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Approaches for mapping susceptibility to rockfalls initiation in carbonate rock-masses: a case study from the Sorrento coast (southern Italy)

DONATELLA APUZZO (*), PANTALEONE DE VITA (**), BIAGIO PALMA (***) & DOMENICO CALCATERRA (**)

ABSTRACT

Most of the shoreline of the Campania region, Southern Italy, is characterized by steep and high rocky slopes, then several localities, densely populated and highly touristic attractive for the worldwide famous landscapes are exposed to an high rockfall risk. Particularly, the touristic localities on the Sorrentine Peninsula, such as Sorrento, Vico Equense and Amalfi, can be considered among the most representative case-studies prone to the recurrent instability of rock blocks. Due to the frequent location of settlements and roads underneath and at very limited or null distances from the carbonate steep slopes, a diffuse condition of high rockfall risk exists. Consequently, the assessment of priorities in directing active remedial works to be carried out on the unstable rock slopes is still a challenging issue.

In order to find an effective method for assessing the susceptibility to rockfall initiation with approaches suitable for detailed mapping, a combined application of standard methods was tested. The Romana's Slope Mass Rating (SMR) and the Matheson's graphical tests, for assessing the number of fundamental instability mechanisms, were applied in a test site of the Sorrento coast. Results of the two methods were separately evaluated and then combined in a new rating approach by indexing the respective susceptibility classes. In addition, the number of joint sets and the macro-structural features of the rock-mass (faults and master joints) were considered. By means of statistical analyses of rockfalls occurred in the test area, the results obtained with the new combined approach were found more accurate in assessing and mapping the most susceptible areas.

KEY WORDS: *Active remedial works, mapping, rockfall, rock slopes, landslide susceptibility*.

INTRODUCTION

The natural propensity to recession of rocky cliffs represents a typical environmental hazard in densely urbanized coastal areas. This particularly occurs in the Southern Italy and especially in Campania region where lifelines and settlements are located along the coast. The Sorrentine Peninsula is one of the most exhaustive examples where rockfalls constitute one of the most recurrent types of landslide that threatens towns, lifelines and touristic settlements.

Rockfall is a generic term used for identifying instability of rock blocks along steep rocky cliffs with relatively low volumes and with high kinetic energy that depends on the relative height of the detachment and the consecutive free-fall, bouncing and rolling kinematics (VARNES, 1978; HUNGR & EVANS, 1988). The detachment of a rock block from a cliff is favored by single discontinuities or discontinuity systems pervading the rock-mass, their geometry relatively to the slope face, the shear strength available along joint surfaces and the weathering processes (HOEK & BRAY, 1981; HOEK & BROWN, 1997). Rockfalls can be caused by several triggering factors such as seismic shaking, intense rainfalls, freeze and thaw, growth of plant roots (DUNCAN & NORMAN, 1996). The assessment of the rockfall hazard is a difficult issue for a number of factors that control the variability of the landslide intensity (kinetic energy) along the trajectory of the rock blocks. Among these, the location of the initial detachment, the complex mobility of the rock block depending on the gravitational potential energy (relative height and mass of rock blocks), the morphology of the ground and its mechanical properties have to be taken into account.

Several methods have been proposed for the assessment of rockfall hazard, following different approaches. A first attempt was made for evaluating rockfall hazards for roadways (PIERSON *et alii*, 1990) by implementing in a practical empirical rating system (Rockfall Hazard Rating System-RHRS) the recognizable factors that control the onset and mobility of rock blocks (e.g. slope height, ditch effectiveness, roadway width, structural conditions, rock block volume, climate and water circulation, local rockfall history, etc.). This type of approach was further improved by adapting it to different geologic and geomorphologic conditions by means of a matrix of 15 parameters (CANCELLI & CROSTA, 1993). A refinement of the RHRS method was also proposed for roadways prone to rockfall hazard in the Campania region (BUDETTA, 2004). Other approaches to rockfall hazard evaluation were based on the statistical and probabilistic analysis of historical occurrences (WIECZOREK *et alii*, 1992; DUSSAGE-PEISSIER *et alii*, 2002; PARISE, 2002; GUZZETTI *et alii*, 2003; BAUER & NEUMAN, 2011) also integrated with physically based models of rock block mobility (CROSTA & AGLIARDI, 2003; GUZZETTI *et alii*, 2003; JABOYEDOFF *et alii*, 2005; FRATTINI *et alii*, 2008). Methods for the rockfall hazard assessment at regional scale, based on the analysis of geological and geomorphometric data with GIS techniques, were also proposed (MARQUÍNEZ *et alii*, 2003; LOYE *et alii*, 2009). A few methods based on features of the rock mass are known in literature for assessing and mapping susceptibility to rockfall onset by applying parametric methods (e.g. GOKCEOGLU *et alii*, 2000; BAILLIFARD *et alii*, 2003; IRIGARAY, 2003; GÜNTHER, 2003; DORREN *et alii*, 2004; GÜNTHER *et alii*, 2004).

In the Sorrentine Peninsula, the recurrent juxtaposition of anthropic structures or touristic areas to unstable rocky cliffs and the difficulty to design passive remedial works, due to the critical logistic conditions, mostly led to choose active remedial works to be carried out for

(*) External collaborator.
(**) Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di Napoli "Federico II".
(***) Idrogeo S.r.l., Vico Equense (NA).

