AP13

Engineering-geological approach to a preliminary landslide susceptibility assessment for complex coastal cliffs of volcanic origin: the case of Ponza island (Italy)

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INTRODUCTION

In May, 2010, a rockfall from a cliff of the Island of Ventotene, in the Pontine Archipelago (Thyrrenian Sea, offshore Latium) caused two casualties (Caso et al., 2014). This event pointed out the need to produce new maps depicting the landslide risk in the Archipelago, that were prepared by the Latium Basin Authority. These maps highlighted a very high risk for large sectors of the Pontine islands, including all the beaches below the rock cliffs, that is about the whole perimeter of the islands of Ventotene and Ponza. For these reasons, the great majority of the beaches were closed to the public. Aimed at ascertaining the effective landslide hazards scenarios, identifying the typology of expected movement, and, eventually, defining the most proper type of engineering works for risk mitigation, surveys on about ten of the most important beaches were carried out by the Authors at Ponza.

Due to the large lithological, structural, morphological, and geomechanical variability in the island, it was soon clear that a methodological approach, suitable to guarantee in short times adequate results, had to be adopted. Choice of the method brought to select a litho-geomorphological approach that allowed to produce detailed landslide susceptibility maps, followed then by maps depicting the mitigation works.

GEOLOGIC AND GEOMORPHOLOGIC SETTING OF PONZA ISLAND

Ponza Island is part of the western group of the Pontine Archipelago, located in the Gaeta Gulf, some 50 km offshore the Thyrrenian coast (Latium, central Italy).

The island consists, almost entirely, of volcanic products belonging to two magmatic associations, ejected in different times, starting from the Pliocene (De Rita et al. 2001; Cadoux et al., 2005).

During the first phase, the island was interested by acid underwater volcanic activity with ryolite-ryodacitic products, whilst in the final phase by subaerial volcanism of potassic type, with trachitic products (Bellucci et al., 1997). Acid vulcanites represent the most ancient and widespread outcroppings of the island, and are present, in particular, along its central and northern sectors. The hyaloclastic origin of most of the products of this cycle of activity has to be related to a underwater environment. These products show different facies with variable lithological characteristics, in function of the degree of interaction between magma and water (Carmassi et al., 1983). Further, the rhyolitic and rhyodacitic products in the northern sector of the island have been deeply altered hydrothermally, resulting in the formation of bentonites, that was exploited in past epochs. The last volcanic cycle found in the island is located in its southern sector (Monte La Guardia), with trachitic lavas and pyroclastic deposits (Bellucci et al., 1997, 1999b; fig. 1).

