Maria Maggiore alla Pietrasanta		6th rebuilt in 17th	GD	4522415 437148
Santa Maria ai Monti/Santa Maria ai Monti dei Pii Operari (Capodimonte)	Church	17th	SD	4525595 438190
Santa Maria della Sanità/San Vincenzo	Church	17th	MD	4523452 436700
Santa Maria del Soccorso all'Arenella	Church	17th	SD	4522767 435228
San Nicola alla Carità	Church	17th	MD	4521870 436689
San Paolo Maggiore	Church	16th	GD	4522531 437358
Santi Severino and Sossio/San Severino dei Benedettini	Church	10th	MD	4522122 437478
San Severo al Pendino	Church	16th	MD	4522275 437666
Santa Teresa degli Scalzi	Church	17th	MD	4522916 436713
San Tomaso d'Aquino	Church	16th demolished in 20th	MD	4522328 436988
Castel Sant'Elmo	Fortress Castle	14th	SD	4521698 435848
Castel Capuano	Fortress Castle	12th	GD	4522729 437980
Castel Nuovo (Maschio Angioino)	Fortress Castle	13th	SD	4521087 436995
Palazzo reale	Palace	17th		4520844 436731
Torione del Carmine	Fortress	14th rebuilt in 16th	SD	4521932 438341

Table A4. The historical buildings of Naples damaged by the 1694 earthquake [2,43]. MD = Minor Damage; SD = Serious Damage; GD = Great Damage.

Original Name	Type of Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Certosa di San Martino	Church	14th	SD	4521651 436027
Croce di Lucca	Church	16th	MD	4522364 437090
Duomo Vescovado	Cathedral	13th	MD	4522649 437588
Gesù e Maria	Church/Monastery	16th	MD	4522553 436290
Gesù Nuovo (ex palazzo Sanseverino di Salerno)	Church	16th	SD	4522111 436931
Girolamini/San Filippo Neri	Church	16th	SD	4522585 437498
Sant'Agostino degli Scalzi/Santa Maria della Verità	Church	17th	MD	4522994 436593
Santissima Annunziata Maggiore a Forcella	Church	13th rebuilt in 16th and 18th	MD	4522498 438049
Sant'Antonio delle Monache a Port'Alba	Church	16th	MD	4522421 436973
Santa Chiara	Church	14th	MD	4521985 437035
San Domenico Maggiore	Church	13th	MD	4522232 437151
San Gaudioso	Church	8th demolished in 20th	SD	4523476 436706
San Giovanni a Carbonara	Church/Monastery	14th	MD	4523037 437661
San Giovanni a Mare	Church	12th	MD	4521981 437896
San Gregorio Armeno/San Liguoro	Church	16th	MD	4522390 437425
Santa Maria del Carmine Maggiore	Church/Monastery	12th	SD	4522010 438260
Santa Maria Donnaregina vecchia	Church	14th	MD	4522873 437498
Santa Maria Maddalena dei Pazzi	Church	17th	SD	4522697 436312
Santa Maria Maggiore alla Pietrasanta	Church	6th rebuilt in 17th	SD	4522415 437148
Santa Maria la Nova	Church	13th	SD	4521684 437042
Santa Maria della Pace	Church	16th	MD	4522624 437788
Santa Maria della Sanità	Church /Monastery	XVII	MD	4523452 436700
San Michele Arcangelo	Church	17th rebuilt in 18th	SD	4522188 436759
San Paolo Maggiore	Church	16th	MD	4522531 437358
Santi Severino e Sossio	Church	10th	SD	4522122 437478
Santa Teresa degli Scalzi	Church/Monastery	17th	MD	4522916 436713
Castel Capuano	Fortress/Castle	12th	SD	4522729 437980
Castel Nuovo (Maschio Angioino)	Fortress/Castle	13th	SD	4521087 436995
Regio Arsenale	Fortress	16th destroyed in the early 20th	SD	4520755 436908
Casamatta a Porta Nolana	Building	16th	GD	4522395 438291
Palazzo Carafa d'Andria	Palace	15th	SD	4522105 437447
Palazzo Carafa di Maddaloni	Palace	16th	SD	4521980 436753
Palazzo Pignatelli di Monteleone	Palace	16th	SD	4522003 436881
Presidio di Pizzofalcone (Caserma Nino Bixio)	Palace	17th	MD	4520342 436470

Table A5. The historical buildings of Naples damaged by the 1805 earthquake [1,5–7,44,45,49,50]. MD = Minor Damage; SD = Serious Damage; GD = Great Damage.

