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ORIGINAL PAPER

Rockfall susceptibility analysis through 3D simulations in marine protected areas of the Portofino coastline: case studies of San Fruttuoso and Paraggi bays

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Abstract

The research focuses on the assessment of the potential geomorphological hazards affecting the stability of the Promontory of Portofino (Regional Natural Park of Portofino, Northern Italy), mainly on the bays of San Fruttuoso and Paraggi. The study area constitutes one of the most representative and most populated environments, both by locals and tourists, of the entire Liguria area. For this reason, there is a growing need for investigation on the natural dynamics of these landscapes, based on detailed topographic information. The research starts from a regional geological and geomorphological analysis specific to the study area, combined with a multi-model comparison algorithm (M3C2), which allows comparing two LiDAR datasets acquired in 2008 and 2020, respectively, to assess the overall dynamics of the promontory development. Then, a detailed study of San Fruttuoso and Paraggi bays, two key points for visitors and therefore for management, is performed. Three-dimensional modeling of rockfalls is carried out, which allows the development of a specific management oriented to the use of nature-based solutions (NBSs) strategies, respecting the environment and increasing safety against instability processes in these areas.

Keywords Geomorphological hazards · Promontory of Portofino · M3C2 algorithm · Three-dimensional rockfall modeling · Nature-based solutions (NBSs)

Introduction

The paper focuses on the risk assessment of ongoing and potential rockfall hazard affecting the Regional Natural Park of Portofino (Roccati et al. 2021). Located at less than 20 km east of Genoa (Liguria region of Italy), the park covers a natural and cultural area of more than 18 km^2 whose 13 km is of coastal strip. Along the whole area, it is possible to walk in a unique natural and cultural heritage, visiting small historical village and sites (e.g., Portofino, Camogli, San Fruttuoso, and Paraggi bays) and, at the same time, in a stunning landscape shaped for thousand years (e.g., track trails along the ancient terraces of vineyards and olive grove) (Brandolini et al. 2006; Faccini et al. 2018; Coratza et al. 2019).

Main geo-hazards that affect the site are rockfalls and landslides, both closely related to the increasing meteo-climatic extreme events, such as windstorms or extreme precipitation, driven by climate changes, and affected by marine erosion due to sea storms (Kabisch et al. 2016; Ruangpan et al. 2019; Roccati et al. 2020; Turconi et al. 2020). As a contribution to

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the short- and long-term sustainable conservation policies of sites, a research team was established in the framework of a collaboration among the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), Geographical Information System International Group (GISIG), Università di Genova (UNIGE) and Universidad del País Vasco (UPV/EHU), under the RECONECT Project (www.reconect.eu). In this sense, a specific survey was carried out both in Paraggi and San Fruttuoso bays with the aim to test and calibrate the 3D simulation of rockfalls in the whole Park. The structural setting of the rock mass, related to the stratigraphical setting and to the geomorphological evolution of the slopes, was identified, collected, and classified. Additional information on local rock mass conditions, potentially triggering rockfall that may affect both the heritage itself and the visitors, were collected. Some focus areas and catchments were tested in order to assess the preliminary exposure and vulnerability level: the San Fruttuoso Abbey and the Paraggi Bay. Morphometric and geo-mechanical parameters, as input for the modeling, were calibrated along the most representative park trails to check the model's reliability. The activities are characterized through a multidisciplinary approach (Perrone et al. 2021) including expertise in geomorphology, engineering geology, rock mechanics, nature and earth science, landslide risk assessment and management, as well as conservation, protection, and sustainable mitigation measures (Crosta et al. 2017; Calista et al. 2019; Pazzi et al. 2019). Reliable and true advanced modeling results are fundamental for proper conservation and mitigation intervention on the Natural Park heritage. The use of nature-based solutions (NBSs) (Naumann et al. 2014; Kumar et al. 2020; Villegas-Palacio et al. 2020) in areas of high cultural, natural, and landscape value is strongly recommended, also because of the high reduction of cost and impact (Debele et al. 2019; Kumar et al. 2020). The above-mentioned collaborative activities, between the different research teams, are aimed at the conservation and protection of cultural landscape sites (Jongman 2002), with the ultimate target of making the area accessible to the public in a complete state of safety from rockfalls and slides (Margottini and Spizzichino 2021).

Laser Imaging Detection and Ranging (LiDAR) technologies developed in this research are now widely used in geological risk management, including rockfall hazard assessment (Kenner et al. 2014; Rieg et al. 2014). LiDAR techniques can provide high-resolution and spatially accurate point clouds making them indispensable tools for accurately capturing dense information to facilitate detailed topographic analysis. With this base information, the point clouds modified using cloud processing tools such as CloudCompare allow the comparison of different LiDARs with specific algorithms, to determine the regional evolution of the terrain. In this sense, adjusted and georeferenced models can be developed, which combined with three-dimensional simulation software for rockfalls and georeferenced aerial orthophotographies in the same common reference system, let realistic modeling of each studied area.

In our research, we pursue making progress in the recognition of instability processes in the Portofino Park, which preserve a natural environment including San Fruttuoso and Paraggi bays, with the aim of proposing nature-based solution strategies. At this point, this paper focuses mainly on rockfalls, which are a highly recurrent process, and whose fast development makes it advisable to implement protection measures in agreement with the values of the environment. The main objective is to advance in the combined use of in situ and remote analysis techniques for the development of three-dimensional models that allow the establishment of specific management measures, adapted to each space, combining constructive friendly actions (Morales et al. 2021), where necessary, within the framework of a global approach based on efficient, environmentally, socially, and economically beneficial solutions, which contribute to increasing resilience (European Commission 2015).

The Portofino cultural heritage site

Thanks to its wide recognized landscape, natural, and cultural values (Fig. 1), the Portofino Promontory has been protected since 1935 with the establishment of the Portofino Natural Park (Coratza et al. 2019). Since 1995, the protected area has been managed by the Regional Park Authority: current protected area is approximately 1056 ha wide, covering the territory of the municipalities of Camogli, Portofino, and Santa Margherita Ligure.

The resident population of the Portofino Park is about 750 (Turconi et al. 2020), while the total population of the three municipalities is about 15,000. The number of tourists is very high throughout the year: along the coast, in Portofino town, there are more than one million tourists/year, while in San Fruttuoso, the boat connections from the Tigullio and Paradiso Gulfs provide around 400,000 tourists/year (Faccini et al. 2018). In addition to tourists, there are also hikers along the more than 80 km of paths (Brandolini et al. 2006): the section from "Portofino Vetta" to "Pietre strette" is travelled by more than 70,000 hikers/year.

In addition to the Portofino Park, there is the Portofino Marine Protected Area, established in 1999; finally, in 2017, the process to convert Portofino into a National Park was started, even if the boundaries are still to be well defined.