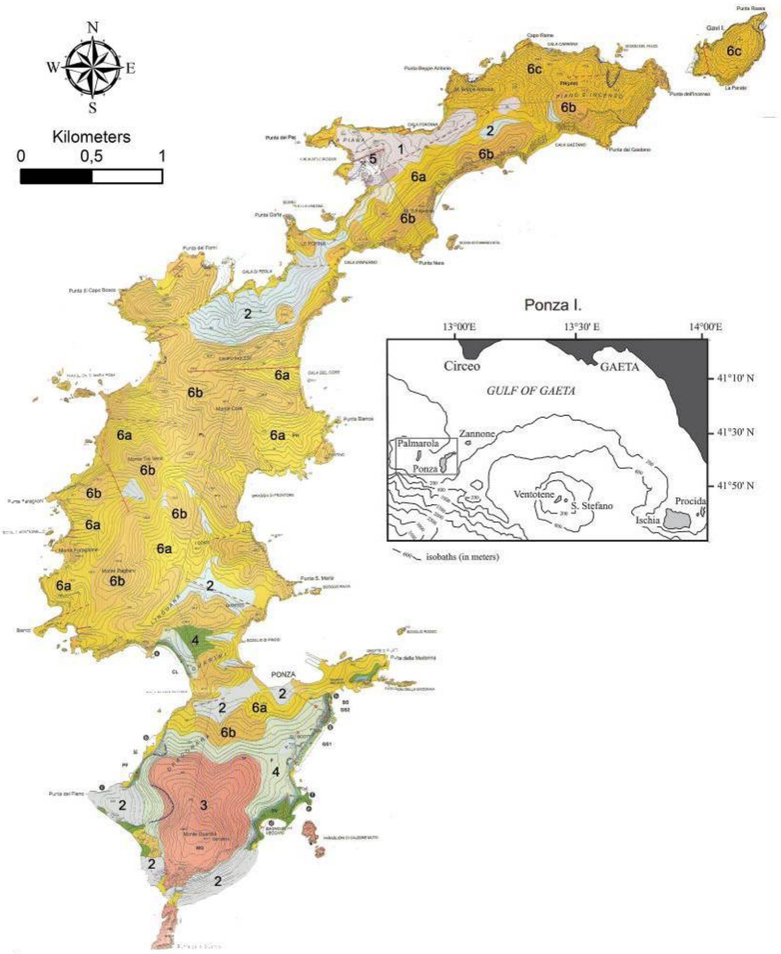

Fig. 1. Geological map of Ponza (after Bellucci et al., 1999b). Key: 1) loose residual tailing products of bentonite mine; 2) superficial loose deposit consisting of fine (a) and coarse (b) pyroclastic materials, reworked by exogenous agents and human activity; 3) Trachytic dome and lava flows (stiff rock); 4) loose and weakly welded pyroclastic fall and flow deposit consisting of ash and pomice beds; 5) bentonite deposit; 6) Rhyolitic gray hyaloclastic deposit (a), rhyolitic dykes (b), rhyolitic yellowish hyaloclastic deposit altered by hydrothermal fluids (c).

The present geomorphological setting of Ponza is the result of the interaction among the lithologic features of volcanic rocks, the volcano-tectonic history, and the processes related to the mechanical and chemical action of exogenous agents (sea waves, wind, erosion by runoff and infiltrating waters). Along the rock cliffs, the intrinsic featires of the rock mass combine to the action by exogenous agents, with very rapid effects. Cliffs, most of which are active, bound about the whole island with height ranging between 10 m and 120 m, and affect the large majority of the beaches, which main trend follows the coast, with elongated pattern.

Weathering of the rock mass, due to wind abrasion, runoff and infiltrating waters into the joints, and seismic activity, have to be added to the marine erosion at the base of the cliffs. These phenomena, combined with the lithologic features of the rocks, favor the development of landslides both in the rock masses and the loose soils.

As a matter of fact, the rock masses are characterized by high fracturing and show morphotypes produced by selective erosion (tafoni, rock shelves, caves or cave systems formed by erosional activity). These conditions affect the slope stability, causing frequent

rockfalls, locally of significant size. The continuous retreat of the cliffs, as an effect of rockfall processes, is testified by the presence of abundant landslide deposits and hanging valleys (Cala Lucia Rosa), by the lack of Quaternary forms of erosion linked to the sea level changes (only locally remnants of the notch are visible), and by the emergence of the galleries of the Roman underground aqueduct.
For long stretches, in particular in the mining districts of the north-western sector of the island, the natural trend of the cliffs was modified by anthropogenic activities, with the formation of man-made scarps, in turn affected by instability processes.
Eventually, the intensity of geomorphic processes acts also on the man-made works, causing the rapid degradation of retaining walls, that are therefore affected by detachment of blocks or can evolve to collapse creating conditions of high risk.

METHODOLOGIC APPROACH

Landslide inventory

To define the expected risk scenarios along the cliffs of the island, the main slope movements along its perimeter have been inventoried and catalogued. The surveys were carried out in 2010-2011, also with observations from the sea; they allowed to identify 46 landslides, and to compile for each of them a datasheet, starting from the proposal by the Latium Basin Authority.
The used classification scheme follows that of the IFFI Project (Inventory of Landslide Phenomena in Italy), in turn based on the indications in Varnes (1978), later updated by Cruden & Varnes (1996).

