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A geodatabase of historical landslide events occurred in the highly urbanized volcanic area of Campi Flegrei, Italy

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Abstract. The analysis of geological processes threatening people and properties in a populated region should be based on a comprehensive knowledge of historical events and related characteristics. This type of information is essential for predisposing event scenarios, validating prediction models, and planning risk mitigation measures. Such activities may be more complex in some geological settings, where urban settlements are exposed to multi-hazard conditions. This is the case of the densely populated Campi Flegrei volcanic area located in the Campania region, southern Italy. Here, volcanic and seismic hazards are associated with landslides, floods, and coastal erosion, which are playing a relevant role in the landscape modelling. The CAmpi Flegrei LAndslide Geodatabase (CAFLAG), here presented, provides information related to 2302 landslides that occurred in the continental, coastal and insular sectors of this area, during the 1828-2017 time interval. Data associated to the collected landslide events permitted to identify the characteristics of both landslides and of the affected sites. Most of the mass movements consist of rock falls, affecting rocky slopes formed by lithified volcanic rocks, such as lava, tuff or ignimbrite. In addition, rainfall-induced earth and debris slides translating into debris flows or avalanches occur along steep slopes mantled by weakly welded pyroclastic airfall deposits, similarly to other areas of the region. The highest density of landslides results along the coastline where they are contributing to the retreat of coastal cliffs, and along inland slopes exposed towards the western directions. Temporal information shows an increase of the annual frequency of landslides since the'80s, with peaks in the years 1986, 1997, 2005. Regarding the human impact, a total of 127 people lost their life as consequence of 53 fatal landslides occurred in the last century. On the other side, the frequency of deadly events is decreasing since the early 1990s. Despite this, landslides continue to represent a societal risk in the area, requiring therefore to be fully addressed with advanced knowledge and accurate scenarios, which need to be developed by taking into account also the effects of the ongoing climate change. The full database is freely available online at https://doi.org/10.4121/14440757.v2 (Esposito and Matano, 2021).

1 Introduction

Landslides are among the most effective agents in the landform evolution, also in areas affected by active volcano-tectonic processes. Here, landslides contribute to the dismantling of volcanic edifices by displacing rock masses that form the volcanic flanks (Siebert and Roverato, 2021; Di Traglia et al., 2020; Williams et al., 2019; Walter et al., 2019; Oehler et al., 2004; Ablay and Hürlimann, 2000), involving in some cases the submarine domain of the edifices (Dufresne et al., 2021; Coombs et al., 2007; Masson et al., 2006; Watts et al., 2012; Casalbore et al., 2020; Chiocci et al., 2008). Weakly welded pyroclastic deposits covering volcanic or non-volcanic slopes can be also mobilized in response to rainfall or snow and ice melting, by means of rapid or extremely rapid debris and hyperconcentrated flows resulting in the so-called "lahars" (Lavigne and Thouret, 2002; Capra et al., 2004; Esposito et al., 2017, 2019; Thouret et al., 2020). Lahars may be "syn-eruptive" if they occur simultaneously with volcanic activity, or "secondary" (i.e. "post-eruptive lahars") when occurring during pauses in volcanic activity or volcano dormancy (Pierson et al., 2014). This poses additional risk for urban settlements already exposed to volcanic processes, also during non-active volcanic phases as demonstrated by several geo-hydrological disasters worldwide.

In Italy, the highly urbanized area of Campi Flegrei (Fig. 1) corresponds to an active volcanic caldera considered among those with the highest volcanic risk in the world (De Natale et al., 2006). For this reason, scientific research on this area has been mostly focused on volcanic and seismic hazards, while relatively poor attention has been paid towards exogenous processes such as landslides, floods, and coastal erosion. As a result, the risk posed by landslides in the Campi Flegrei volcanic area is currently underestimated both among the scientific community and the population.

Landscape of Campi Flegrei has been modelled by landslides since historical times, before the Imperial Roman period (Di Martire et al., 2012). Among the most disastrous recent events, it deserves to mention: 1) the huge tuff collapse occurred along Mt. Echia (Naples) in 1868, causing 60 victims and dozens of injuries (Calcaterra and de Luca Tupputi Schinosa, 2006); 2) the cliff failure occurred along the Maronti beach of the Ischia island in 1978 killing five tourists (Del Prete and Mele, 1999); 3) a series of flow-like mass movements that in 2006 hit some buildings at the footslope of the Monte di Vezzi (Ischia Island), where four people died (De Vita et al., 2007; Di Nocera et al., 2007). Cascini et al. (2008) highlighted that landslides pose a serious societal risk in this area. In fact, several deadly events occurred in the last decades both in the continental and insular sectors, including the islands of Ischia and Procida.

The compilation of an up-to-date and complete landslide database that records location, types and, where known, the date of occurrence of mass movements is the simplest initial approach to any study of landslide hazard (Carrara et al. 1995; Soeters and van Westen 1996; Devoli et al., 2007; Guzzetti et al. 2012). As underlined by Napolitano et al. (2018), information on historical landslides is important to understand the complexities and dynamics of past events, as well as to construct and validate landslide prediction models able to support the designing of appropriate mitigation measures. In the Campi Flegrei area, a first synthesis of landslide processes was reported by Beneduce et al. (1988) and Calcaterra et al. (2003a). With reference to the city of Naples, the landslide activity was reconstructed by Calcaterra et al. (2002, 2003a, 2007) and Di Martire et al. (2012) by means of archival and bibliographic research, as well as by Miele et al. (2022). Failures and retreat rates of coastal cliffs were investigated by Matano et al. (2016), Esposito et al. (2017, 2018a, 2020) and by Caputo et al. (2018). Dozens of events were also included in databases and inventories realized at national scale, based on archive research (AVI database; Guzzetti et al., 1994) and aerial photo interpretation at 1:25.000 scale (IFFI landslide inventory map).

