*Rend. Online Soc. Geol. It.,* Vol. XX (2013), pp. XX-XX, 1 fig., x pl., x tab.


# Rocky cliff landslide hazard: the Capo Noli Promontory case study (western Liguria, NW Mediterranean Sea)

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Document type: Extended Abstract.

ABSTRACT

The modern morphology of the Liguria coastal area was strongly modified by the interaction between the natural environment and human works. Presence of a steep cliffs, rarely alternating sandy-pebbly coastline, produces significant degrees of geo-hazard. On the 16th of January 2008 and again on the 29th of February 2009 rockfalls and topples affected the plunging rocky cliffs above the "Aurelia" main road at the promontory of Capo Noli (NW Mediterranean Sea). Detailed geo–structural and geo–mechanical surveys were carried out on two potentially unstable rocky cliff sectors. These surveys identified the main probable landslide types and instability factors. According to the rock mass mechanical properties and major geomorphological and structural features, a detailed rock mass quality and landslide hazard zoning has been achieved. In accordance with Rock Mass Rating (RMR) and Geological Strength Index (GSI) indexes, the surveyed rock mass usually has poor to very poor quality. Furthermore, the Rockfall Hazard Rating System (RHRS) index values have given evidence of a high probability of rockfall occurrence.

KEY WORDS: plunging cliffs, rockfalls, topples, rocky cliff hazard, Rockfall Hazard Rating System, western Liguria, Italy.

## INTRODUCTION

When a natural environment interacts with human works such as roads or railways, the knowledge of cliff stability becomes essential. Often, rockfalls are a major hazard in rock cuts for roadways and railways and are generally induced by an increase in pore pressure caused by rainfall infiltration, erosion of in-filling material during heavy rain storms, freeze-thaw cycles in cold climates, chemical degradation or weathering of the rock material and rock fractures expansion related to root growth (Hoek, 2001). Usually, rocky cliff stability mainly depends on sea wave action and geological features such as lithology and structure. Whereas the rocky cliffs were not affected by direct sea wave action, however, weathering and structural features played a key role in triggering instability (Moore et al., 2002; USGS, 2004; Marques et al., 2011). For geo-hazard purposes geo-structural studies and rock mass cliff quality assessment are the basic tools. Several authors stressed the important role played by mechanical properties of joints affecting rock masses (Budetta, 2000; Mortimore et al., 2004).

In this study, we carried out detailed surveys on rock mass slopes and by the use of the two main geo-mechanical classifications (RMR by Bieniawsky, 1979 and GSI by Marinos & Hoek, 2000) our aim was the preliminary structural and geo-mechanical characterisation of the Capo Noli rocky cliffs in order to obtain the landslide hazard zoning. On the basis of the expected potentially instable rock volumes, four hazard classes have been detected. Referring to RHRS index (Pierson et al., 1990) a rockfall hazard assessment was performed considering the heavy daily traffic along the Aurelia road. In particular, for this kind of roadway, it is important to improve hazard and risk evaluation regarding rockfall problems.

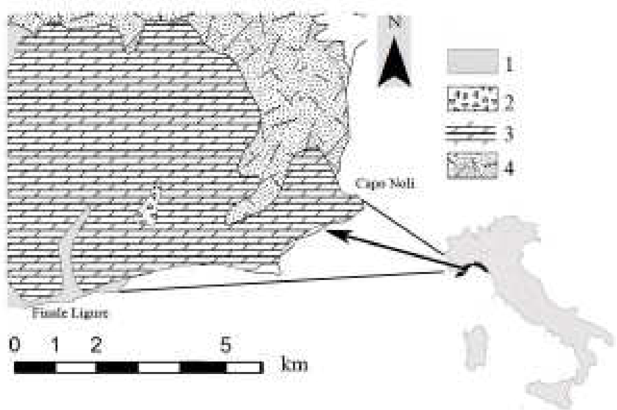


Fig. 1 – Geological sketch map of the study area: 1 – alluvial deposits (Holocene); 2 – colluvial and detrital deposits (Holocene); 3 – dolomitic limestones (Triassic); 4 – quarzites (Triassic).

