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Terrestrial laser scanning for rockfall stability analysis in the cultural heritage site of Pitigliano (Italy)

Abstract Traditional surveying methods are often not sufficient to achieve a complete geomechanical characterization of the rock mass, to analyze the instability mechanisms threatening the cultural heritage of hilltop historic towns. In Pitigliano (Tuscany, Central Italy), terrestrial laser scanning was employed complementarily to conventional geomechanical techniques. The overall 3D survey of the exposed surfaces was combined with scanlines of the inner walls of the subterranean cavities running underneath the historic centre. The rock mass discontinuities geometry was extracted, and the most critical instability mechanisms were mapped, with particular interest in the potential impacts on the ancient buildings located along the cliff edge. The geomechanical analysis of the surveyed joint sets confirmed a structural control on the cliff morphology by two main joint sets. Thanks to the laser scanner-based kinematic analysis, flexural toppling and wedge failure were found as the main hazardous instability mechanisms in Pitigliano. Finally, the conservation criticalities were identified and a pilot monitoring system was installed in a sector highly susceptible to block detachment.

Keywords Terrestrial laser scanning · Kinematic analysis · Rockfall · Hazard assessment · Discontinuity extraction · Pitigliano (Italy)

Introduction

The impact of landslide hazard on the immovable cultural heritage represents a multi-disciplinary theme, which requires several different approaches (Canuti et al. 2009). A complete analysis involves geotechnical, structural and engineering issues and can lead to design adequate countermeasures. In Italy, ancient buildings, archaeological sites and even entire historic towns are frequently threatened by slope instability phenomena (Canuti et al. 2000; Fanti 2005; Lollino and Audisio 2006). In Tuscany, Umbria and Latium (Central Italy), where geological and geomorphological backgrounds determined the formation of hilltop-sites occupied since Etruscan time, well-known dynamics of instability characterize these places. The case of Orvieto (Tommasi et al. 2006) is the most famous, but in the same geological province there are many towns built on the top of volcanic slabs overlying normal- or over-consolidated clays. In these conditions, some landslide mechanisms can develop: slow movements in the clays, toppling and rockfalls of the marginal zones of the slab, deep-seated gravitational slope deformations (Ribacchi et al. 1988).

Pitigliano, situated in Southern Tuscany (Figs. 1 and 2), summarizes several of these aspects and represents a very interesting case in the field of relationship between slope instability and cultural heritage conservation. However, the significance is not only associated with the historical relevance of the site and of its monuments but also with the implementation of an integration approach of different techniques of geomechanical investigation and data collection, whose main results are presented in this paper. In particular, in addition to traditional methods, the rock mass was characterized by means of terrestrial laser scanner along with an extensive survey of the very complex system of chambers and caves excavated underneath the town through the centuries.

Terrestrial laser scanning (TLS) supplies high resolution point clouds of the surveyed surfaces, and new TLS devices with growing range and resolution are increasingly becoming a remarkable tool in landslide characterization. TLS is employed in different task of slope instability analysis: for monitoring of deformations and displacements (Gordon et al. 2001; Abellan et al. 2009; Oppikofer et al. 2009), for the characterization of discontinuities on rock cuts (Feng and Roshoff 2004; Slob et al. 2005; Lato et al. 2009; Sturzenegger and Stead 2009a, b; Gigli and Casagli 2011; Gigli et al. 2011), for geomorphological analyses of coastal cliffs, vertical slopes and freestanding boulders (Lim et al. 2005; Rosser et al. 2005; Armesto et al. 2009). This technique is also used for the documentation and 3D modelling of building and cultural heritage sites (Arayici 2007; Yastikli 2007), and these products can be integrated with geomechanical analysis in the characterization of rock masses (Gigli et al. 2009). For its geometrical and geological features, the tuff rock mass of Pitigliano represents a good site for testing the potentials of TLS for geomechanics.

In regard with this case study, it is to be noted that the rock mass has an unusual distinguishing element, i.e. the presence of a complex network of manmade cavities which allows a survey of the slab from an inner point-of-view, providing significant geostructural data, otherwise not easily collectable. The habit of cutting corridors and rooms under the houses was relatively frequent in the past, especially when the foundation soil was cohesive but not very hard, as in the case of tuff or other volcanic rocks. In Italy, there are several historical cases, including also important cities as Rome (Crescenzi et al. 1995) and Naples (Evangelista 1991), but the case of Pitigliano is extraordinary because of the extension of the underground network and for its possible active role in controlling the rock mass stability.

The present work is mainly focused on the integrated analysis of all the geomechanical data derived from the different surveys and processing phases performed on the case study of Pitigliano. The usefulness of new digital products obtained from the TLS acquisitions is discussed in relation to extracting geomechanical information for the exposed rock surfaces, detecting discontinuities and joint sets and identifying the most critical instability mechanisms affecting different sectors of the rock mass.

Site description

The historic centre of Pitigliano is placed above a flat slab, which provided an ideal location for defence purposes, being a 25-m thick plateau of Pleistocene tuffs (about 310 m a.s.l.).

The tuff cliff, oriented in E–W direction, is the result of extensional tectonics occurred since Miocene to Quaternary and an intense volcanic activity predominantly explosive since the middle-Pleistocene (Varekamp 1980; Vezzoli et al. 1987), which affected the Northern part of the Roman Comagmatic Province

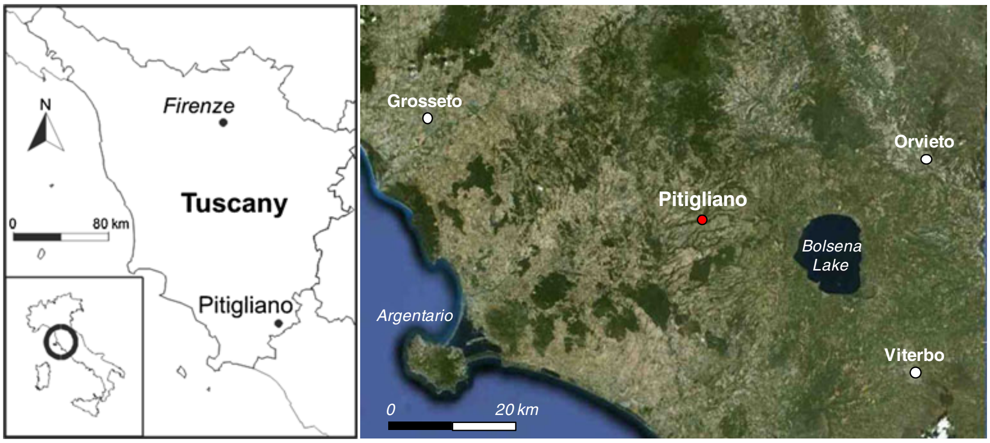


Fig. 1 Location map of Pitigliano (aerial view modified from Google Earth)

in the area of the Vulsini Volcanic District (VVD). Among the four domains recognized in the VVD on a structural and volcanological basis (Conticelli et al. 1987; Vezzoli et al. 1987; Canuti et al. 2004), the Latera Volcanic Complex (LVC) characterizes the study area.

