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Application of Spatial Multi-Criteria Analysis (SMCA) to assess rockfall hazard and plan mitigation strategies along long infrastructures

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Abstract. Long infrastructures often cross areas with a high probability of landslides, causing eventually serious problems to the serviceability and compromising safety. The identification and prediction of hazardous zones are difficult, especially for what concerning rockfalls, as they can occur quickly and suddenly. In order to assess rockfall hazard, detailed data such as slope geometry, geotechnical and geomechanical properties of materials, drainage system pattern, etc. are needed. Even though thematic datasets are available and easily downloadable for the majority of the Italian territory, their scale is not adequate and ad-hoc input data must be gathered. An original multi-disciplinary procedure (GEO4) has been developed by the authors based on a mobile mapping system (ARCHITA) integrated with Airborne Lidar and ILI (In-Line Inspections), geomatics, geological models, geotechnical-geomechanical characterization and geomorphometric approach. A Spatial Multi-Criteria Analysis (SMCA) is then used to create a composed and spatially distributed index of landslide hazard based on normalized values of triggering factors. Such index is used to identify and classify the morphological unstable element along the infrastructure, supporting decision-makers in defining the most appropriate mitigation measures and planning their implementation in a clearer, more repeatable and more objective orientated-way. The presented method has been successfully applied so far to hundreds of km of railway lines in Italy.

1. Introduction

Catastrophic events as landslides can significantly impact society, in term of endangering lives, affecting human activities and infrastructures operativity. To face these issues, it's fundamental having tools that can allow proper management and identification of the risk due to their potential manifestation. The following approach has been mainly developed in the context of the Italian Railway Authority (RFI - Rete Ferroviaria Italiana). On many Italian railway lines, one of the biggest issues for the safety of the operations is hydrogeological instability; even small volumes of rock or debris on the track can cause train derailment [1] [2].

A landslide hazard mapping is needed to help the implementation of global strategies from the Client to accurately plan the funds designated to secure the railway line.

Landslides inventories at different scales are available on the majority of the Italian territory, but they are not homogeneous and their cartographic scale is too low to analyze instabilities along railway corridors. Furthermore, landslide hazard along railway trenches is not considered.

There is also a lack of knowledge about the historical events, occurred on the railway tracks, and the stability conditions on track sides are not well known, both for what concerns natural slopes and artificial trenches.

A homogeneous and objective approach, based on detailed topography, geological and geomorphological conditions, rock and ground material properties, is needed to parametrize the different hazard components along the line and evaluate the exposure to landslide occurrence of every point of the railway corridor. These large-scale analyses are in the framework of the GEO4 service (Geomatics, Geology, Geotechnics and Geomechanics for Slopes Engineering). The GEO4 approach allows slope mapping along infrastructures through the identification of the spatial probability of occurrence of the landslides and other critical events with a Spatial Multi-Criteria Analysis (SMCA). GEO4 produces hazard and priorities maps to promptly help the Authority with the implementation of global strategies and planning of the funds designated to secure the railway line through time.

2. Methodological approach

In order to assess landslide hazard along railway corridors, an approach derived by the Spatial Decision Support Systems (SDSS) was applied.

The described approach complies with the following requirements:

- Scale, adequate to the required level of detail;
- High-productivity surveying techniques to minimize fieldwork and so access to the railway line;
- Repeatable approach to ensure objectivity;
- Calibration on documented case studies.

The Spatial Multi-Criteria Analysis (SMCA) is an approach developed and mainly used as a public planning decision support system [3]. It is needed when the parameter to be measured is a function of many not-directly-comparable variables, which need to be weighted and normalized.

SMCA includes many analysis approaches, all based on the same schema: to explicit the contribution of each criterion and its weight in the final choice (or classification).

The process is typically divided into three phases: the criteria definition, their normalization (the criterion is usually normalized in a range between 0 and 1), and the attribution of the weight (or relative importance) to each criterion.

In geological and environmental fields, it is mainly applied to produce hazard and risk maps, which are typically dependent on heterogeneous variables [4] [5] [6].

In this case, the analysis and the input parameters of the SMCA model were defined according to the main known problems related to slope stabilities along the analysed railway corridors (mainly rock falls, debris and soil slips).

