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Application of Multi-Criteria Analysis (MCA) to assess landslide hazard and plan mitigation strategies along railway corridors in Central Italy.

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ABSTRACT: Because of the long, linear nature of railway corridors, they often cross areas that are highly susceptible to landslides. In order to assess the hazard posed by the probability of landslides occurrence, detailed data such as slope geometry, geotechnical and geomechanical properties of materials, drainage system pattern etc. are needed. Once available, input data must be analyzed with an objective approach in order to obtain landslide susceptibility maps and plan proper remedial works. The Multi-Criteria Analysis (MCA) provides a decision-making tool in complex situations where multiple criteria are involved and a well-structured decision-making process is needed. Moreover, MCA can be applied in a GIS environment when geocoded data are available. This paper presents an application of MCA to map landslide hazard along railway corridors in order to support decision-makers in defining the most appropriate mitigation measures and planning their implementation. Examples of application to some hundreds km long railway lines in Central Italy will be presented.

1. INTRODUCTION

The Italian Railway Company (Rete Ferroviaria Italiana - RFI) has to manage the security along the lines. On many lines one of the biggest issue is the hydrogeological instability; even small amount of slopes material (rocks or debris) on the track ballast cause high-risk situations (Fig. 1) (Geertsema et al., 2009; Guerriero et al., 2013).

A priority map is needed to define where to invest the funds destinated to secure the railway line.

Different scales landslides inventories are available on the majority of the Italian territory, but they are not homogeneous and their cartographic scale is too low to analyse instabilities along railway corridors. Furthermore the potential instability hazard 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 for artificial trenches.

A homogeneous and objective approach, based on local topography, geology and geomorphology conditions and materials properties (in terms of litology, geotechnics, geomechanics, hydrogeology, etc…) it is needed in order to parametrize the different hazard component along the line.

Fig. 1. Train's derailment caused by hydrogeological instability (Photo RFI).

2. METHODOLOGICAL APPROACH

In order to produce the priority map, requested by the Railway Company, an approach derived by the Spatial Decision Support Systems (SDSS) was applied.
Multi Criteria Analysis (MCA) is an approach developed and mainly used as a public planning decision support system (Joerin et al., 2001). 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.
MCA includes many analysis approach, all based on the same schema: to explicit the contribution of each criteria, and so its weight, in the final choice (or classification).
The process is typically divided in three phases: the criteria definition, their normalization (the criterion is usually normalized in a range between 0 and 1), and the attribution of a 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 by heterogeneous variables (Quinn et al., 2010; Sadr et al., 2014, Mancini et al., 2010).

The input parameters of the MCA model were defined on the basis of the main known problems related to slope stabilities along railway corridors (mainly rock falls and debris dynamics).
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 distance representative of all parameter variation.

3. DATA COLLECTION

Data collection is organized on four levels.
The first and lower-scale level is the bibliographic analysis, the collection of existing data on the area, deriving them mainly from National Landslides Inventory (IFFI - www.progettoiffi.isprambiente.it), and from the National Interferometric Satellite Database (www.pcn.minambiente.it/GN/progetti/piano-straordinario-di-telerilevamento).
A second level is represented by a LIDAR flight taken along all the railway line, on a corridor of about 400m wide, that produced a DTM and DSM of the area with a 0.5 metres ground pixel, and a detailed orthoimage.
After the first pre-analysis made on the LIDAR topography and bibliographic data, a rail-trailer-survey is performed. A rail trailer has been equipped with the following set of survey instruments (Fig. 2):

- Two double-frequency, phase recording, GNSS antennas
- Inertial Measurement Unit
- Two rotating terrestrial laser scanners
- Two automatic shooting cameras
- Odometer

Fig. 2. Trailer equipment.