Volumetrically, the eruptive products are dominantly pyroclastic deposits and, secondarily, pyroclastic fall deposits, which are common at various stratigraphic levels throughout the western area of VVD (Palladino and Agosta 1997 *cum biblio*).

Within the stratigraphic sequence of the Pitigliano cliff, the following pyroclastic formations are found from bottom to the top (Fig. 2):

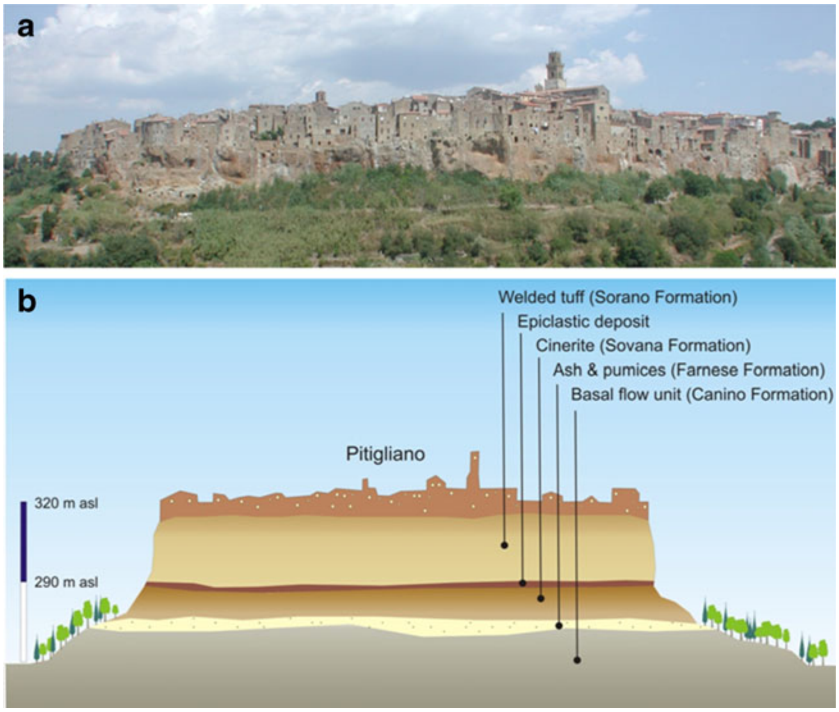
Canino formation—It is the oldest formation of LVC and it lies in direct contact with the Messinian sedimentary basement. This deposit, thick up to 45 m, consists of several pyroclastic flow units, from poorly cohesive up to coherent.

Farnese formation—Thick up to 2–5 m, this non-welded pyroclastic deposit can be locally absent. At its top a basal ash fall, surge levels and a 30-cm thick black paleosoil are detectable (Canuti et al. 2004), as visible along the inner walls of some of the surveyed underground caves.

Sovana formation—This cineritic and pyroclastic deposit, permanently thick of about 10 m, consists of an upper not highly coherent deposit lying above a lower non-welded flow unit.

Epiclastic deposit—Lying between Sovana and Sorano Formations, this alluvial/lacustrine deposit derives from a static phase of the magmatic activity. Very poorly coherent, it

Fig. 2 Overall view of the southern side of Pitigliano (**a**); sketch of the rock formations constituting the geological sequence (**b**)



reaches up to 4-m thickness along the northern side of the cliff. Sometimes it can be totally absent.

Sorano/Grotte di Castro formation—It is the welded tuff plateau on which Pitigliano is built, thick up to 25 m and lying directly on the Epiclastic deposit. Through the centuries it provided solid rock material for cutting underground caves immediately beneath the historic buildings.

Aerial view highlights that the present morphology of the Pitigliano cliff has been influenced by fluvial erosion processes. The exposed rock surfaces are actually similarly spaced from the sides of the rivers flowing along the toe of the cliff.

According to the morphologic features typical for this region, the two sides of the cliff are significantly different. The upper portion of the southern side displays very steep cliffs with a slope inclination of about 40°, which abruptly changes and gradually decreases due to both lithological variation and the presence of debris coverage. The northern side, on the contrary, is more regular, with a constant slope of about 35°, only locally interrupted by the presence of few metre-long scarps. Combined actions of lower thermal variations, higher and more permanent humidity content and more intensive chemical alteration and cryoclastism processes justify the higher thickness and the extension of the debris accumulated at the toe of the northern side in respect to the southern side.

A remarkable historical and structural feature of Pitigliano is the huge underground network of chambers and passages excavated during Etruscan and Medieval ages, crossing the rock mass with tunnels long from few metres up to over a hundred metres and characterized by a 1- to 2-m wide rectangular cross-section (Fig. 3). Formerly used as local quarries to extract tuff blocks for building construction and volcanic ash for packing cements and mortars, the caves also constituted systems of naturally air-conditioned wine cellars.

In absence of any architectonical or security criteria, most part of the caves were excavated within Sorano/Grotte di Castro Formation due to the higher cementation degree and the rock strength, jointly to the major proximity to the surface. Few caves are found in Canino e Sovana Formations, no one within Farnese Formation, whereas the ones within Epiclastic deposit have been frequently affected by structural collapses.

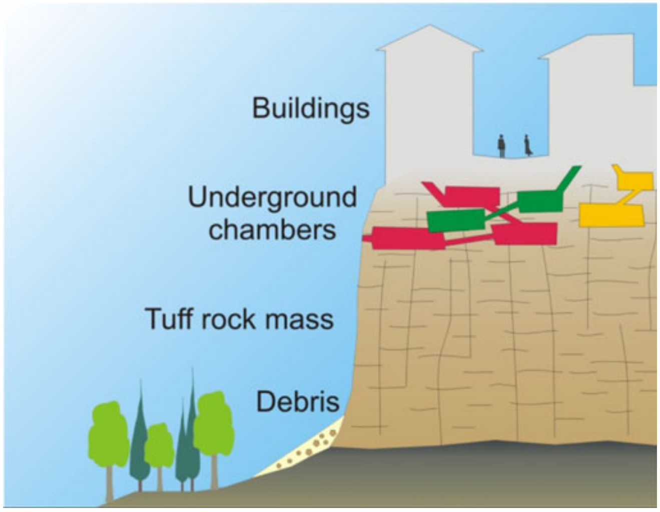


Fig. 3 Schematic representation of the spatial relationship between the underground network of chambers and passages and the overlying buildings. Debris produced by weathering, and rock falls is accumulated at the cliff toe

Undoubtedly, a complete and reliable landslide risk assessment for the historic site of Pitigliano should take into account the influence of this huge underground system on the general weakening of the rock mass and its related stability.

