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An integrated multiscale approach for characterization of rock masses subjected to tunnel excavation

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ABSTRACT

The design of tunnels must be conducted based on the knowledge of the territory. The longer the structure, the larger the area to be investigated, and the greater the number of surveys and tests to be performed in order to thoroughly examine all the relevant features. Therefore, optimization of the investigation process is strongly required to obtain complete and reliable data for the design of the infrastructure. The fast development of remote sensing technologies and the affordability of their products have contributed to proving 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 representing geometrical features of rock masses, and the benefits of non-contact surveys in terms of safety and time consumption are acknowledged. Unfortunately, in most cases, data obtained at different scales of investigations are only partially integrated or compared, probably due to the missing exchange of knowledge among experts of different fields (e.g. geologists and geotechnical engineers). The authors, after experiencing such a lack of connection among the results of different surveys concerning tunnels, propose a multiscale approach for the optimization of the investigation process, starting from the regional scale, to obtain the data that can be useful not only for planning more detailed surveys in a preliminary phase, but also for making previsions on the discontinuity sets that are present in the rock masses subjected to excavations. A methodological process is proposed and illustrated by means of a case study. Preliminary results are discussed to highlight the potentiality of this method and its limitations.

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Q1 1. Introduction

An in-depth knowledge of the geological aspects of the area in which a tunnel will be excavated is fundamental for optimizing the layout. In fact, costs, duration of the work and possible issues are strictly correlated to the geological, geomechanical and hydrogeological variables of the strata. The investigation process needs to be optimized to obtain complete and reliable data for the preliminary design of the infrastructure.

The stratigraphic, structural and hydrogeological settings 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 to validate and integrate the data. During this step, information regarding the most favorable direction of the tunnel layout is inferred, and detailed surveys (geognostic investigations, geophysical surveys, etc.) to be performed along this direction are then planned to establish the definitive layout.

Anyway, the onsite survey alone could be insufficient to obtain the missing data due to the limited scale of observation, costs and duration of the operations and safety conditions. Therefore, particularly in the first steps of the design, the use of remote sensing technologies is fundamental, and their fast development and the affordability of their products have contributed to extensively proving their benefits as supports for geological lineaments identification (Clark and Wilson, 1994; Davis and Reynolds, 1996; Florinsky, 1998; Suzen and Toprak, 1998; Chorowicz et al., 1999; Morelli and Piana, 2006; Marghany and Hashim, 2010; van der Meer et al., 2012; Hashim et al., 2013), encouraging the spreading of automatic or semi-automatic methods for regional scale surveys (Deffontaines et al., 1994; Koike et al., 1995; Wladis, 1999; Tripathi et al., 2000; Mavrantza and Argialas, 2003, 2008; Ramli et al., 2010; Lee et al.,

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2012; Vaz et al., 2012; Soto-Pinto et al., 2013; Al-Obeidat et al., 2016). The need to overcome possible limitations of the use of satellite images due to the characteristics of sensor, landform, lighting and weather conditions (Shepherd and Dymond, 2003; Smith and Wise, 2007) has promoted the use of digital terrain models (DTMs) for lineament mapping (Ganas et al., 2005; Jordan et al., 2005; Masoud and Koike, 2006, 2011; 2017; Jacques et al., 2012; Seleem, 2013; Rahnama and Gloaguen, 2014; Bonetto et al., 2015).

In many cases, a repetition on a small scale of structural elements is 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 also influence the arrangement of local tectonics, where structural elements can be often observed, whose orientation is similar to those identified at regional scale. For example, a fold axis could produce a foliation parallel to the axial plane, visible at mesoscale and microscale; similarly, a significant fault could produce discontinuity sets parallel to it, visible at the scale of rock face. 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. This is the main assumption of the integrated multiscale method presented hereinafter.

Once the definitive layout has been chosen, the final design requires creating a geological-technical section, in which homogeneous geological domains and their mechanical characteristics are defined. This will have to be continuously checked and updated during the executive phase. In fact, the design does not end till the tunnel is finished. Due to the complexity of the work, the great longitudinal extension and the consequent possible variability of the geological and geotechnical characteristics of the encountered materials, the Eurocode 7 (EN 1997-1:2004, 2004) permits the implementation of the observational method (Peck, 1969), which is a continuous, managed and integrated process of design, construction control, monitoring and review, enabling appropriate, previously defined modifications to be incorporated during (or after) construction (Nicholson et al., 1999).

In this paper, a semi-automatic method for linear features identification at regional scale (Bonetto et al., 2015) is applied to obtaining the information that can be useful for making previsions on the potential discontinuity sets encountered during the excavation. Then a non-contact method for surveying discontinuities orientation (Ferrero et al., 2009) is applied continuously to tunnel fronts in order to update the assumed geomechanical model, check design choices and validate the preliminary data obtained at regional scale. 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. The Finestra Val Lemme case study

The Rhine-Alpine Corridor constitutes one of the busiest freight routes of Europe, connecting the North Sea ports of Rotterdam and Antwerp to the Mediterranean basin in Genoa, via Switzerland and some of the major economic centers in the Rhine-Ruhr and Rhine-Main-Neckar regions and the agglomeration of Milan in Northern Italy (European Commission – Mobility and Transport, 2017). This north-to-south corridor will integrate Priority Projects 5 and 24, ERTMS Corridor A and Rail Freight Corridor 1.