The entire promontory is also extraordinarily rich in cultural heritage, not only represented by the seaside towns of Camogli and Portofino, but above all linked to the ancient medieval religious trails that connected various monastic centers (Figs. 1 and 3): on the western side, there is the Church of San Nicolò di Capodimonte (Fig. 2a), dating back to the twelfth century; in San Fruttuoso, there is the

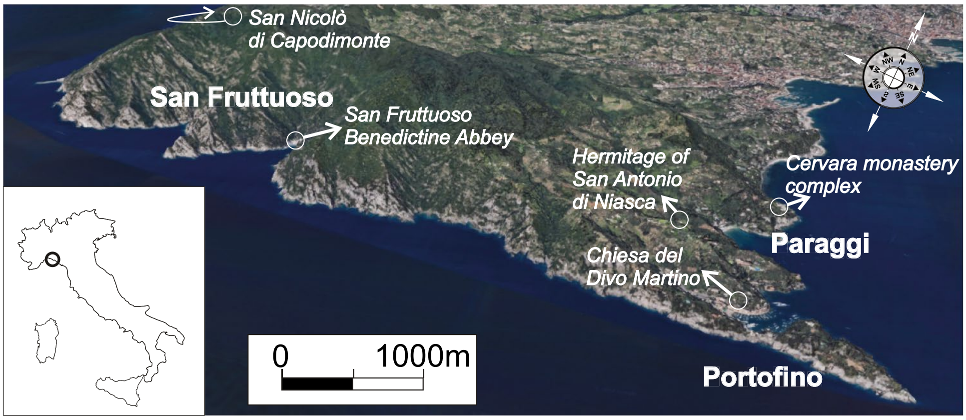


Fig. 1 Geographical context of the study area in Italy and the location of San Fruttuoso, Paraggi, and Portofino bays, along with the cultural heritage in Portofino Promontory

Benedictine abbey (Fig. 2b) dating back to the tenth to eleventh century; and on the eastern side, there is the Cervara monastery complex (Fig. 2c), built in 1361 and maintained by Benedictine monks. Other important buildings of great cultural interest are the Hermitage of S. Antonio di Niasca and the Church of Divo Martino in Portofino (Figs. 1 and 3).

Most of this cultural heritage is however threatened by geomorphological hazards: many of these centers were built on ancient and relict landslides (San Nicolò, Divo Martino, S. Antonio di Niasca, Abbazia della Cervara), but occasionally they are reactivated, especially by heavy, short-term rainfall triggered by the atmospheric low depression over the gulf of Genoa (the so-called Genoa Low) (Roccati et al. 2020). On September 25, 1915, an intense and concentrated rainfall triggered a debris-mud flow that channeled into the hydrographic network and partially destroyed the San Fruttuoso abbey and surrounding houses (Paliaga et al. 2022). In fact, it is located exactly at the mouth of the Fontanini valley, which is also subject to frequent rockfall phenomena (Faccini et al. 2008b, 2009). Noteworthy is the event that occurred in 2016, where a 3-m-diameter block impacted a house in San Fruttuoso, causing considerable material damage (Roccati et al. 2021). The Cervara complex was severely threatened by the effects of the 2018 Vaia sea storm surge (Turconi et al. 2020; Betti et al. 2021).

Geological setting

The geology of the whole area is dominated by two formations (Fig. 3): the “Mt. Antola Flysch” on the north (Elter and Pertusati 1973; Corsi et al. 2001), dated between 90 and 55 million years ago, and the “Portofino Conglomerate” at the south, dated about 30 million years ago

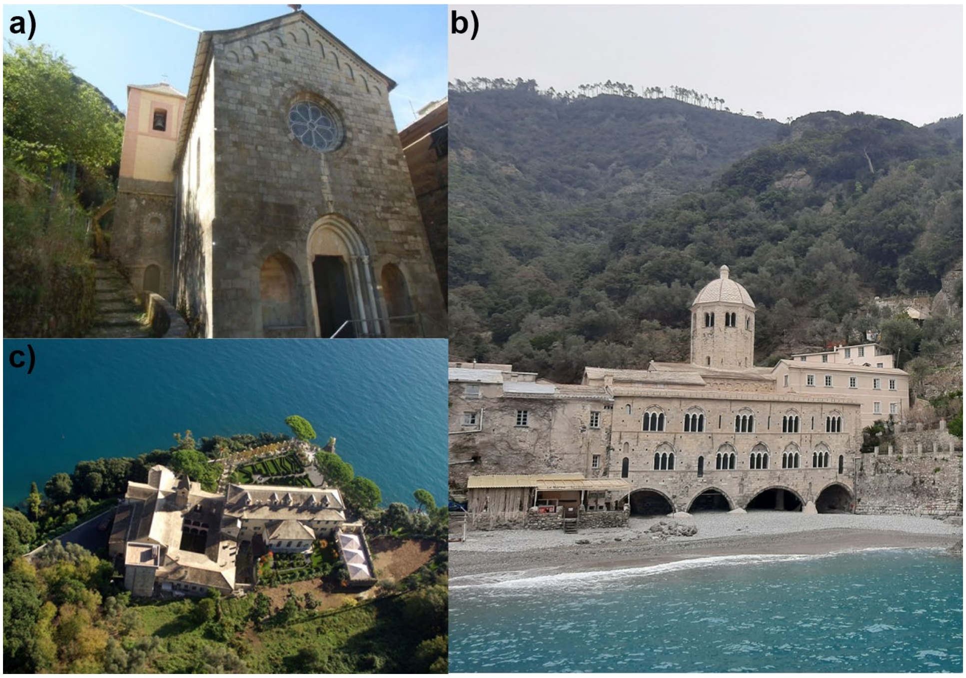


Fig. 2 Some examples of Portofino’s cultural heritage: **a** Church of San Nicolò di Capodimonte; **b** San Fruttuoso Benedictine abbey; **c** Cervara monastery complex