The geomorphologic evolution caused by the combination of physical weathering and erosion processes on exposed tuff surfaces, the existing joint systems and the anthropic impact have triggered slope instability phenomena, significantly damaging the historic centre and cultural heritage of Pitigliano.

An overall survey of the main geomorphological and structural features of the exposed rock surfaces suggests flexural toppling and wedge failure represent the main instability mechanisms affecting the cliff. Such instability mechanisms could have affected the exposed surfaces several times in the past, causing a progressive retreat along the edge of the cliffs and, consequently, involving the overlying buildings of the historic centre.

Field observations and comparisons with the ancient graphic documentation and maps confirm that impression. Holes and caves visible at different heights on the cliff surfaces were formerly exterior entrances to the underground cavities and, at the present, they are not accessible anymore due to past localized rock falls and/or erosion processes that have severely damaged pre-existing stairs and terraces.

The comparison with the ancient map known as *Pianta della Terra di Pitigliano* (Giachi XVIII century) testifies the disappearance of a bastion originally located near the centre of the northern sector and the rock spur on which it was built, as well as some buildings at the western corner of the cliff. Some portions of the edge along the southern side seem to have been involved by the cliff retreat. It is reasonable to suppose that such phenomenon severely affected the conservation of several pre-existing constructions.

Although it is only a qualitative estimation of past impacts on historic heritage, this evaluation based on historical documentation confirms the key role of the geomorphological processes and weathering for the triggering of instability phenomena in Pitigliano, and suggests the occurrence of dynamics of progressive evolution of the rock mass strictly related to the most critical instability mechanisms.

Methods

Geomechanical survey

The volcanic origin and the tectonic history of the formations outcropping in the Pitigliano area represent the geological background of the rock mass joint geometry, that, in turn, controls the observed mechanisms of instability.

The geomechanical characterization of discontinuities has been carried out starting from a traditional geomechanical survey of the rock mass, following prescriptions of ISRM (1978) in a significant number of scanlines along the cliff. A wide set of information on discontinuities (orientation, spacing, persistence, roughness, aperture, filling and seepage) has been collected.

However, in Pitigliano some additional data on the rock mass geometry can be gathered from a geomechanical survey in the cave network, whose presence points out the following issues:

(a) The underground network allows an unusual inner look-out of the rock mass, from which some additional data on joints geometry can be obtained;
(b) The role of the underground tunnels and chambers in the general behaviour of the rock slab could be assessed, considering these elements as non-persistent discontinuities, in particular if their spatial distribution showed some preferential directions; and
(c) The position of the caves could form an obstacle in the realization of stabilisation measures as anchors, which efficiency could be strongly diminished if the tie bar went through an unexpected hollow.

Concerning the spatial distribution of subterranean passages, an extensive survey of the most relevant of such tunnels and chambers has been realized, in order to obtain the exact reconstruction of their dimension and length. The survey has been rationalized on the basis of special speleological criteria: starting from the georeferenced position of the entrance (mostly constituted of some descending steps carved in the tuff at the ground floor of the buildings), the dimensions of rooms and passages and the trend and plunge of their axes have been measured.

The final result of the survey is the complete geometric description of 93 cavities, organized as underground systems formed by one or more corridors (typical section, 2×1.5 m) and rooms (up to 5×10×2 m). In general, the total length of each system is about 15–20 m, and the slope is quite gentle. Nevertheless, there are also intricate structures, crossing several tuff layers through flight of stairs (difference in level up to 8 m), and very long system, as the most famous of them, i.e. a tunnel (106 m along the main direction, with a total linear length of 252 m) excavated underneath the historic centre of Pitigliano along SSE–NNW direction, connecting the two sides of the rock mass.

During the field surveys of the present work, a very interesting historical document has been found in the municipal archive of Pitigliano, i.e. the report of a similar survey work carried out in 1832 (Anonymous 1832), describing the caves used at that time, with several data about their dimension and extent.

The comparison between the two surveys (Anonymous 1832 vs. present time) has led to the conclusion that a relevant number of caves had been modified in the last 180 years, with the construction of parting walls and even the sealing of entire sectors, not accessible nowadays. For this reason, the present survey cannot be considered as completely exhaustive, being possible the presence of some unknown blocked chambers inside the tuff slab.

As regards to the role of the caves as inner point of view for rock mass survey and geomechanical analysis, this could help to minimize the orientation bias of scanlines surveyed on the cliff surfaces, complementarily to the traditional line sampling methodologies (Priest 1993; Brady and Brown 2004), and it could improve the quality and reliability of the datasets concerning the rock mass features. However, the fact that the caves themselves have been probably excavated along some weakness direction of the tuff mass could reduce this potentiality. Spatial distributions of the underground network and the natural joint system could be not independent.

Some considerations in this matter are presented in the next section, together with a synoptic view of the results obtained from laser scanning and speleological surveys, as elements useful for the assessment of the relationship between the external surface of the cliff and the inner manmade architecture.

Terrestrial laser scanning

The morphology of the Pitigliano cliff is continuously changing due to progressive retreat processes and localized rock falls that have been affecting the northern and southern sides. An updated survey of the entire site, including both the exposed exterior surfaces and underground caves, was considered fundamental in order to assess the current state of the geomorphological evolution of the cliff.

The risk assessment presented in this paper has been carried out, primarily, through the employment of the innovative digital technology of TLS. Survey activities have been undertaken using a Long Range and High Accuracy 3D Terrestrial Laser Scanner system, Riegl LMS-Z420i (RIEGL 2010a), associated operating and processing RiSCAN PRO software package (RIEGL 2010b).

As a time-of-flight laser scanner, this remote sensing ground-based device allows measurements of scanner–object distances, up to about 1,000 m, by calculating the round-trip time a laser pulse (near-infrared wavelength) takes to reach the object surface from the point of emission and come back. The entire field of view is scanned by changing view directions of the laser rangefinder through a system of rotating mirrors, and the related horizontal and vertical angles are measured, with maximum data acquisition rate of 12,000 points/s.

The Cartesian coordinates (X, Y and Z) of each point on the scanned object surface are worked out on the basis of the measured distance and scan angles, allowing the acquisition of point clouds available for the reconstruction of 3D models. These products can also be textured in true colours, thanks to the calibrated and definitely oriented high-resolution digital camera associated to the scanner.

The acquisition of point clouds and subsequent processing of digital products allowed a highly detailed documentation of the present state of the entire rock mass. Developing some efficient tools for a reliable characterization of the rock mass discontinuities, the following issues have been taken into account:

(a) The cliff morphology, the geomorphologic difference between the northern and southern sides and the limited accessibility required the designation of point-of-views distributed in order to avoid, as much as possible, ‘shadow zones’ and
(b) The acquisition and registration approach employed in the present case has been properly selected to achieve an optimal quality of the image registration process and related final accuracy of the 3D models suitable for the specific study purposes.

Seven points-of-view have been distributed on stable places located around the Pitigliano cliff, ensuring efficient overlapping between the neighbouring scans as a fundamental requirement for successful matching.

