An innovative multiscale approach for the characterization of rock masses subject to tunnel excavation

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ABSTRACT: The design of a tunnel must be solidly based on the knowledge of the territory. An optimization of the investigation process is strongly required in order to obtain complete and reliable data for the design. The fast development of remote sensing technologies and the affordability of their products have contributed to extensively prove their benefits as supports for investigation, encouraging the spreading of automatic or semi-automatic methods for regional scale surveys. Similarly, considering the scale of the rock outcrop, photogrammetric and laser scanner techniques are well-established techniques for the representation of the geometrical features of rock masses: the benefits of non-contact surveys in terms of safety and time consumption are acknowledged not only by the research community but also by experts and companies. Unfortunately, in most cases data obtained at the different scales of investigations are only partially integrated or compared, probably due to a missing exchange of knowledge among experts of different fields (e.g. geologists and geotechnical engineers). The authors propose a multiscale approach for the optimization of the investigation process: starting from the regional scale, the aim is to obtain data than can be useful not only to plan more detailed surveys, but also to make previsions on the potential discontinuity sets that could be present in the rock masses subject to the excavation. A methodological process is proposed and illustrated by means of an application to a case study. Preliminary results are discussed in order to highlight the potentiality of this method and its limitations.

1 INTRODUCTION

The design of a tunnel must be solidly based on the knowledge of the geological, hydrogeological and morphological characteristics of the territory. The bigger the structure, the larger the area to be investigated, the greater the number of surveys and tests to be performed in order to examine in depth all the relevant features: therefore, an optimization of the investigation process is strongly required in order to obtain complete and reliable data for the design of the infrastructure.

An in-depth knowledge of the geological aspects of the area in which a tunnel will be excavated is fundamental for choosing the best layout: in fact, costs, duration of the work and possible issues are strictly correlated to them. The best layout is thus the optimal compromise between the length and the characteristics of the rock masses to be excavated.

The stratigraphic, structural and hydrogeological setting can be preliminarily acquired from literature data, aerial and satellite images, particularly in case of scarce bibliography or limited accessibility of the area; then, onsite surveys are usually performed in order to validate and integrate data. Therefore, particularly in the first steps of the design, the contribution of remote sensing technologies is fundamental: their fast development and the affordability of their products have contributed to extensively prove their benefits as supports for investigation for geological lineaments identification (Suzen & Toprak, 1998; Morelli & Piana, 2006; Marghany & Hashim, 2010), encouraging the spreading of automatic or semi-automatic methods for regional scale surveys (Koike et al., 1995; Wladis, 1999; Tripathi et al., 2000; Mavrantza & Argialas 2003, 2008; Vaz et al., 2012; Hashim et al., 2013; Soto-Pinto et al., 2013). In particular, the need to overcome possible limitations of the use of satellite images due to the characteristics of sensor, landform, lighting and weather conditions (Shepherd & Dymond, 2003; Smith & Wiseb, 2007), has promoted the use of Digital Terrain Models (DTM) for lineament mapping (Ganas et al., 2005; Jordan et al., 2005; Masoud & Koike, 2006, 2011, 2017; Seleem, 2013; Rahnama & Gloaguen, 2014; Bonetto et al., 2015, 2017).

A preliminary reconstruction of the structural layout at regional scale is fundamental, since it can strongly influence the choice of the tunnel layout. In fact the mechanical behavior of a rock mass is deeply conditioned by the structural features of the area: these features are usually a manifestation of the deformative style at regional scale. Therefore, regional scale investigation in preliminary design, if accurately performed, could give very useful information to make hypothesis and previsions on what one could expect to find at local scale.

In any case it is necessary to perform a structural analysis at the scale of the single rock mass, in order to examine in depth the characteristics observed at regional scale: the choice of the excavation procedures and the support systems should be based on the inferred data.