With the aim of providing a comprehensive landslide geodatabase of the Campi Flegrei area, we gathered all the landslide-related information made available from several sources, including a series of events collected by means of local press, news websites and fieldworks. Data were organized in GIS environment to guarantee an easy access, management, updating and sharing with different users. All the collected and revised data were used to develop a series of statistics about spatial and temporal distribution of the events, failure types, impact, and relationships with geological and geomorphological properties of the affected hillslopes. The CAmpi Flegrei LAndslide Geodatabase (CAFLAG) here described may be used for future analyses aimed at evaluating the landslide susceptibility, hazard, and risk conditions, as well as to understand the geomorphic evolution of the study area. In addition, the CAFLAG data may be of relevant interest for the international landslide research community to understand landslide dynamics in volcanic settings during dormant phases, and to implement specific numerical models aimed at evaluating the landslide susceptibility in similar areas.

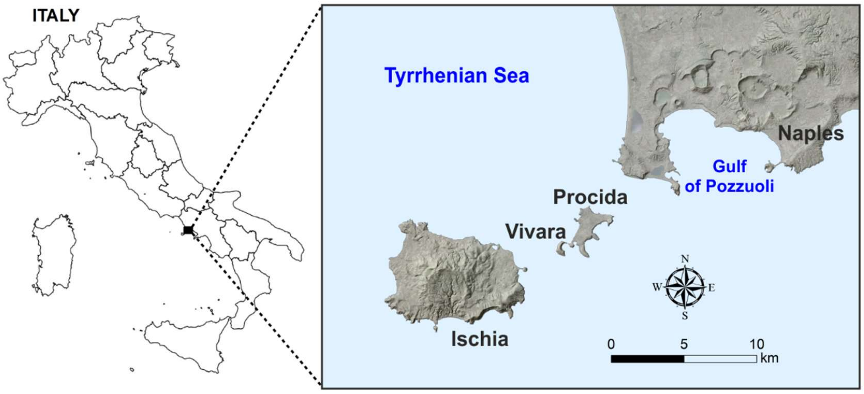


Figure 1: Location and shaded relief of the Campi Flegrei volcanic area. The shaded relief was developed from elevation data of the *SIT Regione Campania*.

2 Data and methods

2.1 Landslide source data

The CAFLAG geodatabase referred to the Campi Flegrei area shown in Fig. 1, including the western part of the city of Naples. All the considered landslide data sources were listed below. The first seven sources were considered as "archive" sources, whereas the last two as "new" sources:

- IFFI landslide inventory map (*Inventario Fenomeni Franosi in Italia*) (Trigila et al., 2010) (www.progettoiffi.isprambiente.it/en/ accessed on 26 May 2022);
- AVI Catalog (*Aree storicamente Vulnerate in Italia da calamità geologiche ed idrauliche*) (sici.irpi.cnr.it/avi.htm, accessed on 26 May 2022);
- Landslide database and inventory map of the hydrographic Basin Authority (AdB) (namely Campania Centrale Basin Authority) (www.distrettoappenninomeridionale.it/index.php/elaborati-di-piano-menu/bacini-reg-nord-occidentali-bacino-reg-sarno-ex-adb-reg-campania-centrale-menu/piano-assetto-idrogeologico-rischio-da-frana-menu, accessed on 26 May 2022);
- Geological map of Italy - CARG (*Carta Geologica d'Italia*) project (Sheets 446-447, 464, 465; 1:25.000-1:50.000 scale) (www.isprambiente.gov.it/Media/carg/campania.html, accessed on 26 May 2022);
- Landslide inventories of the city of Naples (Calcaterra et al. 2002, 2003a, 2007; Di Martire et al., 2012);
- Seismically induced landslide inventory of the Ischia Island (Caccavale et al., 2017, Rapolla et al., 2012);
- Scientific papers (Beneduce et al., 1988; Calcaterra et al., 2003b, 2010; Di Nocera et al., 2007);
- Field geomorphological surveys performed on coastal sectors during 2013-2018, documented by Esposito et al. (2015, 2017, 2018a, 2020) and Caputo et al. (2018);
- Landslide reports collected from digital archives of the principal newspapers and news websites in the study area (https://napoli.repubblica.it/; www.ilmattino.it; www.cronacaflegrea.it; www.montediprocida.com; www.freebacoli.net; accessed several times during 2013-2018).

All of the events contained in the CAFLAG database were geocoded in a point shapefile, where each point referred to the center of the landslide scars. Pre-existing catalogues (IFFI, AVI, AdB) were available in shapefile formats, so that each event was already associated to a georeferenced point. The other sources, instead, provided static map images requiring a manual digitalization of the location points, or information allowing to place the representative point on the corresponding hillslope, by using as support the WMS services of the Campania Region webgis (https://sit2.regione.campania.it/content/servizi-wms, accessed on 26 May 2022), such as: topographic map at 1:5000 scale; ii) the derived Digital Terrain Model (DTM) with a pixel size of 5 m; iii) and orthophoto at 1:10000 scale. All these datasets refer to the years 2004-2005.

Given that the used sources included sometimes redundant events, a preliminary data filtering was performed manually by deleting those characterized by the same attributes and location, indicating therefore the same landslide event. Generally, the level of completeness of information associated to the collected events was quite heterogeneous, as well as the level of accuracy, as highlighted in the following section.