Fig. 4 Holistic true coloured point cloud of the Pitigliano cliff and the historic centre

Simultaneously to the TLS survey, a network of some targets was created in order to allow the subsequent registration phase of the scans relative to each other in a single coordinate system. The coordinates of the selected targets have been exactly detected by using a couple of GPS Leica SR530 and they have been georeferenced to a reference point established in correspondence of the local Archaeological Museum, within an area easily accessible and totally covered by the satellites.

Each 3D point cloud has been projected into the corresponding registered 2D image, and true colour values of the image pixels have been assigned to the projected 3D points.

As final digital product, the holistic point cloud representation of the Pitigliano cliff has been realized by merging the seven point clouds acquired from the correspondent points-of-view (Fig. 4).

Results

Conventional surveys

Several data on the rock mass have been collected during the geomechanical survey, leading to characterization of the tuff layer of the cliff (Sorano Formation). The geomechanical characterization of discontinuities has been carried out starting from a traditional geomechanical survey of the rock mass, following prescriptions of ISRM (1978) in a significant number of scanlines along the cliff. A wide set of information on discontinuities (orientation, spacing, persistence, roughness, aperture, filling and seepage) has been collected.

As above mentioned (cf. 'Geomechanical survey'), an in situ characterization of rock mass discontinuities was performed according to the indications of ISRM (1978), coupled with point load and tilt tests on laboratory samples.

The obtained data, representative of the geomechanical properties of the rock mass, are summarized in the Table 1, and they were used as input parameters for the kinematic analysis described in 'Kinematic analysis'.

From these results, in order to accomplish the distinctive featuring of the rock mass, its geomechanical classification has been carried out by applying the most widespread classification systems (Bieniawski 1989; Grimstad and Barton 1993; Palmstrom 1995, 2000, 2009; Palmstrom and Broch 2006).

For the definition of geometry of the main joint sets, the discontinuity system of the rock mass has been analyzed starting from the results of the scanline surveys (i.e. those surveyed both on the cliff and along the tunnel walls in the underground cavities).

The synthesis of the collected data is represented in Fig. 5 where two sub-vertical perpendicular joint systems, with orientation JN1=073/87°, and JN2=163/86° are highlighted. At a first glance, the latter seems the less important, but the orientation bias must be considered, as most of the surveyed scanlines result parallel to JN2 and, consequently, the set is under-represented.

Particular attention has been reserved to the results of the underground survey, starting from its use for the evaluation of the cavities spatial position in comparison with the cliff geometry.

As stated before, these results can be important during the realization of structural works for the stabilization of the rock mass, but a more challenging task is represented by the identification of the more effective approach for the data elaboration and output. A solution has been found in the integration in a CAD environment of the topographic data and the output of laser scanner software that allows the visualization of the exact position of the caves with reference to the cliff and to the buildings. The result is a dynamic 3D model of the town which includes its hidden underground elements that can be surfed from different points of view, as shown in Fig. 6.

Such 3D product is quite easily understandable and provides an efficient and smart tool for localizing the cavities in relation to the cliff surfaces and overlying buildings. At a first glance, it is clearly visible that the historic centre of Pitigliano is actually superimposed to another 'town', excavated underneath the building. This constitutes a relevant part of the cultural heritage in Pitigliano that needs to be preserved and documented, also in regard with its role in the general behaviour of the rock mass.

Such 3D products could be useful in the perspective of stabilization and consolidation works, especially in order to avoid some mishaps, like the injection of a big amount of concrete on unknown caves during the realization of anchors, as what happened in the past.

As regards to the spatial orientation of these tunnels and chambers, the amount of collected data has been considered statistically significant, and the analysis of their spatial distribution has been carried out (Fig. 5d). The surveyed caves are mostly E–W oriented, in

Table 1 Geomechanical properties of the rock mass of Pitigliano obtained from conventional surveys

Set_id	α (deg)	β (deg)	ϕ (deg)	c (MPa)	RMR	Q	RMi
JN1	073	87	48	0.14	62	3.8	1.65
JN2	163	86					

Set_id discontinuity set, α dip direction, β dip, ϕ average friction angle, c average cohesion, *RMR* rock mass rating according to Bieniawski (1989), *Q* Q-index according to Barton (in Palmström 2009), *RMi* Rock Mass Index according to Palmström (2009)

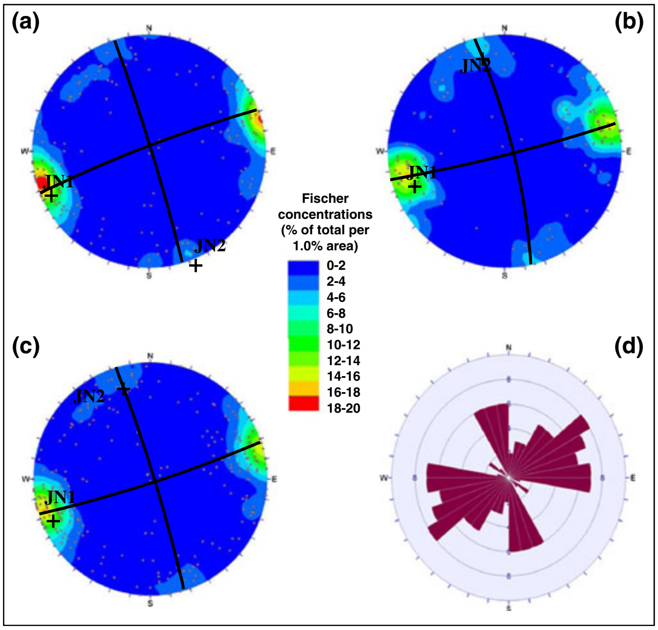


Fig. 5 Synthesis of the geomechanical survey data. Stereographic representations of the surveyed discontinuities: *a* underground, *b* on cliff surfaces, *c* total number, and *d* rose diagram of the directions of the underground chambers and corridors

the same direction of the joint set JN2 and it is possible to infer that this is a direction of weakness of the rock mass, as confirmed by the morphology of the slab (Fig. 7).

The hypothetical role of the man-made riddling as factor for the rock-mass instability has been finally assessed, coming to the conclusion that the number and the total volume of the underground elements are largely insufficient to act in this sense. In fact, it should be borne in mind that the total volume of surveyed caves is about 9,000 m^3, i.e. almost 1 % of the total volume of the rock slab. Similar considerations can be made on the significance of the set of excavation plans as non-persistent discontinuities, even if single cases (tunnels and chambers very close to the cliff) can be relevant for the stability of some tuff blocks.

Laser scanner-based survey

Among the results obtained from the TLS survey of the Pitigliano rock mass, the acquired point clouds represent the raw product of laser scanning. Merging all the point clouds in the holistic one (Fig. 4) provides an overall and true colour 3D representation of the natural and built environment; this product contains a large amount of data (about 68 million points and related measurements of spatial coordinates and colour parameters) available for further processing.