Trailer data are collected travelling at a speed of about 10 km/h. Survey speed is derived from the mobile laser scan speed, in order to obtain the desired point cloud density. The mobile laser point cloud and the LIDAR point cloud can be integrated/overlapped, thanks to an high-accuracy georeferencing method based on different GNSS base stations placed outside the railway line. The trailer survey outputs are a 10cm point cloud and a continuous series of georeferenced digital pictures on both sides (Fig. 3).

Fig. 3. Trailer laser scanner point cloud.

The last survey level is the on-foot geological survey along the line, which is complementary to the previous ones, and it is aimed to collect data regarding:

- Local geology and geomorphology, including geotechnical and geomechanical characterization of the trenches materials, performing on-site tests.
- Existing defense structures
- Local hydrogeological hazards (instabilities, erosion and runoff areas, etc.)

Furthermore, some material samples are collected during the on-foot surveys. These samples are representative of each litology and will be used for the soil and rock mechanics laboratory tests, to define the parameters that allows to measure the stability index on each 10m-portion of the railway trenches.

4. DATA ANALYSIS

Since all the collected data are georeferenced, geomorphometrics analysis in a GIS environment can be computed in order to extract some parameters as trenches geometry (height, slope, aspect), runoff analysis towards the track ballast, vegetation height map, geomechanic characterization of rock walls, runout modelling, rock-fall propagation zones.

A detailed geomorphologic map is produced by integrating geomorphometric analysis, orthoimages and trailer photos.

To evaluate the stability index of each trench, both geomorphometric data and geological tests (on site and lab tests) have been used. Depending on trench materials, to measure the stability index a geotechnical or geomechanical approach have been followed. The geotechnical approach is based on the analysis of the safety factor at different saturations ratio. The geomechanical one is based on the SMR (Slope Mass Rating) index, as representative of the quality of the rock (Fig. 4).

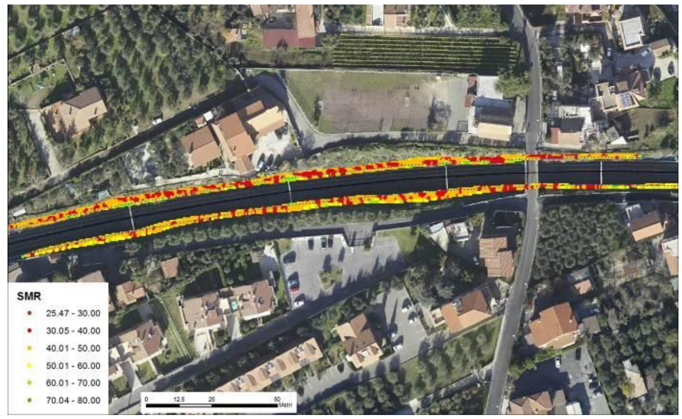

Fig. 4. SMR distribution map.

For incoherent material slopes, the stability index is measured by associating each slope portion to one of the standard slope typologies, defined by analysing the distribution of the geomechanical, geometrical and lithological properties inside the dataset.
The rock walls stability index is based on the SMR parameter, which can be measured and distributed on the slope by extracting the needed parameters from the laser dense point cloud. Where both rock and incoherent material coexist, both analysis are performed.

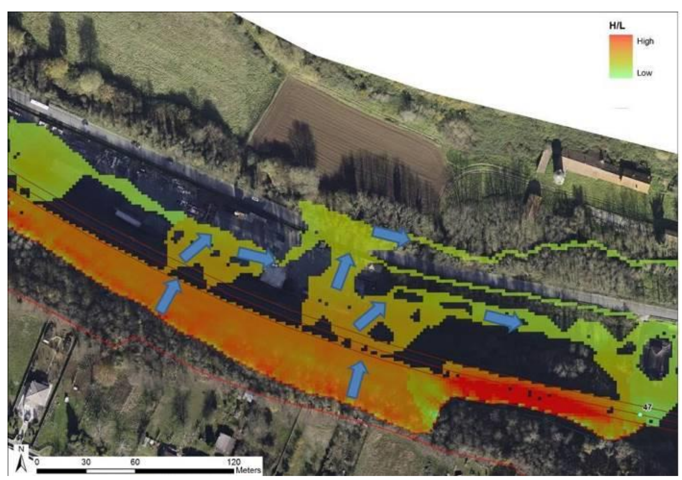

Fig. 5. Example of the runoff modelling and H/L ratio.