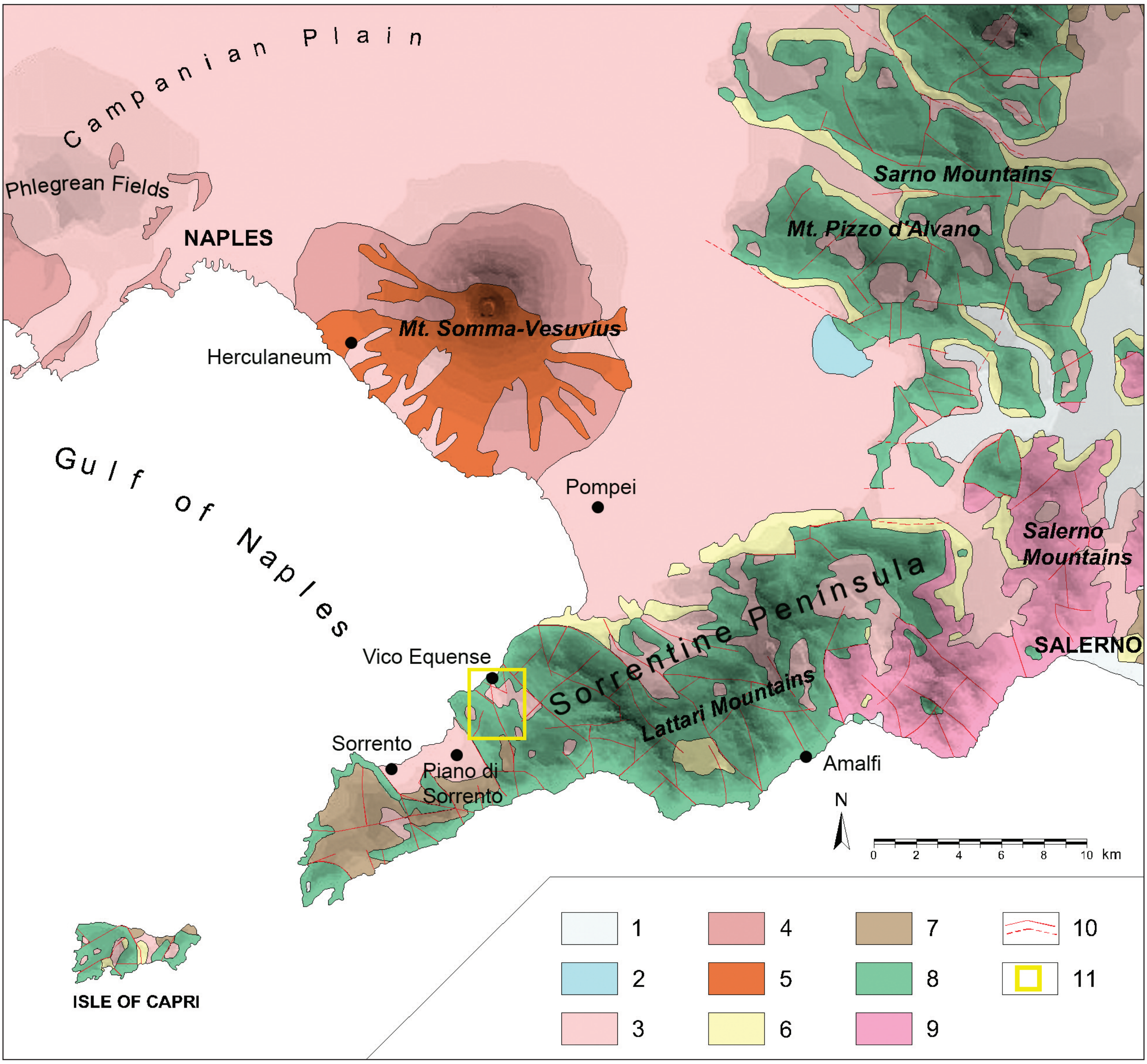

Fig. 1 - Geological map of the area surrounding the Sorrentine Peninsula. Key to symbols: 1) alluvial deposits; 2) travertine; 3) incoherent ash-fall deposits; 4) mainly coherent ash-flow deposits; 5) lavas; 6) detrital deposits; 7) Miocene flysch; 8) Middle Jurassic-Upper Cretaceous limestones; 9) Lower Triassic-Middle Jurassic dolomites and calcareous limestones; 10) outcropping and buried faults; 11) frame of the fig. 2.

reducing rockfall hazard. For the most hazardous cases, the detailed assessment and mapping of susceptibility to rockfall initiation along the unstable rock slopes is a challenging issue in order to direct effectively active remedial works such as rock bolts combined with retaining nets.

In this paper, standard methods for assessing and mapping susceptibility to rockfall initiation are discussed and tested comparatively with a new parametric approach. The fundamental aim of this paper is to provide "ordinary" end-users, as consultant geologists, with a practical tool, yet based upon a well-established and updated scientific background, to solve common technical problems related to rockslope stability, which are too often dealt with oversimplified heuristic approaches.

GEOLOGY AND STABILITY OF ROCK SLOPES IN THE SORRENTINE PENINSULA COAST

The Sorrentine Peninsula is a major geological structure of the Campania region consisting of an elongated SW-NE horst that divides the graben of the Campanian Plain-Gulf of Naples, to the North, from the graben of the Sele Plain-Gulf of Salerno, to the South. It is mainly constituted of pre-orogenic sedimentary series of carbonate platform facies, Triassic to Upper Cretaceous in age (D'ARGENIO *et alii*, 1973), with lithotypes varying from limestones to dolostones. In addition, syn-orogenic Miocene deposits of flysch facies are locally present. Quaternary deposits are identified by ash-flows and tuffs derived from the explosive

TABLE 1

Major rock-slope instabilities occurred in the municipality of Vico Equense since the last century.
Asterisks refer to the events surveyed during the present study.

N	Location	Date	Volume (m^3)	Damage	Source
1	"Bikini"	Ancient Landslide	Several thousands	-	Calcaterra and Santo, 2003
2	"Tordigliano"	24 Oct 1910	-	6 victims	Palma, 2005
3	"Bikini"	1961	Several thousands	Road	Civita and Lucini, 1968
4	Vico Equense Jala sinkhole	Different years	Several thousands	-	Civita and Lucini, 1968
5	Pozzano-V.Equense	21 Feb 1967	Few thousands	Road	Palma, 2005
6	"Bikini"	21 Jun 1967	Several thousands	Road	Civita and Lucini, 1969
7	"Bikini"	1968	-	1 victim	Budetta and Panico, 2002
8	"S.Vito" - Vico Equense	14 Aug 1971	-	-	Vallario, 2001
9	"Bikini"	1975	6000	Road	Nicotera, 1995
10	Vico Equense	Nov 1980	-	-	Vallario, 2001
11	"Famous Beach" - Vico Equense	Jul 1982	-	1 victim	Vallario, 2001
12	Pozzano - Vico Equense	22 Feb 1986	Few tens	Road	Guida *et alii*, 1986
13	Vico Equense - Meta	07 Mar 1986	-	-	Vallario, 2001
14	Pozzano - Vico Equense	26 Mar 1986	Few tens	Road	Guida *et alii*, 1986
15	Vico Equense - Meta	24 Aug 1986	-	Car	Vallario, 2001
16	Pozzano-Punta Orlando	Jan 1987	10.000	Road	Budetta and Panico, 2002
17	Seiano	1998	-	-	Budetta and Panico, 2002
18	V.Equense "Vescovado"	27 Dec 1999	-	-	Budetta and Panico, 2002
19	Vico Equense "Vescovado"	2001	-	-	Budetta and Panico, 2002
20	Punta Orlando	2001	-	-	Budetta and Panico, 2002
21	"Scrajo"	10 Jan 2003	-	-	*
22	Vico Equense "Vescovado"	2005	-	-	*
23	Pozzano - Vico Equense	09 Mar 2008	-	Road	*
24	Seiano - Entrance to the gallery	22 Jan 2009	-	Road	*
25	Vico Equense	Jan 2009	-	-	*
26	Vico Equense "Vescovado"	17 Feb 2009	100	Cliff Top	*
27	Road to Vico Equense's marine	Jan 2010	-	Roman villa I c.A.D.	*
28	Corso Filangieri (below Seiano's bridge)	11 Feb 2010	-	Car	*
29	Road to Seiano's marine	25 Feb 2010	50	Road	*
30	Giusso Castle	Nov 2010	-	-	*
31	Giusso Castle	Nov 2010	-	-	*
32	Giusso Castle	Various years	-	-	*
33	Vico Equense “S.Maria del Toro”	2011	-	Road	*

activity of the Phlegrean Fields, still preserved in structural depressions (ISPRA, 2012), as well as ash-fall deposits derived from the volcanic activity of the Somma-Vesuvius (e.g. the 79 A.D. eruption which destroyed Pompei and Herculaneum) that mantle mountain slopes (CALCATERRA & SANTO, 2004). The geological structure of the Sorrentine Peninsula determined the current morphostructural setting of the Lattari Mountain Range (fig. 1) and then of shoreline cliffs. This geological structure is characterized by a series of NW dipping monoclines, dislocated by normal faults and thrusts with a strike-slip component (PATACCA & SCANDONE, 1987). The morphology is generally characterised by very steep slopes derived by the recession of fault line scarps (CINQUE *et alii*, 1993). Therefore, mass wasting processes are very active also for the predisposition of this mountain range, bordered by the Tyrrhenian Sea, to generate rainfalls of extreme intensity that caused a number of catastrophic events both for rockfalls (GUIDA *et alii*, 1986; BUDETTA & SANTO, 1994; NICOTERA, 1995; PALMA, 2005) and for instability of slope-mantling pyroclastic ash-fall deposits (CALCATERRA & SANTO, 2004).

The steep morphology conditioned the location of settlements and roads limiting their construction to narrow flat areas close to the coast line, which correspond typically to relict erosional surfaces and marine terraces. The closeness of anthropic structures to the base of high rocky cliff determines a high exposure to rockfall hazard (BUDETTA & SANTO, 1994; PALMA *et alii*, 2011).

The study area is located within the municipality of Vico Equense (figs. 1, 2 and 3), one of the human settlements of the Sorrentine Peninsula most damaged by rockfalls as also testified by the 33 occurrences of damaging rockfalls known for this municipality since the beginning of the 20th century (tab. 1).

The Vico Equense area is characterised by Mesozoic carbonate rocks, locally represented by the Upper Cretaceous limestones and dolomitic limestones, with slopes mantled by a thin cover of pyroclastic deposits, belonging to explosive eruptions of the Mount Somma-Vesuvius and, subordinately, of the Phlegrean Fields (ISPRA, 2012). Among the volcanic rocks deriving from Phlegrean Fields volcanic field is the Campanian Ignimbrite, a pyroclastic flow produced by a parossistic explosive eruption at 39ka (Barberi *et alii*, 1978; Pappalardo *et alii*, 1999; De Vivo *et alii*, 2001). In the study area, the Ignimbrite Campana mainly crops out along the coastal cliffs of Vico Equense (fig. 2) and Piano di Sorrento (fig. 1). Quaternary talus and alluvial fan deposits are also of some importance, occupying a large part of the footslope areas and constituting the local bedrock for the most part of the urbanized areas. Recent and actual detrital and anthropic deposits of various origins are also present at the footslopes (fig. 2).