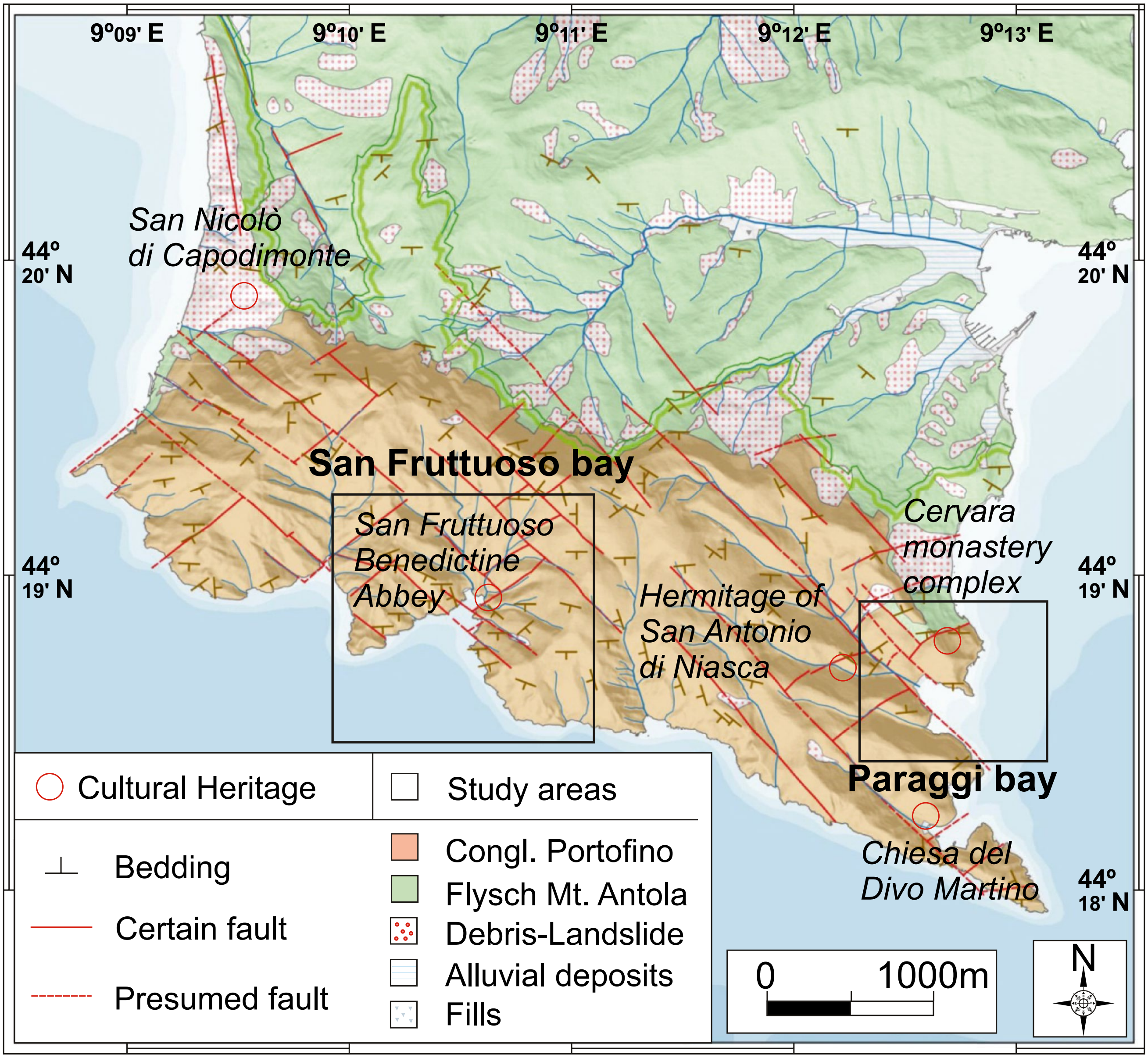


Fig. 3 Geological sketch map of the study area along with the cultural heritage locations (modified from Faccini et al. 2018)

(Terranova 1964). Conglomerates, which outcrop at the entire southern slope of the promontory, are made by of heterogeneous pebbles, mainly from marly limestone and secondarily from other lithotypes, in a sandy-limestone matrix (Faccini et al. 2008a). The formation shows a fragile tectonic deformation, with several fault and fracture systems oriented mainly NW–SE and NE-SW (Fig. 3) (Bonaria et al. 2016; Terrone et al. 2021). Regarding the quality indexes of the Portofino Conglomerate, its high resistance stands out (Table 1). At rock mass scale, the Geological Strength Index (GSI) (Marinos and Hoek 2000) ranges from 65 to 70, consequence of the good surface conditions together with a blocky structure (Faccini et al. 2008a). In a detailed scale, field tests using the Schmidt

Table 1 Rock mass characteristics

Materials	Date	GSI	Schmidt rebound number (modal)	Uniaxial compressive strength (σ_{ci})
Mt. Antola Flysch	55–90 M.a	35–40	15–35	30–70 MPa
Portofino Conglom	30 M.a	65–70	25–50	50–100 MPa

hammer, distinguishing between limestone, arenaceous clasts, and matrix (Cevasco et al. 2004), with a modal rate between 25 and 50 were calculated (Faccini et al. 2008a). Besides, laboratory tests have been developed using a point load test, carried out directly on rock samples, and providing compressive strength ranges between 50 and 100 MPa (Faccini et al. 2008a).

This characterization serves as a basis for the definition of different terrains in the modeling part, depending on the values obtained by the techniques used, in addition to the calibration and adjustment process. The tectonic structures, along with the high resistance of the conglomerate, control the development of instability processes along the entire coastline, which are especially evident in the south-facing conglomeratic outcrops, such as those identified in San Fruttuoso area (Fig. 3).

At present, the bays of San Fruttuoso and Paraggi, respectively, located to the south and east of the promontory, have different morphologies. San Fruttuoso has local outcrops of conglomerate, which are found among abundant vegetation of various types, where a deeper terrain is developed, which means that during heavy rainfall, several debris and mudflow processes have historically developed. Shallow landslides often occur in terraced areas with dry stone walls (Paliaga et al. 2016, 2020). In the case of the rocky outcrops, which are relatively isolated and with metric continuity of fractures in the rock mass, rockfalls with a largely spherical shape (Roccati et al. 2021) develop, not exceeding 1 m in diameter. These dimensions of spacing and block sizes were obtained during the days of fieldwork developed in the area, with a classical tape measure, in order to make more accurate measurements for the simulation. On the other side, in Paraggi Bay, the coastal zone draws practically a continuous line of rocky cliffs, where diverse processes of rockfalls with decimeters size take place.

Methodology

Large-scale base data and analysis

The study began with the acquisition of the basic topographic information of the ground surface, in order to carry out a general morphometric and geomorphological analyses at the scale of the Promontory of Portofino. This preliminary study was conducted to perform then detailed analyses of the areas of greatest activity and interest, in those that demonstrate modifications on a general scale, and where numerous events have been identified over the last few years.

In the regional context, a comparison was made between the LiDARs 2008 (by the Italian Ministry of the Environment) and 2020 (acquired by EUROSENSE in the framework of RECONECT project), after the necessary Coordinate Reference System alignment using the Open Access Geographical Information System QGIS 3.14 Pi. This preliminary work was made based on the multiscale model-to-model cloud comparison (M3C2) algorithm through CloudCompare software (James et al. 2017; DiFrancesco et al. 2020; Bernard et al. 2021; Hu et al. 2022).

Detailed topographic information

Once the general framework was completed, based on this information, a local study of San Fruttuoso and Paraggi bays, south sector of the Promontory, was carried out. Using the free CloudCompare v.2.12 Alpha software, the original LiDAR was modified and the specific digital terrain model (DTM) of each zone was elaborated, for analysis in raster format, by projecting the point cloud perpendicularly onto a flat raster surface, with a cell size of 0.5 m. The raster was then combined with georeferenced orthophotos, which is combined with above-mentioned information through QGIS 3.14 Pi.

From the detailed DTMs, the basic point cloud was extracted and, by means of a triangulation process using the Delaunay method performed in RocPro3D software (RocPro3D 2018), a three-dimensional mesh reflecting the real relief of the environment was obtained. All the data regarding terrain properties and instability processes were added to the model, and were represented over the orthophoto, allowing working with detailed realistic three-dimensional models of the study area.