Part of the Rhine-Alpine Corridor 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 (37 km in tunnels). It consists of two tubes, each being equipped with a single track. This means that train traffic through the tubes is one-way. The two tubes are linked by connecting side tunnels, which 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 drill-and-blast method, 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 N102.28°, and the maximum cover height is 240 m. The excavation process was carried out following the design criteria of the ADECO-RS method (Lunardi, 2006, 2008). The Finestra Val Lemme tunnel was dug in the "Argilloscisti di Costagiutta" and "Argilloscisti di Murta" formations (Fig. 1). They consist of dark gray 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).

3. Regional scale investigation

CurvaTool code (Umili et al., 2013; Bonetto et al., 2015) has been developed considering the following assumption: on a DTM, a geological lineament can be geometrically identified as a convex or concave edge, particularly where there is evidence of a structural control of the geomorphological evolution of the analyzed area.

CurvaTool performs the identification of all the significant linear features of a DTM, e.g. polylines composed of points whose principal curvature values are above the thresholds assigned by the user (this method is called semi-automatic because the user is asked for two thresholds, and then the linear features extraction procedure is automatic) (Umili et al., 2013). Next, the obtained 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 (Bonetto et al., 2015) 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. Instead, if the mean directions of lineaments sets are known, Filter code classifies each edge, attributing it to the correspondent input cluster.

By plotting the obtained database on the DTM, domains characterized by different deformation styles could be recognized. The overall positive aspects of this semi-automatic process were found to be the informativeness on geological structure for preliminary geological assessment and set identification, the possibility to identify the most interesting portions of the area to be investigated, and the possibility to analyze zones that are not directly accessible (Bonetto et al., 2015). Certainly, a residual possibility that some of the extracted linear features could be false lineaments, namely natural or artificial linear elements that do not represent geological lineaments, exists and must be taken into account. However, this is reduced by two conditions: lineaments whose dimensions are smaller or similar to the ground resolution are not – or only partially – represented by the DTM; moreover, the most common artificial linear elements, such as roads and railroads, are almost flat and therefore, even if detectable on the DTM surface, they belong to regions with non-significant curvature values. Since the purpose of the application of CurvaTool is not only to create a lineament map, but also to obtain information about the average direction of lineament sets, a single false lineament cannot invalidate the result of a

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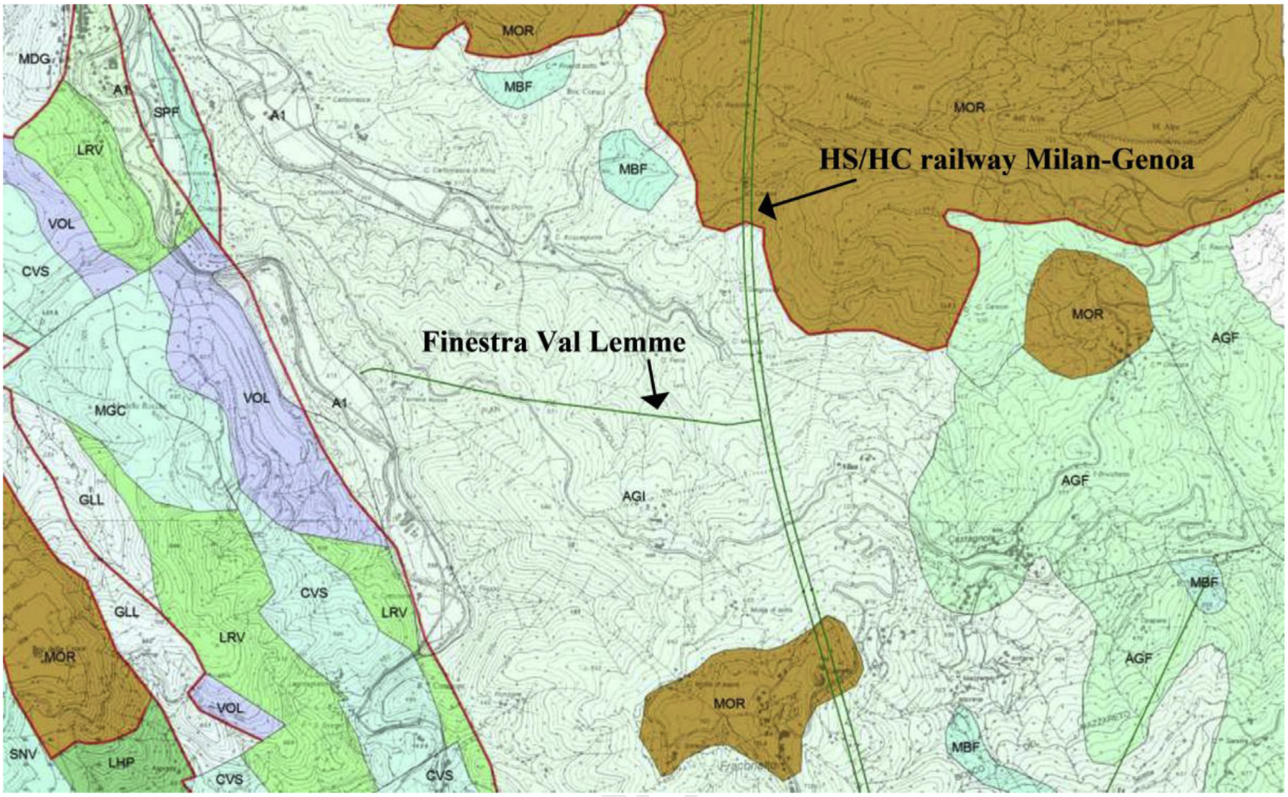