Considering now the scale of the rock outcrop, that is a more detailed scale with respect to the regional one, photogrammetric and laser scanner techniques are well-established methods for the representation of the geometrical features of rock masses: a Digital Surface Model (DSM) can be rapidly created, without direct access to the rock face. In tunnels excavated with drill and blast or mechanical methods (e.g. roadheaders, hydraulic cutters), that is tunnels in which the face is visible, the acquisition of images or point clouds interferes for only a few minutes with the operations and can be easily integrated within the process (Gaich et al., 1999; Fekete et al., 2010; Roncella et al., 2012; Racaniello et al., 2015). The georeferenced DSM and the associated images can be then used as input for codes able to measure orientation and spacing of the recognizable discontinuities (Kemeny & Donovan, 2005; Trinks et al., 2005; Haneberg, 2006; Slob et al., 2007; Ferrero et al., 2009; Sturzenegger & Stead, 2009; Gigli & Casagli, 2011; Lato & Vöge, 2012; Riquelme et al., 2014). The benefits of non-contact surveys in terms of statistical reliability, safety and time consumption are acknowledged not only by the research community but also by experts and companies.

Unfortunately, in most cases data obtained at the different scales of investigations are only partially integrated or compared, probably due to a missing exchange of knowledge among experts of different fields (e.g. geologists and geotechnical engineers). In general, data obtained during the analysis step regarding regional features are not converted into equivalent information to be used in order to be aware of the possible features that can be encountered while performing detailed surveys at the single rock mass scale.

The authors, after experiencing such a lack of connection among results of different surveys concerning tunnels, propose a multiscale approach for the optimization of the investigation process: starting from the regional scale, the aim is to obtain data for making previsions on the potential discontinuity sets that could be present in the rock masses subject to the excavation.

A methodological process is proposed and illustrated by means of an application to a portion of the tunnel called Finestra Val Lemme, a lateral access of the Terzo Valico tunnel. Preliminary results are discussed in order to highlight the potentiality of this method and its limitations.

2 REGIONAL SCALE INVESTIGATION

CurvaTool code (Umili et al., 2013; Bonetto et al., 2015, 2017) has been used to perform linear features mapping on the analyzed DTMs. The software performs the identification of all the significant linear features (crests and valleys), composed of points whose principal curvature values are above the thresholds assigned by the user. Then the linear features database can be statistically analyzed, according to the geological knowledge of the area, in order to identify the orientation, length and spatial distribution of the lineaments.

Post-processing, performed by Filter code, can follow two different approaches: if no literature data are available for the studied area, the resulting rosette of directions can be used to make observations useful for a preliminary tectonic assessment. If instead mean directions of lineaments sets are known, Filter code classifies each edge attributing it to the correspondent input cluster. This allows the user to define different domains characterized by different deformation styles. This is particularly true as the morphological layout of the area is influenced by the tectonics, so that morphological elements could have a morphotectonic value and could be associated to potential structural lineaments.

3 DETAILED SCALE INVESTIGATION

It would be fundamental that at least in tunnels in which the face is visible, the most advanced non-contact survey methods were used to continuously update a database of the rock mass characteristics: the possibility to investigate something as a rock face that will not exist anymore after a short time is very important to allow the operations to be repeated and to justify the construction choices.

The survey should interfere as little as possible with the excavation process: therefore the authors think that a well-designed photogrammetric approach could be the best solution, since image acquisition is very fast and moving a digital camera is much easier than a heavy Terrestrial Laser Scanner (TLS) (Roncella et al., 2012). In this research a very fast non-contact survey method was used (Racaniello et al., 2015): the required equipment consists of a digital reflex camera, a tripod and a level staff equipped with a bubble. The camera and the appropriate lens were previously calibrated, in order to quantify the distortion produced on the image and allow for its correction.

The camera was mounted on a tripod in order to reduce the possible vibrations during the shooting. The level staff was inserted in another tripod in order to guarantee its uprightness during the shooting. After the face was excavated, the muck loaded and the dust was deposited, it was necessary to verify that the light was sufficient and homogeneous (and, in case it was not, light could be added by using portable spotlights). After that, the user placed the level staff (that must be vertical) approximately in correspondence of the tunnel axis, as near as possible the rock face, according to the safety conditions. Then the camera was placed at a distance to the face so that the entire face was contained in the image and it covered quite completely the image, at the same time.

Three images were shot from three different positions (Fig. 1), then the level staff was removed. This procedure took less than 10 minutes to be performed and could be easily integrated in the excavation process. The commercial software PhotoScan (Agisoft) was then used to reconstruct the DTM from the three images.