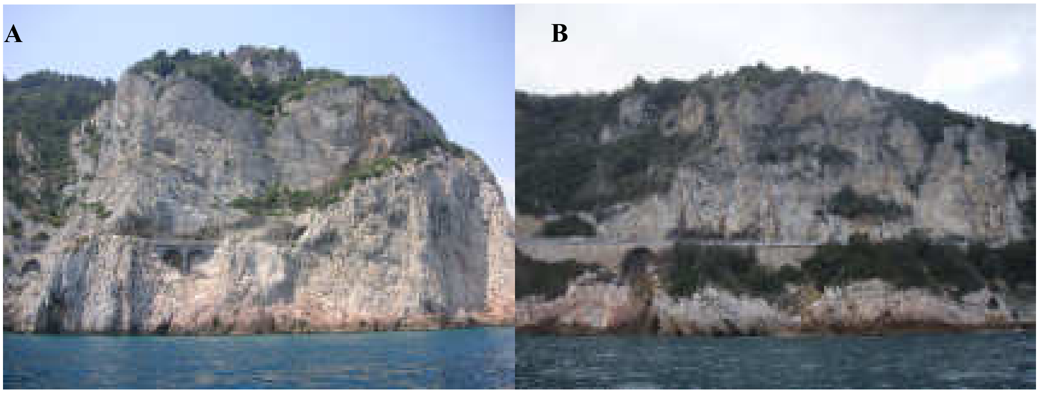


Fig. 2 – The Capo Noli Promontory rocky plunging cliffs: A) NE-SW trending section; B) NW-SE trending section.

## STUDY AREA

The study area (Fig. 1) is located on the western coast of the Liguria Region (NW Italy) along a stretch of about 1,5 km of rocky cliffs on the promontory of Capo Noli, between the towns of Finale Ligure and Noli. From a geological point of view, the area represents the southern continuation of the Western Alps (Vanossi et al., 1984). Offshore morphostructural studies (Corradi et al., 1984, Fanucci & Nicolich, 1984) indicated this sector as part of the steep Alpine margin, with narrow shelves often cut by several canyons. The Capo Noli coastal geomorphology setting consists in rocky plunging cliffs (Sunamura, 1992) composed by dolomitic to calcareous dolomitic rocks of "Dolomie di San Pietro dei Monti" formation. Such calcareous-dolomitic complex has been affected by two main direct fault systems WSW-ENE or E-W oriented and by several secondary tectonic discontinuities which together control the rocky shoreline structure (Biancotti & Motta, 1988). Modern tidal notches and karst landforms above present sea level have been detected (Rovere et al., 2011).

Surveys have been carried out on two main cliff zones with different orientations which are, from west to east: a NE-SW trending section (at the 591+100 progressive milestone) exposed to SE (Fig. 2) and the NW-SE trending section (between 591+700 and 591+800 progressive milestones). The cliff heights range from 50 to 90 m with slope angles ranging from 80° to vertical. Less inclined zones near the cliff top suggest the presence of relicts of wave-cut terraces. The rocky cliffs are not urbanized with the exception of the existing coastal road ("Aurelia" State Road n.1) built in the early 1880s by the Napoleonic Empire. Consequently, although the rocky cliffs suffer slight wave erosion below the road, the magnitude of the hazard depends on rock mass mechanical quality and geometric relationship between joint sets and plunging cliffs. The landslides occurring on the promontory of Capo Noli (Liguria Region, NW Mediterranean Sea) on the 16th of January 2008 and on the 29th of February 2009 have resulted in the shutdown of the main road for several months leading to considerable inconveniences concerning economic and tourist activities (Fig. 3). Sudden rockfalls occurred from heights of about 20 and 40m along the vertical rock faces, tearing rockfall nets and support cables.

The available historical information indicate the area has frequently been affected by rockfall phenomena, particularly since the 1990s with annual and seasonal frequency due to heavy and prolonged rainfalls in this period. However, small coastal rockfall deposits lying at the cliff toe and at the basal undercutting of the terraced surface have been identified (Rovere, 2011) and this could testify the presence of instability events before the construction of the road.

## METHODS

The landslide hazard zonation performed on the Capo Noli cliffs is based on the rock mass mechanical behaviour and the analyses of instability predisposing factors. Among rock mass mechanical properties, geometrical and mechanical discontinuity properties are undoubtedly the most important in causing failure.