Modeling and simulation of rockfalls

The development on the ground of rockfalls is limited by the dispersion of their energy, which is usually approximated by two coefficients (Pfeiffer and Bowen 1989; Morales et al. 2021): the normal coefficient of restitution (*Rn*), which indicates the degree of elasticity in a collision perpendicular to the slope surface; and the tangential coefficient of restitution (*Rt*), which is a measure of the resistance to movement parallel to the slope (Pfeiffer and Bowen 1989). Both values are calculated using the following expressions (Li et al. 2020; Wang et al. 2020; Morales et al. 2021; Zhang et al. 2021):

Reflected normal velocity ($v_{n,r}$):

$$v_{n,r=} = \frac{v_{n,i} \cdot Rn}{1 + \left(\frac{|v_{n,i}|}{K}\right)^2} \tag{1}$$

where $v_{n,i}$ is the incident normal velocity and K is the empirical reference velocity.

Reflected tangential velocity ($v_{t,r}$)

$$v_{t,r=}\sqrt{\frac{R^2 \cdot \left(I \cdot {\omega_{(1)}}^2 + m \cdot {v_{t,i}}^2\right) \cdot FF \cdot SF}{I + m \cdot R^2}} \tag{2}$$

where R is the radius of the rock, $\omega_{(1)}$ is the initial rotational velocity, m is the rock mass, $v_{t,i}$ is the initial tangential velocity, FF is the friction function, SF is the scaling factor, and I is the rock moment of inertia.

By means of these two equations, the restitution coefficients that will be fundamental in the rockfall modeling process and which are characteristic of each differentiated terrain are acquired, in addition to other factors such as dynamic friction (k) and vertical and lateral deviation acquired from contrasted previous researches.

Three-dimensional rockfall modeling

The modeling process was approached by using RocPro3D software (RocPro3D 2018). This software performs three-dimensional simulations of individual trajectories from a digital terrain model (DTM), which is extracted from the above-mentioned acquired topography. Software permits generating a mesh developed by triangulation as stated before. The mesh is the beginning of the model, which represents the real relief of the studied environment, on which the simulation of rockfall from the identified source areas is carried out. This type of modeling allows including the lateral evolution of rockfalls (Li and Lan 2015).

For the definition of the source areas, it is essential to carry out fieldwork to identify and locate exactly the origin of the rockfalls, evaluating scars in the rock mass (Palmstrom 2005; Corominas et al. 2017), which will then be reflected in the models. Regarding the volume of blocks, in the absence of a specific inventory of rockfalls, priority has been given to the study of spherical blocks of 1-m diameter, which is the largest size recorded in the area during the fieldwork and, therefore, the one with the highest energy (Corominas et al. 2017; Morales et al. 2021). In our case, a rigid body approach was used for the modeling. In order to calibrate the input parameters of the modeling, the first step has been to carry out a recent papers review of several authors working in different terrains (Ji et al. 2020, 2021; Tang et al. 2021; Ye et al. 2021; Prades-Valls et al. 2022; Sardana et al. 2022; Shadabfar et al. 2022), with the aim of framing each of those defined in San Fruttuoso and Paraggi within established limits. From this starting point, rebound values were calibrated via 3D back analysis to achieve the best agreement between observations and modeling estimates (Sarro et al. 2018; Fanos and Pradhan 2019).

Finally, it should be noted that in the modeling the densely vegetated areas have also been characterized and established, since they represent a degree of protection that less abundant vegetation does not provide. Likewise, in this case, land uses as such have not been taken into account, since this section is contemplated in the proposed solutions of the mitigation plan. However, anthropic materials are defined, such as roads and walkways, with resistance values different from other identified materials, since they condition the rebound and evolution of the blocks in a completely different way.

Results

Large-scale DTM comparison through M3C2 algorithm

The DTM assessment, obtained via the CloudCompare (v. 2.12 Alpha) software, has been established using the multiscale model-to-model comparison (M3C2) algorithm, which is a robust way to compute distances directly between two point clouds, established with limits of − 1 to 1 m, since, being 12 years apart, it is estimated that the vast majority of ground movements are local and with a decimeter difference (Fig. 4).

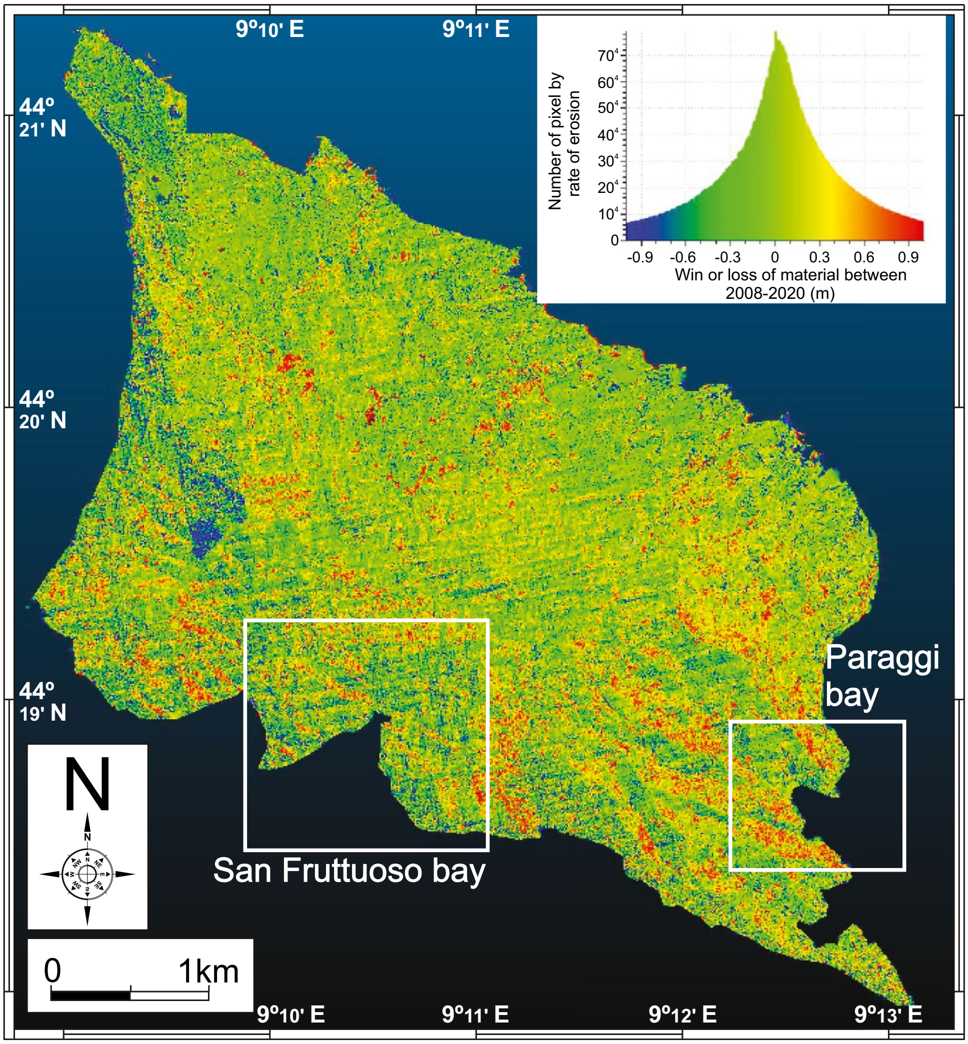
This comparison makes it possible to identify that the study area is relatively stable from the viewpoint of slope stability and erosion, since differences close to zero (green color) predominate throughout the sector. However, significant differences can be identified between the northern area, with less evolution, and the southern area, where significant settlements of around 1 m (blue color) and raise of up to 1 m (red color) can be identified. Often, especially remarkable in San Fruttuoso, these zones of gain or losses of terrain elevation are aligned to NW–SE orientation (structural patterns that control hydrographic network evolution) that fits with the ground movements highlighted by the ISPRA (2018) in the “Dissesto idrogeologico in Italia: pericolosità e indicatori di rischio – Edizione 2018”, where the landslide hazard of the area under study was collected (Fig. 5).