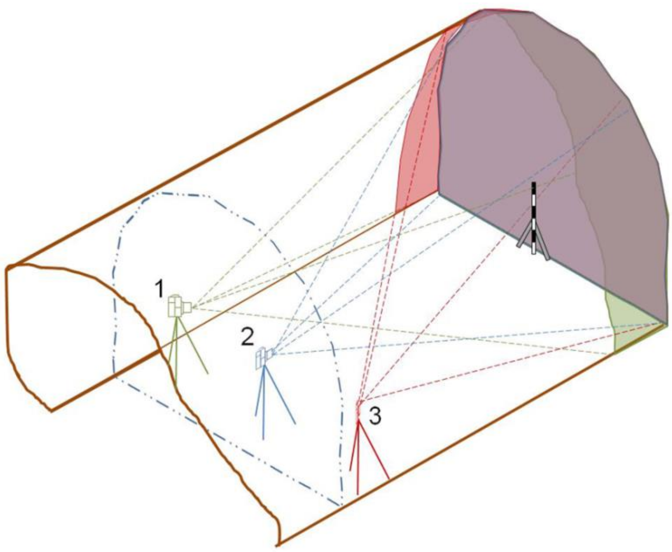

Figure 1. Scheme of the relative positions of the three shooting points (left: 1, center: 2, right:3), the level staff and the rock face (modified after Roncella et al., 2012).

Rockscan software (Ferrero et al., 2009) was used to perform a detailed structural survey combining photographs taken during the photogrammetric survey and a DSM. Basically, the operator delimits the discontinuity planes manually on a photograph and, since the exterior and interior orientation parameters are given for each photograph, the DSM can be projected onto the chosen photo. The software then estimates the plane that best fits the points within the delimited region and calculates its dip and dip direction.

This method allows a large number of planes to be defined quickly and the examined rock face can be studied using a larger statistical sample than that obtained sampling along a few scan lines (Curtaz et al., 2014).Thanks to the vertical reference system materialized by the level staff, dip data obtained from the survey do not require to be corrected. On the contrary, dip direction data must be corrected by simply adding the angle corresponding to the tunnel direction (referred to the considered rock face location) with respect to the North.

4 THE FINESTRA VAL LEMME CASE STUDY

Part of the Rhine-Alpine Corridor (European Commission - Mobility and Transport, 2017) is represented by the High Speed/High Capacity railway from Milan to Genoa, denominated "Terzo Valico dei Giovi" (Terzo Valico, 2017), currently in progress. The layout covers an overall distance of 53 km of which 37 km in tunnels. It consists of two tubes, each equipped with a single track, meaning that train traffic through the tubes is one-way. The two tubes are linked by connecting side tunnels: these can be used in emergencies as escape routes. This configuration conforms to the highest security standards for tunnels. The tunnels will be mainly excavated by drilling and blasting, except for some sections in which mechanical methods will be used.

For construction and safety reasons, the main tunnel is intersected by four lateral access tunnels (Polcevera, Cravasco, Castagnola and Val Lemme). In particular, the Val Lemme one, currently being completed (Terzo Valico, 2017), is located on the right side of the Lemme Valley (Alessandria Province, Italy): it is about 1.7 km long, its direction is 102.28° respect to the North and maximum cover height is 240 m. The excavation process was carried out following the design criteria of the ADECO-RS method (Lunardi, 2008). The Finestra Val Lemme tunnel was dug in the “Argilloscisti di Costagiutta” and “Argilloscisti di Murta” formations: they consist of dark grey shale with pervasive schistosity characterized by the presence of small spacing and graphite-sericite coats caused by fluid circulated during deformation stages (Capponi et al., 2009).

Rock mass was found to be averagely fractured, with spacing of the different sets ranging between 0.2 and 0.6 m. Foliation, oriented in a more or less normal direction respect to the rock face, forms a variable angle from 80° up to 100° with the tunnel axis. Schistosity, highlighted by the presence of the sericite coats, represents not only a group of weak surfaces but also the main predisposing factor of instability of the tunnel.

A DTM (Fig. 2) with ground resolution of 1 point every 10 m (Piedmont Region GeoNetwork, 2008), covering an area of about 104 km2 containing the location of the Finestra Val Lemme, was used as input for the CurvaTool code. Since the area is mountainous, with an elevation difference of 842 m, the DTM surface contains a large number of recognizable crests and valleys, making the area suitable for semi-automatic linear feature extraction.