Original Name	Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Certosa di San Martino	Church/Monastery	14th	SD	4521651 436027
Croce di Lucca		16th	SD	4522364 437090
Divino Amore	Church	18th	SD	4522306 437609
Duomo (Vescovado)	Church	13th	SD	4522649 437588
Gesù e Maria	Church/Monastery	16th	MD	4522553 436290
Gesù vecchio		16 threbuilt in 17th	SD	4522009 437369
Girolamini o San Filippo Neri		16th	SD	4522585 437498
Sant' Agnello Maggiore	Church/Monastery	9th	SD	4522738 437000
Sant' Agostino alla Zecca o Sant' Agostino Maggiore	Church/Monastery	13th rebuilt after 1456 earthquake	SD	4522283 437870
Sant' Agrippino a Forcella		13th	SD	4522431 437800
Sant' Anna dei Lombardi/Monteoliveto	Church/Monastery	15th	SD	4521801 436820
Sant' Anna di Palazzo/San Rosario di Palazzo	Church/Monastery	16th	MD	
Santissimi Apostoli	Church	5th	SD	4522875 437657
Santa Brigida a Toledo	Church/Monastery	17th	SD	4521152 436699
San Carlo alle Mortelle	Church/Monastery	17th	MD	4521123 436034
Santa Caterina di Siena	Church/Monastery	16th	SD	4521177 436169
Santa Chiara	Church/Monastery	14th	SD	4521985 437035
San Demetrio e Bonifacio ai Banchi nuovi	Church	18th	SD	4521808 437163
San Domenico Maggiore	Church/Monastery	13th	SD	4522232 437151
Sant' Efreimo nuovo	Church/Monastery	17th	SD	4522809 436357
San Francesco delle Monache	Church	14th	SD	
San Geronimo delle Monache	Church	15th	SD	4522064 437241
San Giovanni Maggiore	Church	4th rebuilt in 6th	MD	4521869 437242
San Luigi a Palazzo	Church/Monastery		MD	4520747 436555
Santa Maria degli Angeli a Pizzofalcone	Church/Monastery	16 threbuilt in 17th	MD	4520751 436311
Santa Maria Apparente	Church	16th	MD	4521269 435796
Santa Maria del Carmine Maggiore	Church/Monastery	12th	SD	4522010 438260
Santa Maria Donnalbina	Church/Monastery	9th rebuilt in 17th	SD	4521772 436991
Santa Maria Donnaregina vecchia	Church/	14th	SD	4522873 437498
Santa Maria Egiziaca a Pizzofalcone	Church/Monastery	17th	SD	4520617 436504
Santa Maria delle Grazie (Monastero dei Teatini di Santa Maria delle Grazie a Toledo)	Church/Monastery	17th	SD	4521564 436669
Santa Maria Maddalena dei Pazzi e del SS. Sacramento	Church/Monastery	17th	MD	4522697 436312
Santa Maria della Mercede a Montecalvario dell'Ordine Franciscano	Church	16th	SD	4521557 436418
Santa Maria la Nova	Church/Monastery	13th	SD	4521684 437042
Santa Maria della Sapienza;	Church/Monastery	17th	SD	4522492 436956
Santa Maria della Solitaria	Church/Monastery	16th demolished in 19th	MD	4520622 436612
Santa Maria della Vittoria	Church/Monastery	16th	SD	4520482 436077
San Paolo Maggiore	Church/Monastery	16th	SD	4522531 437358
San Pietro ad Aram	Church	12th rebuilt in 17th	SD	4522511 438192

Table A5. Cont.

Original Name	Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
San Potito	Church/Monastery	17th	MD	4522600 436728
San Severo fuori le mura (Conventuali a Capodimonte)	Church	16th	SD	4523579 436923
Santissimo Spirito dei padri Verginiani	Church/Monastery	16th	SD	4522055 436698
San Tommaso d'Aquino	Church/Monastery	16th demolished in 20th	SD	4522328 436988
Castel Capuano	Fortress/Castle	12th	SD	4522729 437980
Castel Nuovo (Maschio Angioino)	Fortress /Castle	13th	SD	4521087 436995
Castel dell'Ovo	Fortress/Castle	12th	SD	4519963 436531
Albergo dei Poveri	Palace	18th	SD	4523860 438097
Collegio militare dell' Annunziata	Palace	16th	MD	4520452 436290
Reggia di Capodimonte	Palace	18th	MD	4524258 436839
Palazzo Cellammare/Francavilla	Palace H	16th	SD	4520834 436108
Palazzo del Duca della Regina	Palace	15th	SD	4522234 437286
Palazzo dei Granili	Palace	18th	SD	4521587 439667
Palazzo Salluzzo di Corigliano	Palace	16th	GD	4522210 437225
Palazzo del Principe d'Angri (Palazzo Doria d'Angri)	Palace	18th	SD	4522029 436745
Palazzo dei Principi di Roccella (Carafa di Roccella)	Palace	17th	SD	4520935 435668
Palazzo Reale	Palace	17th	MD	4520844 436731
Palazzo dei Regi studi (Museo Archeologico Nazionale)	Palace	16th	SD	4522751 436825
Palazzo de Sangro di Sansevero	Palace	16th	SD	4522252 437179
Ponte della Maddalena	Bridge	16th	SD	4523495 436666

Table A6. The historical buildings of Naples damaged by the 1980 earthquake [5–7,14,56–58] and the estimated level of damage. (GD Great damage; SD Serious damage; MD Minor damage).