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

For artificial trenches, the aggregated index produced by the MCA is a function of:

- Stability test
- Connectivity index (Cavalli et al., 2013, Messenzhel et al., 2014)
- Slope Mass Rating (Delgado and Seròn, 2007)
- Vegetation height
- Existing defense structures
- Visible instability areas

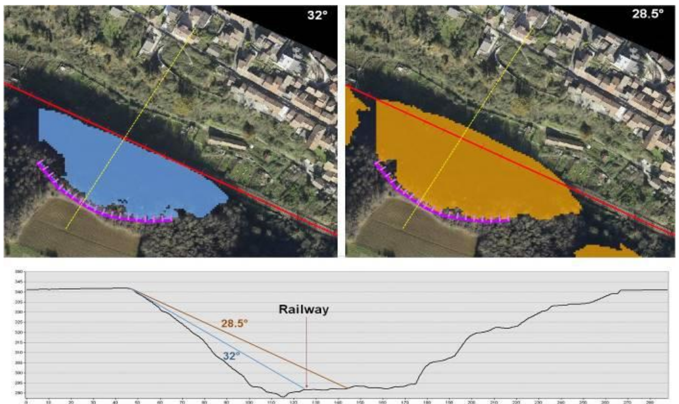

Fig. 6. Conefall map. The limit angles used in this work are represented in the section graphic.

For natural slopes, the index is a function of:

- Debris impact measured on the basis of the Height/Length (H/L) ratio (Hengl and Reuter, 2008) (Fig. 5)
- Rock fall impact measured by the conefall method (Fig. 6) (Jaboyedoff and Labiouse, 2011; Evans and Hungr, 1997)
- Existing defense structures
- Visible instability areas

A final index value is produced every 10m, then each single trench and slope is classified by weighting all the values it intersects.

The final classification lead to a map of the trenches and slopes classified into 4 priority class, as requested by the Railway Company.

5. CASE STUDY

The described method has been applied to 280 km of railway corridors in central Italy, between 2015 and 2017. The lines have length between 50 and 120 km. All the lines are located in central Italy, between the Appennines, in a very dynamical geological and morphological context. Lithotypes are mainly volcanic and sedimentary, with a low geotechnical quality.

The main hazard dynamics are related to landslides, debris flows, rock falls.

The railway lines are mainly single-track, and for the majority run inside artificial trenches.