2.2 Geodatabase structure

Attributes associated to the landslide events of the CAFLAG geodatabase were specified in Table 1. The primary set of information referred to data sources, spatial and temporal properties of the events with related accuracy. High spatial accuracy was attributed to events associated with accurate geographical information, as for example accurate spatial coordinates provided in available databases, indications about the affected road section, specific buildings or sites. Where this type of information was unavailable, a low spatial accuracy was indicated, providing rough coordinates of the landslide-affected site (e.g. center of the locality, road or beach hit by the mass movement). High temporal accuracy was attributed to events associated with a complete date (i.e. dd/mm/yyyy), moderate accuracy to events characterized by both month and year of occurrence, and low accuracy to events which could be placed in a wide period of time, before or within a specific year. The movement type (fall, flow, slide, complex) and the involved material (earth, debris, rock) were defined according to the classification of Cruden and Varnes (1996). A secondary set of information referred to geomorphological properties of the landslide-affected sites, such as: i) type and name of the affected watersheds; ii) geomorphological context in terms of inner slope (i.e. not related to direct sea action), coastal slope, or quarry; iii) and morphometric properties of the affected hillslopes (elevation, slope, aspect) resulted from the intersection of each vector point with the DTM. By overlapping the point shapefile with engineering geological maps available for the area (Caccavale et al., 2017; Sacchi et al., 2015), both geotechnical and seismic properties of lithotypes involved in the landslides were provided, as well as the landslide hazard and susceptibility levels of the sites extracted from the Landslide Risk Plain of the Campania Centrale Basin Authority (www.distrettoappenninomeridionale.it/index.php/elaborati-di-piano-menu/bacini-reg-nord-occidentali-bacino-reg-sarno-ex-adb-reg-campania-centrale-menu/piano-assetto-idrogeologico-rischio-da-frana-menu, accessed on 26 May 2022). Further attributes described the impact of the cataloged landslides in terms of damage to anthropic structures and people, and in few cases only, indications about the factors predisposing or triggering the mass movements (e.g., rainfall, digging activities).

All the statistical analyses were performed by means of the Microsoft^{TM} Excel software, and results were displayed in a series of histograms and pie-charts. Statistics related to deadly events, based on the Frequency-Number relations, were aimed at analyzing the societal risk by continuing the work of Cascini et al. (2008).

Table 1 – Attribute list of the CAFLAG database.

ATTRIBUTE	BRIEF DESCRIPTION	TYPE	FEATURES (range, classes, measure unit, etc.)
ID	A unique, incremental number as identifier for each landslide event	numeric	4 digits
SOURCE_T	Typology of data source	text	2 classes (archive, new)
SOURCE	Name of data source	text	free
LATITUDE	Latitude of the landslide-related vector point	UTM km coordinate	EPSG:32633
LONGITUDE	Longitude of the landslide-related vector point	UTM km coordinate	EPSG:32633
TOWN	Affected town	text	13 towns
LOCALITY	Affected locality (local name of the involved area)	text	free
LOCAT_ACC	Location accuracy	text	2 classes (low, high)
TEMP_IND	Temporal indication	text	4 classes (time period, year, partial or full date of occurrence)
TEMP_ACC	Temporal accuracy	text	3 classes (low, moderate, high)
YEAR	Year of occurrence	numeric	4 digits (yyyy)
MONTH	Month of occurrence	numeric	2 digits (mm)
DAY	Day of occurrence	numeric	2 digits (dd)
TIME	Time of occurrence	Time or day phase	hh:mm or 3 classes (morning, afternoon, night)
MOV_TYPE	Type of movement according to the classification of Cruden and Varnes (1996)	text	4 classes (fall, flow, slide, complex)
MAT_TYPE	Type of displaced material according to the classification of Cruden and Varnes (1996)	text	3 classes (earth, debris, rock)
ROUGH_VOL	Rough volume of the displaced material	numeric	expressed in m^3
WATER_TYPE	Type of watershed in which the landslide-affected site occurs	text	3 classes (coastal, endorheic, inland)
WATER_NAME	Name of the watershed in which the landslide-affected site occurs	text	free
GEOM_CONT	Geomorphological context in which the landslide-affected site occurs	text	3 classes (inner slope, coastal slope, quarry)
ELEVATION	Elevation of the landslide-affected site	numeric	expressed in m a.s.l. (2-682)
SLOPE	Slope of the landslide-affected site	numeric	expressed in angular degree (4-77)
ASPECT	Aspect of the landslide-affected site	numeric	expressed in angular degree (1-360)
UNIT_W	Unit weight of the involved lithological unit (average)	numeric	expressed in kN/m^3 (13.0-27.25)
FRICTION_A	Friction angle of the involved lithological unit (average)	numeric	expressed in angular degree (25-40)
COHESION	Cohesion of the involved lithological unit (average)	numeric	expressed in KPa (1-800)

Vs30	Average shear-wave velocity in the first 30 m of the site stratigraphic succession	numeric	expressed in m/s (150-1275)
AVG_THICK	Average thickness of the pyroclastic cover	numeric	expressed in m (7-150)
HAZARD	Hazard level related to the landslide-affected site, as evaluated by the local Basin Authority	numeric	4 classes (1, 2, 3, 4)
SUSC	Susceptibility level related to the landslide-affected site, as evaluated by the local Basin Authority	numeric	3 classes (1, 2, 3)
DAMAGE	Type of damage	text	free
INJURED	People injured	numeric	number (1-7)
FATAL	People killed	numeric	number (1-25)
CAUSE	Landslide predisposing or triggering factor	text	7 classes (digging, dumping, earthquake, mining, rainfall, water leak, wildfire)

3 Study area

The Campi Flegrei (Fig. 1) is an active volcanic area located in southern Italy, within the central part of the Campanian Plain, a graben-like structure resulted from the tectonic displacement of a Mesozoic carbonate basement. The Campi Flegrei corresponds to a quasi-circular depression extending for about 200 km^2, a large part of which develops off the Pozzuoli Bay (Sacchi et al., 2011), whereas the continental sector is located on the Tyrrhenian coast. The insular sector is represented by the islands of Ischia, Procida and Vivara (Fig. 1).