3D modeling terrains adjusted parameters

In order to perform a detailed analysis of the rockfall processes in San Fruttuoso and Paraggi bays, specific models of both areas have been generated from the topographic information described above.

For an accurate representation of the rockfalls occurring in the study area, the terrains must be differentiated and defined in the field (Pfeiffer and Bowen 1989), as well as their values of dynamic friction (k), normal and tangential restitution coefficients (R_n and R_t, respectively) and final degree of lateral and vertical deviation (Guzzetti et al. 2003), which absolutely affect the development of the rock fragments. These parameters were calibrated by 3D back analysis to achieve the highest similarity between the spatial distribution of the recorded events and modeling estimates (Sarro et al. 2018; Fanos and Pradhan 2019; Clemente et al. 2023). Calibration

Fig. 4 Comparison between the elevations of the 2008 and 2020 DTMs on the Portofino's Promontory



accuracies were found to be 95%, ending with the values for each differentiated terrain shown in Table 2. These values are within the ranges given in the literature for similar materials in comparable environments (Bourrier et al. 2012).

3D local simulation of rockfalls: San Fruttuoso and Paraggi bays

With this baseline information, 350 fall trajectories have been simulated from the 14 source areas identified in San

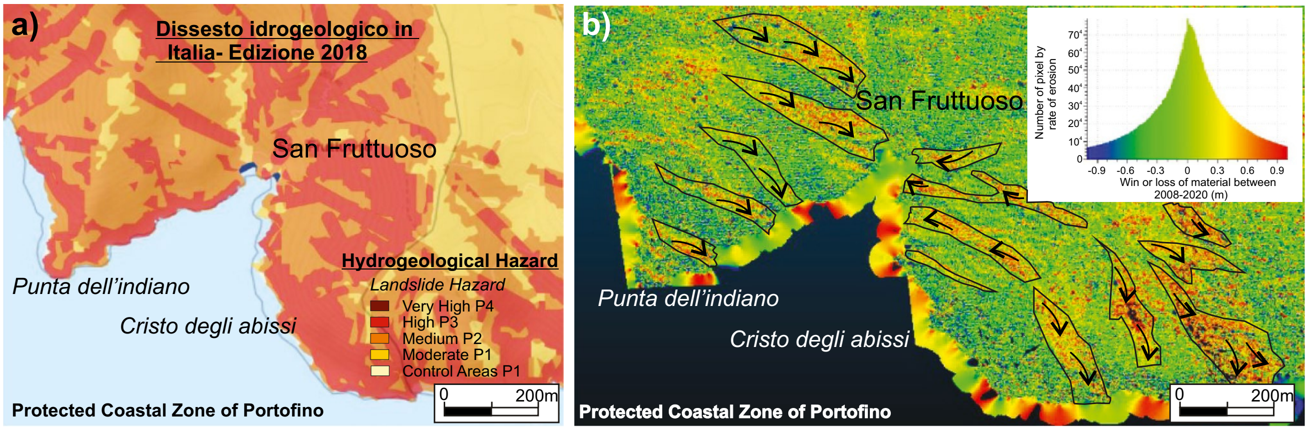


Fig. 5 Comparison between **a** the landslide hazard analysis map developed by the ISPRA and **b** our comparison between DTMs

Table 2 Terrain properties and adjusted parameters in San Fruttuoso and Paraggi bays

Material properties		Porto. conglomerate	Loose soil with vegetation	Access area	Water surface
Restitution coefficients (*R*)	Units				
Mean normal value μ _Rn		0.55	0.3	0.5	0
Mean tangential value μ_Rt		0.9	0.8	0.8	0
Std.-Dev. σ_R		0.011	0.012	0.016	0
Limit velocity V_R (lim)	(m/s)	10	10	10	0
Limit Std.-Dev. σ_R (lim)		0.0055	0.006	0.012	0
Lateral deviation (θh)					
Std.-Dev. σ_θh	(°)	10	5	7.5	0
Limit velocity V_θh	(m/s)	10	10	10	0
Limit Std.-Dev.σ_θh (lim)	(°)	5	2.5	3.75	0
Vertical deviation (θv)					
Std.-Dev. σ_θv	(°)	1	1	1	0
Limit velocity V_θv	(m/s)	10	10	10	0
Limit Std.-Dev. σ_θv (lim)	(°)	2	2	2	0
Friction coefficient (*k*)					
Mean value μ_k	(m/s)	0.45	0.6	0.5	0
Std.-Dev. σ_k		0.036	0.045	0.045	0
Limit velocity V_k (lim)		10	10	10	0
Limit Std.-Dev. σ_k (lim)		0.03	0.03	0.03	0

Fruttuoso and 120 trajectories from the 8 areas recognized in the Paraggi. Regarding block size, a necessary input for developing a model (Hungr et al. 1999), although there are areas with relatively smaller blocks, a diameter of 1 m has been standardized for spherical blocks detached from conglomeratic outcrops. Only one exception has been made, and that is the source area identified in 25 October 2016 rockfall in San Fruttuoso, where a detached block of 3-m diameter, much larger than those currently identified in the bay, destroyed a house (Fig. 7f).

The development of the trajectories obtained from the simulation were ground-truthed with field observations, and geomorphological and historical evidences. Thus, due to the geomorphology of the San Fruttuoso Bay, and mainly on its northwest flank, rockfall trajectories tend to concentrate in small canyons, identifiable with the field survey, which are in turn the preferential waterways. The southeastern flank, however, due to the proximity and the verticality of the conglomeratic cliffs to the sea, develops almost straight trajectories (Fig. 6a). Paraggi Bay, on the other hand, depicts a much more direct rockfall dynamic, with vertical cliffs close to the main road and the sea, which address this evolution (Fig. 6b).