Fig. 1. Extract (not in scale) of the new Piedmont geological map in scale 1:250,000 (Piana et al., 2017) and Finestra Val Lemme tunnel layout. AGI: Shale of Costagiutta; AGF: Shale of Murta; MOR: Formation of Molare; MBF: Metabasalt of M. Figogna; VOL: Limestone of Voltaggio; LRV: Phyllitic Schist of M. Larvego; CVS/MGC: Metabasalt of Cravasco; GLL: Limestone of Gallaneto; LHP: Lherzolitic Peridotite of M. Tobbio; SNV: Antigoritic Serpentine Schist and Serpentinite.

Q4

cluster analysis performed on all extracted linear features (Bonetto et al., 2017).

Results of the regional scale investigation presented in Section 5.1 have been obtained by using CurvaTool code combined with Filter code.

4. Detailed scale investigation

A geostructural survey devoted to a systematic and quantitative description of rock discontinuities (ISRM, 1978; Priest, 1993) is a fundamental part of the characterization of a rock mass. Traditionally, surveys in tunnels are based on a visual interpretation more than a really quantitative sampling, particularly for the geometrical characteristics of discontinuities. Their orientation is measured by means of a geological compass. Anyway, where discontinuities cannot be easily accessed (e.g. upper part of the face), a simple estimate is reported; moreover, due to the limited time available for the survey, not all the discontinuities are considered and only a sketch of the main discontinuity sets is reported.

In order to follow the requirements of the limit state design (LSD) (EN 1997-1:2004, 2004), survey methods should guarantee the high level of accuracy and precision of the results to reduce the uncertainties of the estimate of the design parameters. This is particularly relevant for the geometrical characteristics of discontinuities, since dimension and shape of potentially detachable blocks depend on their values. Therefore, 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.

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. road-headers, hydraulic cutters), namely the tunnels in which the face is visible, the acquisition of images or point cloud interferes for only a few minutes with the operations and can be easily integrated within the process (Gaich et al., 1999; Nakai et al., 2003; Fekete et al., 2010; Roncella et al., 2012; Racaniello et al., 2015). The georeferenced DSM and the associated images can be then used as inputs for codes able to measure orientation and spacing of the recognizable discontinuities (Kemeny and Donovan, 2005; Roncella and Forlani, 2005; Trinks et al., 2005; Feng and Roshoff, 2006; Haneberg, 2006; Slob et al., 2007; Ferrero et al., 2009; Sturzenegger and Stead, 2009; Gigli and Casagli, 2011; Lato and Vöge, 2012; Riquelme et al., 2014). The benefits of non-contact surveys in terms of statistical reliability, safety and time consumption are appreciated both by the scientific community and companies.

The survey should interfere as little as possible with the excavation process. Therefore, it is likely that a well-designed photogrammetric survey could be the best choice, since image acquisition is very fast and moving a digital camera is much easier than moving a heavy terrestrial laser scanner (TLS) (Roncella et al., 2012).

In this context, in order to validate the regional scale data, a very fast non-contact survey method was used. 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 to quantify the distortion produced on the image and allow for its correction. The camera was mounted on the tripod in order to reduce the possible vibrations during the shooting.

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The level staff was inserted in another tripod in order to guarantee its uprightness during the shooting.

The shooting was performed after the face was excavated, the muck was loaded and the dust was deposited. At this point, 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 with 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, as described in Fig. 2, and then the level staff was removed. This procedure took less than 10 min to be performed and could be easily integrated in the excavation process.

The commercial software PhotoScan (Agisoft LLC, 2013) was then used in order to obtain a DSM. The three images were input, as well as the calibration parameters. Moreover, in order to assign the local reference system and the scale, two well recognizable points P1 and P2 of the level staff were collimated on each photo. The distance (L) between them was measured on the level staff and assigned as a vertical scale bar. Moreover, P1 (located well below P2) was chosen as the origin of the reference system and coordinates (0, 0, 0) were assigned to it. Therefore, coordinates of P2 are (0, 0, L). The x- and y-axes were chosen to be parallel and perpendicular, respectively, to the rock face.

Considering that the discontinuity orientation measurements are influenced by the point density of the DSM (Ferrero et al., 2009), an average ground resolution of 2 cm was considered as suitable for the following non-contact survey. Rockscan software (Roncella and Forlani, 2005; Ferrero et al., 2009) was used to perform a detailed structural survey by combining, for each of the considered rock faces, the three photographs taken during the photogrammetric survey and the reconstructed 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 by sampling along a few scan lines (Curtaz et al., 2014).