The most ancient volcanic activity is associated to the volcanism of the Ischia island, probably started more than 150 ka BP (Poli et al., 1987; Vezzoli, 1988), whereas the activity of the Procida Island occurred mostly about 70 ka BP (De Astis et al., 2004). About 39 ka BP, the catastrophic eruption of the Campanian Ignimbrite took place, causing the formation of a large caldera (Rosi and Sbrana, 1987; Orsi et al., 1996; Perrotta et al., 2006) that was reshaped by the more recent phreato-plinian eruption of the Neapolitan Yellow Tuff (NYT), dated at 15 ka BP (Scarpati et al., 1993; Insinga et al., 2004; Deino et al., 2004). Volcanic activity occurred after the NYT eruption is subdivided in three main epochs (Di Vito et al., 1999), which were interrupted by long periods of quiescence. In these epochs, minor explosive events occurred within the rim of the NYT caldera, creating at least 52 monogenic phreato-magmatic vents, including tuff rings, tuff cones, cinder and spatter cones (Di Vito et al., 1999; Insinga et al., 2006; Perrotta et al., 2011). The latest eruption, known as "Monte Nuovo Eruption", occurred in the 1538 A.D. Currently, the Campi Flegrei is characterized by very high levels of volcanic risk due to many towns lying in the caldera characterized by unrest conditions, as demonstrated by widespread fumaroles, thermal springs, earthquakes and ongoing ground deformation.

The current geomorphological configuration of the continental and insular sectors of the Campi Flegrei was determined by the action of volcanic and geomorphic processes occurred in the last 15 ka, after the NYT eruption. Relics of volcanic edifices partially dismantled by sea erosion and landslides were identified along or near the present coastline and in the submarine part of the NYT caldera (e.g. Sacchi et al., 2009; 2011). The inland volcanoes were also affected by slope instability processes, and some of them result partially collapsed because of volcano-tectonics forming crater lakes. Landslides due to earthquakes, rainstorms, marine erosion or human actions have repeatedly affected the slopes of ravine and streams, as well as the steep scarps of gullies and coastal cliffs through time (Ducci & Napolitano, 1994; Guadagno and Mele, 1995; Mele and Del Prete, 1998; Del Prete and Mele, 1999, 2006; De Vita et al., 2006; Santo et al., 2012; Esposito et al., 2018a, 2020). Besides volcanic morphologies, the geomorphic setting of Campi Flegrei also includes lowlands that are located between volcanic edifices or close to the NYT caldera rims.

3.1. Weather and climate

The study area is characterized by a Mediterranean climate with hot, dry summers and moderately cool rainy winters. Mean annual temperatures are in the range of 10° at the hilly altitudes, 18°C along the coastline, and 15.5°C in the plains surrounding the inland reliefs (Ducci and Tranfaglia, 2005). The mean temperature of the warmest month (July) ranges between 24-28°C, whereas the mean temperature of the coldest month (January) ranges between 4°-6°C. The rainfall regime is characterized by the maximum amounts in autumn/winter, with a mean annual precipitation of about 700 mm. It is worth noting that during the summer and autumn seasons, the coastal sector is often hit by convective cells forming offshore. Such cells are able to release high amounts of rain in short times, with max 10-min rain rates higher than 100 mm/h, as highlighted by Esposito et al. (2015) and Fortelli et al. (2019). Waterspouts in front of the Flegrean coast are also associated with these cells. Winds blow mainly from three directions: west, north-east, south. They can reach wind gusts up to 140 km/h in the winter season, able to generate sea storms leading to severe damage on coastal settlements (Fortelli et al., 2021).

4 Results

The CAFLAG geodatabase encompasses 2302 landslides occurred throughout the continental, coastal and insular sectors of the Campi Flegrei, during the 1828 - 2017 time span (Fig. 2). Landslides characterized by high accurate position are 2122 (about 92 % of the total). Those with a temporal accuracy ranging from moderate to high are 482, corresponding to about 21 % of the total. Statistics showed in the following sections describe some general features of the collected data, which are useful to characterize the landslide phenomena in the area.

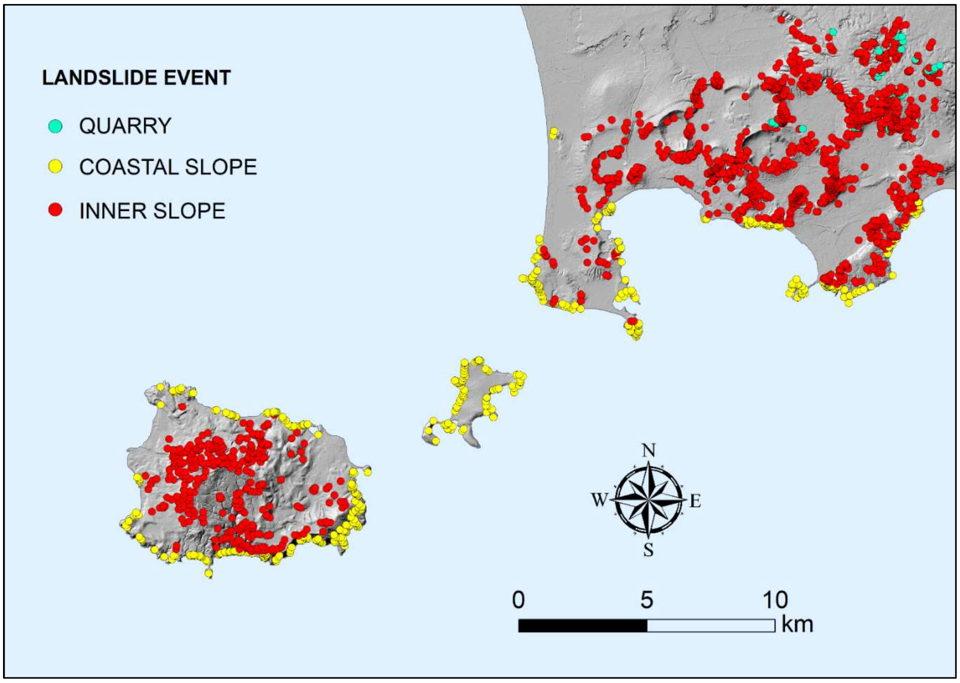


Figure 2: Map of the cataloged landslides, classified according to the geomorphological context (quarry, coastal and inner slopes). The shaded relief in the background was developed from elevation data of the *SIT Regione Campania*.