The granularity (or spatial resolution) of the analysis is 10m. One value of each parameter has been calculated every 10 meters, along the line. The 10m unit has been chosen as the best common resolution representative of all parameter variation.

3. Data collection

Data collection is organized on four levels, as described in the following sections.

3.1. Bibliographic analysis

The first and lower-scale level is the bibliographic analysis with the collection of existing data on the area: geological maps, official landslide inventories [www.progettoiffi.isprambiente.it], surface displacement data from the National Satellite Interferometry (InSAR) Database [www.pcn.minambiente.it/GN/progetti/piano-straordinario-di-telerilevamento] and other open GeoData sources [https://geoportale.lamma.rete.toscana.it/difesa_suolo/#/viewer/openlayers/326)].

Thanks to its capability in detecting millimetre level displacements over long periods and large areas, satellite interferometry can be considered complementary to conventional geological and geomorphological studies in landslide detection and monitoring, supporting also the effectiveness of landslide inventories at a regional scale and landslide areal extent evaluation.

The available satellite radar archives presently cover a time span of about 30 years over the whole Italian territory. The exploitation of these archives can support the performance of landslide studies at both large and small scale, supporting:

- Landslide areal extent evaluation;
- Unmapped phenomena detection;
- Landslide activity assessment.

3.2. Airborne LIDAR survey

The second layer of information is represented by a LIDAR flight taken along all the railway line, on a corridor about 400m wide, from which a high-resolution DTM and DSM of the area with a 0.5 meters ground pixel and a detailed orthoimage (10 cm pixel) can be obtained.

3.3. Mobile Mapping survey

After the first pre-analysis made on the LIDAR topography and bibliographic data, a mobile mapping system developed by ETS Srl [7] is used in order to survey the slopes of the trenches, generally visible only from the line. ARCHITA (Figure 1) is a multi-dimensional mobile mapping system equipped with a laser scanner, thermal cameras, multi-channel GPR and high-resolution cameras to guarantee an integrated set of data without frequent and long disruptions of the traffic.

ARCHITA guarantees acquisition velocity of 15-30 km/h on average with minimal impact on rail/road traffic, reducing the time on the in-situ activities and increasing the safety for men at work and users. Mobile laser and airborne LIDAR point clouds can be integrated/overlapped thanks to the high-accuracy georeferencing method adopted for the surveying systems.

Figure 1. ARCHITA mobile mapping system.

3.4. In-Line Inspections

The last survey level is the field geological survey along the line, which is complementary to the previous ones, and is aimed at collecting direct data about:

- Local geology and geomorphology, including geotechnical and geomechanical characterization of the trenches materials, performing on-site tests;
- Existing slope remedial works/structures and their conditions;
- Evidence of instabilities, erosional phenomena, etc.

Furthermore, some soil/rock samples representative of each lithotype is collected during field surveys and are used for the soil and rock mechanics laboratory tests to define the constitutive parameters for the preliminary slope stability analysis on each 10m-portion of the railway trenches.

4. Data processing and analysis

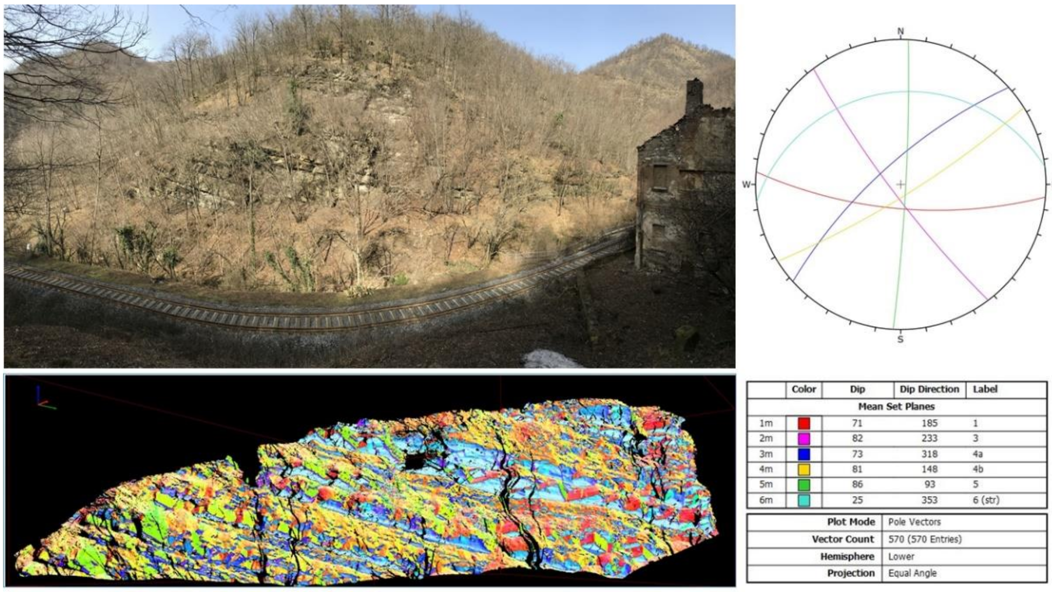
Since all the collected data are georeferenced, they can be processed in a GIS environment to extract all the input parameters needed for the SMCA analysis, supporting the identification of potential landslide sources as well as the extent of the possible spreading areas. This information is necessary to assess landslide hazard along railways.