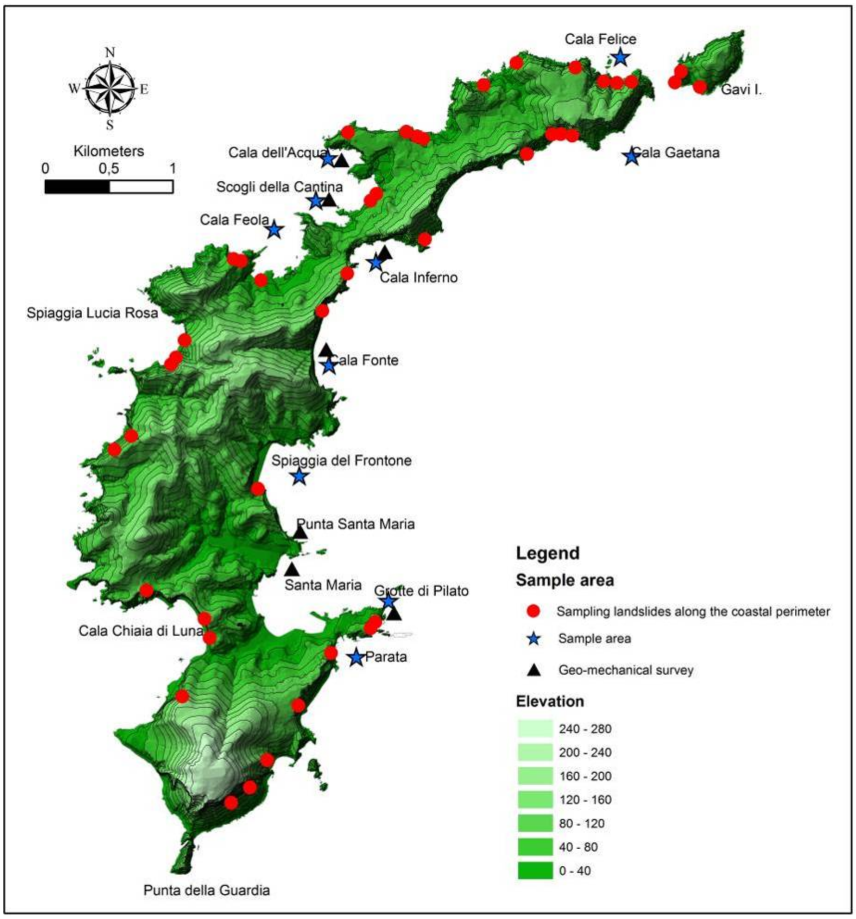

Fig. 2. Location of the main landslides observed along the cliffs of Ponza Island, also showing the studied areas (Frontone, Fonte, Inferno, Gaetana, Felice, dell'Acqua, Feola, Lucia Rosa, Parata, Grotte di Pilato and Santa Maria).

The main slope movement typologies are rockfalls and complex landslides as slide-fall (fig. 2), involving extremely variable volumes (from fall of single blocks on the order of cubic decimeters or meters, to mobilization of landslide body involving several tens of cubic meters). The database of the slope movements includes also indications about the state and the style of activity (fig. 3).
Landslides activate in both rock masses (lavas) and loose soils (pyroclastic deposits, regolith).
The sliding surfaces in the rock masses are both first-time failures and re-activations of pre-existing ones. In particular, where the rock mass presents a wide dispersion of the discontinuity data (fig. 4a), the failure planes appear to have a pseudo-circular shape, and are first-time failures; on the other hand, where the discontinuities group into families and the rock mass release allowed to break the intervening rock bridges, the failure surfaces developed along pre-existing planes. This typically occurred in a few cases, mainly involving less fractured lava rocks.
Table 1 lists the main morphometric features of the inventoried slope movements.