4.1. Landslide general features

In this section, the statistical distribution of landslide kinematics, type of displaced material, and displaced volume are described. Data in Fig. 3 highlight that most of the cataloged landslides were characterized by a complex kinematics (1115). Among them, specific information about the failure mechanism was available for 343 complex landslides only (15%), whereas no indication was available for the others 772 (34 %). The further 1187 landslides were characterized by different kinematics, as shown in Fig. 3. Overall, by considering all the 1530 events with detailed kinematics information, the most recurrent failure mechanisms were fall (621 events – 41 %) and slide (614 events – 40 %).

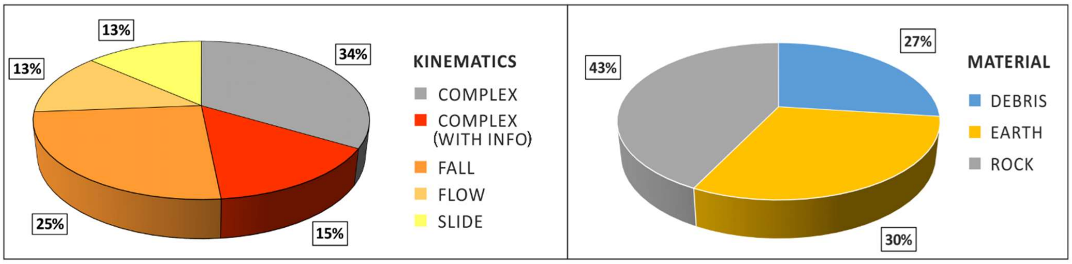


Figure 3: Landslide events classified according to kinematics, on the left, and type of displaced material, on the right.

Examples of rock fall are showed in Fig. 4. These failures are quite frequent both along the coastal and inner tuffaceous cliffs, determining episodic and localized cliff retreats that pose a serious risk for nearby buildings and people. They are able to displace huge rock masses, mobilizing up to thousands cubic meters of volcaniclastic rocks.

Figure 4: Examples of rock fall affecting the Campi Flegrei coastal cliffs: Punta Miseno (2015) on the left, and Trentaremi - Capo Posillipo (2017) on the right. (Image credits: Alessandro Fedele, INGV).

The Figure 5 shows instead a series of rainfall-induced shallow landslides displacing unconsolidated pyroclastic deposits and soils. Images refer to two different events affecting the Monte di Vezzi (Ischia Island) in April 2006, and the coastal cliff of Monte di Procida in 2010. Rocky cliffs like those represented in Fig. 4 resulted the most affected by landslides (43 %), whereas slopes covered by soils and fine pyroclastic deposits (earth) (Fig. 5) were affected by 30 % of the events. Coarser pyroclastic deposits or ancient landslide and debris deposits (debris) were those less involved by mass movements (27 %) (Fig. 3).

Figure 5: Examples of flow-like mass movements at Ischia Island (2006), on the left, and at Monte di Procida (2010), on the right. (Image credits: Nucleo elicotteri Vigili del Fuoco Salerno; Prof. Paola Romano).

Volumetric data were available for 277 landslides (Fig. 6), about 12 % of the whole dataset. Values ranged from 1 to 7.500 m^3 with a mean of about 123 m^3 per event. About 40 % of the landslides displaced a volume lower or equal to 10 m^3, and 23 % a volume higher or equal to 100 m^3.

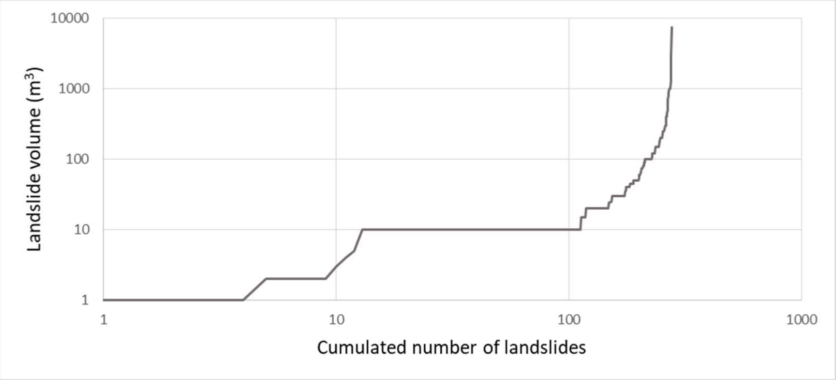


Figure 6: Cumulated frequency distribution of landslides volume.

4.2. Geomorphic and engineering geological properties of the affected hillslopes

Statistics related to the 2122 landslides characterized by an accurate location (high) show that 53 % of them occurred in steep terrains characterized by slope angles ranging from 30 to 77 degrees, whereas 47 % occurred in more gentle slopes characterized by slope angles lower than 30 degrees. The highest frequency of events resulted in the slope class from 30 to 40 degrees (22 %) (Fig. 7).

Aspect data (Fig. 7) show a prevalence of landslides along slopes exposed towards the western directions. A lower frequency of events resulted instead for slopes exposed towards East; this can be linked to the direction from which the rainstorms usually came (i.e. Tyrrhenian sea located to the west of the study area - Fig. 1).