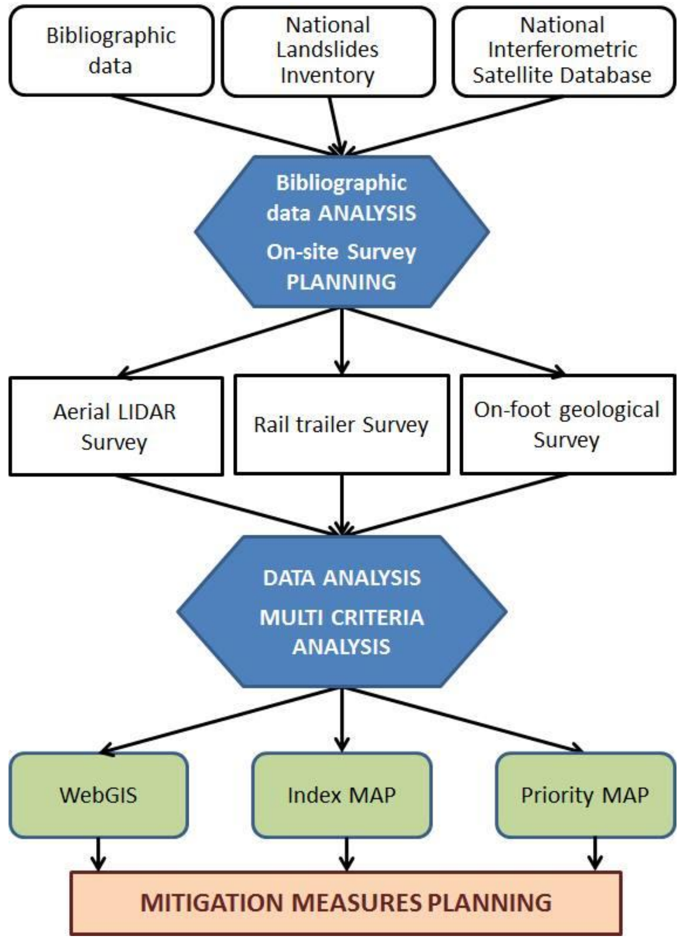

Fig. 7. Work flowchart.

The logistics of the ground surveys along the lines was one of the limiting factor of the work. Due to the impossibility to stop the train traffic and to respect all the safety standards of the on-rail-works, the survey time had to be done in a rigid and limited time intervals which were limited to few hours, mainly during the night.

Both trailer and on-foot surveys had to be precisely planned, in order to collect all the needed data in the shortest possible time.

The final parameters aggregation was made by using an algebraic formula which has been calibrated on all the available case history of slope instabilities, mapped by RFI technicians.

In the last two years some instabilities events occurred on the analyzed lines (luckily without causing major damages). Each one of them happened in correspondence of a higher-class value of the final indicator.

In order to make all the data easily available and to give the possibility to keep them updated, all the collected and processed data and the results analysis have been organized in a WebGIS service. It is easy to consult by using a common browser, both from pc and mobile, and gives the possibility to send georeferenced warning or information in forms of documents, notes or pictures.

6. CONCLUSIONS

The aim of the work was to define an analysis procedure of a rail track line, by using objective and globally applicable criteria, in order to produce a synthetic priority map.
The described method has been successfully applied to 280 km of railway lines; the results provided a synoptic view of the main hydrogeological problems along each railway line, and a priority map which is being used to plan where to make detailed studies in order to plan new defense structures.

Even if the method is basically statistic and do not provide deterministic analysis, the correspondence between the index and the occurred events shows that the method well describes the phenomena in the area.

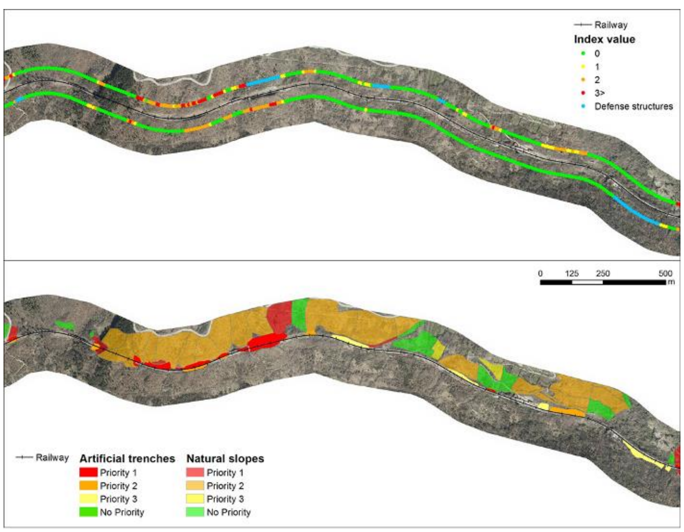

Fig. 8. Upper image: final index value, calculated every 10m along the line, on both sides. Lower image: priority map, where the index value are summarized to classify each trench and slope.

One of the added value of a wide mapping work is the constant update of the data; for this reason a WebGIS platform has been implemented, in order to guarantee an easy access to the data and to provide an easy-to-use update web service.

After the application of the method on railways, other project are going to start, trying to adapt this survey configuration and procedure to analyze Highways and river banks.

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