4.1. Slope stability evaluation

To evaluate the stability index of each trench, both geomorphometric data and geological tests (on-site and lab tests) are generally used. A geotechnical or geomechanical approach can be followed depending on the slope type and processes.

The distribution of significant geomechanical parameters of inaccessible rock cliffs can be obtained by processing the dense point cloud provided by mobile scanning.

Commercial software tools can be used to calculate the local orientation of the slope at each point of the dense point cloud. An example is represented by Coltop3D [8]. This software exploits the idea of having a unique colour for both dip and dip direction of a discontinuity plane by adapting a computer graphics Hue Saturation Value (HSV) wheel to a standard stereonet (Figure 2).



	Color	Dip	Dip Direction	Label
Mean Set Planes				
1m	🟥	71	185	1
2m	🟪	82	233	3
3m	🟦	73	318	4a
4m	🟨	81	148	4b
5m	🟩	86	93	5
6m	■	25	353	6 (str)

Plot Mode	Pole Vectors
Vector Count	570 (570 Entries)
Hemisphere	Lower
Projection	Equal Angle

Figure 2. False-colour image (lower left) representing the orientation of the main discontinuity sets of the above cliff; right: stereonet (lower hemisphere) representing the main sets identified by the analysis according to the same colour codes. The example refers to a scarp located along the Borgo San Lorenzo – Faenza railway.

Once the main discontinuity sets have been identified, further processing can be carried out to extract relevant data for each set and at the rock cliff scale. It can reasonably be assumed that curvature changes of the DSM (Digital Surface Model) correspond to fracture traces when projected onto a vertical plane having the average orientation of the slope surface [9]. A vector plot of projected fracture traces can be obtained by applying proper mesh processing software. Once fracture traces are extracted from the mesh of the slope, they are projected onto a view plane representing the local orientation of the slope and simplified, so becoming 2D polylines. Traces are then classified based on their apparent angle and grouped according to the main discontinuity set orientation and analyzed with the approach of the observation window [10]. The study area is split into circular observation windows; for each of them, the following parameters can be calculated: frequency and spacing for each discontinuity set, cumulative fracture length per unit area (P21, [11]); elementary rock volume (Vb); volumetric joint count (Jv); etc.

In the example of Figure 3, starting from the spacing distribution of the main discontinuity sets, an average elementary rock volume of 0.01 m^3 was estimated.