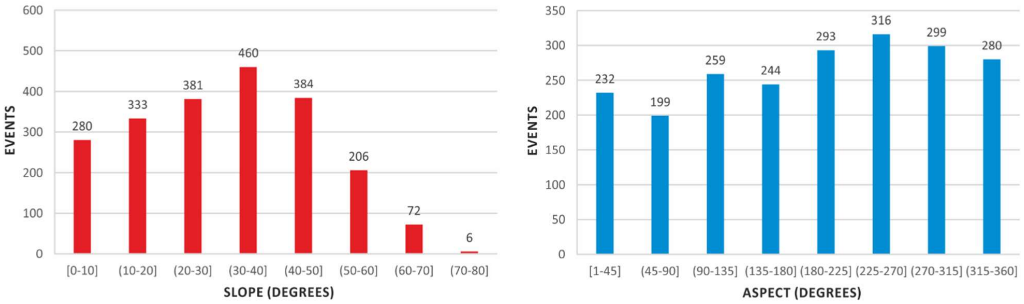


Figure 7: Distribution of the landslide events according to the slope gradient and aspect of the affected hillslopes.

Most of the landslides occurred along the inner hillslopes (78 %), about 21 % affected coastal cliffs, and 1 % occurred along quarry cliffs. On the other side, by considering the relative area of these three geomorphological contexts, the highest concentration of landslides was found along the coastal sector (Fig. 8).

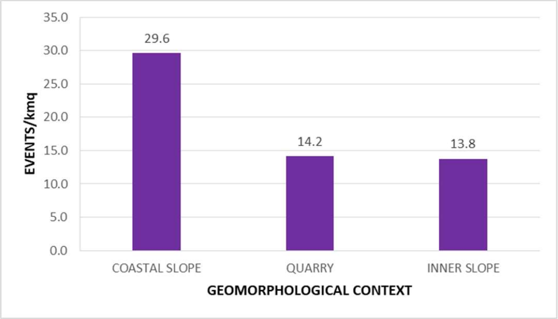


Figure 8: Distribution of the landslide events according to the geomorphological context.

Statistics of the average unit weights characterizing lithologies involved in 2106 mass movements reveal a concentration of records (92 %) in correspondence of typical values of volcaniclastic deposits, in a range from 13 to 17 kN/m^3 (Fig. 9A). Few events (8 %) displaced lithologies characterized by higher values, corresponding to lavas and other lithoid rocks outcropping in the area. Histogram of the friction angle highlights values typical of pyroclastic rocks (Caccavale et al, 2017 and reference therein) ranging from 25° to 40°, depending on the degree of density and mineral composition, with highest frequency in the ranges from 25° to 31° (Fig. 9B). At the same time, cohesion also concentrates in the typical interval of weakly welded pyroclastic deposits, and specifically below 50 kPa, whereas higher values refer to the most lithified rocks (Fig. 9C). Statistical distribution of the Vs30 parameter related to 2078 landslides indicates that 73 % affected lithologies characterized by low Vs30 values, ranging from 100 to 400 m/s (Fig. 9D), which are due to the cohesionless properties of pyroclastic deposits.

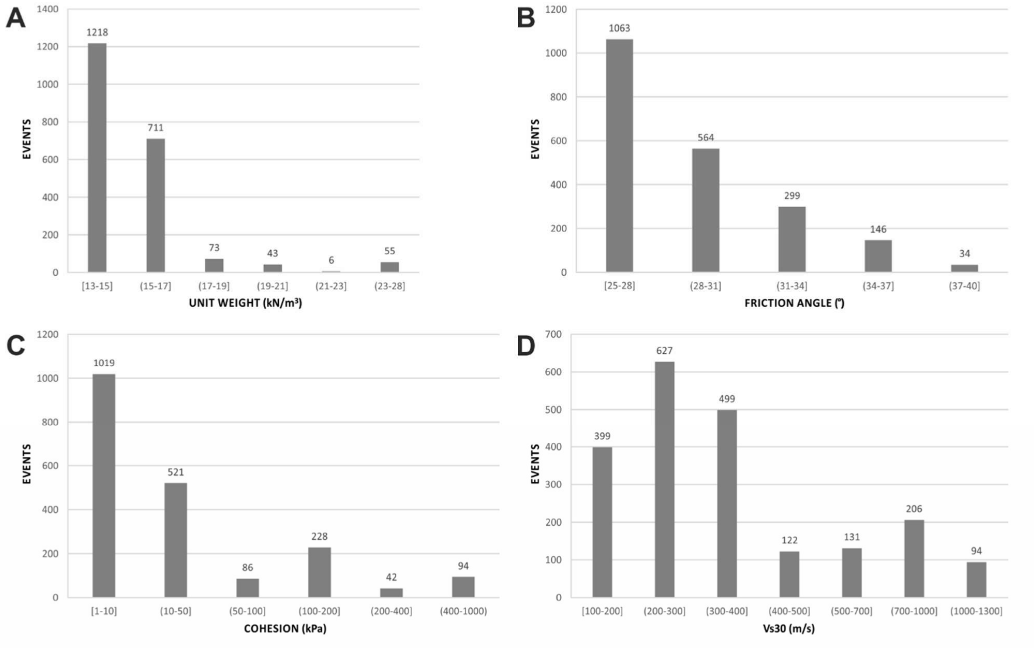


Figure 9: Distribution of the landslide events according to the unit weight (A), friction angle (B), cohesion (C) and Vs30 (D) of the displaced lithologies.

4.3. Temporal distribution

The year of occurrence was known for 517 landslides only, with monthly information available for 482 of them. The yearly trend (Fig. 10A) shows that, generally, the study area was affected by an approximately linear increase in the number of landslides until the half of the’80s. After this period, the increase climbed up with peaks in the years 1986, 1997, 2005 (i.e. 50, 91, 70 events, respectively), exceeding significantly the average value of 2.4 events per year. Most of the events occurred in the winter season, and specifically in the months from January to March, whereas fewer events resulted in the other months (Fig. 10B).