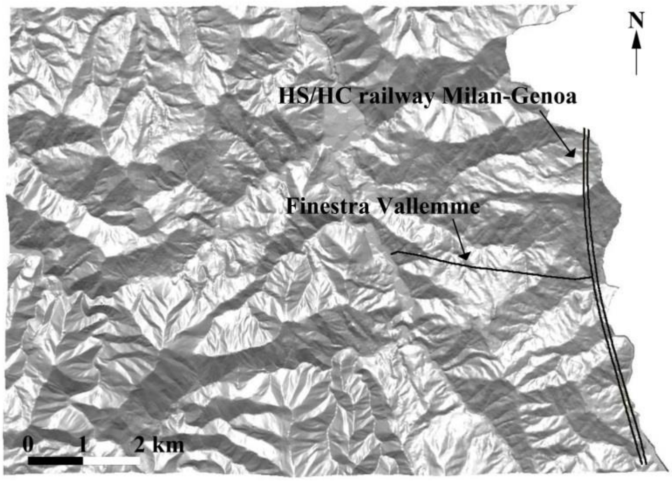

Figure 2. Shaded DTM of the area including Finestra Val Lemme (923’898 points)

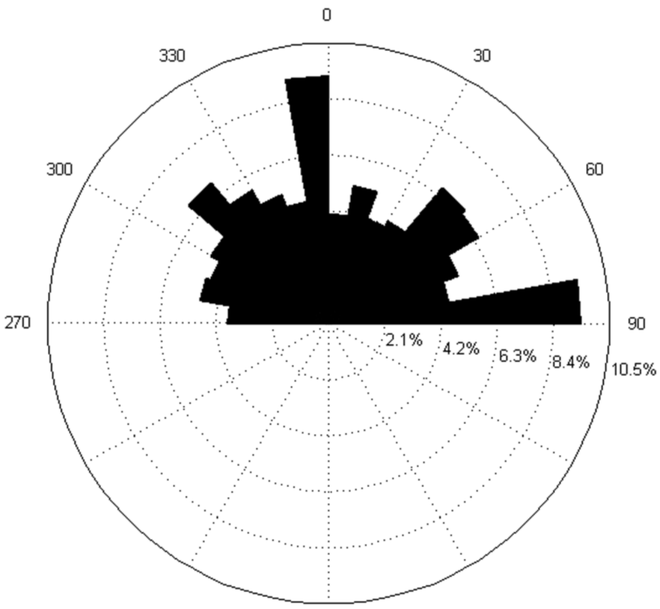

Figure 3. Rosette diagram representing azimuthal frequencies (expressed as percentages of the total number of extracted linear features). Only the upper hemisphere is considered, since diametrically opposed directions are equivalent.

Based on the rosette diagram (Fig. 3) obtained from the database produced by CurvaTool, four main sets have been identified (Table 1) and assigned to Filter code in order to perform a cluster analysis. Observing the obtained linear features map (Fig. 4), one can recognize three sectors, in function of linear features density and main orientation.

Non-contact survey was performed on 18 DSM of progressive rock faces and it allowed for the collection of a statistically significant number of measures of orientation, spacing and trace length (Racaniello et al., 2015). Four principal sets were identified (Table 2) and compared to those identified during a traditional expeditious survey. It must be underlined that the photogrammetric approach allowed to collect hundreds of measurements from each front, instead of the few ones obtained from the traditional method.

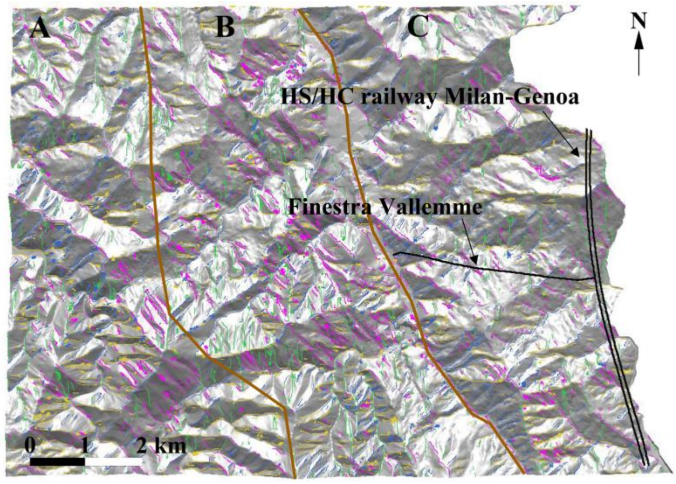

Figure 4. Map of linear features extracted by CurvaTool and processed by Filter: set L1 (green), set L2 (yellow), set L3 (fuchsia), set L4 (blue). The three sectors (A,B,C) are delimited.