Original Name	Type of Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Cappella Sansevero/chiesa di Santa Maria della Pietà		16th-	MD	4522283 437191
Compagnia della Disciplina della Croce	Church	13th	SD	4522328 437891
Divino Amore/San Camillo	Church	17th	SD	4522306 437609
Duomo/Vescovado	Church	13th	SD	4522649 437588
Eremo dei Camaldoli	Church	16th	MD	4523330 431905
Gesù e Maria	Church	16th	SD	4522553 436290
Gesù delle Monache	Church/Monastery	16th	SD	4522891 437330
Gesù Nuovo	Church	16th	MD	4522111 436931
Girolamini	Church/Monastery	16th	SD	4522585 437498
Monte di Pietà	Church	16th	MD	4522249 437430
Nunziata/Santissima Annunziata	Church	16th	MD	4520482 436315
Padri della Missione Vincenziani	Church	17th	MD	4523166 437203
Pio Monte della Misericordia	Church	17th	MD	4522577 437661
Regina Paradisi ai Guantai ai Camaldoli	Church	19th	MD	4524483 431849
Sant'Agostino degli Scalzi/Santa Maria della Verità	Church	17th	SD	4522994 436593

Table A6. Cont.

Original Name	Type of Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Sant' Agostino alla Zecca o Maggiore	Church	13th rebuilt after 1456 earthquake	SD	4522283 437870
Sant' Anna dei Lombardi/Santa Maria di Monteoliveto	Church	15th	SD	4521801 436820
Sant' Anna di Palazzo/San Rosario di Palazzo	Church	16th	SD	4521076 436432
Santissima Annunziata Maggiore a Forcella	Church	13th rebuilt in 16th and 18th	SD	4522498 438049
Sant' Antonio Abate	Church	13th	MD	4523619 438068
Santi Antonio e Alfonso a Tarsia	Church	16th	MD	4522261 436453
Santissimi Apostoli	Church	5th	SD	4522875 437657
Sant' Aspreno ai Crociferi	Church	17th	SD	4523076 437293
San Biagio Maggiore	Church	17th	MD	4522311 437484
Santa Caterina a Chiaia	Church	17th	MD	4520730 436096
Santa Caterina a Forniello	Church	16th	SD	4522860 438026
Santa Chiara	Church	14th	MD	4521985 437035
San Demetrio e Bonifacio ai Banchi Nuovi	Church	18th	SD	4521808 437163
San Diego all'Ospedaletto o San Giuseppe Maggiore	Church	16th	MD	4521526 437022
San Domenico Maggiore	Church	13th	MD	4522232 437151
San Domenico Soriano	Church	17th	SD	4522281 436745
Santi Filippo e Giacomo	Church	16th	SD	4522245 437383
San Gennaro al Vomero	Church	19th	SD	4521828 435199
Santa Geltrude	Church	20th	MD	4522668 436411
San Giorgio Maggiore	Church	4th–5th rebuilt after 17th	SD	4522332 437677
San Giovanni a Carbonara	Church	14th	SD	4523037 437661
San Giovanni dei Fiorentini al Vomero	Church	20th	MD	4522253 434946
San Giovanni del Sovrano Ordine di Malta o (Santi Bernardo e Margherita) Chiesa dell'Ordine di Malta	Church	17th–18th	MD	4522698 436527
San Giuseppe dei Nudi	Church	17th	MD	4522690 436613
San Giuseppe dei Vecchi	Church	17th	MD	4522587 436500
San Gregorio Armeno	Church	16th	MD	4522390 437425
San Lorenzo Maggiore	Church	13th	SD	4522474 437466
Santi Marcellino e Festo	Church	Monasterys 7th–8th Church 17th	MD	4522047 437495
Santa Maria degli Angeli alle Croci	Church	16th	MD	4523651 437646
Santa Maria degli Angeli a Pizzofalcone	Church	16th rebuilt in 17th	MD	4520751 436311
Santa Maria delle Anime del Purgatorio ad Arco	Church	17th	MD	4522436 437262
Santa Maria Avvocata	Church	16th	MD	4522410 436664
Santa Maria di Caravaggio	Church	17th	MD	4522384 436750
Santa Maria del Carmine Maggiore	Church	12th	SD	4522010 438260
Santa Maria della Consolazione (centro storico)	Church	16th	MD	4522854 437270
Santa Maria Donnalbina	Church	9th rebuilt in 17th	SD	4521772 436991
Santa Maria Donnaregina nuova	Church	17th	MD	4522814 437517

Table A6. Cont.