DATA AND METHODS

In this study, in order to test an appropriate method for assessing and mapping the susceptibility to rock-slope instability, finalized to a proper selection of remedial measures, comparisons and modifications to methods commonly applied for the assessment of susceptibility to rockfall onset were experimented. A sample rocky cliff close to the Giusso Castle (figs. 2 and 3) was identified as representative of typical conditions of rock block instability throughout the municipal area as well as of potential risk for tourists that stay or pass close to it. The area investigated for the rocky cliff is extended in plain view for about 4,000 m^2 but, considering its median average slope angle of 62°, its surface extension was estimated in about 8,500 m^2 by the projection of the plain area over the inclined plane.

The results of this study have been mapped using the Regional Technical Map of Campania, scale 1:5,000 (Regione Campania, 2004), which is the most detailed and reliable digital contour map available for the municipality of Vico Equense area.

The first phase of the analysis consisted in detailed geomorphological and macro-structural analyses of the rocky cliff. Subsequently, geomechanical surveys were executed through sixteen measurement stations (figs. 5, 6 and 7) carried out in accessible points, mainly located at the cliff base. In some cases, surveys were executed along the slope by means of rock climbers. In all cases a double perpendicular scan lines technique was adopted in order to reduce biases due to unfavorable orientation or spacing of joint sets (Terzaghi, 1965). Surveys were focused on the acquisition of rock-mass standard parameters (ISRM, 1978; Priest & Hudson, 1981; Priest, 1993). A total number of 1740 structural data were collected. The Rock Quality Designation (RQD) and the Uniaxial Compression Strength (UCS) were also characterized respectively adopting an indirect technique based on joint density (Priest & Hudson, 1981) and field measurements carried out with the Schmidt hammer (ISRM, 1978; ASTM, 2001; Aydin & Basu, 2005). Moreover, other macro-structural features, such as faults and master joints were considered and recorded in order to account for the lower rock mass quality within their damage zones (Cowie & Scholz, 1992; McGrath & Davison, 1995; Kim *et alii*, 2004).

To test the applicability of common methods for mapping the susceptibility of rockfall initiation, results derived from the Slope Mass Rating method (Romana, 1985, 1993; Romana *et alii*, 2003) and Matheson (1983) graphical methods were compared.

The Slope Mass Rating is a parametric method that expresses the susceptibility to instability of a rock slope (Irigaray *et alii*, 2003) by means of a rating system, taking into account both the rock-mass quality and corrective factors depending on geometric relationships between joint sets and the slope face. Specifically, it modifies the basic value of the Rock Mass Rating (RMR_b - Bieniawski, 1979) by means of four corrective factors (F_1, F_2, F_3 and F_4).

$$SMR = RMR_b + [(F_1 \cdot F_2 \cdot F_3) + F_4] \quad (1)$$

The first three factors, estimated for each joint set, depend on: F_1) parallelism between strikes of a joint set and the slope face, ranging from 0.15 (non parallelism) to 1 (parallelism); F_2) dip angle of a joint set, ranging from 0.15 (<20°) to 1 (>45°); F_3) daylighting of a joint set, ranging from 0 (non daylighting) to –60 (daylighting). Each factor is differently estimated for every fundamental instability mechanism (plane sliding, wedge sliding and toppling) and it is evaluated for every joint set. The fourth factor (F_4) is a constant that depends on the methods of excavation, ranging from –8 (deficient blasting) to +15 (natural slope). Romana (1985) defined five classes, describing the conditions and common types of rock-slope failure as well as the suitable support measures (tab. 2).

The Matheson's graphical tests (Matheson, 1983) are a useful method to identify type and number of possible fundamental mechanisms of instability (plane sliding, wedge sliding, direct and flexural toppling), considering a simplified calculation of the limit-equilibrium condition (Hoek & Bray, 1981). It consists of four graphical overlays suitable for each mechanism of instability to be used together with stereoplots of discontinuities data. Each graphical overlay allows verifying the possibility to rock block instability both considering the geometrical relationships between joint sets and the slope face and comparing dip angle and the total friction angle of the joint sets. The Matheson's graphical tests were applied for evaluating the number of possible fundamental mechanisms of instability, considering it as an indicator of susceptibility to rockfall initiation.

Considering the Barton criterion (Barton, 1973)

$$\tau = \sigma_n \cdot tg\left[\varphi_b + JRC \cdot \log_{10}\left(\frac{JCS}{\sigma_n}\right)\right] \quad (2)$$

where:

σ_n = effective vertical stress;
φ_b = basic friction angle (°);
JRC = Joint Roughness Coefficient;
JCS = Joint Compressive Strength.