3D trajectories, energy, and runout analysis

Given that the Paraggi sector has undergone numerous instability processes in recent years, it is an area where the managing authorities have carried out numerous constructive actions, making it a relatively less natural area and therefore

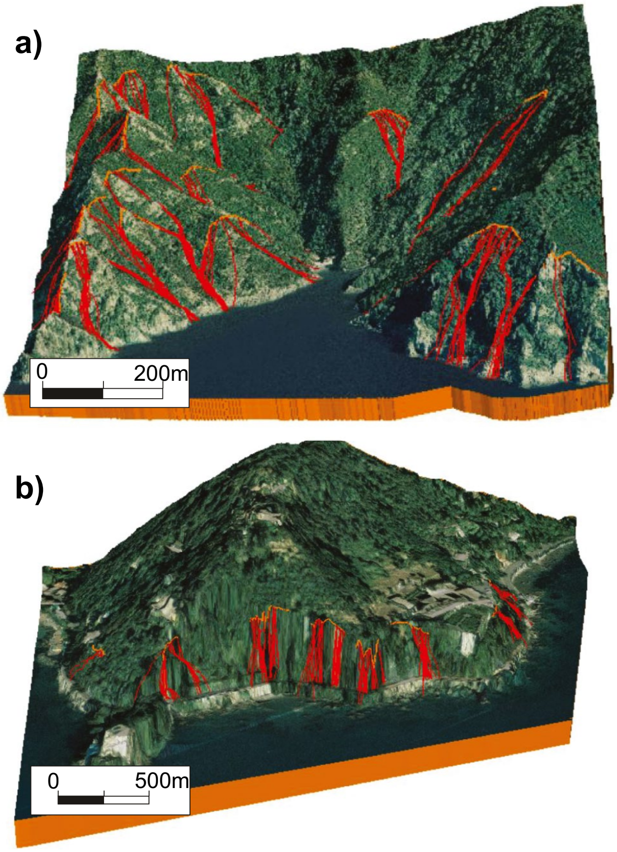


Fig. 6 3D model showing scarp main active source areas (orange lines) and trajectories (red lines) of **a** San Fruttuoso Bay and **b** high rocky coast on the eastern side Paraggi Bay

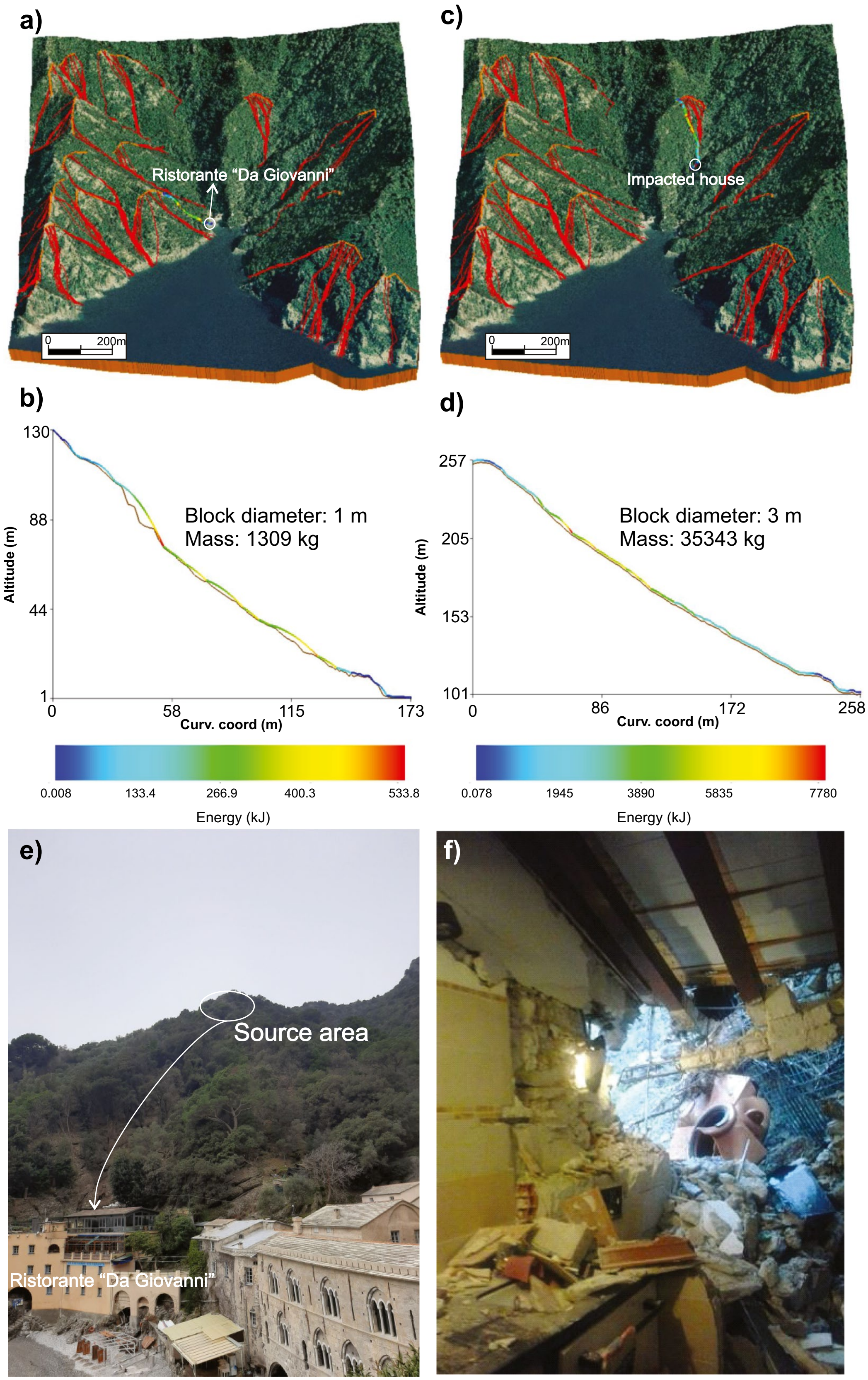


Fig. 7 Analysis of individual trajectories of rockfalls: **a** rockfall trajectories (red lines); trajectory 198 (colored line) in the 3D simulation; **b** energy profile of trajectory 198; **c** trajectory 304 (colored line) in the 3D simulation; **d** energy profile of trajectory 304; **e** potential rockfall trajectory 198; and **f** house destroyed by rockfall in 2016, trajectory 304