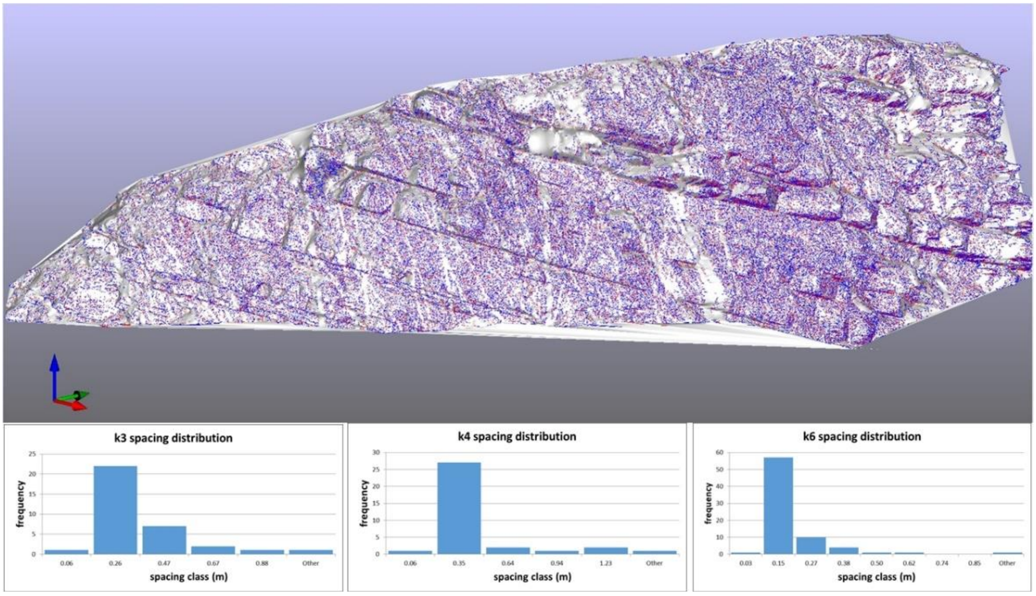


Figure 3. Joint traces and spacing distribution histograms for three main discontinuity sets (same slope as figure 2).

As a further step of the analysis, commonly used rock quality indices, e.g. Slope Mass Rating SMR, can be derived from the previous parameters and mapped (Figure 4).

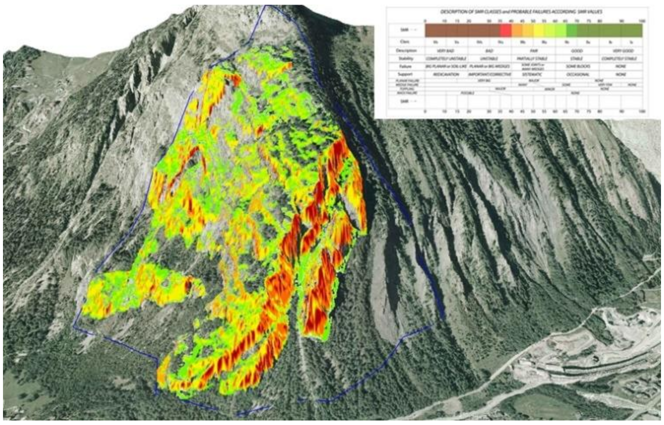


Figure 4. Slope Mass Rating (SMR) map draped over a 3D model of a slope.

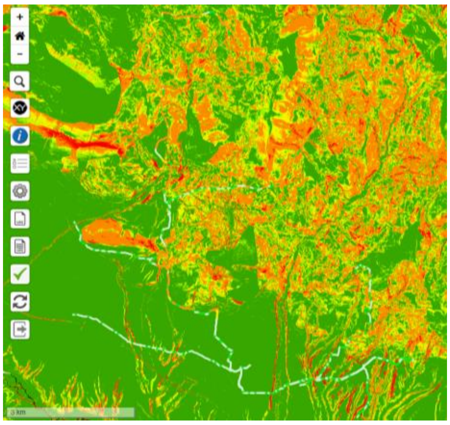


Figure 5. Stability Index by SINMAP.

When studying long railway corridors, shallow landslides in loose materials must be considered too. The GEO4 approach applies physically-based models to this aim. SINMAP [12] and SHALSTAB

[13] are open-source GIS models implemented in GEO4 which exploit digital elevation models to obtain the necessary input information in terms of slope and hydrology. An initial range of values is assigned to the constitutive parameters of slope materials and are then optimized on “calibration regions” based upon the soil, vegetation or geologic data. This approach provides maps with a spatially distributed “Stability Index” (Figure 5) that can be used as input in the SMCA analysis.

4.2. Geomorphometric analyses

Thanks to the availability of a high-resolution DEM of the railway corridor, detailed geomorphometric analyses can be carried out, providing valuable data to evaluate the possible impact of landslides, both rock and earth fall, onto the railway which can wholly or partially block the track.