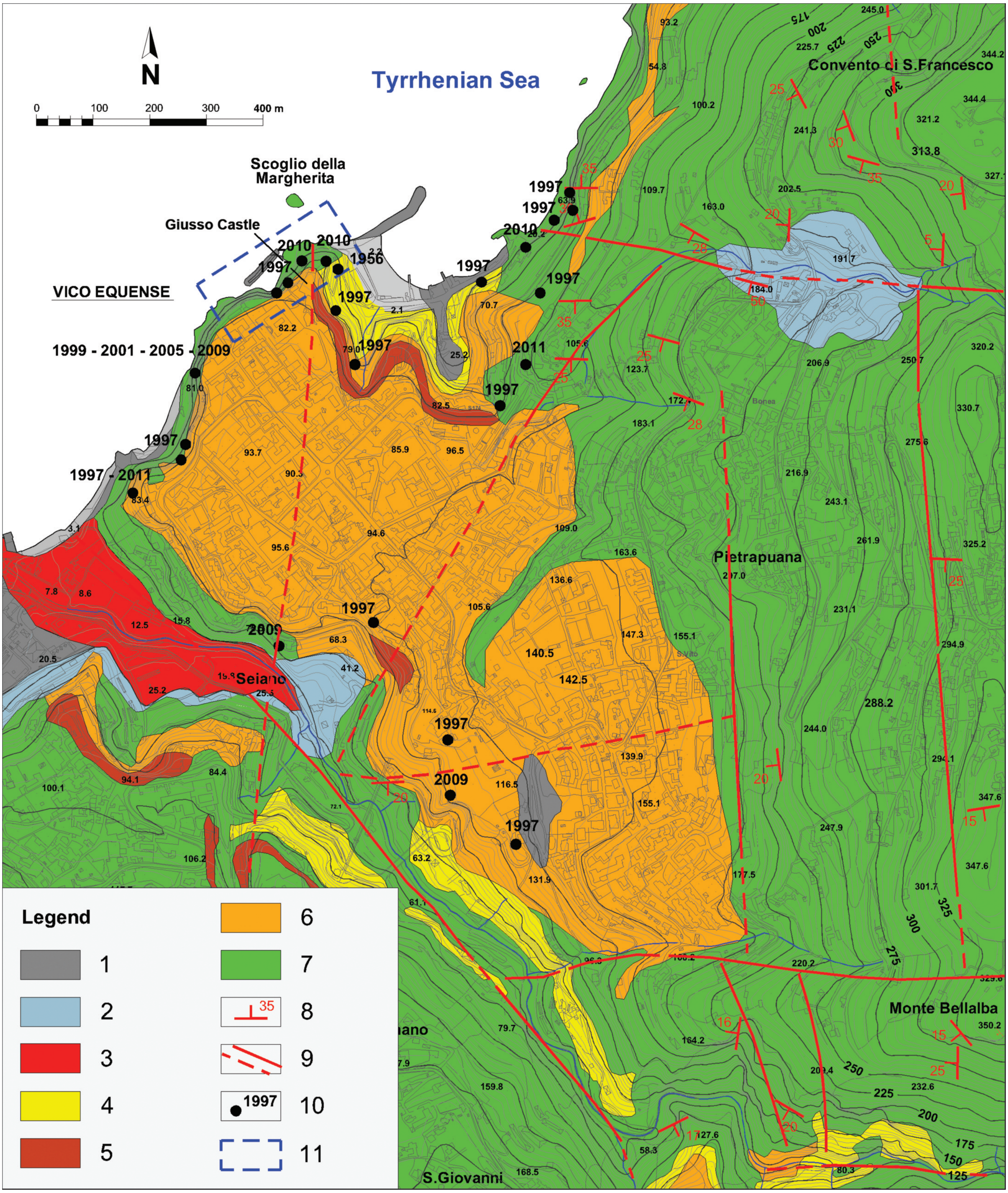

Fig. 2 - Geological map of the Vico Equense's territory. Key to symbols: 1) urban and land-fill deposits; 2) beach deposits (Holocene); 3) colluvial and talus deposits (Holocene); 4) talus and alluvial fan deposits (Pleistocene); 5) Campanian Ignimbrite deposits (Late Pleistocene-39 ka); 6) ancient ash-flow deposits (Pleistocene); 7) limestones and dolomitic limestones (Upper Cretaceous); 8) bedding attitude; 9) fault, buried-expected fault; 10) recent rock-slope instability (1980-2010); 11) test area.

and the expression for the total friction angle (φ) derived from it:

$$\varphi = \varphi_b + \left[\mathrm{JRC} \cdot \log_{10} \left(\frac{\mathrm{JCS}}{\sigma_n} \right) \right] \qquad (3)$$

a reference value was estimated for joint sets (φ = 56°), by using median values of those measured in geomechanical stations (JRC = 7 and JCS = 53 MPa), values partly derived from literature (φ_b = 36°; BUDETTA & CALCATERRA, 1991) and partly resulting from field observations (σ_n was set conservatively as corresponding to a depth of 3 m).

The results obtained for each geomechanical station were compared in terms of Slope Mass Rating value and number of instability mechanisms. Subsequently, results were extrapolated to the whole slope face by means of a geostatistical technique and adopting a best fitting algorithm. This type of spatial extrapolation was considered acceptable because of the homogeneous distribution of the geomechanical stations along the slope and the quite regular aspect of the slope face (figs. 3 and 6).

Considering the reciprocal advantages and drawbacks of both methods, a new technique was experimented based on the sum of the rating attributed to Slope Mass Rating class, number of fundamental instability mechanisms, number of joint sets and macro-structural features of the rock-mass (fault and master joints) (tab. 3). The number of joint sets was intended as related to those, which singularly or in mutual combination, allow potential instability of rock blocks. This rating method gives the Susceptibility to Rock Fall index (SRF) as:

Fig. 3 - The rocky cliff of Vico Equense with the Giusso castle resting on the cliff-top.

$$\mathrm{SRF} = \mathrm{SMR}_s + \mathrm{Nm}_s + \mathrm{N}j_s + \mathrm{FM}_s \qquad (4)$$

where:

SMR_s = number of the Slope Mass Rating class;
Nm_s = number of mechanisms as obtained by Matheson's tests (1983);
$\mathrm{N}j_s$ = number of joint sets;
FM_s = presence of faults/master joints.

TABLE 2

SMR classification (ROMANA, 1985) and related description of stability conditions, failures and support measures.

<table>
<tr><th>SMR</th><th colspan="14">0 10 15 20 30 40 45 50 55 60 65 70 75 80 90 100</th></tr>
<tr><td>Class</td><td></td><td colspan="2">V</td><td colspan="2">IV</td><td colspan="3">III</td><td colspan="4">II</td><td colspan="2">I</td></tr>
<tr><td>SMR Interval</td><td></td><td colspan="2">11-20</td><td colspan="2">21-40</td><td colspan="3">41-60</td><td colspan="4">61-80</td><td colspan="2">81-100</td></tr>
<tr><td>Description</td><td></td><td colspan="2">Very bad</td><td colspan="2">Bad</td><td colspan="3">Normal</td><td colspan="4">Good</td><td colspan="2">Very Good</td></tr>
<tr><td>Stability</td><td></td><td colspan="2">Completely unstable</td><td colspan="2">Unstable</td><td colspan="3">Partially stable</td><td colspan="4">Stable</td><td colspan="2">Completely stable</td></tr>
<tr><td colspan="15">Probable failure types</td></tr>
<tr><td>Plane failure</td><td colspan="2"></td><td colspan="3">Very big</td><td colspan="3">Major</td><td colspan="6">None</td></tr>
<tr><td>Wedge failure</td><td colspan="5"></td><td colspan="2">Many</td><td colspan="4">Some</td><td colspan="2">Very few</td><td>None</td></tr>
<tr><td>Toppling</td><td colspan="4"></td><td>Major</td><td colspan="2"></td><td colspan="2">Minor</td><td colspan="5">None</td></tr>
<tr><td>Mass failure</td><td></td><td colspan="4">Possible</td><td colspan="9">None</td></tr>
<tr><td colspan="15">Support measures</td></tr>
<tr><td>Reexcavation</td><td></td><td colspan="3">Reexcavation
Walls</td><td colspan="10"></td></tr>
<tr><td>Drainage</td><td></td><td colspan="4">Surface drainage
Deep drainage</td><td colspan="9"></td></tr>
<tr><td>Concrete</td><td colspan="3"></td><td colspan="5">Shotcrete
Dental concrete
Ribs and/or Beams
Toe walls</td><td colspan="6"></td></tr>
<tr><td>Reinforcement</td><td colspan="4"></td><td colspan="8">Bolts
Anchors</td><td colspan="2"></td></tr>
<tr><td>Protection</td><td colspan="6"></td><td colspan="4">Toe ditch
Toe or Slope fences
Nets</td><td colspan="4"></td></tr>
<tr><td>No support</td><td colspan="9"></td><td colspan="5">Scaling
None</td></tr>
</table>

TABLE 3

Grid of scores for SRF calculation. As regards NO/YES, two conditions only were considered for fault and master joints: absent (score 0) and present (score 3).

	Score	0	1	2	3	4
SMR class	**SMR_s**	I	II	III	IV	V
No. of mechanisms	**Nm_s**	0	1	2	3	4
No. of joint sets	**Nj_s**	0	1	2	3	≥ 4
Fault – Master joints	**FM_s**	NO			YES	

The weight of each of the four parameters was set equal.

Accordingly, Susceptibility to Rock Fall (SRF) varies from 0 to 15 and it is further subdivided into five susceptibility classes (tab. 4). To evaluate the performance of the landslide susceptibility methods (CHUNG & FABBRI, 2003; GUZZETTI *et alii*, 2006; FRATTINI *et alii*, 2010), information regarding the location of slope failures along the rocky cliff that occurred in recent years were gathered. No data about areal extension and volume of rockfalls were considered reliable enough to perform statistical analyses, due to the lack of quantitative surveys; consequently the events' location was considered only. This dataset, consisting of 12 landslides, reconstructed for the period 1980-2011, was used to test the susceptibility zoning methods with a statistic approach aimed at evaluating the landslide frequency for different susceptibility classes (CROSTA & FRATTINI, 2003). The only availability of rockfall locations and of approximate estimation of their volume (<2 m^3) prevented the proper application of success-rate curves methods (CHUNG & FABBRI, 2003; GUZZETTI *et alii*, 2006). Thus, assuming the rockfall susceptibility as expressed by the value obtained by means of the above mentioned three methods (Slope Mass Rating, number of mechanisms by Matheson's tests and Susceptibility to Rock Fall), the performance of these methods was tested by comparing the areal distribution of susceptibility classes (A_i) and the susceptibility frequency corresponding to zones in which rockfalls have occurred (S_j), by means of cumulative statistics. A_i and S_j factors were defined as follows:

$$A_i = \frac{a_i}{\sum_{i=1}^{n} a_i} \quad (5)$$

where:

a_i = areal extension of the i class of susceptibility;
n = number of the susceptibility classes;

$$S_j = \frac{s_j}{\sum_{j=1}^{m} s_j} \quad (6)$$

where:

s_j = susceptibility value (Slope Mass Rating, number of Matheson mechanisms and Susceptibility to Rock Fall) for the area in which the j rockfall occurred;
m = number of rockfalls.