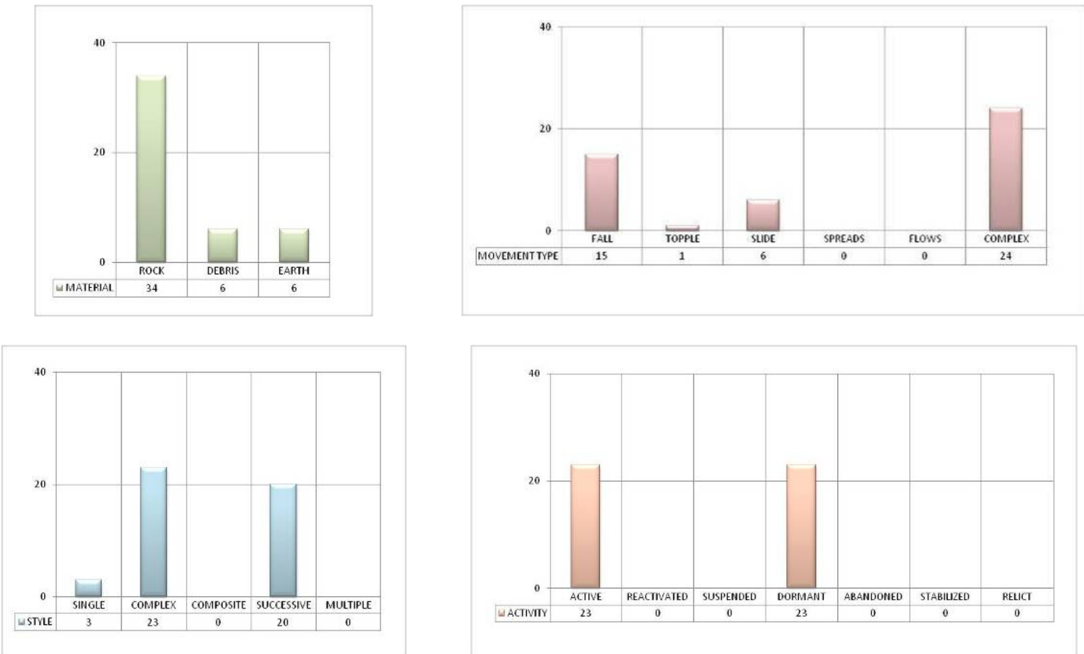

Fig. 3. The main frequency-characteristics distribution of the landslides

Tab. 1. Main morphometric features of inventoried landslides (class. after Varnes,1978). Key: Location (L); Material (M); Movement Type (MT); Activity (Ac); Style (S); Main Scarp Length (MS); Difference in level crown-toe (CT); Zone Of Depletion Length (DL); Landslide Area (A)

ID	**L**	**M**	**MT**	**Ac**	**S**	**MS-m**	**CT-m**	**DL-m**	**A-mq**
1	Frontone	earth	complex	active	complex	17	10	5	170
2	Core	rock	fall	active	successive	12	60	25	720
3	Inferno	rock	fall	dormant	successive	45	75	50	3375
3a	Punta Nera	rock	complex	active	complex	6	40	10	240
4	Gaetana	rock	complex	active	complex	15	50	10	750
4a	Gaetana	rock	slide	active	successive	12	45	61	540
4b	Gaetana	rock	slide	dormant	successive	8	40	38	320
4c	Gaetana	rock	complex	active	complex	7	50	20	350
5	I. Gavi	rock	fall	dormant	successive	60	45	15	2700
6	I. Gavi	rock	fall	dormant	successive	62	40	30	2480

7	I. Gavi	rock	fall	dormant	successive	50	40	50	2000
8	Felice	rock	fall	dormant	successive	27	50	15	1350
9	Felice	rock	fall	dormant	successive	45	50	18	2250
10	Felice	rock	complex	dormant	complex	60	50	60	3000
11	Felice	debris	slide	active	single	12	100	40	1200
12a	Felice	debris	slide	active	single	20	25	21	500
12b	Felice	rock	fall	active	successive	10	45	50	450
13	Felice	rock	fall	dormant	successive	51	25	25	1275
15	Cecata	debris	complex	active	complex	15	25	22	375
16	Cecata	rock	complex	dormant	complex	11	26	10	286
17	Cecata	rock	fall	active	successive	13	10	11	130
18	Fontana	rock	fall	active	successive	15	8	10	120
19	Dell'acqua	debris	complex	active	complex	16	23	12	368
20	Dell'acqua	earth	complex	dormant	complex	8	15	25	120
21	Feola	earth	complex	active	complex	7	23	13	161
22	Aurora	rock	complex	dormant	complex	9	45	11	405
23	Aurora	rock	complex	dormant	complex	8	30	16	240
24	Lucia Rosa	rock	complex	dormant	complex	95	95	51	9025
25	Lucia Rosa	rock	complex	dormant	complex	41	45	19	1845
26	Lucia Rosa	debris	slide	active	single	8	35	60	280
27a	P. Faraglioni	rock	fall	dormant	successive	67	115	103	7705
27b	P Faraglioni	rock	slide	dormant	successive	75	105	71	7875
28	P. Faraglioni	rock	complex	active	complex	35	85	80	2975
30	Chiaia Luna	rock	complex	dormant	complex	20	85	66	1700
31	Chiaia Luna	earth	complex	dormant	complex	29	90	17	2610
32	Chiaia Luna	debris	complex	active	complex	18	55	13	990
33	Dragonara	rock	complex	dormant	complex	96	160	115	15360
34	Parata	rock	crollo	active	successive	11	45	7	495
35	Scotti	rock	complex	dormant	complex	80	90	85	7200
36	F. Calz. Muto	rock	complex	dormant	complex	128	95	52	12160
37	P. Guardia	rock	fall	active	successive	30	125	146	3750
38a	P. Guardia	rock	complex	active	successive	67	235	130	15745
38b	P. Guardia	rock	topple	active	successive	42	175	120	7350
39a	Parata	earth	complex	active	complex	13	45	43	585
39b	Parata	earth	complex	active	complex	13	50	43	650
40	Parata	rock	fall	dormant	successive	43	50	20	2150

Production of high resolution photo-mosaics

One of the main problems encountered in the production of thematic maps on cliffs is the impossibility to represent the themes on maps with horizontal contour lines. Frontal views are, on the other hand, produced by means of laser scanner technique or of photogrammetry from helicopter, where vertical contour lines are portrayed.