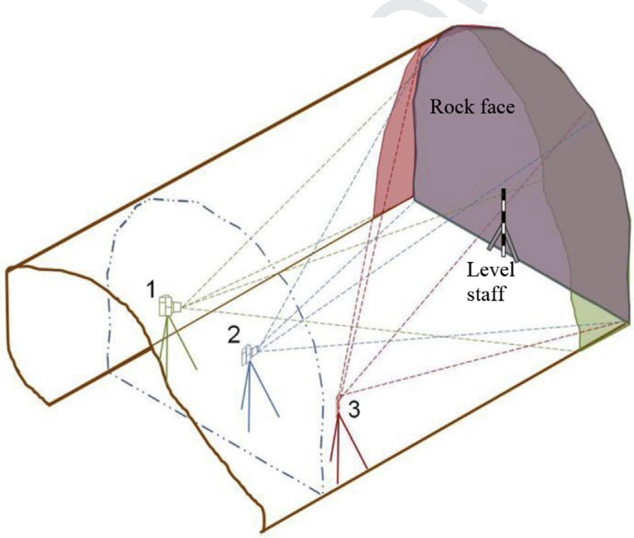

Fig. 2. Scheme of the relative positions of the three shooting points (1: left; 2: center; 3: right), the level staff and the rock face (modified after Roncella et al., 2012).

Planes selection was carried out uniformly on the rock face. In order not to bias the sampling (e.g. favoring the selection of the most represented discontinuity sets), all the outcropping faces were selected on rock dihedrals, where present.

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 (referring to the considered rock face location) with respect to the north. This correction is required since the data are expressed in a local reference system, which considers the north as the direction that is orthogonal to the rock face. Therefore, it is necessary to refer the dip direction data to an absolute reference system considering the true north. After the correction, orientation data were statistically treated and compared to those obtained from the traditional survey in order to check their congruence (see Section 5.2).

5. Application of the proposed multiscale method to the case study

5.1. *Regional scale investigation of the area*

A DTM (Fig. 3) with ground resolution of 1 point every 10 m (Piedmont Region GeoNetwork, 2008), covering an area of about 104 km^2 containing the location of the Finestra Val Lemme, was used as input for 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. Observing the map (Fig. 4) obtained by plotting on the DTM the 4772 linear elements given by CurvaTool, one can recognize three sectors, which extend along the NNW-SSE direction. The central sector (B) is characterized by a high density of linear features, striking mainly towards NW-SE and, followed by NE-SW. Linear features are less frequent in the areas adjacent to the sector B, but their directions are almost the same. In particular, the eastern sector (C) shows the lowest density of linear features, which are short and in some cases striking E-W. The western sector (A) shows instead a high density, even lower than that of sector B. Based on the rosette diagram (Fig. 5) 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. After the application of Filter, linear features belonging to different sets were automatically

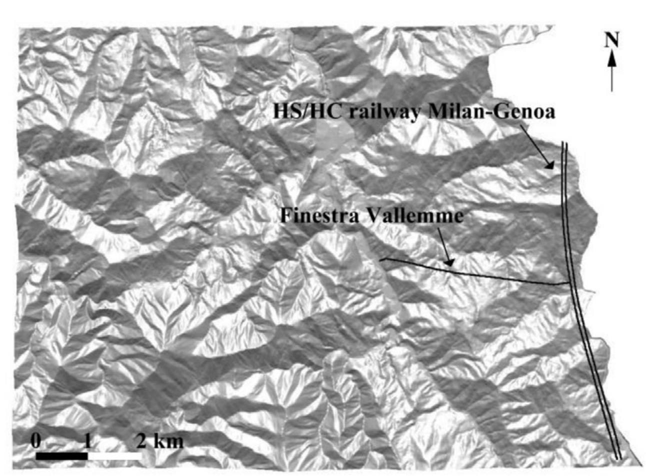

Fig. 3. Shaded DTM of the area including Finestra Val Lemme (923,898 points).

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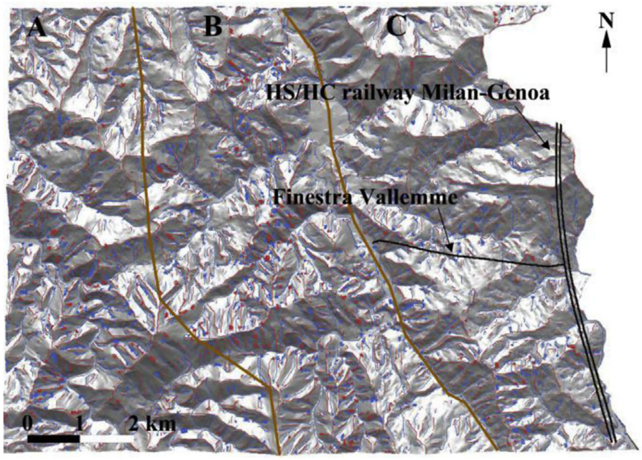

Fig. 4. Map of linear features extracted by CurvaTool, subdivided in crests (red) and valleys (blue). Three distinct sectors (A, B, and C) are delimited.

represented in distinct colors (Fig. 6) and the map representing CurvaTool results could be easily interpreted, confirming what has already been described for the three different sectors.