TABLE 4

Susceptibility classification by SRF.

SRF	Class	Susceptibility
0 - 2	I	Very Low
3 - 5	II	Low
6 - 8	III	Moderate
9 - 11	IV	High
12 - 15	V	Very High

RESULTS

The structural data of the rock-mass were aggregated and plotted in equal-area (Schmidt) projection with the calculation of the pole density. Then, considering a cutoff frequency value of 5% (SHANLEY & MATHAB, 1976) it was possible to identify five principal joint sets (fig. 4). In each geomechanical station the bedding (B) was always observed. Differently, other joint sets were observed with an uneven distribution among the geomechanical stations

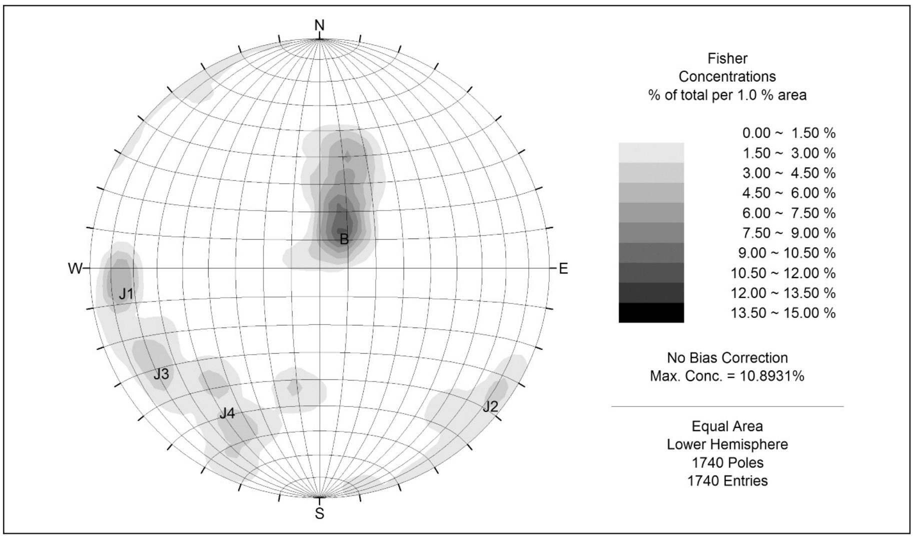

Fig. 4 - Aggregated results of 16 geomechanical stations (1740 data). Major joint sets (Dip direction/dip): Bedding (B) – 210/14; J_1 – 85/75; J_2 – 306/84; J_3 – 59/70; J_4 – 34/61.

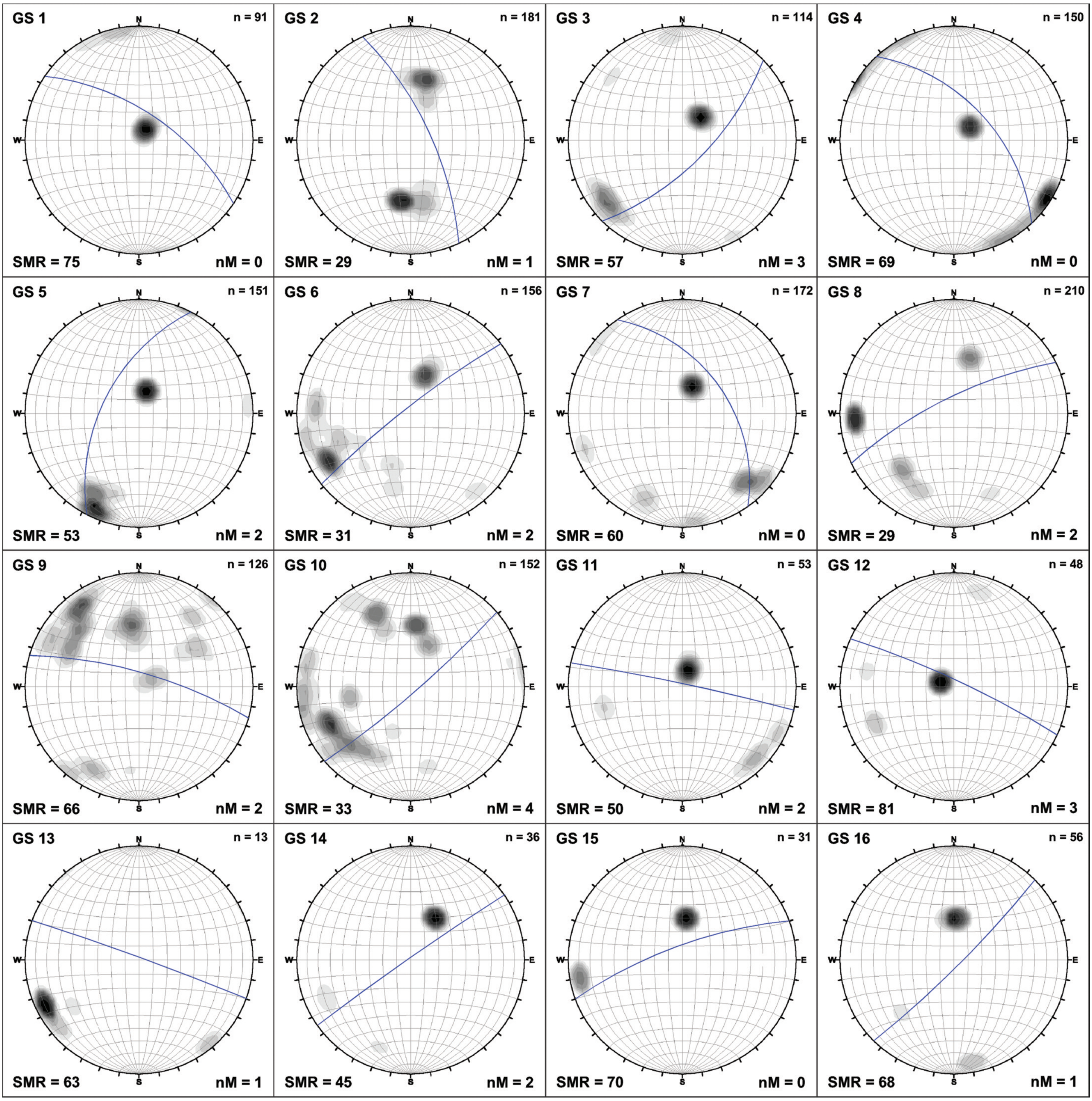

Fig. 5 - Density plots for the geomechanical stations from GS 1 to GS 16, with indication of the number of discontinuities measured (n), estimated SMR value (SMR) and number of mechanisms by Matheson tests (nM). Great blue circles represents the local slope face.

(fig. 5): J1 is present in geomechanical stations no. 4, 6, 8, 10, 11, 12 and 15; J2 is present in geomechanical stations no. 3, 4, 6, 7, 11 and 13; J3 is present in geomechanical stations no. 3, 5, 6, 7, 8, 9, 10, 14 and 16; J4 is present in geomechanical stations no. 5, 6, 7, 8, 9, 14 and 16.

The application of the Bieniawski's method allowed estimating the RMR_b values, ranging from 53 (Class III – Fair) to 76 (Class II – Good) with an average value of 63 ± 7, if considering null the adjustment for joint orientation. The estimated Slope Mass Rating values were observed ranging from 29 to 81 (average 55 ± 17), thus varying from the class IV (Unstable) to the class I (Completely stable) (tab. 2). A maximum number of 4 joint sets and of 4 fundamental mechanisms (by Matheson's tests) were observed for the analyzed geomechanical stations (fig. 5); faults or master joints were recognized for 6 of them (tab. 5).

To understand correlations among RMR_b, Slope Mass Rating, number of fundamental mechanisms and number of joint sets (tab. 5), a mutual correlation analysis was carried out by means of a correlation matrix technique (fig. 6). Beyond the positive correlations, proved by the correlation coefficient values and by the *t*-Student tests, between RMR_b

TABLE 5

Application of the RMR and SMR methods to rock mass data derived from the 16 geomechanical stations.
Keys to symbols: PS = plane sliding; WS = wedge sliding; DT = direct toppling; FT = flexural toppling.