Some commonly used geomorphometric indices are briefly described below. The index of sediment connectivity IC [14] is a distributed geomorphometric index that can be easily derived from a Digital Elevation Model (DEM). It mainly focuses on the influence of topography on sediment connectivity, whereas other aspects such as type, extent and location of sources are not taken into account. IC value can be used as a dimensionless indicator of those sections of the linear infrastructure which are characterized by higher water and/or sediment flow. In Figure 8 geomorphological and IC maps (first and second from left) of the same railway section shown a very good correlation, highlighting more hazardous areas, as confirmed by the hazard map in the right part of the figure.

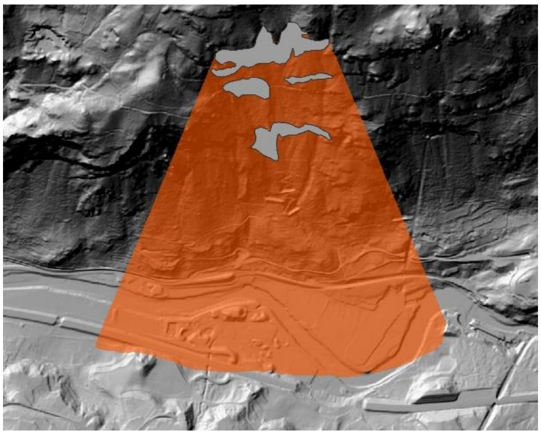


Figure 6. Rockfall propagation area (source areas in light grey).

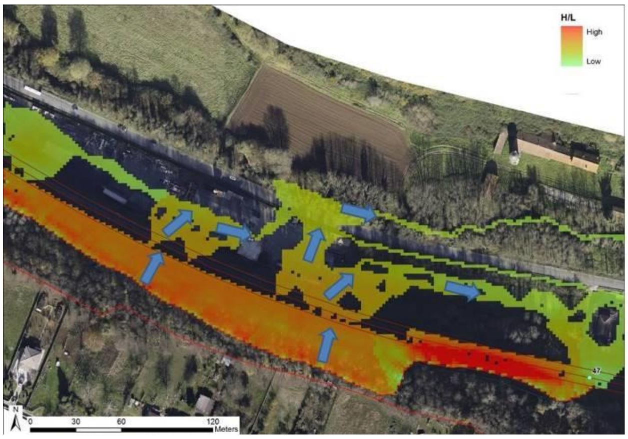


Figure 7. Predicted mass movement spreading area.

A simplified approach to outline rockfall propagation areas is provided by the application of the shadow angle or energy line method. This approach is described by several authors [15] and has been implemented in the CONEFALL software [16]. A simple GIS tool has been developed to highlight the runout area according to the selected shadow angle. Results can be plotted on a map or an orthoimage for better visualization and analysis (Figure 6). This simple geometric approach is very useful for preliminary zoning along hundreds of kilometres of linear infrastructure corridors aimed at identifying those areas where further detailed trajectory analyses with 2D and 3D software are needed.

For what concerning mass movement (e.g. mudflow, debris flow) propagation, the Modified Single Flow (MSF) algorithm [17] can be used to obtain an estimation of the spreading area based on the available DEM. The algorithm is based on a single flow direction approach from a specified initiation point, where the central flow line follows the direction of the steepest descent. MSF provides only the extent of the expected spreading area, not velocity and landslide deposit thickness. This hampers the possibility to carry out any further analysis on the impact of the landslide with structures and infrastructures present within the landslide spreading area. In order to stop the flow, a reaching angle must be set. Many authors have proposed empirical expressions for the inverse relationship between the tangent of the reach angle α (H/L; which represents the ratio between the vertical drop H and the horizontal component of the runout distance L) and the landslide volume. This ratio corresponds to the average slope of a line connecting the highest point of the detachment area with the farthest point of the accumulation area and represents the average coefficient of friction (Figure 7). A proper H/L threshold value must be assumed to stop flow in MSF and mass movement runout.

4.3. Spatialized Multi-Criteria Analysis (SMCA)

Each input parameter is described by a georeferenced vector or raster layer, thus forming the geo-database needed to perform the Spatial Multi-Criteria Analysis.