In the studied area, the Italian geological map (Fig. 7) reports a deformation zone associated with the Voltaggio fault. In particular, this zone cartographically corresponds to sector B (Figs. 6 and 7), in which linear features mainly strike along the direction of the Voltaggio fault (NW-SE) and its conjugate system (NE-SW), which is characterized by shorter lineaments.

Comparing the three sectors on the DTM to geological literature, they correspond to the tectono-stratigraphic domains respectively named, from west to east, the Voltri Group (A), the Sestri-Voltaggio Zone (B) and the Ligurian Units (C). The Voltri Group is an Alpine basement-related domain and it mainly consists of ophiolitic metamorphic rock, whereas the Ligurian Units consist of non-metamorphic ophiolitic units lying on an Apennine basement. The Sestri-Voltaggio Zone is located at the eastern margin of the Voltri Group and corresponds to a deformation area that includes three tectono-stratigraphic units (Cortesogno and Haccard, 1984) involved in the Alpine subduction-related tectonic events. The tectonic limit between the Voltri Group and the Sestri-Voltaggio Zone is known as the Sestri-Voltaggio Line. All the sectors are characterized by ductile deformation during the Alpine stage over-printed by brittle deformation during the Apenninic stage. The Sestri-Voltaggio fault is the main tectonic lineament, and it is considered as a deformation zone and structural domain including Alpine tectono-metamorphic units.

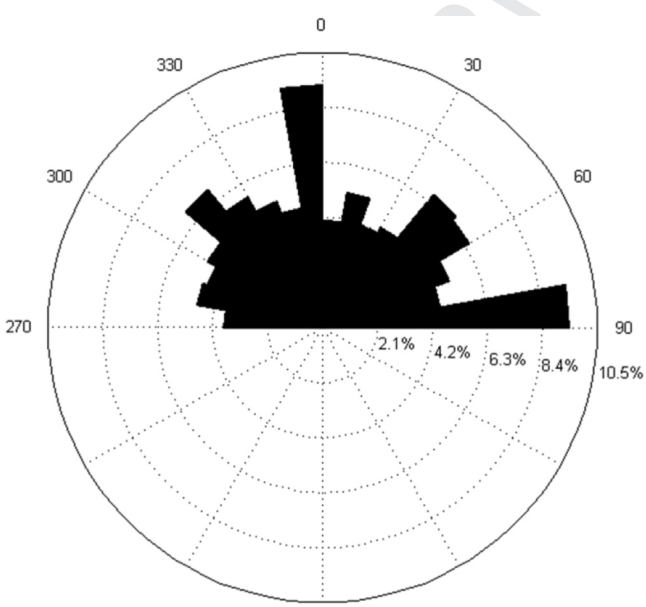

Fig. 5. Rosette diagram representing azimuthal frequencies (expressed as percentages of the total number of extracted linear features). Only the upper hemisphere is considered since diametrically opposed directions are equivalent.

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

Set ID	Main direction	Azimuthal direction (°)	Standard deviation (°)
L1	N-S	0	20
L2	E-W	90	20
L3	NW-SE	135	20
L4	NE-SW	45	20

The tectono-stratigraphic domains and the tectonic boundaries of the Sestri-Voltaggio Zone in literature are very similar to the contacts between the sectors observed in Fig. 4.

The Finestra Val Lemme tunnel is located in the sector C, in the area where the shale formations, recently named “Argilloscisti di Murta” and “Argilloscisti di Costagiutta”, outcrop (named “Argille a Palombini” formation according to Fig. 7). In these formations, brittle deformation generally acts along the pre-existing schistosity and generates the main set of discontinuities observed in the area. A few joints and faults describing high angle to the schistosity are also present, showing low persistence and high spacing. In this sector, CurvaTool shows the presence of NW-SE and NE-SW linear features, according to the structures expected from preliminary surveys and found during the excavation. Similar orientations are also recognized with higher density in sector A and, particularly, in sector B, which appears to be the most deformed.

5.2. Detailed scale investigation of tunnel rock faces: traditional and non-contact surveys

Traditional expeditious geomechanical surveys were carried out on 62 rock faces. For each face, a specific datasheet was filled in with the technical and geological information, with particular

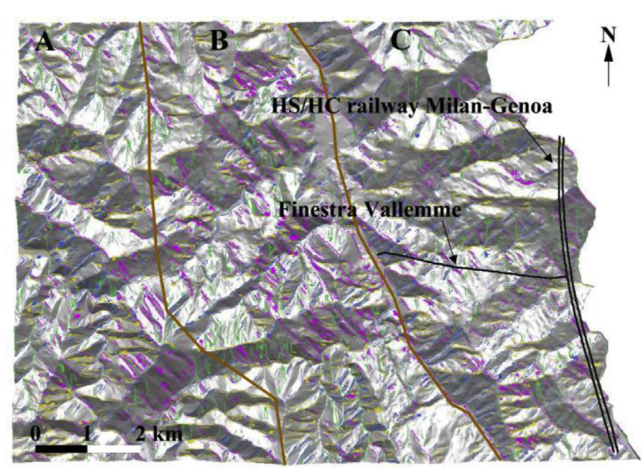

Fig. 6. Map of linear features extracted by CurvaTool and processed by Filter: Set L1 in green, L2 in yellow, L3 in fuchsia, and L4 in blue. The three sectors (A, B, and C) are delimited.