Geomechanical station	RMRb	SMR	SMR class - Stability	No. of joint sets	Failure mechanisms by Matheson tests		Fault - Master joint
GS1	63	75	II - Stable	0	0		
GS2	53	29	IV - Unstable	2	1	PS	YES
GS3	62	57	III – Partially Stable	4	3	PS-DT-FT	
GS4	57	69	II - Stable	0	0		
GS5	58	53	III – Partially Stable	1	2	PS-FT	YES
GS6	59	31	IV - Unstable	3	2	PS-WS	YES
GS7	58	60	II - Stable	0	0		
GS8	58	29	IV - Unstable	3	2	PS-WS	YES
GS9	63	66	II - Stable	2	2	PS-FT	
GS10	57	33	IV - Unstable	4	4	PS-WS-DT-FT	
GS11	69	50	III – Partially Stable	2	2	WS-FT	
GS12	72	81	I - Very Stable	4	3	WS-DT-FT	
GS13	76	63	II - Stable	2	1	WS	YES
GS14	69	45	III – Partially Stable	4	2	PS-WS	YES
GS15	72	70	II - Stable	0	0		
GS16	64	68	II - Stable	1	1	DT	

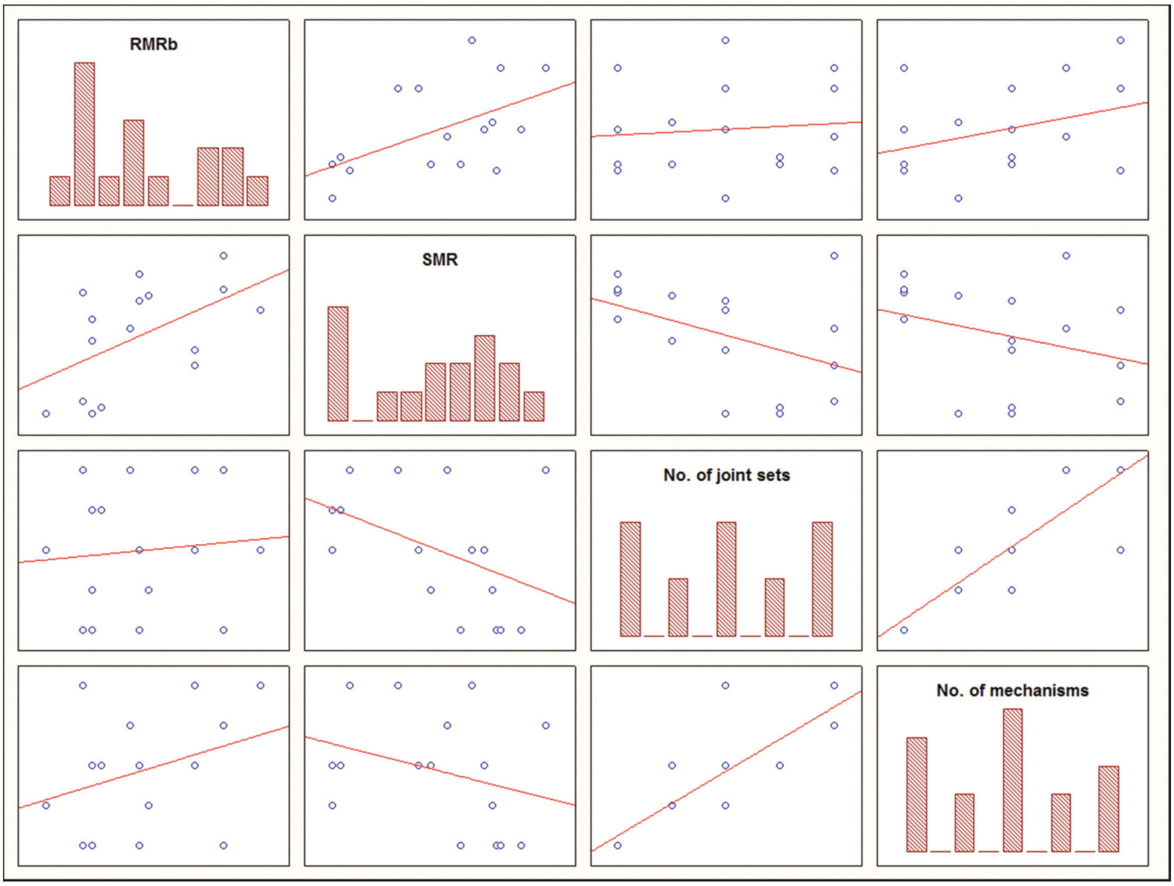

Fig. 6 - Correlation matrix among RMR_b, SMR, number of joint sets and number of mechanisms by Matheson tests, estimated for each geomechanical station.

TABLE 6

SRF values calculated for each geomechanical station.

Geomechanical station	SRF	SRF class
GS1	1	I – Very Low
GS2	9	IV - High
GS3	8	III - Moderate
GS4	1	I - Very Low
GS5	7	III - Moderate
GS6	11	IV - High
GS7	1	I – Very Low
GS8	11	IV - High
GS9	5	II - Low
GS10	11	IV - High
GS11	6	III - Moderate
GS12	8	III - Moderate
GS13	11	IV - High
GS14	13	V – Very High
GS15	1	I – Very Low
GS16	6	III - Moderate

and Slope Mass Rating (r = 0.541 with p <5%) as well as between the number of joint sets and of mechanisms by Matheson's tests (r = 0.756 with p <5%), other less statistically robust but conceptually significant negative correlations were observed between Slope Mass Rating and number of mechanisms by Matheson's tests (r = –0.345 with p <15%) as well as between Slope Mass Rating and number of joint sets (r = –0.337 with p <15%). All these correlations among Slope Mass Rating, number of mechanisms and number of joint sets demonstrated the possibility that a parametric method based on the sum of indexes derived from Slope Mass Rating, number of joint sets and number of fundamental mechanisms by Matheson's tests tends to enhance the assessment of susceptibility to rockfall, reducing the uncertainty derived by the use of a single parameter. No statistically significant correlations were found between RMR_b and number of mechanisms as well as number of joint sets.

The SRF values obtained for each geomechanical station were observed varying from class I (Very Low) to class V (Very High) with a prevalence of the classes III (Moderate) and IV (High) (tab. 6).

To test the relative performance of the three methods in assessing and mapping susceptibility to rockfall, statistical analyses of numerical maps derived by geomechanical stations were carried out. For such a purpose, Slope Mass Rating, number of fundamental mechanisms by Matheson tests and Susceptibility to Rock Fall were mapped (figs. 7a, b and c) by means of geostatistical techniques, calculating numerical grids with resolution of 2×2 m. Among the different techniques tested, the ordinary kriging was adopted for have best fitted available geospatial data (cross-validation function: R^2 = 0.621; angular coefficient = 0.881). Numerical maps of Slope Mass Rating, number of joint sets and number of fundamental mechanisms were extracted and statistically analyzed with reference to the area corresponding to the cartographic projection of the cliff face (slope angle >30°).

Statistical analyses were focused on verifying the capability of each method to identify susceptible zones where rockfalls have occurred in recent years. Particularly the areal distribution of each susceptibility index (Slope Mass Rating, number of mechanisms by Matheson's tests and Susceptibility to Rock Fall) and the frequency of the same indexes in zones where rockfall have occurred were comparatively analyzed by means of the cumulative statistics. In detail, for the three susceptibility methods, A_i and S_j parameters were estimated (figs. 8, 9 and 10; tabs. 7, 8 and 9).

Due to the prevalent distribution of Slope Mass Rating in the classes II and III (fig. 8) and the dominant wedge failure type, the occurrences of big planar failures or mass failures were considered unlikely. Further evidence of this assumption were recognized in the type of landslide occurrences recorded, which were limited to the instability of small rock blocks (volume <2 m^3) and in the morphological setting of the rocky cliff, with no evidences of big planar or mass failures. These observations were found consistent with the structural setting of the rock mass, which is typically characterized by a bedding set dipping upslope, with an inclination lower than the total friction angle, and intersecting with other approximately vertical joint sets (figs. 4 and 5). Therefore the number of rockfall occurrences was recognized as consistently related to Slope Mass Rating (tab. 2) by means of an inverse relationship.