In the present paper, aimed at the most proper and accurate cartographic representation of the considered geo-themes, we choose to produce frontal photo-mosaics, acquired through high-resolution pictures, mostly taken from offshore (Di Crescenzo & Santo, 2007). A particular care was therefore focused on the phase of photographic survey, aimed at:

a) having the possibility to produce high quality photo-mosaics;

b) treating the pictures with softwares able to produce point clouds and 3D views (AA.VV., 2004);

c) acquiring even small features for those critical elements that characterize the rock cliffs (pinnacles, layers or beds close to toppling, rock shelves without support below, etc).
As concerns points *a)* and *b)* above, the pictures were shot keeping a constant distance from the cliff, with the focal of the axis perpendicular to the portion of cliff to be acquired, using always the same focal of the lens, and guaranteeing at least a 60% image superimposition. These expedients allowed to get ortophoto, point clouds and meshes that were later used for the data analysis and mapping.
As regards the point *c)* above, a 210 mm Nikon was used, with exposition time greater than 1/125 sec; each single shot was positioned on the previously acquired photo-mosaics.
This procedure allows also to produce geographically referred ortophotos that, through the use of softwares as AVG, Pix4D, meshlab, etc., may perform estimates on the size of unstable areas, or to take measurements of the attitude of the main discontinuities.

Susceptibility Maps based upon litho-geomorphologic criteria
From a geomorphological standpoint, the island of Ponza is bounded by active cliffs, with heights ranging between 10 and 120 meters, directly above the sea or on gravel and sand beaches, typically narrow and elongated along the coast.
The cliffs show frequently a high lithological and structural variability, with outcroppings of materials such as loose soils and hard rock masses with discontinuity planes at high scattering of attitude (fig. 4b).

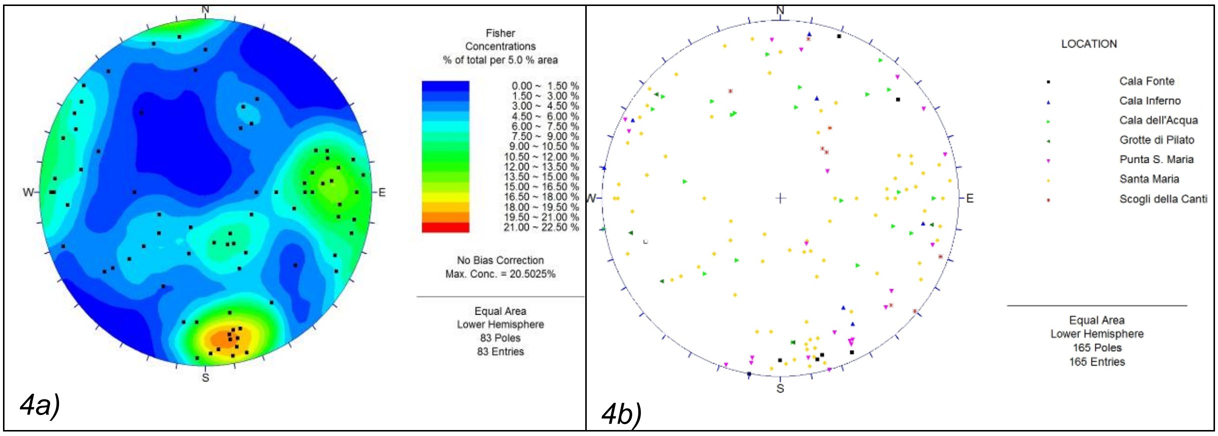

Fig. 4. Poles of stereographic projection of the main discontinuities in lava rock masses in the Santa Maria sample site (a) and in the overall island (b)

In complex geologic settings as Ponza, the production of landslide susceptibility maps based upon semi-quantitative methods (i.e., Romana, Matheson, etc.) do not provide reliable results. This is due to the high scattering of the discontinuity data (fig. 4) that points out the low quality of the rock masses and, consequently, the likely occurrence of landslides along first-time surfaces of failure (Robertson, 1988) and, on the other hand, the difficulty in grouping portions of cliffs in geo-mechanically omogeneous units.
For the reasons above, we considered more adequate the production of landslide susceptibility maps based upon a litho-geomorphological approach. Specifically, the geo-lithologic study was finalized to subdivide the studied areas in lithologically omogeneous units, in function of the litho-technical behaviour (hard rock, semi-hard rock, loose rock).
Table 2 lists the mapped lithotypes, whilst figure 6 shows an example of a map of the geological and structural features on photo-mosaic.