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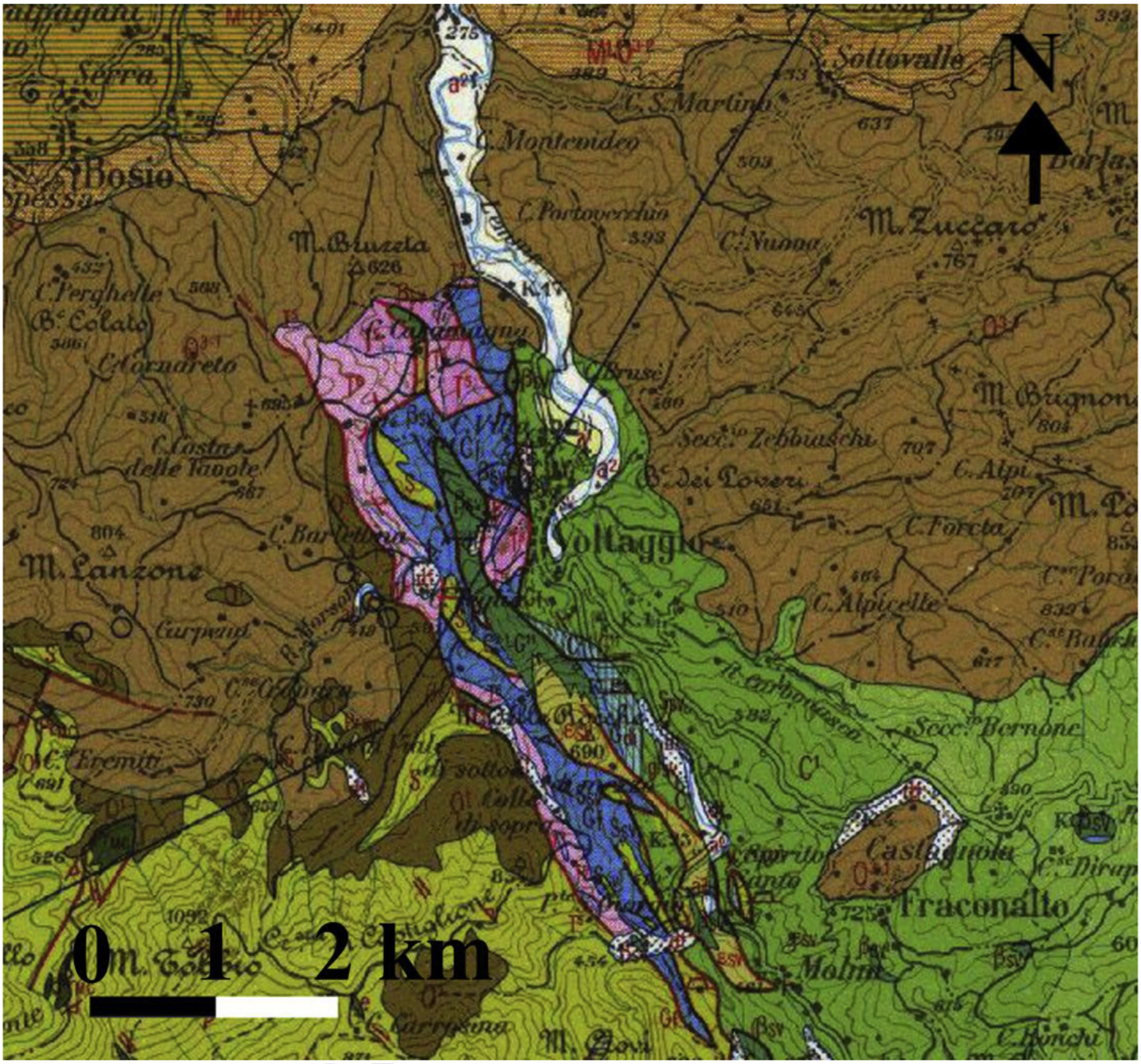

Fig. 7. Italian geological map (scale 1:100,000), sheet No. 82 Genova (http://193.206.192.231/carta_geologica_italia/tavoletta.php?foglio=82).

attention to orientation and hydraulic features of the main observed discontinuities. Foliation was clearly observed, oriented in normal direction with respect to the rock face, forming a variable angle from 80° up to 100° with respect to the tunnel axis. For safety reasons, measures were not directly taken on the face and a safety distance of a few meters was always respected.

Non-contact survey was performed on 18 DSM of progressive rock faces (Fig. 8) and it allowed for the collection of a statistically significant number of measurements of orientation, spacing and trace length (Racaniello, 2014; Racaniello et al., 2015).

An effective bidirectional lighting system on the roof facilitated the application of this type of survey and enhanced the quality of the photogrammetric survey, without further need to use portable spotlights.

The comparison of the results obtained from the application of both methods (traditional and non-contact) to 18 excavation faces shows a significant difference in the number of measurements acquired. The photogrammetric approach allowed collecting hundreds of measurements from each front, instead of the few ones obtained from the traditional method.