DISCUSSION

The statistical analysis of Slope Mass Rating map revealed the distribution of the observed rockfall occurrences in the range of Slope Mass Rating classes from Class IV – Unstable (SMR_{min} = 33) up to Class II – Stable (SMR_{max} = 75), which corresponds to the 100% of the total area (fig. 8 and tab. 7). Particularly the spatial dominance of the class II (Stable) was observed for the 50.4% of the area in which S_j = 64.2% was found. Other susceptibility classes were observed with lower areal extension, varying from 37.5% (Class III – Partially Stable), with S_j = 31.4%, to 12.2% (Class IV - Unstable), with S_j = 4.4%, and to 0% (Class V – Fully Unstable).

The statistical analysis of the map reporting the number of fundamental mechanisms, achieved by the application of the Matheson's graphical tests, confirmed the occurrences of rockfall within zones interested by 1 mechanism at least, corresponding to 95% of the total area (fig. 9 and tab. 8). In detail, the number of fundamental mechanisms showed the areal dominance of the 1 mechanism class for 47.6%, with S_j = 11.5%. Other classes were observed with lower areal extensions, from 24.9% (2 mechanisms), with S_j = 30.8%, to 22.5% (3 mechanisms), with S_j = 57.7%, and to 1% (4 mechanisms) with no rockfall occurrences. The lack of landslide occurrences in the latter class was related to its negligible areal extension.

Finally, the statistical analysis of the SRF map showed a distribution of the occurred rockfalls within the range from 6 (Class III – Moderate) to 9 (Class IV – High), whose areal extension corresponds to the 71.1% of the total area (fig. 10 and tab. 9). In detail, the relative extension for the Class III – Moderate is A_i = 60.1%, with S_j = 89.2%, and the relative extension for class IV – High is A_i = 11.0%, with S_j = 10.8%.

The proposed approach is an attempt to extend the understanding about the practical and suitable approaches for the assessment and mapping of susceptibility to rockfall initiation beyond those previously applied to rocky cliffs, which were based on the adoption of Slope Mass Rating or Matheson's methods (IRIGARAY, 2003; PALMA *et alii*, 2011; DE VITA *et alii*, 2012) or on the implementation of paramet-

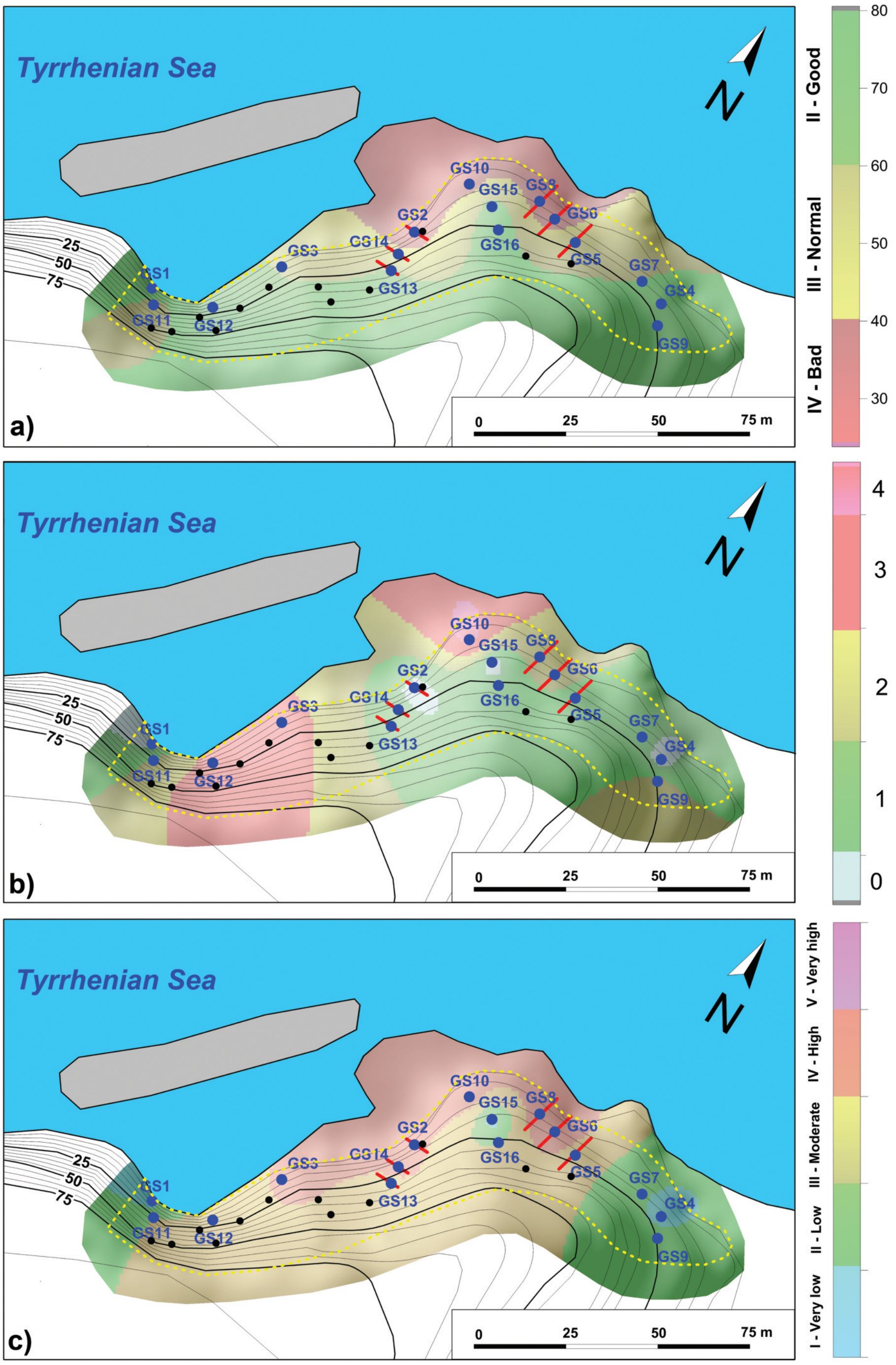

Fig. 7 - Maps of the Vico Equense's sample area (see fig. 2) with location of geomechanical stations: *a)* Slope Mass Rating; *b)* number of fundamental mechanisms by Matheson's tests; *c)* Susceptibility to Rock Fall. Key to symbols: black circles represent the location of rock slope failures known for the period 2000-2011; red lines symbolize faults and master joints; dashed yellow line represents the slope area considered for statistical analyses.

ric procedures (BUDETTA, 2004; BAILLIFARD *et alii*, 2003) or on spatial modeling of kinematic feasibilities to plane and wedge sliding (GÜNTHER *et alii*, 2004). The Susceptibility to Rock Fall was intended as a simple system to reduce reciprocal uncertainties inherent to Slope Mass Rating and Matheson methods and also for taking into account other local factors, not fully considered by the two standard methods themselves, as the number of the joint sets and the proximity to damage zones of faults or master joints. In addition, the intersections among the high-angle dipping joint sets and the bedding set determine a condition for multiple failures of the same type (e.g. wedge or toppling) not fully taken into account by the Romana's method, which considers the worst case and not the effect due to the sum of the possible cases. Similarly, the Matheson's tests identify for each azimuth sector the possible mechanisms among planar, wedge and toppling failures but they do not consider, for the same azimuth sector, the contribute of all possible failures, if taking into consideration the same mechanism. Consequently, the Susceptibility to Rock Fall method succeeds both in equilibrating the susceptibility estimations for those slope sectors where more severe conditions exist (e.g. multiple mechanisms and locally intensely jointed rock masses). For this reason and its balanced rating structure, the proposed Susceptibility to Rock Fall method does not tend to overestimate the susceptibility to rockfall. This capability of the Susceptibility to Rock Fall method is demonstrated by an accuracy in identifying slope sectors in which rockfalls had occurred greater than that obtained by applying singularly the Romana and Matheson methods.