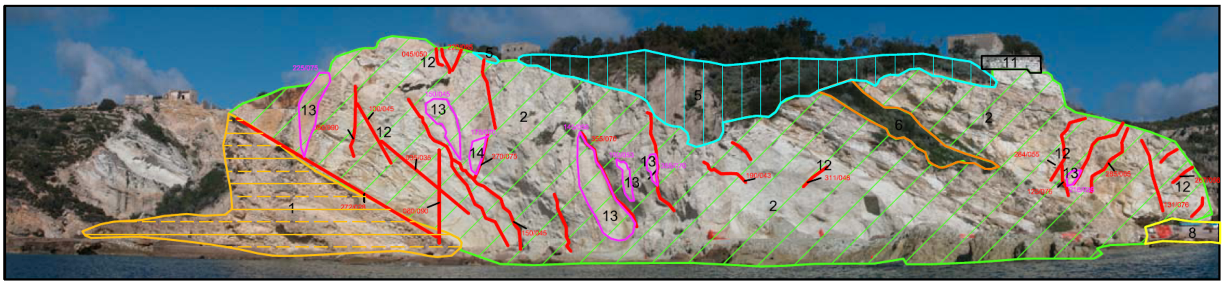

Fig. 6 Geostructural photo-mosaic map at Cala dell'Acqua. Key: 1) massive rhyolitic hyaloclastic deposit in breccia facies, with abundant glassy cement and coarse elements (L1); 2) massive rhyolitic hyaloclastic deposit in microbreccia facies (L2); 5) bentonite deposit (L5); 6) alluvial and colluvial deposits (L6); 8) beach deposits (volcanic gravel and sand) (L8); 11) anthropogenic material (L11); 12) main discontinuity and attitude (L12); 13) plane of discontinuity and attitude (L13).

In this figure the main discontinuities (of stratigraphic, structural, or volcano-tectonic origins) have also been shown, pointing out their relative attitude.
All the geomorphological elements that have been considered significant for predisposing the cliff to instability and/or to erosion have been portrayed in the Geomorphological Map. Grouping in geomorphologically omogeneous units was also performed as a function of the litho-structural features of the cliffs. Actually, after the first field surveys it appeared very clear that the litho-technical and geo-structural variability of the cliffs was responsible for activating different types of movements, both as regards the kinematicsand involved volumes.
This map also shows all the single morphotypes that have been considered significant for the instability, both for gravity-related movements (landslide crown and body, unstable block, cavity, etc.) or for the action of runoff waters and sea waves (downcutting stream, drainage line with torrential character, present notch, ecc).
The lithological-structural (fig. 6) and geomorphological (fig. 7) factors used to produce the landslide susceptibility map on photo-mosaic (fig. 8) are listed in Table 2.