Thanks to the high density of the 3D points, a detailed modelling of the rock mass morphology has been performed as basic tool to evaluate the most hazardous mechanisms of instability for both sides of the cliff. The overall view of the rock mass surfaces has been used as an effective tool to verify the sequence and contacts of the outcropping geological strata and their correspondent thicknesses, with precise referencing and spatial relationship with the overlying historical buildings located along the edge.

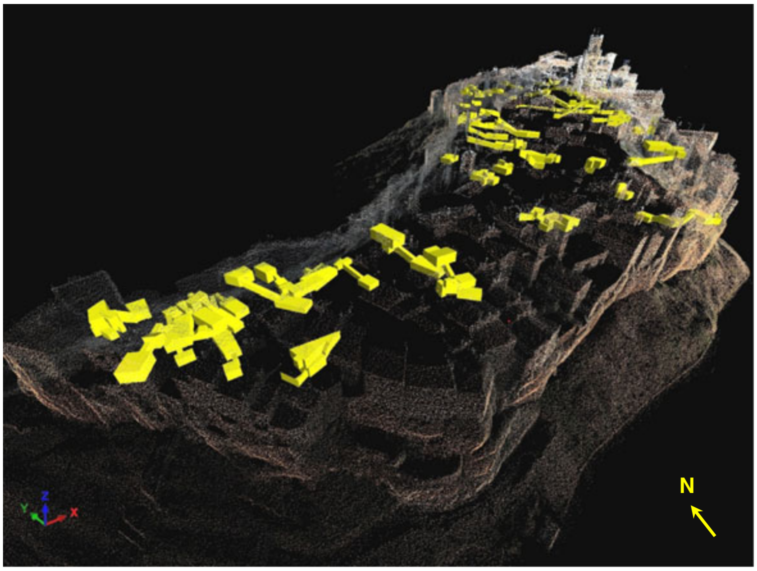
The first outcomes from the laser scanning survey have been an improvement of the geological sketches representing the different sectors of the cliff and the provision of an updated 3D documentation of the present state of the rock mass. The structural relationships between the historic buildings and their rock foundations have also been established and updated at the current state; the sectors more exposed to erosion processes, rock falls and collapses have been identified.

Prior to produce a triangulated mesh necessary for creating a digital terrain model (DTM) of the cliff surfaces from the acquired point clouds, it has been undertaken a pre-processing stage consisting in two main operations:

(a) Removal of the vegetation coverage and
(b) Distinction, within the point clouds, of the rock outcrops respectively from the built environment and the debris at the toe of the cliff.

These segmentation and decimation steps were realized with both automated and manual procedures, also filtering point clouds on the basis of the different intensity of the return signals coming from the scanned materials.

Fig. 6 Decimated point cloud of Pitigliano integrated with the 3D reconstruction of the underground network of the surveyed chambers and corridors



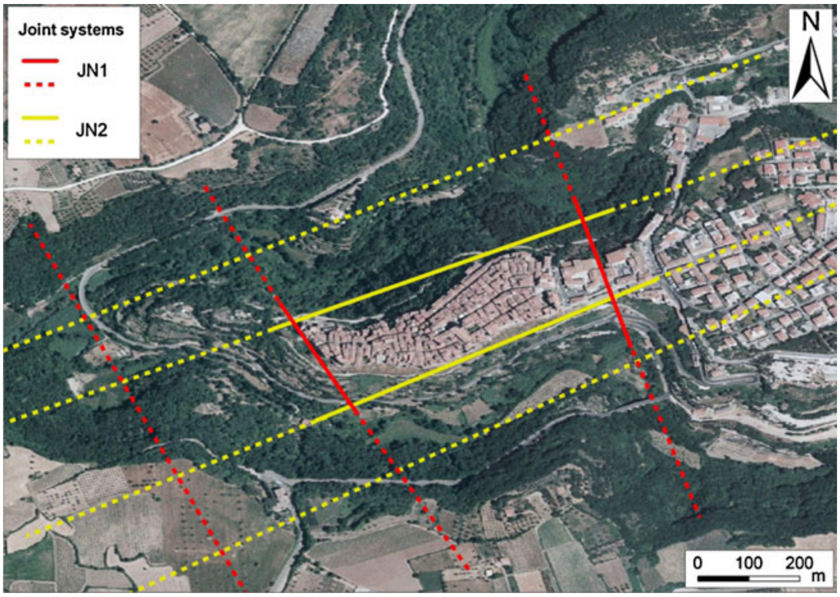


Fig. 7 Synthesis of the structural data and the directions of the two predominant joints sets (JN1 and JN2) overlapped on aerial view of the Pitigliano cliff and surroundings (modified from Google Earth). The joint system geometry (see *continuous lines*) structurally influences the morphology of the Pitigliano cliff

Such time-consuming preparation of point clouds has been justified by the final aim, i.e. the creation of a reliable DTM suitable for the characterization of the rock mass discontinuities. It is quite well known that vegetation and non-geologic points, jointly to registration errors, can contribute to the noise in point clouds and affect automatic meshing procedures (Buckley et al. 2008).

The resulting points extracted on the rock mass outcrop were re-sampled with the aim of obtaining a regular and uniform spatial distribution.

In order to create a continuous surface from discrete data, the sampled point cloud was finally triangulated, taking care to fill holes and to obtain a congruent surface with correctly orientated triangle normals.

After the triangulation procedure, a total of more than 240,000 triangles were obtained and the following parameters were calculated for each of them: dip, dip direction and outwarding normal.

As first processing stage, the cliff has been virtually divided in six sectors, clockwise from the SE limit, and transverse contour lines have been directly extracted from the continuous surfaces of the point clouds, in order to obtain topographic elevation maps allowing morphologic evaluation for each sector in correspondence of the outcrops.

'Contour line models' were realized by coupling a contour line representation with the true coloured point clouds (Fig. 8). By means of the visualization through contour lines, morphologic features of the outcropping surfaces have been highlighted directly on the 3D model, performing an estimation of the elevation values with a centi-decimetre accuracy. Due to the dense vegetation coverage existing at the moment of the TLS survey, the quality of the contour line models for the northern side of the rock mass has not been so high in comparison with the correspondent modelling for the southern side.

As added value of this modelling, such DTMs also represent a suitable archive database for future monitoring campaigns of the temporal evolution of the rock mass morphology. Digital comparisons with new scans can be easily performed. This potential of TLS was taken into account during the selection of the acquisition and registration approach, starting from the localization of the seven point-of-views.

Fig. 8 True coloured point cloud of the southern side of the Pitigliano cliff; *contour line* representation highlights morphologic features of the outcropping rock mass

Analysis

Thanks to the high resolution of the mesh obtained from the laser scanning data, detailed analyses were performed on the whole rock wall with the aim of extracting the discontinuity sets and of identifying those sectors more prone to instability mechanisms.