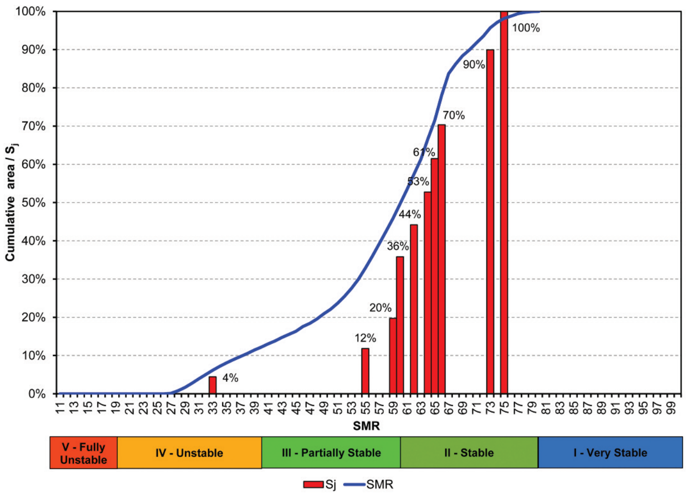

Fig. 8 - Cumulative frequencies of areal distribution of SMR and of susceptibility frequency corresponding to zones in which rockfalls have occurred.

TABLE 7

Areal distribution of SMR classes and of the related rockfalls. Symbols: A_i = normalized areal distribution of susceptibility classes; S_j = susceptibility frequency corresponding to zones in which rockfalls have occurred.

SMR (Romana, 1985)	A_i	S_j
I - Very Stable (80-100)	0.0%	0.0%
II - Stable (60-80)	50.4%	64.2%
III - Partially Stable (40-60)	37.5%	31.4%
IV - Unstable (20-40)	12.2%	4.4%
V - Fully Unstable (11-20)	0.0%	0.0%

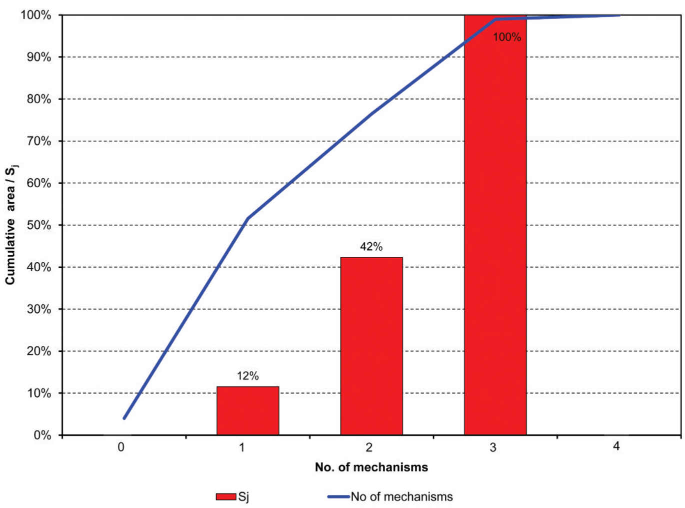

Fig. 9 - Cumulative frequencies of areal distribution of the number of fundamental mechanisms (MATHESON, 1983) and of susceptibility frequency corresponding to zones in which rockfalls have occurred.

CONCLUSIONS

In this paper, results of susceptibility assessment to rockfalls of a steep rocky cliff in the Sorrentine Peninsula (southern Italy) through different methods were shown.

TABLE 8

Areal distribution of the number of fundamental mechanisms (MATHESON, 1983) and of the related rockfalls. Symbols: A_i = normalized areal distribution of susceptibility classes; S_j = susceptibility frequency corresponding to zones in which rockfalls have occurred.

No. of mechanisms (Matheson, 1983)	A_i	S_j
0	4.0%	0.0%
1	47.6%	11.5%
2	24.9%	30.8%
3	22.5%	57.7%
4	1.0%	0.0%

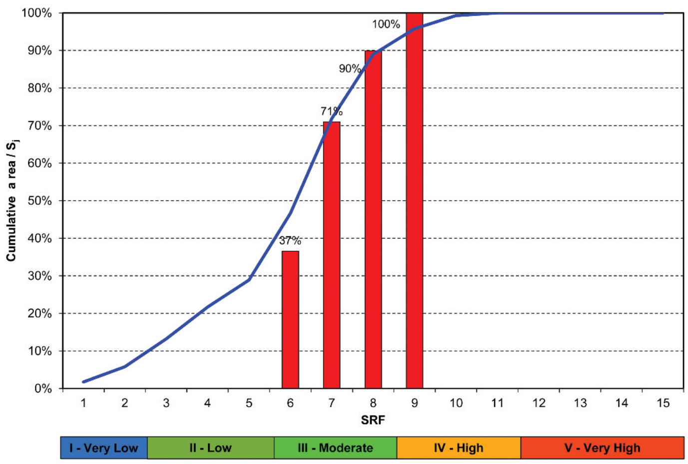

Fig. 10 - Cumulative frequencies of areal distribution of the SRF and susceptibility frequency corresponding to zones in which rockfalls have occurred.

TABLE 9

Areal distribution of SRF classes of the related rockfalls. Symbols: A_i = normalized areal distribution of susceptibility classes; S_j = susceptibility frequency corresponding to zones in which rockfalls have occurred.

SRF	A_i	S_j
I - Very Low (0-2)	5.8%	0.0%
II - Low (3-5)	23.1%	0.0%
III - Moderate (6-8)	60.1%	89.2%
IV - High (9-11)	11.0%	10.8%
V - Very High (> 12)	0.0%	0.0%

An attempt was made to find an effective and practical approach for identifying areas of major susceptibility to rockfall onset, to be stabilized by means of reinforcement (bolts and anchors) and protection (nets) active remedial works. The data and methods discussed can be considered both representative of a particular case study, which is typical of the densely urbanized rocky coasts of the Campania region, and of a specific methodological approach, to be applied in similar geomorphological contexts.

Based on the characterization of the rock-mass by means of direct geomechanical surveys (ISRM, 1978), the effectiveness to assess rockfall susceptibility of Romana and Matheson methods was tested. In addition, a new rating system, which was named Susceptibility to Rock Fall, based on the combination of both and adding weights derived from other features of the rock mass such as the number of joint sets and the existence of macro-structural features (faults and master joints) was also experimented.

Among principal results, by comparing the rockfall occurrences with the susceptibility mapping we proved the better accuracy of the Susceptibility to Rock Fall (SRF) method that identified as susceptible 71.1% of the whole rocky cliff surface respect to the wider areas (>95%) identified by the Romana and Matheson methods. Moreover, statistical analyses showed a more consistent capability in classifying susceptibility to rockfall onset of both the number of fundamental mechanisms and the Susceptibility to Rock Fall (SRF), by means of the specific susceptibility assessment that was proved to increase according to the growth of the two parameters.

The methods were tested in a range of Slope Mass Rating from I to III classes, which typically characterizes rock slopes of the Sorrentine Peninsula as well as the most part of carbonate steep slopes of the Campania region (southern Italy). Therefore, they are suitable in those geological contexts where similar rock masses and stability conditions as well as tight needs to address properly protection and remedial works coexist. Indeed, the application of the discussed methods can be considered a first attempt to increase accuracy in assessing susceptibility to rockfall initiation in a rocky cliff that is particularly significant in those areas where diffuse high hazard and risk levels and difficult logistic conditions require an accurate selection of active remedial works and an optimal use of economic resources.

The proposed approaches can be conceived as an advanced methods for the assessment and mapping of susceptibility to rockfalls at the detailed scale (Fell, 2008) as well as a tool for a deeper insight in those areas, such as the high slope angle rocky cliffs, constantly ranked in the current Landslide Setting Plans of the River Basin Authorities at a very high hazard level. Further refinements and experimentations will be carried out also considering geomechanical characterizations derived from non-contact techniques (Lemy *et alii*, 2003; Haneberg, 2008; Ferrero *et alii*, 2009; De Vita *et alii*, 2012) and with high accurate DTMs derived from oblique digital photogrammetric surveys.

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