Original Name	Type of Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Santa Maria Donnaregina vecchia	Church	14th	MD	4522873 437498
Santa Maria Egiziaca a Forcella	Church	14th	SD	4522326 437984
Santa Maria Egiziaca a Pizzofalcone	Church	17th	MD	4520617 436504
Santa Maria delle Grazie (Monastero dei Teatini di Santa Maria delle Grazie a Toledo)	Church	17th	MD	4521564 436669
Santa Maria Incoronata	Church	14th	MD	4521399 436946
Santa Maria dei Miracoli	Church	17th	MD	4523352 437314
Santa Maria di Montesanto	Church	17th	MD	4522124 436398
Santa Maria ai Monti	Church	17th	GD	4525595 438190
Santa Maria la Nova	Church	13th	SD	4521684 437042
Santa Maria Ognibene	Church	17th	MD	4521739 436399
Santa Maria della Paziienza alla Cesarea	Church	17th	MD	4522529 436051
Santa Maria a Piazza	Church	4th	MD	4522456 437805
Santa Maria del Popolo agli Incurabili	Church	16th	SD	4522817 437193
Santa Maria della Provvidenza alla Salute	Church	18th	SD	4522921 435893
Santa Maria Regina Coeli	Church	16th	SD	4522617 437143
Santa Maria della Sanità	Church	17th	MD	4523452 436700
Santa Maria della Stella	Church	16th	SD	4523025 436926
San Nicola alla Carità	Church	17th	MD	4521870 436689
San Nicola al Nilo	Church	17th	MD	4522270 437350
San Nicola di Tolentino	Church	17th	MD	4521302 436069
San Paolo Maggiore	Church	16th	MD	4522531 437358
San Pasquale a Chiaia	Church	18th	MD	4520645 435593
San Pietro ad Aram	Church	12th rebuilt in 17th	SD	4522511 438192
San Pietro a Maiella	Church	13th	SD	4522321 437031
San Pietro Martire	Church	13th	SD	4521789 437434
San Potito	Church	17th	MD	4522600 436728
San Raffaele a Materdei	Church	18th	MD	4522953 436280
Santa Maria del Rosario alle Pigne/ Rosariello	Church	17th	SD	4522925 437068
Santi Severino e Sossio	Church	10th	SD	4522122 437478
San Severo fuori le mura a Capodimonte	Church	16th	MD	4523579 436923
Santa Teresa dei Carmelitani Scalzi	Church	17th	SD	4522916 436713
Santissima Trinità dei Pellegrini	Church	16th	SD	4522105 436564
Castel Nuovo (Maschio Angioino)	Fortress Castle	13th	MD	4521087 436995
Torre dei Franchi (Soccavo)	Tower	15th	SD	4522682 432058
Albergo dei poveri	Palace	18th	GD	4523860 438097
Archivio di Stato (Monastero Santi Severino e Sossio)	Palace	10th	MD	4522192 437563
Biblioteca Nazionale Vittorio Emanuele III nel Palazzo Reale	Palace	17th	MD	4520844 436731
Biblioteca dei Padri Passionisti	Palace	17th	MD	4525622 438181
Biblioteca Universitaria (Casa del Salvatore)	Palace	16th	MD	4522057 437371

Table A6. Cont.

Original Name	Type of Building	Age of Building (Century)	Damages	Long., Lat. (UTM)
Museo Archeologico Nazionale (Palazzo dei Regi studi)	Palace	16th	GD	4522751 436825
Museo Civico Filangieri (Palazzo Como)	Palace	15th	MD	4522248 437683
Museo Diego Aragona Pignatelli Cortez (Villa Pignatelli, Riviera di Chiaia)	Palace	19th	SD	4520712 435375
Museo Nazionale di San Martino (Certosa di San Martino)	Palace	14th	SD	4521620 435988
Palazzo del Principe d'Angri (Palazzo Doria d'Angri)	Palace	17th	MD	4522029 436745
Palazzo Cellamare/Francavilla	Palace	16th	MD	4520834 436108
Palazzo Sangro di Sansevero	Palace	16th	SD	4522283 437191
Palazzo Spinelli di Laurino	Palace	15th	MD	4522385 437250
Pinacoteca del Pio Monte della Misericordia	Palace	17th	MD	4522577 437661
Villa Patrizi	Palace	17th	MD	4520765 433504

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