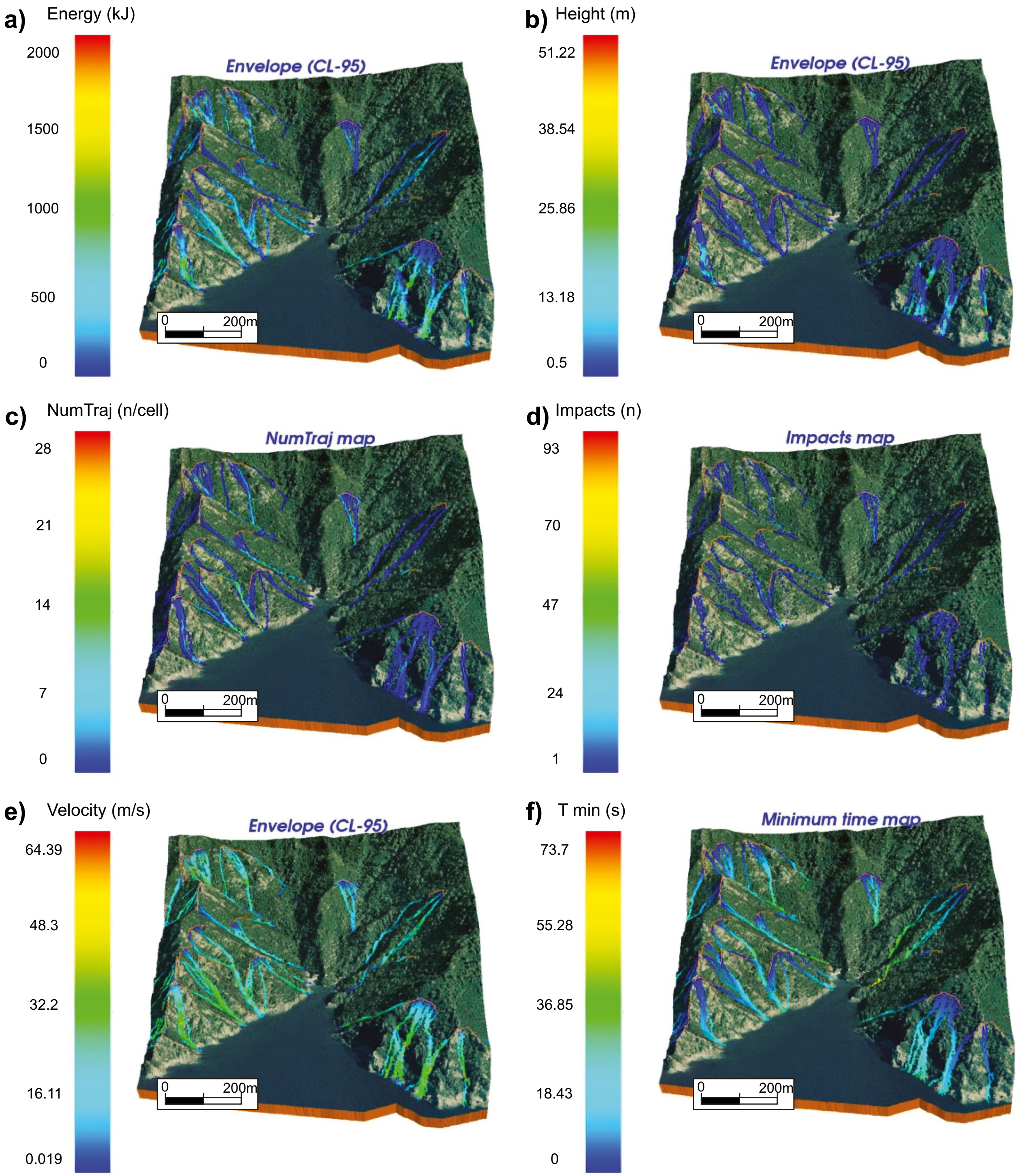


Fig. 8 Cell-based analysis maps of simulated rockfall parameters for a confidence limit (CL) of 95% in the San Fruttuoso Bay: **a** energy; **b** height; **c** number of trajectories; **d** impacts; **e** velocity; and **f** minimum path time

less suitable for the study presented. Thus, a more in-depth analysis was proposed in the San Fruttuoso area, where instability processes are taking place, but on largely natural spaces that have not yet been acted upon, which facilitates the proposal of actions based on the NBSs.

Two trajectories have been selected in San Fruttuoso Bay, representing a higher degree of exposure and hazard for both the structures, tourist and residents in the area. On the one hand, there is an area of special interest and need for protection, which is represented by trajectory 198 (Fig. 7a), on the northwest flank, where a spherical block of 1-m diameter could potentially fall, whose path ends in the restaurant at the foot of the slope (Fig. 7e). On the other hand, trajectory 304 (Fig. 7c) represents the most important recent episode that has occurred in the bay in 2016 (back analysis approach), where a spherical block 3 m wide hit a house and destroyed it (Fig. 7f). The large amount of data collected in this episode allows for a more calibrated and robust model. An individual analysis of these trajectories has been modeled, analyzing the total kinetic energy during their entire trajectory (He et al. 2020), the rebound zones, and the stopping zone (Fig. 7b, d).

Elaboration of maps and valuation of results

In addition to the simulation of individual trajectories, three-dimensional modeling allows the production of maps of different parameters that can address the management of these spaces (Sarro et al. 2018; Fanos and Pradhan 2019; Akin et al. 2021). For the elaboration of these analysis maps, the terrain is divided into cells of 5 × 5 m, which in the case of San Fruttuoso were 308 horizontal and 377 vertical cells, giving almost 120,000 simulation cells. In this way, the fundamental parameters are calculated for each cell resulting from the rockfall modeling (Akin et al. 2021; Clemente et al. 2021a, b). In the case of the present study, all analysis maps are performed for a confidence limit (CL) of 95%, such as (a) energy, representing the maximum kinetic energy recorded; (b) height, the maximum vertical height of the trajectories; (c) density, number of rocks passing through each cell; (d) impacts, the number of impacts by cell; (e) velocity, maximum speed reached by the falls; and (f) minimum time, the time interval between the rock detachment and its stop (Fig. 8).

As for the energy map, the maximum kinetic energy reached is, in specific and scattered cases, 1600 kJ, although practically all the detachments collected in the cells comprise energies of a few hundred at the origin, 800–1200 in the impact zones, which usually evolve towards 1400 kJ (Fig. 8a). Regarding the vertical height of the rockfalls, which is a fundamental input parameter for sizing the mitigation measures (e.g., barriers, meshes, walls) needed to stop the most dangerous blocks, rarely it is greater than 5 m, except in specific cases where the coastal strip is more verticalized, which are mainly located far from the accessible areas (Fig. 8b). The number of trajectories per cell (Fig. 8c) and the impacts (Fig. 8d) are mainly concentrated on the levels previously recognized in the individual trajectories. With respect to the speed of the falls calculated in the maps, three phases are evidenced: the first 5–10 m of the trajectories, with speeds of less than 5 m/s; an intermediate and longest zone, between 60 and 90 m, with speeds around 16 m/s where the blocks accelerate; and final part, 10–30 m long, where speeds of more than 30 m/s are reached (Fig. 8e), exhibiting maximum fall times of 70 s, although times around 30 are more common (Fig. 8f).