In order to define the major geo-structural features of the study area, preliminary aerial photos analysis was performed. Then detailed geo-structural and geo-mechanical surveys were conducted using climbing techniques. During the survey the two rocky cliff zones were divided into 11 vertical sectors with widths ranging between 10–20 meters. Within each sector according to lithology, structural features, weathering degree and water condition several homogeneous areas were defined.

For the quantitative and qualitative analysis of stratigraphic and tectonic discontinuity, the parameters suggested by ISRM

Fig. 3 – Rockfall affecting the Capo Noli cliffs on 16 January 2008.

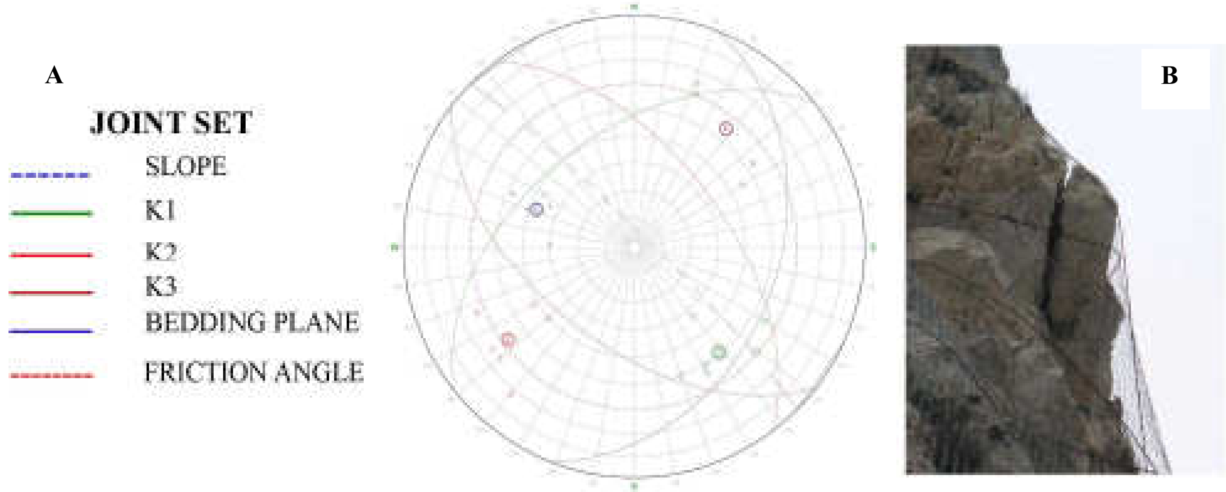


Fig. 4 –Geo-mechanical survey of the study area: A) joint sets detected and Markland's test; B) toppling affecting the rocky plunging cliffs.

(1978) were adopted. The orientation data was plotted on equal area polar Lambert-Schimdt projections and rose diagram in order to define the main discontinuity sets contained in the rock mass. Rock mass quality was evaluated by means Rock Mass Rating (RMR) and Geological Strength Index (GSI). The compressive strength of joint surface was obtained by Schmidt hammer test (Deere & Miller, 1966) while RQD was estimated by means empirical correlation (Palström, 1982).

The main failure type mechanisms have been identified according to geometrical and mechanical properties of detected rock mass discontinuities and on principal variables that influence the stability. In certain areas, assuming anisotropy rock mass behaviour, potential topple and wedge instabilities were investigated by means Markland's test, assuming a basic friction angle of 30°. The hazard assessment was carried out considering the potential rock volume that could be involved in the landslide and the qualitatively expected probability of occurrence. After assessing an average daily traffic of about 477 cars/hour, applying the RHRS system a rockfall hazard was estimated.

## RESULTS

Aerial photo analysis allowed detecting a double direct fault system: the first along an ENE orientation and the second one with an opposite attitude. In the study area these major tectonic discontinuities have the same average strike but different inclinations separating the promontory in both longitudinal and transverse direction.