An aggregated index is then calculated by using an algebraic formula which is calibrated on available case histories. Such an index is a function of at least the following parameters: Slope stability index, Connectivity index, Slope Mass Rating, Vegetation height, Existing slope remedial works/structures and their conditions, Evidence of instabilities, erosional phenomena, etc, Mass movement runout, Rockfall travel distance, Intersection with inventoried landslides.

The final classification leads to a map of the corridor classified into four hazard classes (“priority” classes in Figure 8). The examples shown in Figure 8 refer to a recent study carried out along a 76 km long railway line (Borgo San Lorenzo – Faenza, Central Italy).

A WebGIS platform has been implemented to allow easy access to the data and to provide an easy-to-use update web service.

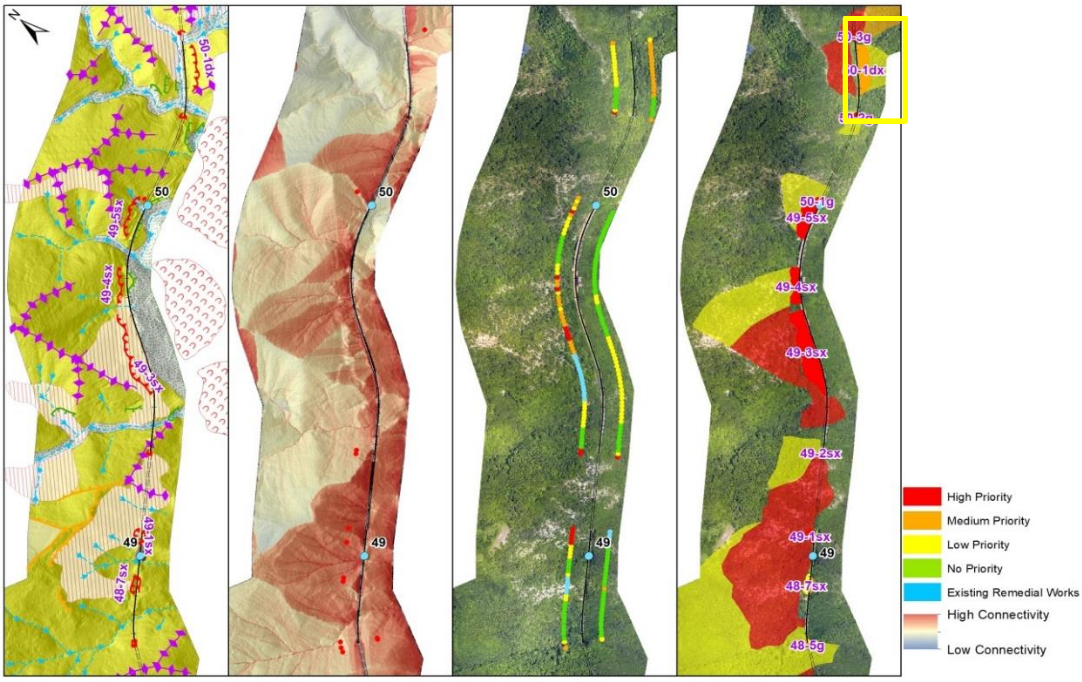


Figure 8. Thematic maps produced to assess the landslide hazard along the “Borgo San Lorenzo – Faenza” railway line. From left to right: geomorphological map, Connectivity Index map (red dots indicate overcomes of a threshold value), the final index value, calculated every 10m along the line, on both sides, and the landslide hazard map, where the index value is summarized to classify each trench and slope. Four priority classes are usually adopted. The scarp shown in figure 2 is located in the yellow box.

5. Future developments

The described approach can be extended to other linear structures, i.e. roads, pipelines, power lines.

Moreover, it is possible to integrate the WebGIS structure with a real-time Early Warning System module capable of acquiring and processing real-time monitoring data. Warning messages can be automatically generated by comparing acquired data with pre-established threshold values on a wide spectrum of triggering parameters, e.g. precipitation, surface and underground displacements, pore pressure, etc. The WebGIS frontend will allow users to see and query the data and interact with the system by providing feedbacks on automatic warnings generated by the EWS, supporting the calibration and optimization of threshold values and reference scenarios.

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