In order to simplify the visualizations of the results, the poles of the sets of discontinuities recognized on each front were directly reported on the Schmidt stereograms by distinguishing those obtained from the non-contact method (Fig. 9) and those from the traditional method (Fig. 10). With both approaches, at least 4 main sets could be recognized (Table 2). The main set is the NNE-SSW trending one (K1), which appears in all the investigated fronts. This is mainly represented by a high–medium angle double-vergent (W-WNW and E-ESE) set in the non-contact survey and a predominant E-ESE high-angle dipping set in the traditional survey. In the latter case, a medium angle WNW-dipping set has been interpreted as a separate set (K5), but it should be compared to the medium angle WNW-dipping discontinuities associated with the set K1 in the non-contact data analysis, due to the scattered and denser cloud of measurements. Other sets were identified without continuity in the investigated

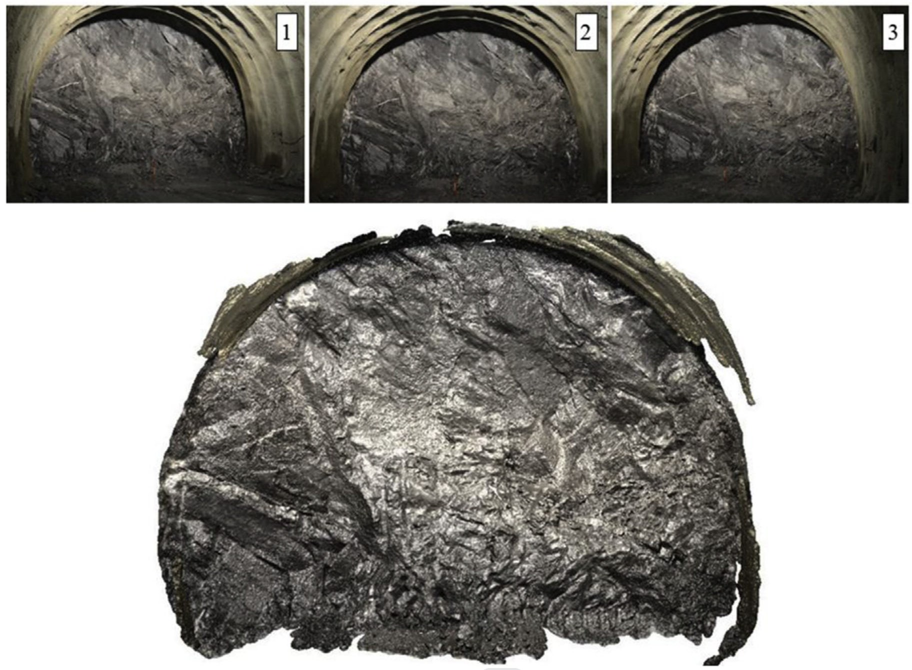

Fig. 8. Example of a set of (three) images shot following the scheme in Fig. 1 and the obtained DSM.

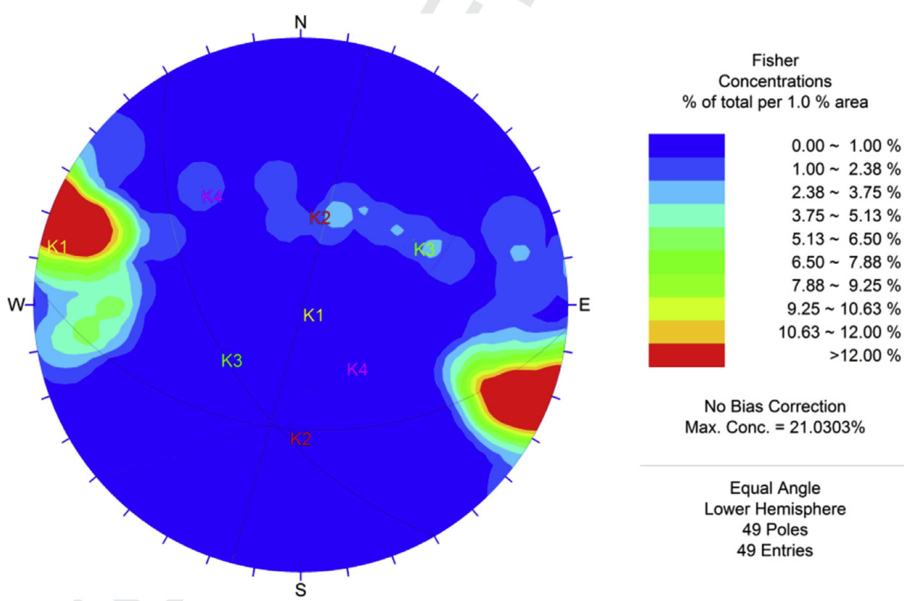

Fig. 9. Stereographic projection of the pole of the discontinuities sets identified with the non-contact method in correspondence with 18 fronts of the Finestra Val Lemme tunnel.

fronts. They consisted of medium angle S-, SW- and SE-dipping sets named K2, K3 and K4, respectively, which were present commonly for the both approaches.