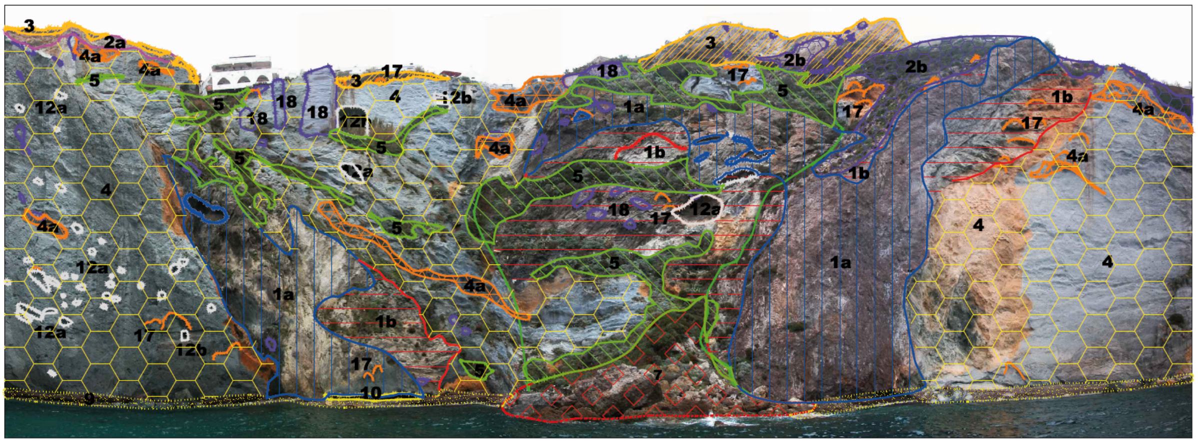

Fig. 7. Geomorphological photo-mosaic map at Cala Inferno. Key: 1) columnar-jointed (a – M1a) or cataclasized (b – M1b) rhyolitic cliff; 2) hyaloclastic rock slope with medium-high gradient covered by soils in accelerated erosion (a – M2a) or with vegetation (b – M2b); 3) cantilever rock slope sector (H/L <<1 – M3); 4) hyaloclastic cliff (a – M4a), with overhanging sectors (b – M4b); 5) rock slope with medium-low gradient covered by detrital and eluvial-colluvial deposits (M5); 10) beach (M11); 12) erosional (a – M10) or anthropogenic (b – M10) cavities; 17) landslides crown (M9); 18) slope sector with unstable rock blocks (M8).

The compared analysis of the geolithologic and geomorphologic factors allowed to produce the Landslide Susceptibility Map for hard rocks and loose soils. In this map, starting from the landslide inventory, and superimposing the aforementioned themes with euristic approach (fig. 9), the sectors of slopes have been grouped in:

a) omogeneous areas in terms of typology of expected event (initiation, erosion-transport, and accumulation);
b) expected kinematics (only for the initiation areas);
c) susceptibility level (high, medium, low).

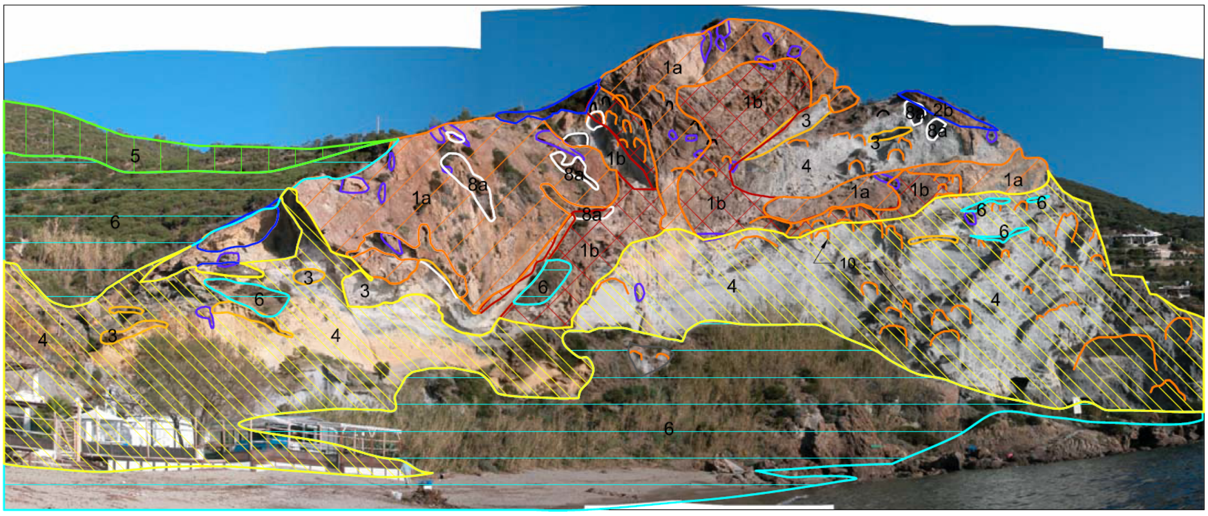

Fig. 8. Susceptibility photo-mosaic map at Frontone beach. Key: 1) high susceptibility landslide on pre-existing (a – S1a) or first-time fractures (b – S1b); 2) medium (a - S2a) to high (b – S2b) linear or areal erosion susceptibility of the cover deposits; 3) high susceptibility on overhanging rock mass (S3); 4) medium landslide susceptibility on first-time fractures (S4); 5) low landslide susceptibility (S5); 6) high landslide transport and accumulation susceptibility (S6); 8) cavities with unstable roof (S8c); 10) landslide crown (S8b); 14) single or multiple unstable rock blocks (S8a).