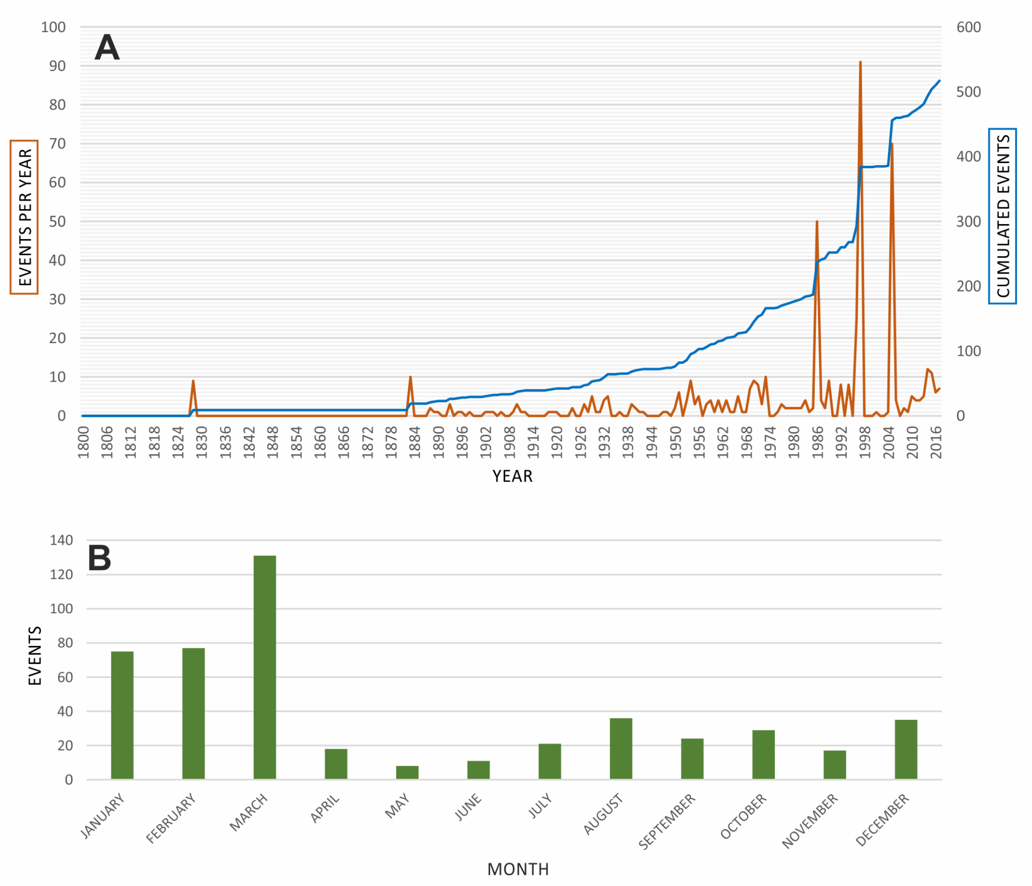


Figure 10: Yearly (A) and monthly (B) distribution of the landslide events characterized by temporal information.

4.4. Deadly impact and societal risk

According to the information collected in the CAFLAG database, 127 people lost their life as consequence of 53 fatal landslides occurred after 1900. The temporal distribution of fatalities is represented in Fig. 11; here, the cumulative curve has a stepped shape, and its slope increases in correspondence of significant events in terms of fatalities, such as the landslide of 1948, corresponding to the deadliest within the analyzed time period (25 fatalities). Since the early 1990s, the frequency of deadly events decreased, as highlighted by a gentler slope of the cumulative curve. This trend can be due to the increased resilience of local communities based on new technologies and prevention measures, as well as on a higher awareness about the risk posed by geo-hydrological processes, as documented also at national scale (Rossi et al., 2019).

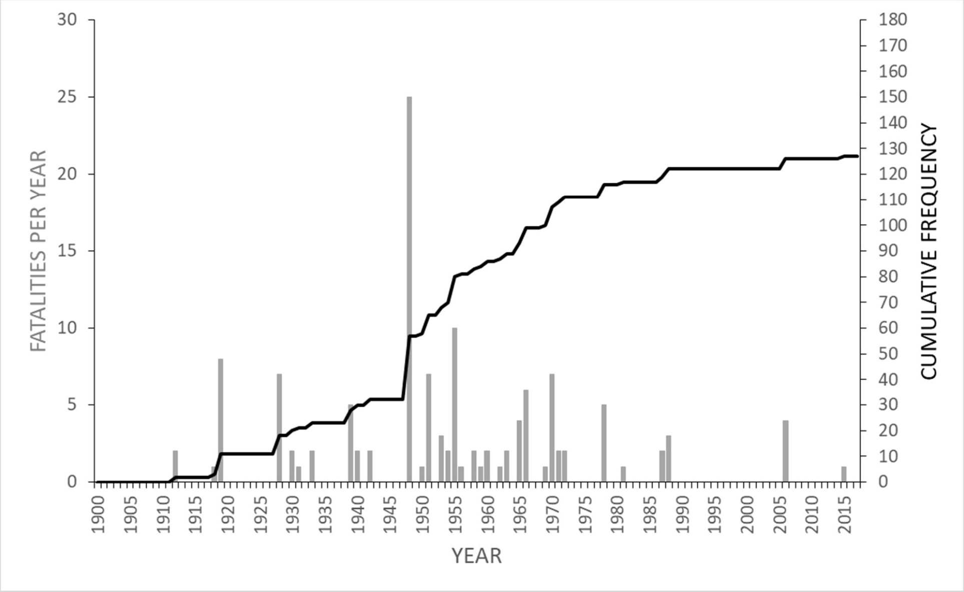
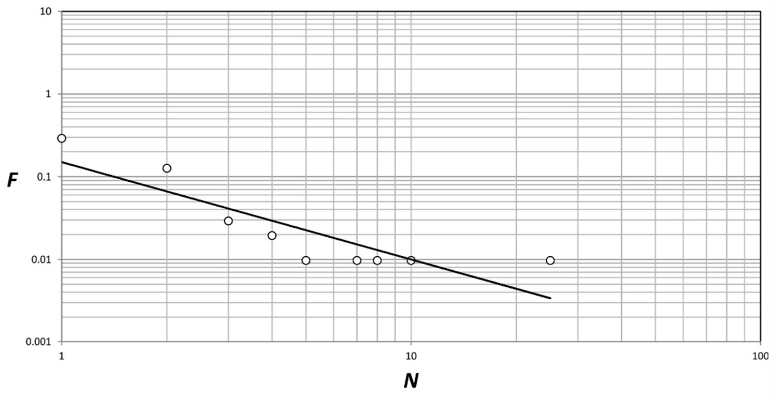