On the basis of the orientation of each triangle of the mesh, and of the direction of its outwarding normal, the overhanging sectors of the rock mass have been extracted and directly localized on the 3D point cloud. Distribution of dip and dip direction values has been also obtained for all the outcropping surfaces and the visualization on the 3D point cloud clarifies that most of the rock mass surfaces are sub-vertical and overhanging (Fig. 9).

Such analysis has contributed to a first fundamental identification of the hazard levels for the different sectors identified along both sides of the rock slab and constitutes the basis of the 3D kinematic analysis presented in 'Kinematic analysis'.

Identification of the discontinuity sets

A specific Visual Basic software was developed (Lombardi 2007) for the semi-automatic extraction of the main discontinuity sets within a rock mass, by analyzing a mesh representing the rock mass outcrop.

Based on the dip and dip-direction of each triangle of the mesh, the modal planes of the discontinuity sets are extracted through a traditional stereoplot analysis. The spreading of the triangle poles around each modal plane is also evaluated.

All the triangles whose orientation lies within the area of influence of a modal plane are associated to the correspondent discontinuity set. All unassigned triangles are given an 'other' label and can be re-assigned to each discontinuity set in successive iterations if closeness and angular divergence conditions are satisfied.

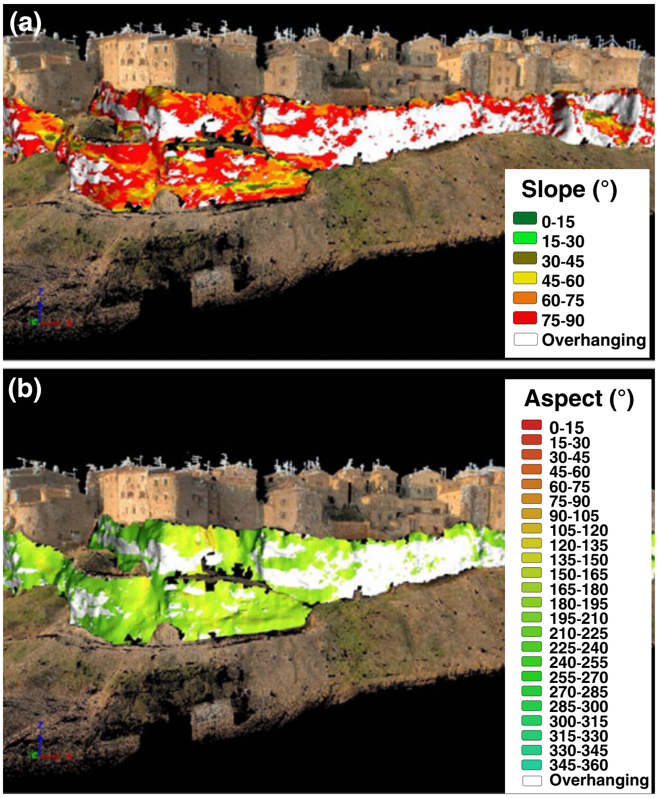


Fig. 9 Point cloud of the southern side of the Pitigliano cliff with the distribution of rock mass dip (**a**) and dip direction values (**b**) calculated and extracted by processing 3D laser scanning data

Figure 10 reports the contour plot of the poles of each triangle constituting the mesh of the southern sector of the cliff. By observing the areas with highest density, two discontinuity sets can be distinguished: JN1 (054/88°) and JN2 (165/88°).

The results of the analysis after three iterations are presented in Fig. 11, where the triangles of the mesh are colored based on the discontinuity set they belong to.

Kinematic analysis

As the orientation of the fractures within the rock mass seems not to be random, but related to the tectonic processes that have been acting in the investigated area, a kinematic analysis can be useful to identify the rock-wall sectors which are more prone to instability processes. These are investigated by combining fracture dip and dip directions with local slope orientations.

The rock plate is, in fact, characterized by very steep slopes, sometimes overhanging and, due to its irregular shape (Fig. 7), by very different slope aspect (Fig. 9).

The main instability mechanisms investigated with this approach are:

- Plane failure (Hoek and Bray 1981);
- Wedge failure (Hoek and Bray 1981);
- Block toppling (Goodman and Bray 1976; Matheson 1983);
- Flexural toppling (Goodman and Bray 1976; Hudson and Harrison 1997).

Casagli and Pini (1993) introduced a Kinematic Hazard Index for each instability mechanism. These values are calculated by counting poles and discontinuities falling in critical areas within the stereographic projection:

$$C_{\mathrm{pf}} = 100 \times \left(N_{\mathrm{pf}}/N\right) \quad \text{for plane failure;}$$

$$C_{\mathrm{wf}} = 100 \times \left(I_{\mathrm{wf}}/I\right) \quad \text{for wedge failure;}$$

$$C_{\mathrm{bt}} = 100 \times \left(N_{\mathrm{bt}}/N\right) \times \left(I_{\mathrm{bt}}/I\right) \quad \text{for block toppling;}$$

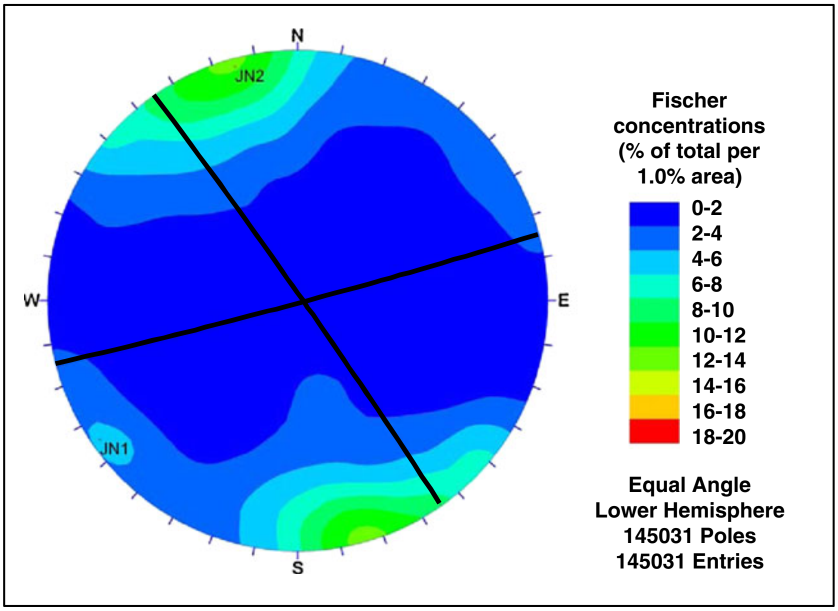
$$C_{\mathrm{ft}} = 100 \times \left(N_{\mathrm{ft}}/N\right) \text{ for flexural toppling,}$$

where

N_{pf}	Number of poles satisfying plane failure conditions
I_{wf}	Number of intersections satisfying wedge failure conditions
N_{bt}	Number of poles satisfying block toppling conditions
I_{bt}	Number of intersections satisfying block toppling conditions
N_{ft}	Number of poles satisfying flexural toppling conditions.