	M1		M2		M3	M4		M5	M6	M7		M8	M9	M10	M11	M12	M13	M14	M15	IM
	a	b	a	b		a	b			a	b									
L1		S1b			S3	S4	S3					S8a	S8b				S7	S1b		
L2		S1b			S3	S4	S3		S1b/S3			S8a	S8b	S8c		S8e	S7	S1b		
L3		S1b	S2b	S2a	S3							S8a	S8b	S8c			S7	S1b		
L4	S1a				S3				S1a/S3			S8a	S8b			S8e	S7			
L5										S2b	S2a						S7			
L6			S2b	S2a				S6							S6		S7			
L7			S2b	S2a													S7		S5	
L8															S6					
L9															S6					
L10			S2b	S2a											S6		S7			
L11																				S8d
L12																				S9a
L13																				S9a

IM: Indipendente da Morfotipo

High susceptibility (red) — Medium susceptibility (yellow) — Low susceptibility (green)

Fig. 9. Degrees of susceptibility (S) as a function of lithological (L) and geomorphological factors (M).

Tab. 2 Detailed keys to the photo-mosaic maps.

Geo-structural map		Geomorphological map		Landslide susceptibility map	
COD	**Description**	**COD**	**Description**	**COD**	**Description**
L1	Rhyolitic hyaloclastic deposit in breccia facies, with abundant glassy cement	**M1a/ M1b**	Columnar-jointed (a) or cataclasized (b) rhyolitic cliff	**S1a/ S1b**	*High susceptibility landslide on pre-existing (a) or first-time fractures (b)*
L2	Rhyolitic hyaloclastic deposit in microbreccia facies	**M2a/ M2b**	Hyaloclastic rock slope with medium-high gradient with soils in accelerated erosion (a) or with vegetation (b)	**S2a/ S2b**	*Medium (a- S2a) to high (b – S2b) linear or areal erosion susceptibility of the cover deposits*
L3	Rhyolitic hyaloclastic deposit in breccia facies, with rare glassy cement	**M3**	Cantilever rock slope sector (H/L <<1)	**S3**	*High susceptibility on overhanging rock mass*
L4	Rhyolitic lava forming domes and dykes with columnar jointing	**M4a /M4b**	Hyaloclastic rock cliff (a), with overhanging rock slope sectors (b)	**S4**	*Medium landslide susceptibility on first-time fractures*
L5	Bentonite deposit	**M5**	Rock slope with medium-low gradient covered by detrital and eluvial-colluvial deposits	**S5**	*Low landslide susceptibility*
L6	Alluvial and colluvial deposits	M6	Steep rock slope with widespread landslides crowns	**S6**	*High landslide transport and accumulation susceptibility*
L7	Pyroclastic and detrital deposits	**M7a /M7b**	Sector of slope with medium-high gradient, with bentonite cover in accelerated erosion (a) or with vegetation (b)	**S7**	*High susceptibility to passage of rock fall debris*
L8	Beach deposits	**M8**	Slope sector with unstable rock blocks	**S8**	Susceptibility to be determined after further detailed studies with:
L9	Depleted mass	**M9**	Landslide crown	**a**	*Single or multiple unstable rock blocks*
L10	Reworked pyroclastic deposits	**M10**	Erosional (a) or anthropogenic (b) cavity	**b**	*Landslide crown*
L11	Anthropogenic material	**M11**	Deposits of various genesis: a) detrital-alluvial; b) reworked pyroclastic deposits; c) depleted masses; d) beach	**c**	*Cavities with unstable roof*
L12	Discontinuity and attitude	**M12**	Present notch	**d**	*Deteriorated or partially collapsed wall*
L13	Plane of discontinuity and attitude	**M13**	Concentrated runoff (a), locally in an embryonic phase (b)	**e**	*Present notch*
		M14	Sector suffering linear accelerated erosion	**S9**	Morpho-structural singolarities:
		M15	Top surface at low gradient	**a**	*Discontinuity and attitude*

CONCLUSIONS

The production of Landslide Susceptibility Maps for high cliffs presents a series of problems due to difficulties in obtaining reliable topographic maps, adequate to correctly represent the themes of interest, and in acquiring the geological data. Further, in a complex volcanic setting as at Ponza, where an extreme geo-mechanical variability of the rock mass is present as the effect of a wide range in the attitude of discontinuities, the traditional semi-quantitative methods (Romana, Matheson, etc.) do not provide reliable results. These latter, on the other hand, may be reached through qualitative methods based upon the litho-morpho-structural analysis of the cliffs, that also provides useful indications as regards the most suitable mitigation works in the areas at risk.

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