Proposal for a short- and long-term low impact (NBSs) mitigation master plan

In the whole investigated area, the present and active morphological processes should be framed within a management and conservation master plan having two different timeline references: emergency mitigation measures, to be defined and undertaken in the short-medium term, and preventive mitigation measures to be implemented in the medium-long term (Spizzichino et al. 2016).

Short-medium-term actions should be always preceded by an investigation phase including the following:

- Field survey and detailed geomatics terrestrial laser scanner (TLS) acquisition coupled with UAV flight acquisition, in order to provide high-resolution 3D topographical models of the whole heritage area.
- Laboratory and in situ test execution.
- Detailed geomorphological and geo-mechanical survey of the rock slope.
- Global kinematic analysis of the rock including the calculation of the most probable rockfall trajectories (3D rockfall modeling).
- Exposure and vulnerability assessment and mapping of the natural and cultural heritage in the area.
- Detailed landslide hazard and risk assessment.
- Slope stability modeling (2D and 3D) for specific blocks and/or unstable portions of the cliff.
- Temporary supports of unstable rock portions.
- Urgent reinforcement in the most instable volumes to avoid detachments.
- Redefinition of touristic paths and accesses, to prevent tourists from being exposed to potential collapses or instabilities.
- New communication plan and billboard for touristic management.

The long-term actions include the following:

- General master plan with detailed design of mitigation through NBSs approach.
- Design of an integrated monitoring system. The adopted monitoring integrated system could also be set, with some small modifications and thresholds definition, as a warning system for flash flood as well as for detection of large rock block deformations.

In both cases, the mitigation options must be supported by scientific and technical analysis in a holistic framework. The proposed numerical 3D rockfall modeling is a fundamental tool to support the above-mentioned strategies in the case of rockfalls, the process that is the focus of this work. The incorporation of complementary studies more focused on landslide susceptibility analysis (e.g., Roccati et al. 2021), will complete the information for the development of comprehensive management strategies.

Discussion

The management of coastal areas needs to advance in methodological approaches that allow detailed studies of the current dynamics, in order to develop specific management plans for each environment, based on the guidelines of the NBSs (Villegas-Palacio et al. 2020; Kumar et al. 2021; Vojinovic et al. 2021). In previous works, a large number of authors have assessed these strategies as a line of action for natural hazards in different environments (Pontee et al. 2016; Castelle et al. 2019; Van der Meulen, 2022), but rarely dedicated to geological hazards.

The proposed study in the Portofino Natural Park has allowed the development of a methodology that combines remote sensing techniques with local digital terrain models, as long as with data collection through fieldwork. This detailed topographic information is derived to the design of three-dimensional point clouds, which are modified and adjusted by means of specific software, which serve as a basis for the elaboration of investigations on slopes that present complex morphology (Abellán et al. 2010; Pham et al. 2016; Ansari et al. 2018), such as the coastline of Portofino, and especially the San Fruttuoso Bay, where a realistic representation of the relief is the only way to develop geo-hazard studies useful in future management strategies (Ratter 2013; Jia et al. 2016; Preti et al. 2021).

The advance of adding a third dimension to traditional 2D rockfall modeling involves taking into account the lateral deviation of block trajectories (Bourrier et al. 2012; Asteriou and Tsiambaos 2018; Ji et al. 2020), which was previously overlooked considering only terrain profiles, and which is essential to understand the processes in detail in order to mitigate their negative impacts (Volkwein et al. 2011). This is especially important in coastal environments, where sometimes the shape of the cliffs tends to develop trajectories with lateral evolutions almost in their entirety.

With respect to the detached blocks, the worst-case scenario is generally that of the largest rock which remains intact while traveling down a slope (Pfeiffer and Bowen 1989), attaining the highest energy (Akin et al. 2021; Morales et al. 2021). In addition, the shape of the blocks determines the mechanical responses on impact with the ground, which has a remarkable implication for rockfall hazard assessment (Bonneau et al. 2019; Caviezel et al. 2021). In the case of spherical blocks, which are the prevalent ones throughout the study areas in this research, the shape is especially relevant, because it yields a maximum volume for a given radius, which will tend towards the worst case (Pfeiffer and Bowen 1989).

The detailed analysis of the most important rockfall trajectories studied in the past (most of them of 1 m^3) that reach high energies and volumes up to 3 m^3, even destroying local structures, lead to study and recognize the potential new events in the selected environments, with which evaluate, adjust, and simulate detachments occurring in the near and far future. Thus, it will be possible to develop management strategies that adhere to the environment in a more respectful, environmentally friendly, controlled, and efficient way, improving in turn the safety against geo-hazards (Morales et al. 2021; Domínguez-Cuesta et al. 2022). These actions that combine constructive elements with warning campaigns and delimitation of access and use areas, will result in establishing a base methodology applicable to other environments with similar characteristics, where the population's negative perception because of these interventions will be significantly reduced (Touili et al. 2014; Gray et al. 2017).

The development of analysis maps of different parameters that define rockfalls makes it possible to analyze the necessary height and the minimum kinetic energy that the hypothetical control structures to be installed in the area should withstand, or the response time and velocity against possible block falls (Sarro et al. 2018; Fanos and Pradhan 2019; Akin et al. 2021). This information provides a deeper understanding of the dynamics of instability processes in the environment, which in any case must constantly update its data and add new information, in order to progressively generate more realistic and accurate models of the environment.

Conclusions

The investigated area of Portofino Natural Park covers a wide natural and cultural area where it is possible to visit remarkable heritage sites walking in an incredible high-value landscape. The entire area is characterized by the presence of conglomerate rocks. The geological and geo-mechanical characteristics of this formation affect the potential instability of the natural and cultural heritages sites, especially during heavy rainfall and extreme events.

In the present paper, a comprehensive analysis of potential instability mechanisms (rockfall) and their spatial evolution (e.g., runout distance, trajectories and impact energy) is described for the selected area of San Fruttuoso and Paraggi bays. Such approach and methodology allow to carry out further studies and analysis supporting the adoption of the so-called nature-based solutions (NBSs), aiming to reduce the impact by the construction of mitigation measures and to increase resilience in high-value natural and cultural areas.

At the same time, the proposed advanced modeling constitutes a useful tool for the verification and calibration of the adopted design choices (e.g., size and correct location of the barriers, hypothesis of structural interventions for the protection of exposed elements such as paths, terraces, and cultural heritage), as well as a useful guidance for the implementation of medium-/long-term non-structural measures, such as in situ monitoring systems to be eventually transformed into early warning systems.

The detailed knowledge of the morphological dynamics of the area is in fact a fundamental cognitive element to develop participatory planning, directly involving stakeholders and providing the tools for a correct cost–benefit analysis to policy makers and funders. A co-creation process, in fact, runs across all the steps for the implementation of NBS interventions, from the initial co-design, to co-monitoring of their performance, to maintenance and finally decommissioning.

The advanced 3D modeling phase here proposed, in addition to being a real digital twin of the natural dynamics of the area, is expected to be integrated into this co-creation process for the sustainable management of high-value areas.

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Declarations

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