6. Comparison of data obtained at two different scales of investigation

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, for example, the detailed surveys carried out with the traditional and non-contact methods showed the presence of similar discontinuity sets respectively striking NNE-SSW, E-W, NW-SE and NE-SW. These directions can be directly compared with those of the ranging intervals of the main linear elements identified at regional scale by CurvaTool (Fig. 11).

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 the absence of literature data.

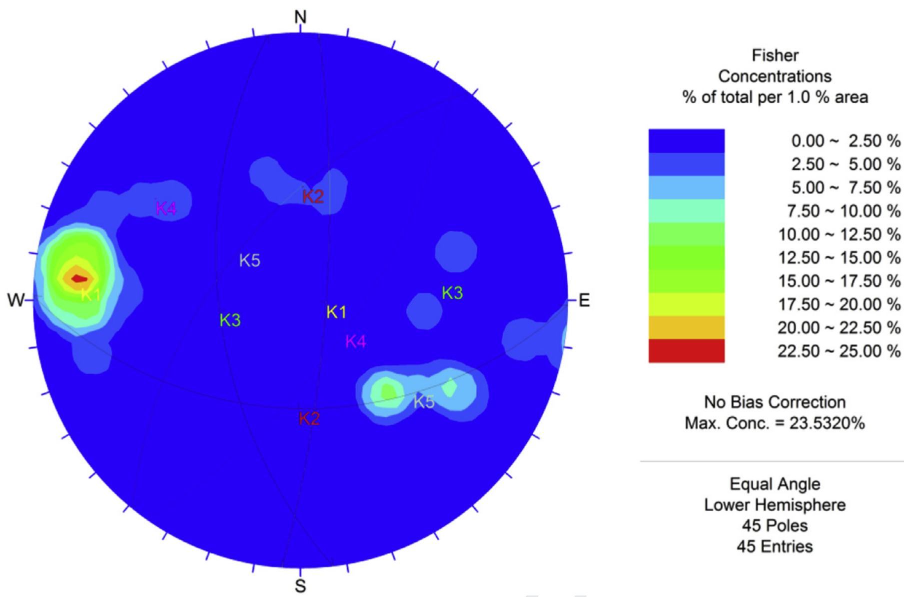

Fig. 10. Stereographic projection of the pole of the discontinuities sets identified with the traditional expeditious method in correspondence with 18 fronts of the Finestra Val Lemme tunnel.

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

Set ID	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

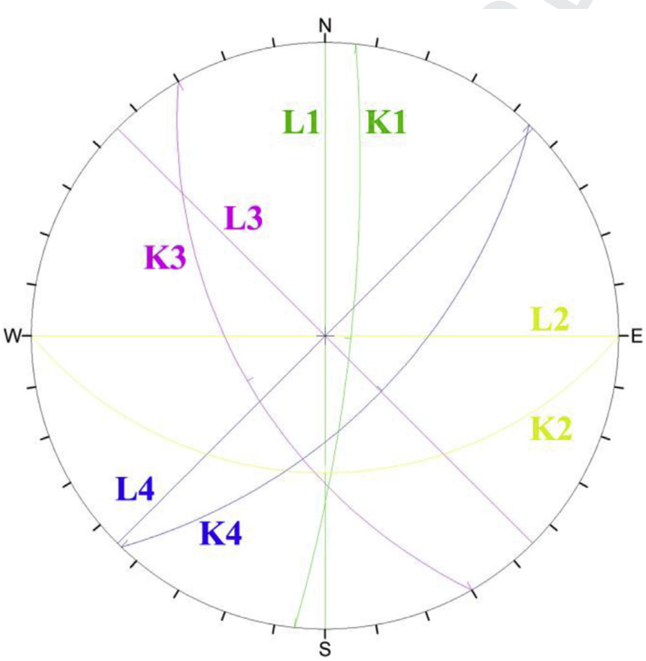

Fig. 11. Comparison between the average strike of the main set identified at the scale of the rock face with both non-contact and traditional survey (great circles) and the main orientations of the linear elements identified by CurvaTool at regional scale (strike lines). Elements with similar strike are represented with the same color.

7. Conclusions

In this text, a method was proposed for the preliminary definition of the tectonic layout of an area, preparatory for planning onsite surveys and the infrastructure layout.

Brittle tectonics aspects, particularly relevant in infrastructures design, are often preliminarily deduced from a morphotectonic analysis, traditionally carried out in a subjective and visual way based on photointerpretation of remotely sensed images. The results of this kind of analysis are strongly influenced by the experience and the awareness of the operator, who in any case requires long time for identifying a significant number of linear features.

It emerges that a semi-automatic approach as the one implemented in CurvaTool code allows to quickly and objectively identify linear morphological elements on a DTM. The obtained results and their comparison with literature data, in this case used in retrospect in order to validate the method, highlight strong agreement and give an encouraging confirmation on the benefit of this method. In case that 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, and 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 with both 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 the absence of literature data. Considering this first application of the multiscale approach to the characterization of rock masses for civil engineering design, it seems promising and could imply important consequences regarding design reliability and expected costs.

Conflicts of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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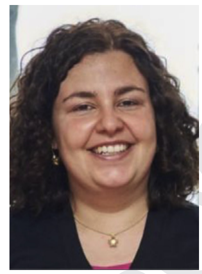

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