The orientation data (Fig. 4) show that the attitude of bedding planes is always more or less normal to the direction of the slope: the trend of the NE-SW section displays dip directions ranging between 340° and 135° while a 92° and 114° trend range was detected in the NW-SE section. The measured dips are very variable, ranging between 45° and 70°. Numerous measured joints have been grouped into three sets (K1-K3). With regards to the potential instabilities, cyclographic projections of some sets respect to the slope, suggest the possible occurrence of toppling and wedge slide. Topples occur along very steep bedding surfaces, the orientations of which are nearly parallel to the slope, intersected by dipping joints of opposite plunge. However, rockfalls are the most likely failure mechanism to occur due to the highly fractured plunging cliffs just above the main road. In fact, due to the high steep or vertical slopes, phenomena such as toppling or slide wedge failure quickly evolve into rockfalls.

The spacing of bedding planes often ranges from 60-200 cm although less frequent 20-60 cm spacing appears. The bedding planes dimension is usually between 3 and 10 m (''average persistence'') and greater than tectonic discontinuity persistence which is lower than 1 m with minimum 20-60 cm range values. Therefore, the discontinuity nets lead to prismatic rock blocks with volumes usually ranging from 0,25 to 8 cubic meters but rock volumes up to hundreds of cubic meters can be reached.

Both bedding and joint surfaces are smooth or slightly rough: JRC measured by means of Barton comb reaches average values of 0–2. Generally, joint apertures are greater than 10 mm with in-filling material composed of calcite or fine soils produced by friction. Where poorly interlocked rock mass portion have been detected, joint apertures up to 100 mm were measured.

The compressive strength of dolomitic limestone joint surfaces (JCS) is very high, ranging from approximately 90 to 100 MPa. The rock mass is shallowly weathered and partially disturbed with a more or less faulted structure, due to more than four intersecting discontinuity sets and with poor to very poor weathered surface conditions and presence of compact infilling materials. The moisture content and the water infiltration processes are low, often related to karst phenomena. According to RMR classification, rock mass quality is poor to very poor (Class IV and Class V) whereas four GSI ranges have been determined: range A (GSI 50-55), range B (GSI 40-45), range C (GSI 30-35), range D (GSI 25-30).


Fig. 5 –Landslide hazard zonation with respect class 1 events.

## DISCUSSION AND CONCLUSION

Results of this study defined the most potential failure geometries and the hazard landslide zonation of two Capo Noli plunging cliff sections. Both bedding planes and joints geometrical and mechanical properties, such as high bedding surface continuity, the orientation of which is nearly parallel to the slope, mutually intersected by joints with opposite plunge, lead to rockfalls and toppling. Generally, this is possible mainly in poorly interlocking rock mass portions, with very open joints. Intersection of joint sets can sometimes form wedge instability, which however instantly evolves into rolling, rebounding and rockfalls. Consequently, the above presented structural and mechanical rock mass layout has allowed to establish four hazard zone classes depending on different potential instable rock volumes: class 1 (small events-less than 3 $m^3$), class 2 (moderate events-between 3 and 10 $m^3$), class 3 (significant events-between 30-300 $m^3$), class 4 (extreme events-greater than 300 $m^3$). Based on direct observations, within each class a probability scale has been assigned.In the study area the hazard analysis shows that the highest landslide susceptibility is related to class 1 and class 2 events (Fig. 5). This is in agreement with the rock mass geometrical and structural features obtained from the surveys. In particular, elements such as bedding planes with normal directions to the slope often mutually intersect joints with small spacing and with opposite orientations leading to the formation of many potentially unstable blocks. Furthermore, the rockfalls susceptibility increases especially during heavy or prolonged rainfalls which can reduce the shear strength of the discontinuities. Landslide susceptibility with respect moderate and extreme event are less probable; due to very poor rock mass quality only a large area of a cliff face could be affected by sustained instability. The Aurelia roadway has an average daily traffic greater than 477 car/hour which confirms the geo-hazard degree of the Capo Noli Promontory when affected by geo-hazard events such as rockfalls. The RHRS rating of 750 highlighted the meaningful hazard degree of the study area. Since the study area is included in a Site of Community Importance (SCI), the proposed method can be regarded as useful tool for carrying out risk degree assessment and suitable risk mitigation measures.

## ACKNOWLEDGMENTS

*The authors are grateful to A. Maifredi, F. Nicosia, F. Costi for the specialized geo-mechanical survey by means climbing techniques.*

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