The analysis input parameters are the slope dip and dip direction (Fig. 9), the discontinuity surface orientations (obtained from the field survey and from laser scanning data analysis) and discontinuity friction angle (obtained from the geomechanical survey).

Fig. 10 Stereographic projection of the orientation of the *triangles* constituting the 3D mesh obtained from laser scanning data



Intersection lines are calculated automatically, together with the equivalent friction angle, based on the intersecting planes friction angles and the shape of the wedge (Casagli and Pini 1993).

A new Visual Basic software developed specifically for true 3D kinematic analyses called Rock Slope Stability (RSS) (Lombardi 2007; Gigli et al. 2012) has been applied in the present study. This tool overcomes many limitations of the traditional kinematic analyses, and even of the more advanced analyses performed on 2.5D surfaces. In fact, it is possible to employ the 3D mesh obtained from laser scanning data, and the kinematic conditions leading to the investigated instability mechanisms have been extended to overhanging slopes.

The resulting analysis has therefore a true 3D character, and can be performed on high resolution surfaces, making it possible to distinguish even small details of the investigated area.

The results from this analysis are summarized in Fig. 12, where the kinematic index of the triangles of the mesh is reported for each instability mechanism for a portion of the southern side of the cliff. The probability of occurrence for each mechanism is expressed by means of a colour scale, varying from green to red as the hazard increases. It means that green areas correspond to sectors with very low, up to negligible, hazard with reference to the specific instability mechanism, while orange/red colours mark the sectors highly prone to instability. The maximum values of the kinematic indexes which were calculated range from 25 to 30 %.

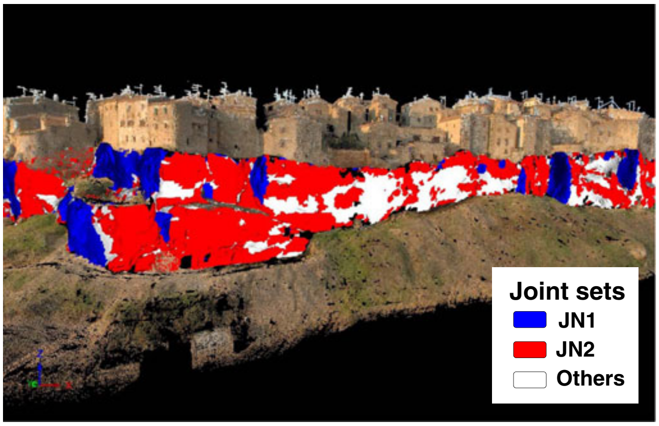


Fig. 11 Point cloud of the southern side of the Pitigliano cliff. The main joint sets are distinguished and localized on the basis of the extraction phase from 3D laser scanning data

In this regard, the highest kinematic index (28 %) is related to the wedge failure (WF; Fig. 12c), with a respective hazard which affects several sectors of the cliff surfaces. The spatial distribution of the WF index confirms that conservation criticalities can be raise both for the tuff blocks located immediately underneath the buildings located along the edge and the lower sectors of the exposed cliff. Consequently, a progressive undermining can destabilize huge portions of the cliff at different heights.

Comparing the spatial distribution of the kinematic indexes for the other instability mechanisms, it is quite evident that block toppling represents a negligible deterioration process (kinematic index up to 2 %; Fig. 12a) while flexural toppling (FT; Fig. 12b) and plane failure (PF; Fig. 12d) reach maximum values, respectively, of 22 and 20 %. In particular, hazard patterns of the FT and PF mechanisms show some similarities in their spatial distribution, with values of kinematic index averagely higher for the FT over the same sectors.

Discussion and conclusions

The usefulness of the proposed procedure mainly consists in remotely having surveyed rock mass discontinuities, especially in correspondence of impervious areas, gathering an overall characterization of the outcropping surfaces and estimating the probability of occurrence of the different instability mechanisms for each sector.

Looking at Fig. 9, we can observe that a considerable portion of the rock wall is overhanging. The analysis of the 3D mesh obtained from the laser scanning data shows that the area of the overhanging sectors is about 33 % of the total area of the rock outcrop.

The advantage of collecting the orientation of rock mass discontinuities by applying different techniques (traditional geomechanical surveys and by analyzing 3D laser scanning data) and from different portions of the rock plate (from chambers inside the rock plate, from

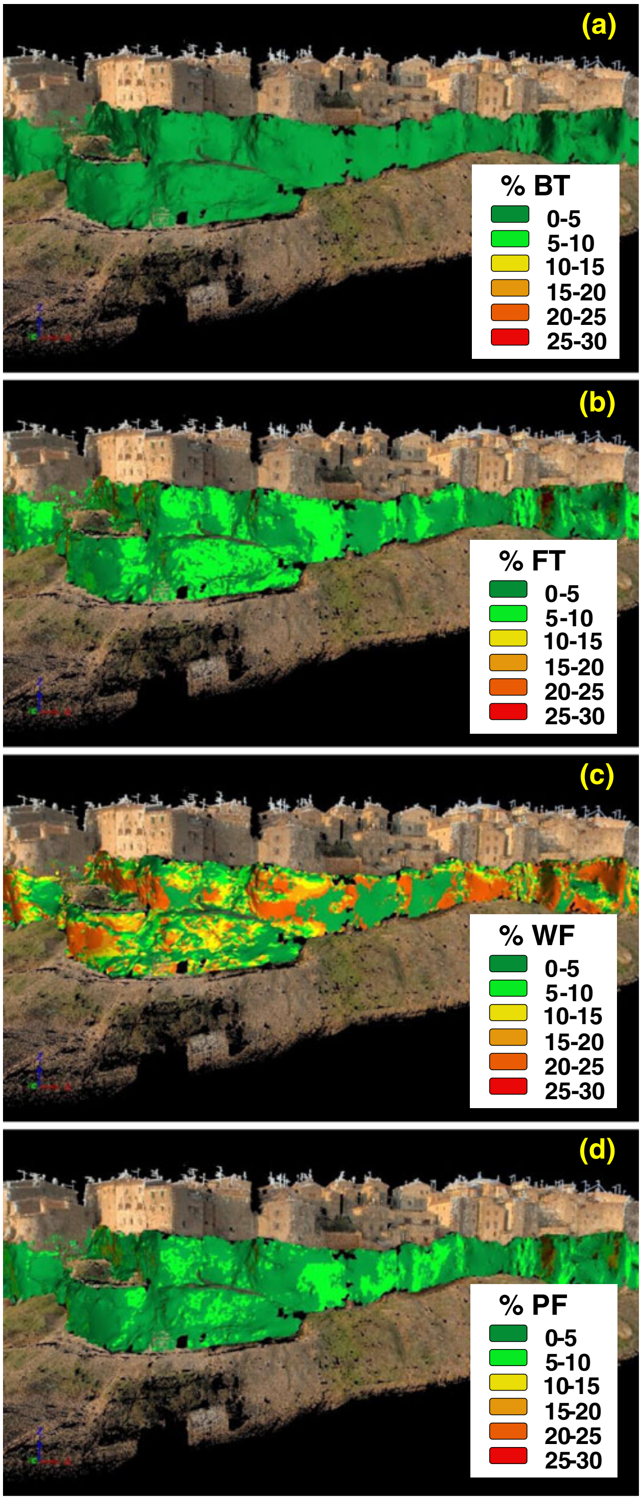


Fig. 12 Results obtained from the 3D kinematic analysis for the different analyzed instability mechanisms in correspondence of the southern side of the cliff: **a** block toppling, **b** flexural toppling, **c** wedge failure, and **d** plane failure. The probability of occurrence (hazard) is expressed following a common colour scale