Table 1. Orientation of lineament sets used as input for Filter.

Id set	Main direction	Azimuthal Direction [deg]	Standard Deviation [deg]
L1	N-S	0	20
L2	E-W	90	20
L3	NW-SE	135	20
L4	NE-SW	45	20

Table 2. Orientation of the main sets identified during non-contact and traditional expeditious surveys.

Id set	Orientation (dip/dip direction)	
	Non-contact survey	Traditional expeditious survey
K1	88/105	80/094
K2	40/185	46/180
K3	52/240	56/260
K4	60/140	67/125
K5	-	57/309

A structural geological overview is fundamental for the prediction about the type and orientation of the local structures that might be encountered during tunnel excavation. In many cases it is observed, in fact, a repetition on a small scale of the structural elements observed at a regional scale. Rocks are able to record permanently the effects of one or more stress fields by deforming in a brittle or ductile way. For this reason, at regional scale the effects of plate tectonics are revealed by folds and faults, affecting large portions of territory, which represent different evolutive phases of the tectonic history of the area. Those structures influence also the local tectonic arrangement, in which can be often found structural elements whose orientation is similar to those identified at regional scale.

In this regard, the application of the methodologies proposed in this paper made it possible to highlight the "similarities" between the structural features recognized in detail during excavation and the ones identified with CurvaTool analysis at regional scale and confirmed by the existing literature and geological maps. In the case of the Val Lemme tunnel, the detail surveys carried out with the traditional and non-contact methods showed the presence of similar discontinuity sets respectively NNE-SSW, E-W, NW-SE and NE-SW striking. Those directions can be directly compared with those of the ranging intervals of the main linear elements identified at regional scale by CurvaTool showing similar orientations (Fig. 5).

Results of this comparison should suggest how the application of the semi-automatic method for linear features extraction in a preliminary phase of the survey could provide useful and reliable indications with regard to the preferential orientations expected during excavation, especially in absence of literature data.

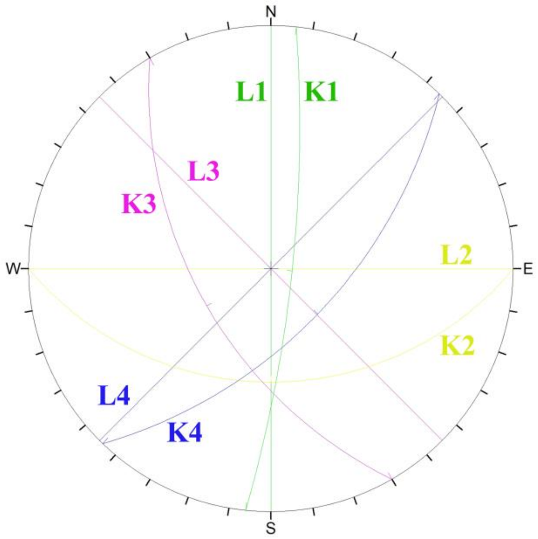

Figure 5. Comparison between the average strike of the main set identified at the scale of the rock face with both non-contact and traditional survey (great circles) and the main orientations of the linear elements identified by CurvaTool at regional scale (strike lines). Elements with similar strike are represented with the same color.

5 CONCLUSIONS

In this research the authors propose a method for the preliminary definition of the tectonic layout of an area, preparatory for planning onsite surveys and the infrastructure layout.

A semi-automatic approach as the one implemented in CurvaTool code allows to quickly and objectively identify linear morphological elements on a DTM. In case literature would offer limited or insufficiently detailed geological, geomorphological and structural information, the use of CurvaTool could help in the identification of possible geological anomalies. This is particularly true as the morphological layout of the area is influenced by the tectonics: the reliability of the obtained results increases in case of an active neotectonics.

Furthermore, directions of the main linear elements identified at regional scale by CurvaTool are similar to those of the sets identified at local scale both with traditional and non-contact approaches, suggesting that the semi-automatic method of extraction of linear features should be useful in a preliminary phase to obtain reliable indications with regard to the preferential orientations expected during excavation, especially in absence of literature data. Considering this first application of a multiscale approach for the characterization of rock masses aimed to civil engineering design, it seems promising and could imply important consequences regarding design reliability and expected costs.

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