Figure 11: Statistics of fatalities caused by landslides in the analyzed time span.

In order to analyze the societal risk posed by landslides in the study area, a F-N curve was also developed. This curve represents the cumulative probability per year (F) that landslides will cause N or more fatalities versus the number of fatalities resulting from landslides (Fell and Hartford, 1997). The F-N curve displayed in Fig. 12 is in accordance with that developed by Cascini et al. (2008) which encompasses events occurred also in the whole city of Naples, in the time interval 1640-2006.



FATALITIES (N)	CUMULATED FREQUENCY	ANNUAL FREQUENCY (F)
1	30	0.291262136
2	13	0.126213592
3	3	0.029126214
4	2	0.019417476
5	1	0.009708738
7	1	0.009708738
8	1	0.009708738
10	1	0.009708738
25	1	0.009708738

Figure 12: F-N curve and related parameters.

5 Data availability

The CAmpi Flegrei LAndslide Geodatabase (CAFLAG) is freely available in the 4TU.ResearchData repository at https://doi.org/10.4121/14440757.v2 (Esposito and Matano, 2021).

6 Summary and conclusions

The CAFLAG database presented in this study confirms that besides volcanic and seismic hazards, the Campi Flegrei area is also affected by a widespread landslide hazard. Mass wasting processes are contributing to the geomorphological evolution of the whole area and, specifically, of the coastal sector. Recent studies have indicated decadal retreat rates of volcaniclastic coastal cliffs in the order of 1.20 m/yr (i.e. Torrefumo cliff during 1956-74; Esposito et al., 2018a), and short-term (annual) retreat rates within 0.01-0.10 m/yr on average (i.e. Coroglio cliff during 2013-15 – Caputo et al. 2018, and Torrefumo cliff during 2013-16 – Esposito et al., 2018a).

The cataloged events were of different types and magnitudes, and some of them resulted in fatalities. Statistics show that rocky slopes formed by lithified volcanic rocks, such as lava, tuff or ignimbrite, were mostly affected by rock falls. In the coastal area, this was documented by Ducci and Napolitano (1991), who analyzed the cliff failures along the Procida island coastline observing that all of the identified collapses were rock falls and topples involving tuffaceous formations. Similar results were achieved by Del Prete and Mele (1999) for the cliffs of the Ischia Island. Collapses of the coastal cliffs can be considered the most important agents leading to cliff retreat in the area, also because are able to remove large volumes of rocks in short times. In the inland areas, however, many landslides affected the walls of old and abandoned quarries or digging front (Calcaterra et al., 2007). Discontinuity systems characterizing rock masses play a fundamental role in predisposing rocky slopes to failure processes, as well as in controlling the volume of the mobilized rocks. In the study area, discontinuities consist of faults, joints and fractures associated to volcano-tectonic processes (Vitale and Isaia, 2014). Other failure-predisposing factors include geotechnical properties (e.g. low cohesion in Fig. 9) and weathering processes typical of the Flegrean area, such as the zeolitization and argillification of pyroclastic rocks. Water circulation, earthquakes, sea wave action, or anthropic vibrations can be considered among the main triggering factors. Besides the dominance of landslides involving lithoid rocks, the shallow sliding of loose pyroclastic deposits (i.e. pumices, scoria, ashes and lapilli) and soils covering the lithified formations is also frequent. Commonly, these failures start as translational slide and evolve into debris flows within gullies or avalanches along the steep volcanic slopes (Fig. 5) (Calcaterra et al., 2003a). Intense rainfall represents the triggering factor of the initial slide. Elevated slope angles and geotechnical properties of the involved material (Fig. 9) lead to a rapid or very rapid evolution in flow processes.

Further statistics show that many events affected hillslopes exposed towards west, north and south. This may be explained by the frequent impact of these hillslopes with convective cells and low-pressures systems coming from the Tyrrhenian Sea. These meteorological structures are able to release high amounts of rainfall, causing also flash flood processes (e.g. Esposito et al., 2015, 2018b), and are often associated with strong winds and storm surges damaging coastal infrastructures, as documented in the city of Naples in 2020 (Fortelli et al., 2021).

Another relevant finding of the current analysis is that in the analyzed time period, 53 landslide events caused 127 fatalities (Fig. 11). Most of the people died in the city of Naples, hit by rocky blocks detached from steep tuffaceous slopes; others died because of flow-like mass movements, mostly recurrent in the Ischia Island (e.g. Santo et al., 2012). The intense urbanization of the area developed after the Second World War determined an increase of fatal landslides (Fig. 11) and risk conditions in a way that, as highlighted also by the F-N curve (Fig. 12), landslides in the area represent a relevant societal risk. Even whether fatalities decreased after the'90s, this situation requires still more efforts to local and national authorities to reduce the risk affecting the local population.

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