scanline surveys at the base of the rock walls, and from the whole rock exposure by analyzing 3D laser scanning data) is useful to reduce the bias introduced due to the employed technique (sampling method) and to the direction of analysis. A clear inversion of concentration values and a slight different orientation of JN1 modal plane are evident by comparing Figs. 5 and 10. Such differences can be explained by considering the bias introduced by the traditional geomechanical survey in favour of discontinuity set JN1. In fact, most of the scanline surveys were performed along the southern portion of the cliff, which is almost parallel to the discontinuity set JN2 modal plane (Fig. 7). For the same reason, the analysis of the 3D mesh obtained from laser scanning data tends to overestimate the surfaces belonging to JN2 discontinuity set, as these are parallel to the mean rock slope direction (Fig. 11).

These integrated geomechanical analysis is very useful to reduce some of the uncertainties due to partial data collection and provides reliable data for a complete 3D kinematic analysis.

Thanks to georeferencing of all 3D data, it is possible to identify the most critical sectors directly on 3D mapping products and compare their localization with the correspondent on the cliff surfaces, in order to verify the present conditions at the most critical points.

Classification of hazardous areas based on discontinuity extraction and subsequent processing of 3D laser scanner data should find a fundamental validation in the in situ evidence, such as in the present case. Considering the southern side, several sectors have been classified as prone to wedge failure (Figs. 12c and 13a) and some of them are, hazardously, located directly beneath the buildings of the historic centre situated along the edge of the cliff. In particular, Fig. 13b shows

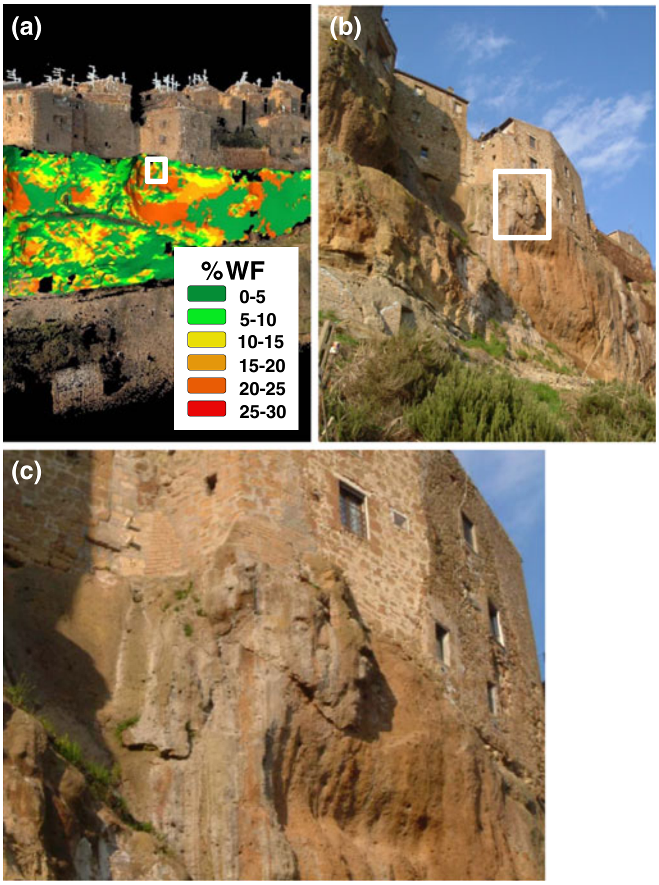


Fig. 13 Example of area on the cliff surface prone to wedge failure (*WF*) as identified on **a** the n mapping of WF instability mechanism (detail of Fig. 12c) and **b** correspondent photograph. **c** Detailed view shows the wedge geometry of the block and recent repair works on the overlying masonry

Fig. 14 Test area selected on the southern side of the Pitigliano cliff. Deformometers were installed to monitor the joint (*dashed line*) which controls the wedge geometry. Spatial relationship with the overlying building suggests probable direct impacts on the preservation of the built heritage

a block located in an area classified at high wedge failure hazard (Fig. 13a). A close view of this block highlights the presence of cracks which undoubtedly define wedge geometry, suggesting a probable future detachment of the block by wedge failure (Fig. 13c).

This example is also interesting in terms of evaluation of the direct impacts on the built heritage due to instability mechanisms. The buildings overlying the block show quite recent repair interventions on the masonry structures, with new construction phases made using blocks of the local tuff (Fig. 13c). Such repairs suggest the occurrence, in the past, of damages and structural collapses, hinted also by the niche located directly east to the block, where a similar detachment plausibly has taken place.

Identifying and localizing the critical points represents the first step in order to plan and realize adequate countermeasures for the preservation of the built heritage of the historic centre of Pitigliano. Permanent monitoring could be one of the best strategies to tackle instability issues, especially when consolidation works cannot be cost-effective and not easily to carry out, as it is frequent in case of historic contexts.

Based on the results of the integrated geomechanical analysis, a test area has been selected on the southern side of the Pitigliano cliff, in correspondence of an area classified as highly prone to the occurrence of wedge failure or flexural toppling, and a monitoring system was installed.

Figure 14 shows the test area where the buildings are built above a tuff block affected by a joint suggesting the presence of a probable plane of failure. Detachment of the block would compromise the stability of the overlying buildings, even causing structural collapses. A further element of instability is here constituted by the presence of the underground cave, whose excavation could have influenced the overall structural setting of the rock mass underneath the buildings. This case clarifies how a geomechanical analysis of instability mechanisms in built-up contexts requires a wider approach which would take into account all different geological and not-geological hazard factors.

In particular, to monitor eventual deformations and displacements along the joint, a 24-h/24 real-time monitoring system has been installed, employing some deformometers with automatic data collection and radio systems to transmit the deformometric data. A local gateway has been positioned in order to receive the data directly from the radios and forward them by GPRS to a remote server, allowing visualization of the data on an easy-to-use website, available for the end-users for constant control activity.

Such monitoring network, specifically adapted for reducing the impact on the buildings and the landscape, has to be considered as a pilot system, potentially extendable to others critical sectors of the Pitigliano cliff or even exportable to other similar contexts.

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